**USE OF CEMENT KILNS IN MANAGING SOLID AND
HAZARDOUS WASTES: IMPLEMENTATION IN
AUSTRALIA**

by

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ABSTRACT

The use of solid and hazardous wastes as supplementary fuel or raw material substitutes in cement kilns is rapidly being accepted worldwide as one of the best technologies for complete and safe destruction of these wastes, while simultaneously recovering their resource values for the use in cement manufacture. High temperatures ($>1500^{\circ}\text{C}$), long gas residence times (up to 10 seconds) and high turbulence in the cement kiln ensure complete destruction of organic constituents in the waste materials. The main benefits in using solid and hazardous wastes in cement kilns include energy recovery, conservation of non-renewable fuels, reduction in cement production costs and the use of existing facilities.

Although the technology of using cement kilns in waste management was first developed in 1975, this technically innovative and environmentally safe technology is not presently implemented to the extent one would expect in many countries including Australia. There is also opposition from environmental groups to implement this technology in Australia. This thesis investigates the key technical, environmental and social issues preventing or delaying the introduction of this technology in Australia and suggests solutions to some of these concerns.

Unburnt wastes in stack gases, emissions of Products of Incomplete Combustion (PICs) such as chlorinated dioxins and furans and the fate of metal constituents in waste materials were identified as three major concerns in using cement kilns to manage solid and hazardous wastes.

The principal source of metals entering a cement kiln was identified as the raw material feed and not the waste derived fuels. The metals such as arsenic, barium, vanadium and zinc are added by coal fuel and the major source of metals cadmium, chromium, lead and nickel was identified as the waste derived fuels.

The metals entering a cement kiln via waste derived fuels or raw material feed were categorised as volatile, semi-volatile and refractory, based on their volatilities. The analysis of data on metal emissions indicated that the emissions of refractory metals

are not increased as a result of an increase in the input of these metals. A moderate correlation was found between the semi-volatile metal emissions and their input. The study found no correlation between the chlorine input and the metal emissions in stack gases.

The comparison of metal emissions with total metal input demonstrated that less than 0.1% of the total input of refractory metals appear in the stack gases indicating that over 99.9% of these metals are retained by the cement kiln. A similar comparison for semi-volatile metals demonstrated that only less than 0.75% of their input appear in the stack gas indicating over 99% retained by the cement kiln. Although, the semi-volatile metals such as lead and cadmium were found to concentrate more on the cement kiln dust than cement clinker, it was found that the use of waste derived fuels is not the determining factor for this distribution. All the refractory metals were found to concentrate in the cement clinker.

The analysis of organic compound emissions indicated that extreme high combustion conditions in a cement kiln combined with high turbulence and long residence times readily overcome any oxygen deficiencies inside the kiln to achieve destruction efficiencies exceeding the 99.99% regulatory requirement and even reaching 99.9999% in many cases.

The emissions of chlorinated dioxins/furans from a cement kiln burning hazardous wastes, under worst case scenarios, were found to be very much lower than the emissions of such compounds from a properly operated commercial waste incinerators. The data on the emissions of dioxins/furans also suggested that if the cement kiln operators can control the kiln exit temperatures below 250°C, then it will be possible to reduce the emissions of these compounds to even lower levels. No correlations were found between dioxin/furan emissions and chlorine input or waste fuel input. However, a strong correlation was found between the dioxin/furan emissions and carbon monoxide emissions suggesting that completeness of combustion has a major influence on the emissions of these compounds.

Investigations into waste generation in Australia indicate that Australia generates about 12.8 million tonnes of solid wastes and about 400,000 tonnes of industrial hazardous wastes annually. Furthermore, over 100,000 tonnes of scheduled wastes are stockpiled around the country. There are 22 cement kilns around Australia burning about a 1 million tonne of coal to produce 5.6 million tonnes of cement each year. The present study found that if the Australian cement kilns could replace 31 % of its thermal energy requirement by hazardous wastes, then it would totally dispose the industrial hazardous wastes generated in Australia annually. Public perception, incomplete waste profiles and lack of regulatory guidelines were identified as the main constraints to implement this technology in Australia.

Public involvement, which comprises public education and public consultation, was identified as the most important task in the implementation of this technology in any country. The present study discusses some of the techniques that can be used for effective public involvement and the role of international conferences to enhance the public education process. It was recommended that the cement plant management should allocate the necessary resources to the public involvement process rather than allocating all the available resources for conducting test burns, as has been done in the past.

DECLARATION OF ORIGINALITY

This thesis presents the original work of the author. This work has never previously been submitted for any previous degree or diploma in any university and that to the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Signed by: Date:

(Sunil Herat)

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LIST OF ABBREVIATIONS

BLA	Baseline Conditions
BTU	British Thermal Units
CKD	Cement Kiln Dust
CO	Carbon Monoxide
cum	cubic metre
DCB	Decachlorobenzene
DRE	Destruction and Removal Efficiency
dscm	dry standard cubic metre
dscf	dry standard cubic foot
ESP	Electrostatic Precipitators
GJ	Gigajoules
g/l	grams per litre
μg	microgram
HCl	Hydrogen Chloride
MCB	Monochlorobenzene
MJ	Megajoules
MSW	Municipal Solid Waste
ND	Not Detected
ng	nanograms
NO _x	Nitrogen Oxides
PAHs	Polynuclear hydrocarbons
PCA	Portland Cement Association
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PICs	Products of Incomplete Combustion
POHCs	Principal Organic Hazardous Constituents
ppb	parts per billion
ppm	parts per million
RCRA	Resource Conservation and Recovery Act
RDF	Refuse Derived Fuel
SO ₂	Sulphur Dioxide

LIST OF ABBREVIATIONS

SPL	Spent Potlinings
TCB	Trichlorobenzene
TCDD	Tetrachlorodibenzodioxin
TDF	Tyre Derived Fuel
TEF	Toxicity Equivalent Factor
THC	Total Hydrocarbons
TOC	Total Organic Carbon
tpd	tonnes per day
tpy	tonnes per year
USEPA	United States Environmental Protection Agency
WBA	Chlorinated Aliphatic Stream
WBB	Chlorinated Aromatic Stream
WBC	Chlorinated Aromatic and PCB Stream
WDF	Waste Derived Fuel
WDLF	Waste Derived Liquid Fuel
W_{in}	Mass Feed Rate of a POHC in Waste Feed
W_{out}	Mass Flow Rate of a POHC in Exhaust Gas

CHAPTER ONE

INTRODUCTION

Safe management of solid and hazardous wastes represents one of the most serious problems faced by many countries around the world today. Ever increasing quantities of these wastes have over-burdened the receiving environment of air, water and land, which cannot handle the increased rate of hazardous waste production resulting from our high standard of living. Even under a scenario of maximum waste reduction, significant amount of these wastes will continue to be generated requiring safe management. Even the approved landfill sites, which need to be considered as merely a temporary storage rather than final disposal, are becoming increasingly difficult to find. Furthermore, due to technical and economic limitations many of the solid and hazardous wastes cannot be recycled. Therefore, there is a urgent demand to develop innovative and advanced technologies to safely manage solid and hazardous wastes.

Incineration is being increasingly considered in many parts of the developed world to be the most appropriate and environmentally safe method of disposal for hazardous wastes. Properly designed and operated incineration systems are capable of achieving very high degree of destruction of hazardous wastes. However, custom designed or built incineration facilities create a new emission source and typically do not recover the resource value of waste materials, thus requiring additional non-renewable fuel to support operation. It will also involve a high capital cost to construct commercially operated waste incinerators.

In contrast to commercial waste incinerators, resource recovery of waste materials through the use of solid and hazardous wastes as supplementary fuel or raw material substitution in an industrial furnace such as a cement kiln is one of the best technologies for completely and safely destroying these wastes. Compared to conventional incinerators, high temperatures ($>1500^{\circ}\text{C}$), high gas

retention times (up to 10 seconds) and high turbulence in the cement kiln ensure complete destruction of the organic constituents in the waste materials without any adverse effects to the environment. Further, compared to the high capital cost involved in construction of a conventional incinerator, the modification of a cement kiln to accept wastes as fuel or raw materials requires a relatively small capital expenditure. The costs involved in the modification and operation of a cement kiln to accommodate waste materials can readily be recovered from the savings made from substituting expensive fossil fuel with cheap waste fuels.

The technology of using solid and hazardous wastes in cement kilns was first developed in Canada in 1975 when a Canadian cement kiln successfully destroyed polychlorinated biphenyls (PCBs), which are considered to be one of the most stable and difficult to destroy organic compounds. Since then, several cement kilns in the United States and Europe have experimented with this technology and are successfully burning solid and hazardous wastes to achieve significant economic advantages. However, this technically innovative and environmentally safe technology is not presently implemented to the extent one would expect in many countries including Australia. Further, there is mounting pressure from the environmental groups to avoid this fundamentally sound technology claiming it as environmentally unsafe. Therefore, the main theme of this thesis is to investigate the key technical, environmental and social issues that prevent or delay the introduction of this technology in Australia and to address them with real scientific facts and data.

The main objectives of the thesis are as follows:

- * A detailed study into the technology of using cement kilns in waste management

- * Investigate and address technical, environmental and social concerns of using cement kilns in waste management with special emphasis on the use of hazardous wastes as supplementary fuel.
- * Assess the opportunities currently available in Australia to manage wastes in cement kilns.
- * Investigate and address the aspects of implementing the technology of using wastes in cement kilns in Australia.

The detailed contents of this thesis are as follows:

- * Chapter 1 describes the research topic and its background, objectives of the thesis, contents of the thesis and the implications of the study.
- * Chapter 2 of the thesis describes the state-of-the-art-review of using cement kilns in waste management. This chapter overviews the cement manufacturing process, the technology of managing wastes in cement kilns and describes the test burns conducted in cement kilns to date. The chapter concludes with a description of present experiences and practices in managing wastes in cement kilns.
- * Chapter 3 identifies the technical, environmental and social concerns in managing wastes in cement kilns. This chapter includes concerns expressed by major environmental groups and individual critics of using cement kilns in waste management.
- * Chapter 4 of the thesis addresses most of the environmental concerns described in the above chapter. Emphasis is given in this chapter to the fate of metal bearing wastes when used as supplementary fuel and the

destruction of organics in the waste materials and the emissions of products of incomplete combustion. The behaviour of metals within the cement kiln system is studied in detail and important relationships derived between the input and the emissions of metals. The emissions of dioxins and furans during combustion of chlorinated wastes are studied in detail with important correlations derived between these emissions and other dependent variables.

- * Chapter 5 assesses the social concerns described in Chapter 3 with special emphasis on the potential effects to human health due to managing wastes in cement kilns. The public involvement is described in this chapter as one of the most critical aspects of the implementation of this technology. Useful techniques are described to facilitate public education and public consultation.
- * Chapter 6 describes the aspects of implementing this technology in Australia. This chapter describes the present solid and hazardous waste situation and the present structure of cement industry in Australia. The regional distribution of the availability of industrial hazardous wastes and its relationship to the cement kiln capacities available in Australia is studied in detail. The chapter concludes with the identification and assessment of major constraints in implementing this technology in Australia.
- * Chapter 7 of the thesis describes an experiment conducted in a local cement kiln to use waste materials as raw material substitutes in cement manufacture. This chapter confirms that waste materials can not only be used as supplementary fuels in cement kilns but also can be used as raw material substitutes.

- * Chapter 8 describes the conclusions from the above research.

The findings of this thesis will have significant implications for the present knowledge and the attitude towards implementing this technology by the cement industry, environmental groups, government departments and the general public in Australia. Any strategy to implement this technology in Australia should look beyond conducting test burns and should include public education and public consultation from the inception of the project. The findings of this thesis will greatly assist achieving these goals.

CHAPTER 2

STATE-OF-THE-ART-REVIEW

2.1 INTRODUCTION

This chapter describes the state-of-the-art-review of using cement kilns in managing solid and hazardous wastes. It discusses the cement manufacturing process, the technology of managing wastes in cement kilns and describes the studies conducted in cement kilns to date. The chapter also discusses the aspects of implementing a waste program for a cement kiln and finally reports on the present experience and practice in managing solid and hazardous wastes in cement kilns.

2.2 CEMENT KILN TECHNOLOGY

This section of the thesis introduces the cement kiln technology by describing the raw materials used for the manufacture of cement, the process of cement manufacture and the different types of kilns used in the industry.

2.2.1 Raw Materials Used for Cement Production

The principal chemical components required for the production of cement are calcium, silicon, aluminium and iron. Calcium is provided by limestone, which is usually quarried near the cement plant site. Silicon and aluminium are provided by an appropriate mixture of clay, shale or sand. Iron is provided by iron ore or steel mill scale. These raw materials contain approximately 75% calcium carbonate, 15% silicon dioxide, 3% aluminium oxide, 2% ferric oxide and 5% other minerals (Portland Cement Association, 1992). Since raw materials for cement production usually come from earth's crust they contain variety of metals, halogens and some organic compounds (Garg, 1990).

2.2.2 Cement Production Process

The production of cement usually consists of following major steps:

- a) acquisition and transportation of raw materials
- b) preparation of raw materials
- c) pyroprocessing (high temperature reacting) of raw materials to form cement clinker
- d) grinding clinker into cement

Figure 2.1 illustrates a typical base flow diagram of the cement production process. The raw materials are selected, crushed, ground and proportioned so that the resulting mixture has the desired fineness and chemical composition for the pyroprocessing system. The pyroprocessing takes place in a cylindrical rotary kiln which is an elongated steel cylinder ranging in size up to 250m in length and 8m in diameter lined with refractory brick and inclined at an angle 3-6 degrees. The kiln rotates at about 70 revolutions per hour in older generation plants and about 180 revolutions per hour in newer plants. The raw material feed is introduced at the elevated end and is moved slowly by the rotation of the kiln down towards the firing end where heat is applied with a coal, gas or oil flame.

There are three distinct thermal zones within an operating cement kiln, as described below.

- a) drying and preheating zone
- b) calcining zone
- c) burning zone (clinkering zone)

The material in the drying and preheating zone reaches a temperature of about 800°C. In this zone, all water in the feed is evaporated. The preheating zone is followed by the calcining zone where carbon dioxide is driven off from the

Figure 2.1 BASIC FLOW DIAGRAM OF THE PORTLAND CEMENT MANUFACTURING PROCESS

limestone material, thus forming calcium oxide. The feed temperatures in this zone reach 1000°C. Following calcination is the burning or clinkering zone where, at a temperature of 1450°C, the chemical reactions leading to the formation of clinker occurs. The clinker contains following complex compounds:

- a) Tricalcium silicate ($3\text{CaO}.\text{SiO}_2$)
- b) Dicalcium silicate ($2\text{CaO}.\text{SiO}_2$)
- c) Tricalcium aluminate ($3\text{CaO}.\text{Al}_2\text{O}_3$)
- d) Tricalcium alumino ferrite ($4\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3$)

The material, in a semi-liquid state at this stage, when cooled in the clinker cooler, is referred to as cement clinker. The clinker is then finely ground with addition of about 5% gypsum (calcium sulphate) to give the final cement product.

During the cement manufacturing process, it is essential that the temperature in the feed material reaches 1400°C in order to form the clinker. To achieve this clinkering temperature, combustion gas temperature in the burning zone of the kiln must generally exceed 1650°C. In addition, combustion gas residence time in the burning zone of the kiln ranges from 2-5 seconds depending on the size of the kiln and the overall gas residence times during the process can reach 10 seconds.

Cement kilns operate in a counter current manner. The combustion gases and waste dust flow counter to the material, exiting at the elevated end of the kiln. Exhaust gases consist primarily of nitrogen, carbon dioxide, water, sulphur and nitrogen oxides together with the fine particles of the feed and clinker material. These particles are entrained in the gases flowing through the kiln and are removed by electrostatic precipitators or baghouse filters fitted in the kiln and returned back to the kiln as feed material, disposed on-site in a landfill or sold as a cement by-product for other industrial uses. The alkaline nature of the feed material in the kiln acts as a trap for sulphur dioxide. Thus, after passing through the pollution

control devices, the combustible gases primarily contain carbon dioxide and water vapour and are discharged to the atmosphere through a stack.

2.2.3 Types of Cement Production Processes

The principal processes employed in cement production can be broadly classified into:

- Wet-Process Kilns
- Semidry Kilns
- Dry Kilns
- Preheater Kilns
- Preheater/Precalciner Kilns

2.2.3.1 Wet Process Cement Kilns

In wet process cement kilns material feed is prepared in the form of a slurry containing 30-40% water (Portland Cement Association, 1992). The raw materials are interground with water to produce the slurry, which can be blended in tanks to produce a chemically uniform kiln feed. The kiln slurry is pumped into the elevated end of the kiln. The counter current flow of slurry and hot gases evaporates water from the slurry to form a dry powder. A typical wet process kiln is shown in Fig.2.2.

Wet process kilns typically use steel chains hung inside the kiln near the feed end to improve heat transfer from the hot gases to the slurry. In this section water and volatile compounds present in the slurry are evaporated and the materials that are volatilised in the burning zone tend to condense in the chain section. The dust, which is entrained in the exhaust gas from the kiln, is conveyed to air pollution control devices. A portion of the dust is returned back as kiln feed in the wet process kilns. The wet process kilns require additional fuel to evaporate the water

from slurry. The amount of energy required to produce cement by the wet process system is approximately 5.5 GJ/tonne of clinker produced (Nisbet, 1990).

2.2.3.2 Semidry Cement Kilns

The most commonly used group of rotary kilns under this category is widely known as the 'Grate Process Kiln' or 'Lepol Kiln'. In this process, pulverized dry-kiln feed is first pelletized into small nodules by means of 10-15% water addition (Peray, 1986), then the nodules are fed onto a travelling grate where they are partly calcined before entering the kiln. Because the kiln feed is already partly calcined before it enters the kiln, the kiln itself is shorter in length than a wet process kiln.

2.2.3.3 Dry Process Cement Kilns

In the dry process, the material feed enters the kiln in a dry powdered form. An efficient dry process kiln will only consume 60% of the energy required to produce a tonne of clinker using a wet process kiln (Portland Cement Association, 1992). The dry process cement kilns are further classified into three main types as below:

- a) long dry process kiln
- b) preheater dry process kiln
- c) preheater/precalciner dry process kiln

The simplest and oldest of the dry process kilns is the long dry process kiln. This resembles the wet process kiln utilizing a very long kiln length and a chain section at the feed end.

The preheater cement kilns consist of one or more cyclone type preheater vessels arranged vertically and supported by a structure known as the preheater tower. In the preheater section, the dry feed is preheated and partially calcined by the kiln's

hot gases prior to entering the actual kiln. A typical four stage preheater dry process cement kiln is shown in Fig.2.3. The general flow of the raw materials and kiln gases in the preheater section is shown in Fig.2.4.

The preheater/precalciner dry process kiln is a further development of the preheater kiln described above. These kilns are similar to the preheater kiln except that a secondary firing device, called precalciner, is added to the lower stage of the preheater section where further calcining occurs. Approximately 30-60% of the kiln fuel may be burnt in the precalciner to release upto 95% of the carbon dioxide in the raw materials prior to introduction to the kiln (Portland Cement Association, 1992). Thus, the majority of the material that enters the kiln is completely calcined. A typical dry process preheater/precalciner cement kiln is shown in Fig.2.5. A general configuration of the preheater/precalciner section of the kiln is shown in Fig. 2.6.

The typical energy requirement for a dry process cement kiln is 3.5-4.0 GJ/tonne of clinker (Nisbet, 1990).

2.2.3.4. The Alkali By-Pass

In a modern preheater/precalciner kiln systems all of the captured cement kiln dust is returned back to the feed. This closed loop necessitates a system for removing volatilized alkali chlorides and sulphates to prevent condensation of such compounds in the preheater section which can result in operational problems. The alkali by-pass is used for this purpose which is located between the feed end of the rotary kiln and the preheater tower (see Figs.2.4 & 2.6). The alkali by-pass system withdraws a portion of the kiln exit gas stream prior to condensation of volatilized material onto the surface of the feed. This portion of the gas is then quenched using ambient air and water sprays and followed by the removal of entrained particles using a separate electrostatic precipitator.

Preheater kilns equipped with by-pass systems can tolerate higher levels of sodium, potassium, sulphates and chlorides in the feed and fuel system. However, there is an energy penalty associated with the operation of the alkali by-pass. The systems without the by-pass system severely limit the input of above materials (Portland Cement Association, 1992).

2.3 TECHNOLOGY OF MANAGING WASTES IN CEMENT KILNS

The cement industry is an energy intensive industry as very high temperatures are required in order for the proper chemical reactions to occur in the kiln. The energy sources used by the cement industry includes coal, petroleum coke, fuel oil and natural gas and also a wide range of materials having a calorific value such as used oils, waste tyres and organic solvents. The use of secondary fuels reduces the industry's consumption of primary fossil fuels and, therefore, contributes to the principles of energy saving and sustainable development. This section of the thesis summarizes the characteristics of a cement kiln associated with solid and hazardous waste management, the benefits of managing wastes in cement kilns and describes the types of solid and hazardous wastes suitable to the cement industry. This section also discusses the plant modifications required to manage wastes in cement kilns and the economics associated with it.

2.3.1 Characteristics of a Cement Kiln

The characteristics of a cement kiln that makes it an appropriate device for managing solid and hazardous wastes can be summarized as follows:

a) High Temperature and Long Residence Times

Combustion gas temperatures and residence times in cement kilns are much greater than those generally available in commercial incinerators. To produce the cement clinker, the material inside the kiln must reach a temperature of 1500°C while the

combustion gas temperatures reach 2000°C. Figs 2.7 & 2.8 illustrates typical gas/materials temperature distributions for a wet process kiln and a preheater/precalciner dry process kiln respectively. These sustaining high combustion gas temperatures and long gas residence times (6-10 seconds) combined with intense turbulence inside the kiln ensure efficient destruction of even the most stable organic compounds. It is generally recognised that all organic compounds are adequately destroyed if exposed to a temperature of 1200°C for a residence time of 2 seconds under oxidising conditions. The conditions in the burning zone of the cement kiln exceed these requirements by a wide margin.

b) High Thermal Capacity

The large size and amount of heated material in the cement kiln ensures that significant temperature oscillations in kiln temperature are not possible. Thus, in the case of an emergency shutdown due to operational problems, the flow of any organic waste can be halted before the temperatures fall below critical values.

c) Alkaline Environment

The contents inside the kiln are alkaline. Therefore, virtually all of the chlorine entering the kiln and hydrogen chloride formed during the combustion of chlorinated wastes are neutralized to form calcium chloride, sodium chloride and potassium chloride, relatively non-toxic compounds. Thus, emissions of hydrogen chloride are significantly lower than emissions from commercial incinerators. Most of the sulphur oxides are similarly trapped as calcium sulphate.

d) Minimum Amount of Waste generated

The combustion of wastes in commercial incinerators generates ash which needs to be disposed of. In contrast there is no ash equivalent in the cement production process. The only by-product of the process is cement kiln dust, which is recycled back to the kiln or recycled in other processes. Any incombustible material such as metals in the waste becomes incorporated in the cement clinker.

2.3.2 Benefits of Managing Wastes in Cement Kilns

The benefits associated with the management of solid and hazardous wastes in cement kilns can be summarized as follows:

a) Energy Recovery

Burning solid and hazardous waste as supplementary fuel allow for the recovery of significant amounts of energy from these waste materials. This source of energy is one of the primary reasons for the cement industry's interest in burning solid and hazardous wastes as fuel.

b) Conservation of Non Renewable Resources

One of the most significant advantages of using solid and hazardous wastes as a supplemental fuel in the cement kiln is the conservation of non renewable fossil fuels such as coal, gas and oil. It is possible to replace between 25-50% of the energy supplied by coal by using hazardous wastes as fuel. For example, if only 25% of the energy used in the production of cement in the United States were replaced by hazardous waste, then 3.8 million tonnes of domestic coal or 14.4 million barrels of domestic crude oil could be saved each year (Mantus, 1992).

c) Reduction in Cement Production Costs

The production of cement is an energy intensive process. The energy costs generally account for about 40% of the cost of clinker production. Thus, by using the cheaper hazardous waste as a fuel, the industry can significantly reduce their manufacturing costs. The waste fuels typically have a heat value of 24 GJ/tonne which is somewhat less than coal but are available at a fraction of the cost (Canadian Portland Cement Association, 1989).

d) Facilities Already Exist

One of the key advantages of using cement kilns is that the technology and facilities are already in place. Thus, there will be a significant reduction of capital

expenditures required to site new disposal centres. A small capital investment of upto \$5-10 million is required to adapt a cement kiln to manage solid and hazardous wastes whereas building a new incinerator facility could cost around \$50 million (Baxendale, 1990). In addition, use of a cement kiln, as opposed to the construction of a new facility, does not result in the creation of a new source of emissions. Therefore, cement kilns provide an attractive option for the burning of large volumes of wastes.

e) Reduction in Waste Transportation Costs

The use of cement kilns to manage solid and hazardous wastes reduces the amount of waste transportation and transportation costs by having many cement plants sites close to waste generators rather than one central facility.

2.3.3 Types of Wastes Most Suitable for Cement Kilns

Cements kilns offer excellent alternatives for the management of a wide variety of energy bearing solid and hazardous wastes. There are three main areas in the cement manufacturing process where an opportunity exists for the utilization of such wastes as described below:

Kiln Burning Stage

Raw Materials Stage

Clinker Grinding Stage

In the kiln burning stage most of the energy bearing solid and hazardous wastes can be managed as supplementary fuels. At present a variety of waste fuels, both hazardous and non-hazardous are being utilized in cement kilns. In the raw material stage, a variety of waste materials can be combined to produce the correct chemical composition for raw material feed. Finally in the cement grinding stage, gypsum can be replaced with some suitable waste materials. This section of the thesis lists some

of the wastes suitable for the use in cement manufacture either as supplementary fuels or raw material substitutions.

2.3.3.1 Liquid Waste Fuels

Paint thinners, degreasing solvents, solvent washes from ink and printing industries, chemical by-products from pharmaceutical and chemical manufacturing, waste oils and other flammable, readily pumpable waste materials can be used to prepare high quality liquid waste fuels for cement kilns (Chadbourne and Freeman, 1988). Furthermore, metal cleaning fluids such as metal working and machining lubricants, coolants and cutting liquids and cleaning solvents from automotive aftermarket operations such as automobile shops, paint shops and service stations and liquid petroleum and petrochemical wastes can also be used as liquid waste fuels in the cement industry (Gabbard and Gossman, 1990 and Gossman, 1992).

Acid tar produced by several industries which use concentrated sulphuric acid for the treatment of hydrocarbon materials is also considered to be a useful waste fuel for the cement industry (Milne et al., 1986). The other types of liquid waste fuels used by the cement industry include pesticides and insecticides (Marcil, 1990 and Huden, 1989), PCBs and PCB contaminated solvents and coal tars (Mournighan, 1992).

2.3.3.2 Solid Waste Fuels

Municipal solid waste or its separated energetic fraction, commonly known as refuse derived fuel (RDF) have been used in cement industry since early 1970s (Neumann et al., 1990). Depending on the chlorine content of the waste up to 30% of the total fuel consumption may be covered by RDF (Neumann, 1992).

The use of waste tyres as supplementary fuel in cement manufacture is one of most common fuel substitutes used in the industry. Carbon and oxygen amounts to 88%

of a tyre, which accounts for its rapid combustion and relatively high heating value (Blumenthal, 1992). Tyres contain approximately 34900 kJ/kg and compares favourably to coal which, on the average, contain some 27900 kJ/kg. Subsequently, when substituting waste tyres for coal it is possible to reduce coal by 1.25 kg for every kilogram of tyres (Serumgard and Blumenthal, 1992).

Cement kilns also offer the following advantages for the disposal of sewage sludge (Obrist and Lang, 1987):

- * Elimination of heavy metals in sewage sludge.
- * Making use of organic matter in sewage sludge as fuel.
- * Making use of inorganic matter in sewage sludge as raw materials.
- * Complete destruction of organic pollutants in sewage sludge.

The only reservation in using cement kilns for burning sewage sludge is mercury contamination in the sludge, which in the long term may be all emitted to atmosphere. However, the situation is same even if the sludge is utilized in agriculture.

Another type of solid waste receiving attention by the cement industry is spent potlinings from aluminium industry. Spent potliner is a layer of carbon situated between the molten metal and refractory material inside the steel shell of an aluminium reduction cell. Generally the useful life of potliner is 3-7 years and the removal of spent potliner (SPL) is a lasting process. One of the advantages of using SPL in cement kilns is that the fluoride content of the SPL may speed up the clinkering reaction, resulting in lower operating temperatures. However, cement produced by some facilities using SPL have exhibited a relatively high alkali content due to sodium in SPL (Spiegel and Pelis, 1990). The process of incinerating SPL by fluidized bed combustion and offering the ash to cement industry is reported to be very attractive (Tabery and Dangtran, 1990).

A number of cement plants are testing and/or constructing pyrolysis systems to allow organically contaminated soils to be recycled for both fuel value as well as the silicon and aluminium present in most soils (Gabbard and Gossman, 1990). There is an increasing volume of soils being generated from underground storage tanks removal and industrial sites that are contaminated by petroleum products. From the accepted methods of treating the contaminated soils, thermal desorption or incineration appear to be the most suitable options, although these options are costly. The cement kiln offers an economic alternative to thermal desorption in incineration plants (Ferdo and Hawks, 1992). Furthermore, cement kilns with its large capacity are capable of handling large tonnages of soils contaminated either by organic or inorganic contaminants. However, this option has only been used to a limited extent due to public perception and industry concerns (Parker, 1987).

In addition to the above mentioned solid waste fuels there are number of other types which are presently used in the industry. These include coal wastes, low grade lignite, charcoal fines, powdered graphite dust from electrode production, petroleum coke and battery casings (Huhta, 1986). Furthermore, wood chips and saw dust, rice hulls and coconut shells are also used to some extent (Huhta, 1985).

2.3.3.3 Gas Waste Fuels

The cement kilns are also capable of using waste gases to supplement the fuel requirements. The primary waste gas considered for fuel substitution is landfill gas. In the landfill the organic components of the municipal solid waste decomposes producing landfill gas which contains mainly methane and carbon dioxide. The methane content of this gas can be between 40-70% with the possibility of increasing upto 90% by gas separation systems. If the landfill is adjacent to the cement kiln this gas can be utilized easily as a fuel (Neumann et al., 1990).

2.3.3.4 Solid Wastes as Raw Material Substitutes

One of the main growing trends to use cement kilns to properly and safely manage wastes which is not related to fuel substitution is the raw material substitution. By substituting original raw materials with waste materials it is possible conserve the raw materials as well as reduce the expensive mining operation costs. Some sources of raw material substitution that have been demonstrated to be effective in cement making include fly ash from utilities/power plants, petroleum contaminated soils, sludge waste from paper mills, mill scale from steel production and foundry sand (Dawson, 1992). The other types of waste materials that can be used for raw material substitution include aluminium processing residues, contaminated soils, glass and ceramic residues, lime sludges, slags (Zimmerman and Coles, 1992 and Mullick and Ahluwalia, 1992). Roasted pyrites, a residue in the production of sulphuric acid, is also used in the raw meal to supplement iron content (Ahling, 1987).

In addition to the solid wastes mentioned above for raw material substitution, large quantities of aqueous hazardous waste are currently being managed through deep well injection. Many of these wastes can be effectively managed in wet process cement kilns by substituting a percentage of water used for slurry making (Chadbourne and Freeman, 1988).

2.3.3.5 Undesirable Wastes for Cement Kilns

For the solid and hazardous wastes to serve as suitable candidates for supplementary fuel combustibility and energy content are very much critical. The recent regulations require the waste fuel to have an energy content of 5000 BTU/lb (11635 kJ/kg) or above (Peters et al., 1986). The cement kilns also consider highly corrosive, reactive or toxic wastes as undesirable unless they are combustible with a significant energy content (Mantus, 1992).

Although cement kilns can accommodate a wide variety of waste materials, some wastes are poor candidates for burning in cement kilns due to process constraints and public opinion. As metals are not destroyed in the incineration process, wastes containing significant amounts of metallic constituents such as lead, arsenic, cadmium, mercury and chromium are not suitable for cement kilns. Therefore, it is normal for the industry to set maximum acceptable standards for these metals. The typical allowable levels are shown in Table 2.1.

TABLE 2.1 RANGE OF ACCEPTABLE WASTE FEEDS FOR CEMENT KILNS
(Peters et al., 1986; Vogel et al., 1987)

PARAMETER	ACCEPTABLE RANGE
Heating Value	> 23 MJ/kg (10,000 BTU/lb)
Sulphur (%)	1-3
Ash (%)	5-12
Water (%)	1-10
Chlorine (%)	3-10
pH Value	4-11
Lead (mg/kg)	< 4000
Chromium (mg/kg)	1500-3000
Zinc (mg/kg)	1000-3000
Barium (mg/kg)	< 3000
Titanium (mg/kg)	< 6000
Mercury (mg/kg)	< 10
Arsenic (mg/kg)	< 10

Sensitivity and low tolerance of the cement process to the element chlorine is well documented in the studies undertaken during test burns. Most cement kilns limit the chlorine content of the waste feed to less than 10% by weight (Mournighan, 1992). Polychlorinated biphenyls (PCBs), organic pesticides and insecticides are considered to be undesirable for incineration in cement kilns due to considerations other than technical. Although it has been clearly demonstrated that the cement kilns can effectively and safely destroy these compounds, public furore and political maneuvering always seems to surround any attempt to burn PCBs in cement kilns. The only location that has burnt PCBs over an extended period (St. Lawrence Cement, Mississauga, Ontario, Canada) has discontinued this operation since 1977 due to public opposition (Black and Swanson, 1983). This is very unfortunate considering the enormous potential of the cement kiln to destroy these wastes in an environmentally safe manner.

2.3.4 Plant Modifications Required to Manage Wastes

The modifications required in the cement kilns to manage solid and hazardous wastes include the following (Beers, 1987):

- * Installation of laboratory facilities to characterize the wastes
- * Construction of waste receiving, storage, and handling equipment.
- * Modification of kiln's fuel injection system.

Installation of sophisticated analytical laboratory facilities is essential in order to assure that prospective waste fuels meet parameters specified in the operating permit of the facility. This will eliminate the use of wastes with low heating values and wastes having significant amounts of metals and halogens.

The major plant modification required to burn intractable wastes is the construction of waste receiving, storage and handling areas. Standards required for this construction are similar to that specified for industries handling flammable or intractable materials.

A piping system to pump wastes from the storage area and an injection nozzle that atomizes the waste fuel must be installed as a modification of kiln's fuel injection system. As wastes are not used as supplementary fuel during kiln start-up or shut-down, the waste fuel injection system should function independently of the primary fuel system.

2.3.4.1 Introduction of Wastes to Cement Kilns

The different types of cement kilns described in the section 2.2.3 have unique process conditions that are best suited for the utilization of certain waste streams. The long wet and long dry kilns can accept both hazardous and non-hazardous fuel substitutes fired through burners penetrating the firing hood along with the conventional fuels. With some modifications to the kiln shell at the mid-kiln zone, hazardous and non-hazardous fuel and raw material substitutes can be added to approximate the results obtained in precalciner kilns. The preheater kilns can accept hazardous and non-hazardous fuel substitutes fired through the burners along with conventional fuels. These kilns are also capable of accepting wastes at the interface of the preheater and the rotary kiln. The preheater kilns can also absorb large amounts of heat bearing wastes in place of conventional fuels that would be fired in the precalciner chamber (Cemtech, 1990).

2.3.5 Economics of Managing Wastes in Cement Kilns

The economics of burning solid and hazardous wastes in cement kilns depends on four factors (Beers, 1987):

- * Availability of waste fuels
- * Income to the facility for accepting wastes
- * Monetary value of energy savings realised by facility
- * Capital and operational costs of implementing this technology

Hazelwood et al., (1982) have conducted an economic study for a model cement kiln assuming the following conditions:

Kiln production	- 220,000 Mg/year
Fossil fuel cost	- \$2.46/GJ
Waste fuel chlorine content	- 0.6% of clinker
Waste fuel heating value	- 23,000 KJ/kg
Investment + 15% return	- \$15,000/year

Assuming a waste fuel containing 10% by weight chlorine is used, and 90% of the waste fuel's heating value can be recovered, at 17.8% kiln fuel replacement, it was found that a net saving of \$1.37/Mg of cement was obtained if the firm paid \$1/GJ of waste fuel supplied. Thus, a cement kiln could save about \$300,000/kiln in fuel costs per year by burning a 23,000 KJ/kg waste fuel at about 18% fuel replacement, even after paying \$1/GJ for waste fuel.

More detailed examples of capital and operational costs and economic benefits of managing solid and hazardous in cement kilns are discussed in section 2.6 under operational experiences and present practice.

2.4 DESCRIPTION OF STUDIES CONDUCTED IN CEMENT KILNS

The waste materials used by the cement industry contain organic materials as well as various amounts of metal components. In order to determine whether the cement kilns can manage these wastes effectively without any adverse effects, specially to the environment, the fate of both organic and metal constituents must be determined. This task is achieved by conducting a study, commonly known as a test burn, in a cement kiln with various operating conditions and different types of wastes. This section of the thesis describes the reported test burns conducted in cement kilns up to date and examines the fate of organic and metal compounds and other emission parameters.

2.4.1 Overview of Test Burns

The main objective of the test burn is to demonstrate compliance with the performance requirements usually decided by state or national regulatory authorities in the country. This basically involves defining some Principal Organic Hazardous Constituents (POHCs) in the waste stream to be used as supplemental fuel and sampling and analysis of waste feeds to determine the input rate of each POHC, followed by the sampling and analysis of stack effluent to determine the POHC emission rate. From the input and emission rates, the destruction and removal efficiency (DRE) for that particular POHC is determined. Furthermore, the stack effluent is sampled and analysed to determine fate of metals and other pollutants. Therefore, the goals of the test burn can be summarized as follows (Mournighan, 1989):

- * Determine DREs for selected POHCs in waste stream
- * Compare baseline operation (no waste fuel burnt) to the operation with waste fuel

- * Determine what products of incomplete combustion (PICs) are formed
- * Examine the fate and distribution of metals
- * Examine the effect of waste burning on hydrogen chloride emissions and determine the fate and distribution of chlorine
- * Examine the effects of waste fuel burning and process conditions on other pollutants such as particulate matter, nitrogen oxides, sulphur dioxide and total hydrocarbons

A summary of test burns conducted in cement kilns to date and reported in the literature is given in Table 2.2.

TABLE 2.2 SUMMARY OF TEST BURNS

CEMENT PLANT	YEAR	TYPES OF WASTE	REFERENCE
St. Lawrence, Canada	1974	Waste oil	Berry et al., 1975
Blue Circle Cement, UK	1974	Municipal solid waste	Hayley, 1983 & 1985
St. Lawrence, Canada	1975	Chlorinated organics	MacDonald et al., 1977
Peerless Cement, MI, USA	1976	PCB waste	Swanson Environ., 1976
Stora Vika Cement, Sweden	1978	Chlor. organics, PCBs	Ahling, 1978 & 1979
Lehigh Portland, USA	1979	Refuse derived fuel	Willey & Weiberger, 85
Marquette, IL, USA	1981	Liquid waste	Higgins & Helmstetter, 83
Slemmestad, Norway	1981	Chlor. organics, PCBs	Trovaag, 1983
San Juan Cement, PR, USA	1981	Chlorinated organics	Peters et al., 1984
Alpha Cement, NY, USA	1982	Waste solvents	Nesslebeck, 1982
Los Robles, CA, USA	1982	Chlorinated organics	Jenkins et al., 1983
Lafarge Cement, Canada	1982	Shredded rubber	Canada Lafarge, 84
Paulding Cement, OH, USA	1983	Chlor. organic waste	Branscome & Bolstad, 85

CEMENT PLANT	YEAR	TYPES OF WASTE	REFERENCE
Lone Star Indus., IL, USA	1983	Chlor.organic waste	Branscome & Bolstad,84
Dalen Cement, Norway	1983	Waste solvents, PCB	Benestad,89 &Norcem89
Golden Bay Cement, NZ	1983	Waste PCB oil	Holden et al., 1983
Eclepens, Switzerland	1983	Sewage sludge	Obrist, 1987
Lafarge, Ont, Canada	1983	Solvents	Robb, 1984
Medusa Cement, PA, USA	1985	Organic solvents	TRC Environ., 1986
Portland Cement, USA	1986	Spent potlining	Byers & Epstein, 1986
Dalen Cement, Norway	1987	Waste solvents, PCBs	Benestad,89 &Norcem89
Unicem Cement, Italy	1988	Municipal solid waste	De Zorzi, 1988
Ash Grove, NE, USA	1989	Liquid waste organics	Trenholm & Hlustick,90
Ash Grove, NE, USA	1989	Solid organic waste	Benoit, 1990
Ash Grove, AR, USA	1989	Solid waste organics	Benoit,1990; Hansen,90
D G Khan Cement, Pakistan	1989	Organic pesticides	Huden, 1990
Texas Industries, TX, USA	1990	Refuse derived fuel	Hill & Daugherty, 1992
Inland Cement, Canada	1990	Used lubricating oil	Heron, 1992
Continental, MO, USA	1990	Solid & liquid waste	Garg, 1990
Southdown Inc., KY, USA	1990	Hazardous waste fuel	Von Seebach, 1990
Inland Cement, Canada	1991	Used automobile tyres	Alberta Env.Council,93
Blue Circle, Australia	1992	Used whole tyres	McGrath, 1992 & 1993

In order to conduct the above test burn in a minimum time period and cost while achieving maximum information requires careful planning and attention to general experience with trial burns. These can be achieved through detailed literature available on conducting a test burn (eg. Gorman, 1989 and Burton, 1990).

2.4.2 Fate of Organic Constituents in the Waste

The combustion of organic compounds results in various end products depending on the original composition of the compound. If the organic compound is composed only of carbon and hydrogen, combustion produces carbon dioxide and water. In addition, if the compound contains chlorine then the combustion produces hydrogen chloride or chlorine as well. Further if the compound is composed of nitrogen or sulphur, combustion produces nitrogen oxides and sulphur dioxide. An organic compound is considered to be totally destroyed if the end products mentioned above are the only ones formed during the combustion process. The values of Destruction and Removal Efficiency (DRE) reveals the degree of destruction of organic compounds. This section of the thesis discusses the various DREs obtained in test burns described in Table 2.2.

If the organic compounds are not totally destroyed due to process inefficiencies or other reasons, then Products of Incomplete combustion (PICs) can be formed. The PICs of most concern are chlorinated dioxins and chlorinated furans. The latter part of this section discusses the emissions of PICs as well as the emissions of dioxins and furans.

2.4.2.1 Destruction and Emission of Organic Constituents

The hazardous organic constituents in the waste listed by the United States Environmental Protection Agency (US EPA) as a hazardous waste in Appendix VIII of the Federal Register (Code of Federal Regulations, Vol 40, part 261, May19, 1980) are referred to as Principal Organic Hazardous Constituents (POHCs). The POHCs included in a test burn are selected on a case by case basis by considering the expected difficulty of thermal degradation of the compounds and their concentrations in the waste. One of the main objectives of a test burn is to determine the Destruction and Removal Efficiency (DRE) of these selected POHCs. DRE is a simple efficiency calculation determined as below (Mournighan et al., 1987):

$$DRE = (W_{in} - W_{out}) / W_{in} \times 100\%$$

where

DRE = Destruction and Removal Efficiency

W_{in} = Mass feed rate of a specific POHC in waste feed

W_{out} = Mass flow rate of the same POHC in exhaust gas

According to the United States Governments Code of Federal Regulations (Vol 40, parts 264 &270), POHCs designated in each waste feed must be destroyed/or removed to a DRE of 99.99% (four nines) or better; dioxins and PCBs must achieve DRE of 99.9999%(six nines) or better.

The DRE test results for the test burns described in section 2.4.1 are detailed in Appendix A under individual test burn descriptions. The DRE test results are summarized in Table 2.3 below:

TABLE 2.3 SUMMARY OF DESTRUCTION AND REMOVAL EFFICIENCIES

CEMENT PLANT	WASTE TYPE	DRE (%)
St. Lawrence Cement	Chlorinated aliphatics	> 99.990
	Chlorinated aromatics	> 99.989
	PCBs	> 99.986
Peerless Cement	PCBs	99.9981-99.9986
Stora Vika Cement	Methylene chloride	> 99.995
	Trichloroethylene	> 99.9998
	Chlorinated hydrocarbons	> 99.99998
	PCBs	> 99.99998
	Chlorinated phenols	> 99.99999
	Phenoxy acids	> 99.99998
	Freon 113	> 99.99986
Marquette Cement	Methylene chloride	99.879
	Methyl ethyl ketone	99.960
	1,1,1-trichloroethane	99.677
	Toluene	99.961
Slemmestad Cement	PAHs	99.99999
	PCBs	99.99997
San Juan Cement	Methylene chloride	93.292-99.997

CEMENT PLANT	WASTE TYPE	DRE (%)
	Trichloromethane	92.171-99.960
	Carbon tetrachloride	91.043-99.996
Los Robles Cement	Dichloromethane	99.951
	1,1,1-Trichloroethane	99.999
	Carbon tetrachloride	99.999
	Freon 113	99.993
	Trichlorobenzene	99.999
Paulding Cement	Methylene chloride	99.984
	Freon 113	99.999
	Methyl ethyl ketone	99.990
	1,1,1-Trichloroethane	99.995
	Toluene	99.962
Lone Star Industries	Methylene chloride	99.97
	Freon 113	99.999
	Methyl ethyl ketone	99.998
	1,1,1-Trichloroethane	99.999
	Toluene	99.995
Dalen Cement	PCBs	> 99.99997
Golden Bay Cement	PCBs	> 99.999
Medusa Cement	Carbon tetrachloride	99.994-99.998

CEMENT PLANT	WASTE TYPE	DRE (%)
	1,1,1-Trichloroethane	> 99.999
	Toluene	99.973-99.985
Ash Grove Cement	1,1,1-Trichloromethane	99.9999
	Trichlorobenzene	99.9999
	Monochlorobenzene	99.9936
D G Khan Cement	Organophosphates	99.96-99.986
	Organochlorides	99.984-99.907

Note: DRE = Destruction and Removal Efficiency

One of the first test burns to investigate the DREs of hazardous wastes in cement kilns was conducted by St. Lawrence cement company in Canada. Three tests were conducted with batches of waste solvents labeled as chlorinated aliphatics, chlorinated aromatics and polychlorinated biphenyls (PCBs). The chlorinated aliphatics were composed primarily of chloropropane, chloropropene, 1,2-dichloroethane, 1,1,2-trichloroethane and chlorobenzene. The chlorinated aromatics were primarily chlorotoluene and the waste designated as PCBs contained about 50% PCB. The DREs were calculated conservatively by not correcting for background levels or contamination and also with a conservative collection efficiency of 80%.

Emission samples were collected and tested for low molecular weight organic chlorides such as dichloromethane, chloroform, carbon tetrachloride and for high molecular organic chlorides such as PCBs.

During all three tests, none of the stable high molecular compounds present in the fuels including PCBs, were detected in emission samples. Extremely low levels of light weight organic chlorides (mainly dichloromethane) were detected in emission samples. These were found to be present at a maximum emission concentration of 50 parts per billion above baseline conditions. The fact that none of the high molecular weight organics were detected in the emissions indicated that these low molecular organics are not materials that have escaped destruction. Therefore, it was concluded that these compounds originated from feed water used to blend the clinker components or a mechanism exists by which these are formed in the cooler end of the kiln.

The study estimated following overall Destruction and Removal Efficiencies (DREs) for the three waste streams as follows:

<u>Waste Stream</u>	<u>DRE</u>
Chlorinated Aliphatics	> 99.990 %
Chlorinated Aromatics	> 99.989 %
PCBs	> 99.986 %

Because of the high and uncertain background levels, the actual DRE of POHCs entering only with the waste feed would have been higher (MacDonald et al., 1977).

The tests at Peerless Cement used PCBs as the waste feed. Testing during the experiment consisted solely of monitoring PCB emissions in the stack gas. No stack emissions of PCBs were detected which could be attributed to the use of PCB bearing oil in the kiln. However, both during the baseline conditions (when no PCBs were burnt) and during the waste fuel burning, some low level PCBs (0.10-0.75 mg/s) were detected in the stack emissions. The highest concentration of PCBs in the stack occurred when no PCBs were being burnt. These emissions were attributed to PCBs that entered with the river water in slurry feed, which enters the cooler

(feed) end of the kiln. Since the slurry water feed of PCBs was not used in the DRE calculation, the DRE value less than 99.9999% was attributed to the slurry water contamination (Swanson Environmental Inc., 1976).

A test similar to St Lawrence cement was conducted in Sweden at a cement kiln in Stora Vika. Tests were conducted with chlorinated aliphatics, PCBs, chlorophenols and phenoxy acids and freon. The results from flue gas analysis indicated no detectable concentrations of the majority of chlorinated aliphatics studied, which included methylene chloride, chloroform, carbon tetrachloride, dichloromethane and chlorinated benzene. The DREs of methylene chloride and trichloroethane were better than 99.995% and 99.9998% respectively. However, small amounts of chloroform, up to 52 ppb, were detected in the stack emissions during some of the experiments. Although the sample from an experiment without addition of waste contained some chloroform, the concentration of chloroform was substantially higher, indicating the possibility of natural chloroform formation.

During the burning of chlorinated aromatics, the flue gas analysis indicated no analytically detectable concentrations of studied chlorinated substances except chloroform, as before. The DRE of PCB was estimated to be 99.99998%, which means that the emission was less than 0.2 mg/kg of fed PCB.

Analysis also indicated no detectable concentrations of chlorinated phenols and phenoxy acids in the flue gases. The DREs for chlorophenols and phenoxy acids were estimated to be greater than 99.99999% and 99.99998% respectively. Although detectable levels of freon113 (0.03 mg/s) was found during one experiment, the DRE was estimated to be greater than 99.99986% (Ahling, 1979).

The test burn conducted at the Marquette cement plant used methylene chloride, methyl ethyl ketone, 1,1,1-trichloroethane and toluene as the POHCs in the liquid waste feed obtained from the solvents from ink and paint manufacturing and solvent

recovery processes. The resulting DRE values range from 99.677% - 99.961%, which are below the required standards. However, none of the POHCs were detected during either co-firing or coal only combustion at the minimum detection limit of 0.1 parts per million (ppm). Therefore, the DREs expressed in the test burn results can be considered to be minimum values (Higgins and Helmstetter, 1983).

The test conducted at Slemmestad cement works in Norway investigated the incineration of PCBs and tar in cement kilns. Tar contained more than 20% polynuclear aromatic hydrocarbons (PAHs), alkanes and alkabenzenes. During the burning of tar, increased emissions of low molecular aldehydes, alkanes and alkabenzenes were detected, but PAH concentrations were not detected. The DRE value of PAH was estimated to be 99.99999% based on a feed of about 150 kg of PAH/hr.

During the burning of PCB waste, only small changes in emissions of organic compounds were noted, but there was a clear increase in emissions of chlorinated compounds such as chloroform, carbon tetrachloride, trichloroethylene, and tetrachloroethane. These variable emissions of chlorinated organics were assumed to be affected by chlorine in the slurry water. However, the data was insufficient to confirm this assumption. The DRE value of PCB based on a feed of 50 kg PCB/hr was approximately 99.99997% (Trovaag, 1983).

The test burn conducted at San Juan used methylene chloride, chloroform and carbon tetrachloride as the POHCs in the waste feed with a high chlorine content (6.5-35.1%). The primary goal of the program was to evaluate the effects of various waste parameters on the DRE of POHCs and the change in emissions of particulate matter, hydrocarbons, carbon monoxide, sulphur dioxide, nitrogen oxides and hydrogen chloride. The secondary objective was to detect and quantify products of incomplete combustion (PICs) such as polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs).

The following DREs were achieved for the POHCs during the experiment:

<u>POHC</u>	<u>DRE</u>
a) Methylene chloride	93.292 - 99.997%
b) Chloroform	92.171 - 99.960%
c) Carbon tetrachloride	91.043 - 99.996%

Occasional achievement of DREs greater than 99.99% was demonstrated for POHCs.

The inability of this kiln to consistently achieve 99.995% destruction efficiency for POHCs was attributed to unatomized waste introduction to the kiln flame and the difficult incinerability of the POHCs. The combustion of chlorinated species containing less chlorine may have resulted in higher DREs (Peters et al., 1984).

Furthermore, measurable quantities of POHCs were detected during the baseline test when no waste was burnt. Since the blank samples showed no contamination problems, the source of POHC emissions during the baseline test was unexplainable. Therefore, if the measured POHCs originated from sources other than burning waste fuel, the actual DREs may have been higher than those measured. This was attributed to the fact that the waste was not atomized and the high level of chlorine input with the waste feed (Mournighan and Branscome, 1987).

The test burn conducted at the General Portland's Los Robles cement plant studied dichloromethane, 1,1,1-trichloroethane, carbon tetrachloride, freon 113, toluene, ethylbenzene and trichlorobenzene as the POHCs. The DRE values for the above compounds exceed 99.99% except for dichloromethane, which recorded 99.951%. There was no correction made to these DRE values to subtract the contribution to the emissions from the burning of petroleum coke. The DRE values were further complicated due to the finding that test results for some organic compounds showed

that baseline emissions when only coke was burnt often exceeded the emissions when waste fuel was burnt (Jenkins et al., 1983 and Jenkins, 1985).

The POHCs included in the test burn conducted at the General Portland's Paulding cement plant were methylene chloride, freon 113, methyl ethyl ketone, 1,1,1-trichloroethane and toluene. Most of the above compounds achieved DREs greater than 99.99%. The DRE values exceeding 99.999 obtained for freon 113 spiked into the waste fuel indicate that similar destruction efficiencies could be obtained for other POHCs in the waste fuel. The DRE values less than 99.99% recorded for toluene and methylene chloride were related to sample contamination problems. The toluene emissions were shown to originate from coal combustion.

The above DRE values at Los Robles were based on the following assumptions:

- a) All POHCs measured in the stack gas result from waste fuel combustion. This further assumes 100% DRE of any POHCs present in the coal and that the slurry feed does not contribute any POHCs to the stack gas by volatilisation of organics in the water or solids portions of the feed.
- b) All of the POHCs measured on the sample tubes result from stack gas, not from residual blank values or contamination.
- c) The POHCs present in the ambient air (from tank working and fugitive emissions) do not contribute to the measured stack gas concentrations even though there is significant (> 35 %) amount of ambient air entering into the ESP system (Branscome and Bolstad, 1984).

The DRE results of the test burn at Lone Star, which used the same POHCs as Paulding test, showed similar contamination problems for methyl ethyl ketone and methylene chloride. However, the DREs for other compounds were all greater than

99.99% even without any corrections been made for background levels (Branscome and Bolstad, 1984).

Two test burns were conducted at the Dalen cement works in Norway during 1983 and 1987. The wastes used included hydrocarbon solvents, PCB and waste oil. The organic micropollutants measured during the experiments include aliphatics, aromatics, bi and poly cyclic compounds including PAH and halogen compounds including PCB, PCDD, PCDF and 2,3,7,8 TCDD.

The results indicated that emissions of organic micropollutants were of the same order of magnitude in 1983 and 1987. No increase in emissions of organic compounds were measured during the incineration of hazardous wastes compared with the amounts demonstrated during the normal operation using coal as fuel. However, increased emissions recorded when the cement process was disturbed.

The DRE for PCB was estimated to be 99.99997% in 1983 and 99.999976% during 1987 (Benestad, 1989).

In 1983, Golden Bay cement company in New Zealand conducted a test burn to demonstrate the incineration of PCB waste in cement kilns. PCB stored in drums were pumped directly into the feed. No detectable concentrations of PCB were found in stack gas or in the ESP dust. Samples contained low concentrations of decachlorobiphenyls (DCB). This compound was present in the experiments even under baseline conditions. It was found that DCB liberated from the cooler end of the kiln originating from the feed water. The DRE of PCB was estimated to be 99.999% (Holden et al., 1983).

Medusa cement company conducted a trial to evaluate the burning of waste derived liquid fuel. The POHCs considered in this test burn were carbon tetrachloride, 1,1,1-trichloroethane and toluene. The results indicated at least 99.99% DRE for

carbon tetrachloride and 1,1,1-trichloroethane, two of the most difficult POHCs to burn. The calculated DRE for toluene, however, was slightly less than 99.99%. This phenomenon was similar to the previous tests where toluene emissions during the baseline conditions were significant. In addition, the heat content of toluene is 42 times greater than that of carbon tetrachloride, which indicates that toluene is much easier to destroy by thermal means than carbon tetrachloride. The effective DRE for toluene, therefore, probably would have exceeded 99.99% DRE determined for carbon tetrachloride (TRC Environmental Consultants, 1986).

Three separate test burns were conducted by Ash Grove cement company in 1989 to evaluate the incineration of liquid and solid hazardous wastes in cement kilns.

The first test burn used liquid organic wastes and solid waste spiked with monochlorobenzene (MCB) which was fed at the upper end of the kiln. The test burn mainly concentrated on continuous monitoring of carbon dioxide, hydrocarbons, total organic mass and the screening analyses of organic compounds in the stack emissions which included MCB and products of incomplete combustion (PICs).

The levels of hydrocarbon and total organic mass emissions were measured separately for the by-pass duct and the main duct as the levels measured in the by-pass duct were believed to be more reflective of any differences that might exist between waste and coal combustion in the kiln.

The results for the by pass-duct did not provide any definite indication about any relationship between hydrocarbon or total organic mass emissions and other parameters due to the low levels of organic emissions encountered during the test. To further complicate the data interpretation, the hydrocarbon levels in the ambient air were also high enough to have contributed significantly to the measured duct levels. However, it was noted that burning wastes versus coal in the kiln did not result in any significant increase in hydrocarbon and total organic mass emissions.

The measured emission values of hydrocarbon and total organic mass levels in the main duct were higher than those for the by-pass duct. This was possibly due to the evolution of organic compounds from the raw material in the preheater and organic emissions from coal combustion in the pyroclone.

The results also indicated few PICs such as benzene and toluene were emitted at low concentration from the by-pass duct. These species were all compounds commonly detected in combustion gas effluents. The analysis of main duct showed similar results with higher concentration of benzene and toluene.

The results also indicated that MCB was formed as a PIC. The MCB concentrations were relatively high during the test run when no chlorinated waste was burnt. Furthermore, the MCB concentrations remained relatively unchanged during the test runs with or without MCB spiked into the waste. The formation of MCB was related to high levels of benzene and to the level of chlorine input to the kiln and not to the spiking of MCB in the waste (Trenholm and Hlustick, 1990).

In the second and the third test burns, the solid waste was fed at the mid-kiln in both dry and wet kilns. The POHCs used for these two test burns were 1,1,1-trichloromethane and trichlorobenzene. The DRE values for these compounds exceeded 99.9999% even after moving the waste fuel introduction point upstream in the process to a lower temperature zone (Benoit, 1990).

The DRE test results of a test burn conducted by D.G. Khan cement company in Pakistan where organic pesticides were incinerated indicated overall DREs of 99.96% (Huden, 1990).

DRE test results described above indicate that cement kilns, when properly operated, can achieve DREs similar to, in some cases better than, those achieved by well designed and well operated commercial waste incinerators burning hazardous wastes.

Four nines (99.99%) removal was reached in most of the cases even for the most difficult to incinerate organic substances and some test burns even achieved DREs approaching six nines (99.9999%). Those tests in which 99.99% DREs were not achieved appear to have resulted from a failure to properly atomize the wastes. As most of the DRE results were not corrected for baseline condition and contamination, the actual DREs may have been much higher than those summarized in Table 2.3.

2.4.2.2 Emissions of Products of Incomplete Combustion (PICs)

A Product of Incomplete Combustion (PIC) in a cement kiln is identified as any compound which is not identified in the raw material or waste feed streams but is found in the kiln stack emissions. Several kilns have attempted to identify and quantify both volatile and semi volatile organic compounds that are emitted under baseline and waste fuel test conditions. The baseline results have been particularly interesting because of the by products formed from coal combustion. As with the DRE determination of POHCs in the previous section, the interpretation of PIC results are complicated by the presence of many of the same compounds during baseline tests and the potential for high bias from low level contamination or background levels (Mournighan & Branscome, 1987).

At San Juan cement plant, four samples (one baseline and three waste burning) were analysed for PICs. The baseline sample was analysed as normal fuel oil accounted for 87% - 100% of the fuel used in the test burn. The PICs which were not detected during the baseline test and can be considered attributable to hazardous waste burning were:

- a) Trichloroethylene (100 to 100,000 mg/hr)
- b) Phenol (2.4 to 11.0 mg/hr)
- c) C2-naphthalene isomers (10 to 50 mg/hr)
- d) C3-naphthalene isomers (14 to 46 mg/hr)

The emissions of PICs during the test burn at General Portland's Los Robles cement plant are given Table A.22 in Appendix A. The baseline emission of benzene (6.756 kg/day) was much higher than the benzene emissions from waste burns (2.26 to 4.244 kg/day). Similarly, the toluene emission during baseline conditions (1.269 kg/day) was comparable to the toluene emissions during waste burns (0.365 to 1.277 kg/day) (Jenkins et al., 1983).

The emissions of PICs during the test burn at General Portland's Paulding plant is given in Table A.27 in Appendix A. The emissions showed no statistically significant differences between the average PIC emission rates for the baseline and waste fuel burn. Furthermore, the toluene emission rates were approximately the same for the baseline and for the waste fuel burn, and the data suggested that both benzene and toluene were produced in trace (ppb) quantities from the use of coal as the primary fuel (Branscome and Bolstad, 1985).

The Table A.32 in Appendix A shows the PIC emissions during the test burn at Lone Star Industries cement plant. The emission rates of styrene, ethylbenzene and xylenes showed no increase when the replacement of waste fuel increased from 25 % to 42 %. The emission rates of C3- and C4- benzenes increased during the waste burn while C6-benzene emissions decreased with the waste fuel increase. The average emission rates for the baseline and waste burn for other PICs were as follows:

- a) Biphenyl (43 vs 87 $\mu\text{g/s}$)
- b) Benzaldehyde (180 vs 230 $\mu\text{g/s}$)
- c) Naphthalenes (170 vs 530 $\mu\text{g/s}$)

Although an increase in PIC emission rates were observed during the waste burns, the overall emission rates remained in the range of 0.03 to 0.5 mg/s (Mournighan and Branscome, 1987).

The results of PIC emissions at Ash Grove's Louisville cement plant is given in Table A.46 in Appendix A. The results showed that a few PICs at relatively low concentrations were emitted from the bypass stack. The volatile species identified were all compounds commonly detected in normal combustion gas effluents. Similar compounds were detected in the main stack, but individual compound levels were higher. Benzene, toluene and ethylbenzene were found at the highest concentrations and showed little variation between baseline and waste burn conditions. These data further confirm that toluene and benzene are the PICs mainly resulting from fossil fuel combustion. The study also compared the PIC emissions measured in the main and bypass stacks to the PICs historically detected in the stack gases from hazardous waste incinerators to find that they are generally in the same range (Trenholm and Hlustick, 1990).

The PIC emission results at Continental's Hannibal cement plant are given in Table A.57 in Appendix A. The emission levels for both volatile and semivolatile PICs were similar between coal plus waste and baseline (coal plus diesel) conditions. The baseline (coal only) PIC emissions were considerably lower than either of the above two conditions. A comparison of the kiln PIC emissions to typical hazardous waste incinerators showed the kiln PICs to generally be at higher levels, although levels of some individual PICs were lower in concentration (Garg, 1990).

In summary, the test results for PICs reported in this section have shown some minor increases from waste combustion for some tests. The results of several baseline tests have revealed that many of the PIC compounds detected are byproducts of coal combustion.

2.4.2.3 Emissions Chlorinated Dioxins and Furans

Dioxins are members of a family of organic compounds known chemically as dibenzo-p-dioxins. This family is characterised by a three-ring nucleus consisting of two benzene rings interconnected by a pair of oxygen atoms. The term 'dioxin' refers to the chlorinated congeners of dibenzo-p-dioxin. Theoretically, one to eight chlorine atoms can occur at dioxin substituent positions such that 75 chlorinated dioxin congeners are possible. Similarly, furans are members of a family of organic compounds known chemically as dibenzofurans. Theoretically, 135 chlorinated furan congeners are possible with different chlorine atom positions. From a human health hazard viewpoint, the polychlorinated dibenzo-p-dioxins (PCDD) and the polychlorinated dibenzofurans (PCDF) are most significant. These compounds contain four or more chlorine atoms. The most concerned form of these compounds is 2,3,7,8-tetrachlorodibenzo-p-dioxin, commonly known as 2,3,7,8-TCDD.

The presence of PCDDs and PCDFs in the emissions of cement kilns burning hazardous waste as supplemental fuel has been investigated in several studies. One of the first reported study of these compounds was undertaken at the Stora Vika cement plant in Sweden. The investigation was undertaken on the assumption that some of the most serious possible formation products during the combustion of chlorophenols and phenoxy acids are PCDDs and PCDFs. However, the investigation did not find any detectable quantities of dioxins or furans with four or six chlorines, which are considered to be most toxic chlorinated dioxins and furans. In one of the experiments, peaks were observed on the gas chromatograph that showed the same retention time as hepta- and octachlorodibenzo-p-dioxin and octachlorodibenzofuran. As the mass spectrometric analysis was not possible due to very low concentrations, no complete confirmation was established as to whether or not samples contained chlorinated dioxins and furans (Ahling, 1979).

During the test burn at San Juan cement plant PCDDs were not detected at a detection limit ranging from 1.6 ng/m³ for tetrachloro-isomers to 4.9 ng/m³ for octachloro-isomers. However, small quantities of penta chloro, hexachloro and heptachloro PCDFs were detected in one sample. These detectable emissions occurred when the kiln was fed with waste containing 21.4% chlorine, corresponding to a chlorine input of 3.5% of total fuel input, which resulted in the production of off specified clinker and a potential kiln damaging condition. No PCDFs were detected in any other tests. Thus, the generation of detectable quantities of PCDFs occurred only when operating an 'upset' or 'out of control' kiln. Under other conditions the cement process did not emit PCDFs, and it did not emit PCDDs under any any waste burning conditions (Peters et al., 1984).

The stack gas samples at Lone Star Industries cement plant and General Portland's Paulding cement plant test burn were analysed for PCDDs and PCDFs. None of these compounds were detected at a detection limit of 1 g/m³ (Branscome and Bolstad, 1984).

During the test burns at Dalen cement plant in Norway in 1983 and 1987, stack gases were analysed for PCDDs and PCDFs. The stack gas concentrations of PCDD and PCDF were in the same order of magnitude in both studies. In 1987 0.001 µg/m³ of PCDD was detected during incineration of typical hazardous waste while 0.006 µg/m³ during incineration of PCB waste. These concentrations are at least ten times lower than those reported from small municipal waste incinerators (Benestad, 1989).

The test burn at Ash Grove's Louisville cement plant undertook a detailed study of dioxins and furans in the main stack and the bypass stack. The detailed results of the study is shown in Table A.47 in Appendix A. The summary of the PCDD and PCDF emissions is given in Table 2.4 below:

TABLE 2.4 SUMMARY OF PCDD AND PCDF EMISSIONS AT ASHGROVE'S LOUISVILLE PLANT (ng/dscm)

TEST CONDITION	STACK	TOTAL DIOXINS	TOTAL FURANS
Liquid and solid waste	Main	0.41	0.23
Liquid and solid waste	Bypass	0.31	1.0
Baseline	Main	0.44	0.55
Baseline	Bypass	0.37	0.31
Liquid waste	Main	1.8	4.2
Liquid waste	Bypass	0.38	0.67

The concentrations of dioxins and furans measured in the main stack and bypass stack showed little difference between the test conditions which included waste burns as well as baseline conditions. The explanation for high levels of dioxins and furans observed during the liquid waste burn was not found in the study. However, it was noted that all the observed dioxin and furan values were on the low side of the range of concentrations that have been measured in hazardous waste incinerators (Trenholm and Hlustick, 1990).

The results of PCDD and PCDF emissions during the test burn at Continental Cement's Hannibal cement plant are shown in Table A.58 in Appendix A. The summary of the above results is given in Table 2.5 below:

TABLE 2.5 SUMMARY OF TOTAL PCDF AND PCDD EMISSIONS AND 2,3,7,8-TCDD EQUIVALENTS AT CONTINENTAL CEMENT HANNIBAL PLANT (ng/dscm)

Test Condition	Dioxins	Furans	Total Dioxin/Furan	2378 TCDD
Baseline coal	87.2	19.8	107	1.190
Coal and waste	305	131	436	3.323
Coal and waste	603	294	897	5.910
Coal and diesel	951	103	1050	3.43

The PCDD and PCDF emissions during the baseline conditions were lower than either of the other test conditions. Coal plus waste and coal plus diesel fuel conditions both saw higher emissions at nearly the same levels. The total PCDD/PCDF emissions were on the order of 100 to 900 ng/dscm (Garg, 1990).

In summary, PCDD and PCDF emissions were not detected in majority of the test burns described in this section when the kilns were operating properly. However, when these compounds were detected in some test burns, their concentration in the stack gas when hazardous waste fuel is burnt was similar to their concentration in the stack gas when no hazardous waste is burnt.

2.4.3 Emissions of Particulate Matter

The effect of waste combustion on particulate matter emissions has been of interest because the earlier cement kiln tests indicated that burning chlorinated wastes increased particulate emissions. Weitzman (1983) examined the particulate matter results when chlorinated wastes were incinerated at St. Lawrence cement and Stora

Vika cement. He plotted the particulate emission data as a function of chlorine feed and found a linear relation in particulate emissions as a function of chlorine input to the process. Subsequent tests, however, indicated that this conclusion was only true for the test burns conducted at St. Lawrence cement and Stora Vika cement, where the electrostatic precipitators (ESPs) were not adjusted to compensate the change in dust resistivity due to the burning of chlorinated wastes.

An increase in particulate emissions is predicted as chlorinated waste combustion forms hydrogen chloride, which reacts with potassium, sodium and calcium in the kiln to form their respective chlorides. These chlorides volatilize at the temperatures found in the hotter end of the kiln and are carried to the cooler end of the kiln by the hot gases where condensation of these compounds occur. The condensation in gas phase can form a fine particulate that remains in the gas. Alternatively, the compounds may condense on the kiln walls and can form a ring of solids. The ring formation may occur as repeated accumulation and loss of chlorides, or in the extreme case, as a continuing build up which results in a large ring that impedes or stops production (Mournighan and Branscome, 1987).

The particulate matter emission results for the test burns reported in literature are given in Appendix A under individual test results. The summary of above particulate emissions is shown in Table 2.6 below:

TABLE 2.6 SUMMARY OF PARTICULATE EMISSIONS

CEMENT PLANT	TEST CONDITION	PARTICLES kg/hr	CHLORINE %CLINKER
St. Lawrence	Lubricating oil	37.8	
	Baseline	52.5	
St. Lawrence	Chlor.aliphatics	55.8	0.40
	Chlor.aromatics	20.5	0.55
	PCBs	20.0	0.25
	Baseline	9.9	
Stora Vika	Chlor.aliphatics	9.5	0.44
	Baseline	2.1	
	PCBs	5.7	0.36
	Baseline	2.7	
	Chlorophenols	14.0	0.09
	Baseline	3.5	
	Freon 113	15.1	0.17
	Baseline	5.3	
Lehigh Portland	Refuse derived fuel	142.3 mg/cu.m	
	Baseline	54.7 mg/cu.m	
Marquette	Waste solvents	26.2	0.11
	Baseline	22.6	

CEMENT PLANT	TEST CONDITION	PARTICLES kg/hr	CHLORINE %CLINKER
San Juan	Chlorinated wastes	9.8	0.55
	Baseline	10.1	
Alpha	Chlorinated wastes	19.9	
	Baseline	24.0	
Paulding	Waste fuel	8.60	0.22
	Baseline	8.93	
Dalen (1983)	Typical waste	112 mg/cum	
	PCB	74 mg/cum	
	Baseline	81 mg/cu	
Medusa	Waste fuel	6.2	
	Baseline	23.0	
Dalen (1987)	Typical waste	5.5 mg/cum	
	PCB	72 mg/cum	
	Waste oil	74 mg/cum	
	Baseline	140 mg/cum	

The test burn conducted at the St. Lawrence cement plant in Canada showed that burning waste oil contaminated with 6000 ppm lead metal resulted in decreased particulate matter emissions. The particulate emissions decreased from baseline emissions of 37.8 kg/h to 23.77 kg/hr during waste oil burn. The study concluded that part of this improvement may have been due to the additional water introduced

with used oil which can improve the electrostatic precipitator (ESP) efficiency (Berry et al., 1975).

The test burn conducted at St. Lawrence, Canada, in 1977 used various waste streams, namely baseline conditions (BLA), chlorinated aliphatics stream (WBA), chlorinated aromatics stream (WBB) and chlorinated aromatics and PCB stream (WBC). For each series of waste streams, the particulate emission rates were quite consistent except for the WBA stream. The study noted higher particulate emissions during WBA waste burn due to temporary malfunction of the ESP. For the WBA waste stream, the emission rates were about four times the rates obtained during the baseline tests and for the WBB and WBC waste streams the rates were twice those obtained during the baseline tests.

The study concluded that two factors may have contributed to the increased particulate emissions during the waste burns. The first is that combustion of the chloride wastes produces hydrogen chloride and chlorine, which react with the alkali components in the raw feed to form volatile alkali chlorides which condense later to produce particulate emissions. The other factor influencing the emissions of particulate matter were the kiln rings formed while burning chlorinated hydrocarbons. During the WBA waste stream burn, extensive ring formation was noted. The apparent increase in the particulate emissions during the WBA waste stream burn was believed to be partially caused by the change in resistivity of the dust entering the ESP due to its increased alkali content as a result of ring formation. It was suggested that a modification in the design of the ESP could compensate for this change (MacDonald et al., 1977).

The emissions of particulate matter during the test burn at Stora Vika cement plant are summarised in Table 2.6 above. During this test burn particulate emissions increased about four times the baseline conditions when chlorinated aliphatics containing 0.44% chlorine relative to clinker weight were incinerated, increased

about twice when the PCBs containing 0.36% chlorine relative to clinker were incinerated, increased about four times when chlorophenols containing 0.09% chlorine relative to clinker was incinerated and increased about thrice when Freon 113 containing 0.17% of chlorine relative to clinker was incinerated. Again, no attempt was made to compensate for the change in dust's resistivity (Ahling, 1979).

The test burn conducted at Lehigh Portland cement plant used refuse derived fuel as supplemental fuel. Although the stack emission tests were probably affected by a ESP cleaning and kiln shut down, the emissions of particulates do not present any serious problems. However, ash buildup in the ESP was noted with time, after commencing Refuse Derived Fuel (RDF) burn, indicating that RDF may have affected the properties of the fly ash. It was suggested that some adjustment in operating conditions in the ESP might be required if RDF were burnt on a continuous basis (Willey and Wienberger, 1985)

In contrast to the results at St. Lawrence and Stora Vika, the test burn at Marquette cement showed no significant change in particulate emissions when chlorinated wastes were incinerated. The particulate emissions increased slightly from 22.45 kg/hr during baseline conditions to 26.49 kg/hr during waste burn conditions. The kiln used for this test burn is equipped with an ESP control device suggesting that chlorinated wastes can be incinerated in a kiln with properly operated ESPs without a significant change in particulate emissions (Higgins and Helmstetter, 1983).

The test results at San Juan are unique as this kiln is equipped with a bag house type dust control device. The results did not indicate any increase in particulate emissions even when the chlorinated wastes incinerated had chlorine contents up to 0.55% relative to clinker. This suggests that burning chlorinated wastes does not necessarily increase the particulate emissions (Peters et al., 1984).

The test conducted at General Portland's Paulding cement plant showed no

statistically significant difference in particulate emission rates between the baseline and waste fuel test conditions. The particulate emission rates during the baseline condition varied from 6.24 kg/hr to 11.83 kg/hr and all of the waste fuel emission rates lied within this interval. It was further confirmed that the baseline results and waste fuel average results were not statistically different at the 95% confidence limits (Branscome and Bolstad, 1985).

The particulate emissions during the test burn at Lone Star Industries showed a large increase (53 kg/hr to 240 kg/hr) from the baseline to the waste burn test conditions. During the experiment serious maintenance problems developed with the ESP and could not be corrected due to adverse weather conditions. Therefore, the increase in particulate emissions during the waste burn cannot be conclusively attributed to the burning of waste.

The test burns conducted at Dalen cement plant in Norway showed no increase in particulate emissions during the incineration of hazardous waste. Higher particle emissions were detected only during those periods when operating disturbances occurred, that is, during incineration of typical hazardous waste in 1983 and normal operation in 1987 (Benestad, 1989).

During the test burn conducted at Medusa cement plant, four particulate emission tests were performed under background (coal only) operating conditions while an additional three tests were performed while the kiln was firing waste fuel. The particulate emissions from the kiln firing only coal ranged from 2.67 kg/hr to 74.8 kg/hr and averaged 23.1 kg/hr for the four tests performed. The particulate emissions during the waste fuel burn ranged from 5.35 kg/hr to 8.03 kg/hr and averaged 6.25 kg/hr. The results indicated an overall reduction in particulate emissions (TRC Environmental Consultants, 1986).

The results of above test burns indicate that there is little change in particulate

emissions from burning hazardous wastes. However, the major exceptions are tests during which there are process upsets or very high amounts of chlorine fed to the kilns.

The kilns equipped with ESPs encountered increased particulate emissions when high amounts of chlorine was fed and especially if ESP hopper dust was recirculated to the kiln. Recirculation allows the chloride content in the dust to build up to much higher levels and eventually the resistivity of dust changes such that the ESP will cease to function properly. However, the particulate emissions from chlorinated waste combustion can be controlled by properly operating the control device and limiting the chloride loading. Adjustments may be required to optimize the ESP performance to compensate for the change in the dust's resistivity (Hazelwood et al., 1982).

The kilns equipped with baghouse type dust control are not affected by the chlorine contents in the waste. The collection efficiencies were found to be stable for a wide range of chlorine feed rates.

2.4.4 Emissions and Effects of Chlorine

When the chlorinated wastes are incinerated in a cement kiln, the temperatures in the kiln favour the complete conversion of chloride in the waste to hydrogen chloride (HCl), which is absorbed by the calcium, potassium and sodium oxides in the kiln's solids and converted to their respective chlorides. These chlorides are vaporized at the hot end of the kiln and begin to condense on cooler surfaces or in the gas when they travel down the length of the kiln. The condensed chloride particles which are entrained in the gases are finally removed by the dust collection system. It is a routine practice to recycle a major portion of this collected dust back to the kiln effecting the dust particles to pass thorough the same cycle again. This is referred to as the 'chloride cycle'. The portion of dust which is not recycled is discarded.

Thus by increasing the amount of waste dust, the chloride loading on the gas cleaning devices can be effectively decreased. Therefore, disposal of a portion of the waste dust is a common practice adopted by kiln operators and several kilns burning chlorinated wastes increase their dust disposal rates to control the chloride cycle.

Several studies have focussed on the emissions of HCl and the results are given in Appendix A under individual test burn results. A summary of HCl emission results is given in Table 2.7 below:

TABLE 2.7 SUMMARY OF HYDROGEN CHLORIDE EMISSIONS

CEMENT PLANT	TEST CONDITION	HCl EMISSIONS, kg/hr
Marquette	Liquid waste fuel	52.2
	Baseline	86.5
Lehigh Portland	Refuse derived fuel	92.4 ppm
	Baseline	206.7 ppm
San Juan	Chlorinated organics	0.08
	Baseline	0.28
Alpha	Waste solvents	2.62
	Baseline	1.08
Los Robles	Chlorinated organics	1.56
	Baseline	0.61
Paulding	Chlorinated organics	2.09
	Baseline	0.56
Lone Star	Chlorinated organics	11.4

CEMENT PLANT	TEST CONDITION	HCl EMISSIONS, kg/hr
	Baseline	1.31
Dalen (1987)	Waste solvents, PCB	6.4
	Baseline	8.5
Medusa	Organic solvents	5.03
	Baseline	6.76
Ash Grove	Liquid waste organics	7.86
	Baseline	6.4

During the test burn with chlorinated wastes at St. Lawrence cement plant, prior to each sampling period analyses were made for the presence of free chlorine and hydrogen chloride in the kiln emissions. In no instance, either during baseline or waste burn sampling periods, were chlorine or HCl detected. The sensitivity limits used in the analytical procedure was 0.5 ppm for chlorine and 2.0 ppm for HCl (MacDonald et al., 1977).

The test burn using refuse derived fuel as supplemental fuel at the Lehigh cement plant recorded HCl emissions in the range of 7.47 to 191 ppm (average 92.4 ppm) during the coal only operations while the range during coal plus RDF operation was 155 to 223 ppm (average 206.7 ppm). The study concluded that although the HCl emissions may have increased while burning RDF, the levels were much lower than the required regulatory limits (Willey and Weinberger, 1985).

The test at Marquette cement showed unusually high HCl emissions in both the baseline and waste burn conditions ranging from 52-86 kg/hr. Although unstable operational conditions contributed considerable variation within the data, there was

no significant increase of HCl emissions at a 95 % confidence level over the baseline conditions (Higgins and Helmstetter, 1983).

During the test at Stora Vika, chlorine addition averaged 0.35 % relative to clinker and reached a maximum of 0.9 %. At an input of 0.8-0.9 %, a ring was formed. The ring disappeared, however, by itself when the chlorine introduction was decreased. The results showed that the cement process can run without any complications up to a chlorine input of 0.6-0.7 % of clinker (Ahling, 1979).

The test at San Juan showed increased HCl emissions during the waste burn, however, the the total absorption of HCl by the cement kiln process averaged 99.7 % in all the tests. The majority of this chlorine (about 82 %) was removed in the clinker and only a marginal increase in chlorine concentration was observed in the waste dust (Peters et al., 1984).

The results at Alpha cement where about 590 ppm of organic halogens were burnt, the HCl emissions during the baseline tests averaged 1.08 kg/hr while the average during waste burn was 2.62 kg/hr. There was not enough data to determine the HCl removal efficiency but an increase in HCl emissions was noted (Nesselbeck, 1982).

The tests at General Portland's Los Robles and Paulding plants showed between 95-99 % of the chlorine was removed by the process solids. However, both tests indicated an increase in HCl emissions during the waste burn conditions. At Paulding test, most of the additional chlorine (about 90 %) was removed with the waste dust, and less than 5 % left with clinker or stack gas (Jenkins et al., 1983; Branscome and Bolstad, 1985).

The results at Lone Star showed a dramatic increase of HCl over baseline conditions (1.31 to 11.44 kg/hr). Although the reason for this increase was not fully understood, one explanation was the possibility that fine chloride particles escaping

the filter had been measured as HCl emissions (Branscome and Bolstad, 1984).

The HCl emission rates at Medusa cement during the background tests varied significantly from 3.1 - 11.9 kg/hr (average of 6.76 kg/hr) and the emission rate during waste burn averaged 5.03 kg/hr. Due to the variability of background test data it was not possible to draw any conclusions. However, the HCl emission rates were higher than the values recorded at other tests (TRC Environmental Consultants, 1986).

During the test burn at Dalen cement plant in Norway, the HCl emissions with coal only test operation averaged 8.5 mg/m³ and the HCl emissions averaged 7.9 mg/m³ during the burning of typical waste. When PCB waste was burnt HCl emissions averaged 6.9 mg/m³ while with waste oil HCl emissions averaged 4.4 mg/m³. Thus, a reduction in HCl emissions was observed in all the test burns using waste as supplemental fuel (Benestad, 1989).

The chloride emissions measured as HCl during the test burn at Ash Grove's Louisville plant were relatively low, and the total emission rates were less than 1.81 kg/hr for all the tests. A comparison of HCl emission rates with input chlorine resulted in 99% removal efficiency by the kiln process. The most important work undertaken in this study was the examination of the sampling and analysis method used to obtain HCl data.

The sampling and analysis method used for this study was initially developed to measure HCl emissions from commercial incinerators. The method actually measures the amount of chloride ions collected in impingers located behind a filter and is typically considered adequate to determine the emissions from commercial incinerators. However, during the testing at cement kilns it was argued that the measured chloride ion in the sampling train impingers was attributed to ammonium chloride, not HCl. Therefore, this study collected data on potassium, ammonium and

chloride ions separately. The results of this study showed that 100% of the chlorides in the HCl sampling train impinger in the main stack was ammonium chloride, not HCl. The study concluded that it is ammonium chloride which is emitted to the environment and not HCl as the results normally suggested (Trenholm and Hlustick, 1990). Similar results were obtained during the test burn at Continental's Hannibal plant (Garg, 1990).

In summary, burning chlorinated wastes generally increased HCl emission rates during the test burns described in this section. However, up to 95 - 99% of chlorine entering the kiln was retained by the process solids (clinker or dust), thus reducing any risk of HCl emissions to the atmosphere. The test results also indicated that high HCl removal efficiencies can be obtained by increasing the waste discard rates and optimizing the chloride cycle. It was also revealed that the operation of the kiln showed no effects up to a chlorine input of 0.7% relative to clinker.

The test burns reported later in this section investigated the appropriateness of the sampling and analysis methods used to evaluate HCl emissions. It was conclusively confirmed that all the HCl testing conducted during the test burns had some interference from other compounds such as ammonium chloride, potassium chloride and sodium chloride resulting in unrealistically high HCl emissions being recorded. These findings were further substantiated by the investigations of Von Seebach and Gossman (1990). They determined the presence and quantity of other ions in the solution used for HCl analysis besides the chloride ion and discovered that the source of the chloride ion was not HCl but ammonium chloride and other chloride salts. Therefore it can be concluded that before any conclusions can be made on HCl emissions from cement kilns, the applicability of the test methods used must be validated.

2.4.5 Emissions of Metals

Several studies in cement kilns have attempted to study the fate and distribution of metals found in the waste fuels. Although a metal compound is changed during the combustion process, a metal is not destroyed. Therefore, any metal present in the waste fuel, fossil fuel or raw feed will be present in either the kiln stack emissions, the cement kiln dust (CKD) or the clinker. The section of the thesis addresses the metal emissions and the metal concentrations in CKD and cement during test burns reported in literature.

The detailed results of metal emissions during the reported test burns are given in Appendix A under individual test burns. A summary of most commonly studied metal emissions is given in Table 2.8 below:

TABLE 2.8 SUMMARY OF MOST COMMONLY STUDIED METAL EMISSIONS (mg/s)

PLANT	TEST	Pb	Cd	Cr	Ni	Hg	As	Zn
St. Lawrence	Waste oil	1.65	-	-	-	-	-	1.19
	Baseline	1.88	-	-	-	-	-	1.31
Marquette	Liq.waste	9.09	0.25	6.69	12.0	0.25	-	2.27
	Baseline	5.05	0.25	2.52	3.91	0.38	-	0.25
Alpha	Solvents	17	-	-	-	-	-	-
	Baseline	4	-	-	-	-	-	-
Paulding	Chlor.waste	6.9	0.6	-	0.05	0.15	-	-
	Baseline	1.5	.001	-	0.16	.018	-	-
Lone Star	Chlor.waste	153	3.87	-	-	.214	0.46	1.16
	Baseline	1.15	0.33	-	-	.034	.096	0.79

PLANT	TEST	Pb	Cd	Cr	Ni	Hg	As	Zn
Medusa	Solvents	11.6	0.63	134	104	-	0.12	-
	Baseline	6.06	0.63	165	116	-	0.25	-
Dalen (1987)	Solvents	7	<0.4	-	-	-	-	-
	Baseline	11	<0.5	-	-	-	-	-
Ash Grove NE	Solvents	0.63	-	-	-	-	-	-
	Baseline	36.1	-	-	-	-	-	-

According to the above table, lead is the metal most commonly studied in the test burns. The fate of lead in the waste is of special interest due to recognized health effects and the concentration of lead in the waste fuel. Implications are that lead contained in the waste may become widely spread in the environment. Also the effects of chlorine input on metal distribution within the process solids is of particular interest because of the potential of forming volatile metal chlorides (boiling point of lead halides is 900 - 950°C), which could increase the loading on the gas cleaning devices.

The test at St. Lawrence where lead- containing lubricating oil was burnt, most of the lead was removed in the process solids with no increase in stack emissions. This test included a high concentration of lead (6000 ppm) and low concentration of halogens in the waste fuel. The lead entering the kiln was distributed primarily in the clinker (75-85%) with the balance in conditioning tower solids (9%) and by pass dust (4%). The study also concluded that the large concentration of lead in the clinker would suggest that lead injected with fuel must be either oxidized or taken into solid solution in the clinker in the body of the kiln. Zinc was found to be completely contained by the process solids. The containment was almost entirely within the clinker with only very minor percentages reported in the conditioning tower solids and by-pass solids (Berry et al., 1975).

The metal emission test results at Marquette cement indicate that lead emissions can increase during the burning of waste fuels. The lead emissions increased from 5.05 to 9.09 kg/hr during the waste burn tests. The study also noted an increase in lead concentration in the kiln dust from 0.02% during coal only operations to 0.05% during waste fuel operations. There was no such increase with other metals at 95% confidence limits (Higgins & Helmstetter, 1983)

The metal emission results at General Portland's Paulding plant showed increased stack emissions for cadmium, copper, mercury, lead and selenium when waste fuel was substituted for a portion of coal. Nickel emissions showed an apparent decrease, however, many of the concentration results for nickel were near or below detection limit. The study also found that for major metal elements entering kiln such as arsenic, barium, calcium, chromium, magnesium, manganese, vanadium, iron and titanium, the metal distribution appeared to be approximately 90% in clinker and 10% in the cement kiln dust. The only significant change in this distribution pattern was noted for elements lead and zinc. During the baseline test, 27% of the lead was found in the dust with 73% ending up with clinker. However, during the waste burn, 65% of the lead was found in the dust with 35% in the clinker. With regard to zinc, 9% of zinc ended up in kiln dust with 91% in the clinker during the baseline conditions and 21% of zinc in dust and 79% in clinker during the waste burn. The study found no explanation for this behaviour (Branscome and Bolstad, 1985).

During the test burn at Lone Star industries cement plant, all of the metals showed an increase in emissions during the waste burn. This increase was mainly due to the malfunctioning of ESP during the test burn where total particulate emissions increased dramatically. The increase in particulate emission was estimated to be 360%. The study attempted to adjust the metal emissions to a constant particulate matter emission rate and found that only the increase in lead and cadmium emissions could be attributed to the burning of waste fuel. The vast majority of the metals studied in this test burn were removed with the clinker product during the baseline

operations and waste burn operations. However, cadmium, lead and mercury behaved in a different way as seen in Table 2.9 below:

TABLE 2.9 DISTRIBUTION OF LEAD, MERCURY AND CADMIUM DURING THE TEST BURN AT LONE STAR INDUSTRIES (%)

ELEMENT	CONDITION	CLINKER	KILN DUST	STACK
Cadmium	Baseline	78	20	2
	Waste Burn	29	51	20
Mercury	Baseline	99.3	0.6	0.1
	Waste Burn	96.7	2.6	0.7
Lead	Baseline	77	22	1
	Waste Burn	29	58	13

According to the above table, when waste fuel was burnt, a higher percentage of the cadmium, mercury and lead were removed with the kiln dust and stack gas while a smaller percentage remained in clinker (Branscome and Bolstad, 1984).

The emissions of arsenic, cadmium, chromium, lead and nickel during the waste burn at Medusa plant were of the same order of magnitude as those measured during the background tests. The very high emissions of chromium and nickel were attributed to sample contamination (TRC Environmental Consultants, 1985).

In summary, various test results have suggested that the cement kilns have a large potential for retaining metal elements entering with waste fuel. The tests have reported that over 99% of the metals in the waste fuel are retained in the process solids without any adverse effects to cement quality. When chlorinated wastes are

burnt, studies have found that metals such as lead and cadmium tend to appear more in the waste dust.

The test results have also indicated that, with high lead loading in chlorinated solvents, lead chloride is formed and removed by the pollution control devices. It is also important to note that lead emissions during all the tests were lower than 10 mg/s which is approximately comparable to the emission of lead from automobiles burning leaded fuel.

4.6 Emissions of Nitrogen Oxides and Sulphur Dioxide

Several studies have attempted to trace the effects of waste combustion on nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions with varying results from kiln to kiln. SO_2 emissions vary due to factors such as sulphur content in primary fuel, alkali content of raw feed, HCl emissions and oxygen input rate.

NO_x emissions can vary considerably in the same kiln within few hours. Peters and Mournighan (1984) suggests that there is a direct functional relationship between NO_x emissions and secondary air (heated air from clinker cooler) with little to no NO_x found from the nitrogen in the fuel. Excess air and its temperature are the main determinants in NO_x emissions implying that NO_x emissions are very much dependent upon the operating conditions of a given kiln rather than waste burning.

The results of NO_x and SO_2 during the test burns are detailed in Appendix A under individual test burns. A summary of NO_x and SO_2 emissions is given in Table 2.10 below:

TABLE 2.10 SUMMARY OF SULPHUR DIOXIDE (SO₂) AND NITROGEN OXIDES (NO_x) EMISSIONS (kg/hr)

Cement Plant	Test	SO ₂ Emissions	NO _x Emissions
Lehigh Portland	RDF	615	120.6
	Baseline	96.3	181
Marquette	Liquid waste	5.2	124.3
	Baseline	25.8	182.6
San Juan	Chlor. organics	119.3	27.3
	Baseline	76.8	14.1
Alpha	Waste solvents	26.4	-
	Baseline	62.4	-
Los Robles	Chlor. organics	63 ppm	948.3 ppm
	Baseline	54 ppm	1000 ppm
Paulding	Chlor. organics	93.9	79.3
	Baseline	239	63.6
Lone Star	Chlor. organics	18.6 ppm	814 ppm
	Baseline	6.7 ppm	620 ppm
Lafarge	Solvents	134.9	91.1
	Baseline	183.2	144.7
Medusa	Solvents	28.6	219.1
	Baseline	124.5	415

Cement Plant	Test	SO ₂ Emissions	NO _x Emissions
Texas Industries	RDF	168.2	95.4
	Baseline	209.1	145.5

Note: RDF - Refuse Derived Fuel

The test results at Alpha cement, Marquette cement, General Portland's Paulding plant, Lafarge cement, Medusa cement and Texas Industries indicate that the substitution of sulphur containing primary fuel with low sulphur waste fuel results in a decrease of SO₂ emissions. An increase of SO₂ emissions indicated at San Juan test was attributed to a lower oxygen input rate and the competition from HCl in a relatively low alkali kiln when burning highly chlorinated wastes. This explanation was confirmed by a decrease in NO_x emissions. No significant increase of NO_x emissions were indicated at the General Portland's Los Robles plant.

A definite relationship between oxygen, NO_x and SO₂ in calcination kilns has been shown by Tiddona et al., (1983). NO_x emissions increase with increasing input oxygen and degree of preheating while SO₂ emissions decrease for such conditions. Continuous monitoring indicates that shifts in NO_x concentration are often accompanied by SO₂ swing in the opposite direction.

In summary, SO₂ emissions are generally decreased when the waste fuel replaces sulphur containing fuel. The NO_x emissions are not significantly affected by waste fuel combustion. The emissions of SO₂ and NO_x are found to be more dependent on operational parameters rather than the waste combustion.

2.4.7 Emissions of Total Hydrocarbons (THCs)

A summary of total hydrocarbon emissions during the test burns is given in Table 2.11 below:

TABLE 2.11 SUMMARY OF TOTAL HYDROCARBON EMISSIONS

CEMENT PLANT	TEST	THC (ppm)
Marquette	Liquid waste	470
	Baseline	1250
San Juan	Chlorinated organics	12.7
	Baseline	8.3
Los Robles	Chlorinated organics	7
	Baseline	10
Paulding	Chlorinated organics	1.87 kg/hr
	Baseline	0.97 kg/hr
Lone Star	Chlorinated organics	5
	Baseline	2.45
Medusa	Organic solvents	5.3 kg/hr
	Baseline	10.9 kg/hr

The THC emissions show varying results with three tests showing increased THC emissions and three tests showing decreased THC emissions.

2.5 IMPLEMENTATION OF A WASTE FUEL PROGRAM FOR A CEMENT KILN

Some of the major implementation activities involved in a waste fuel project for a cement kiln include the following:

- a) Feasibility Assessment
- b) Facility Design
- c) Permitting

This section of the thesis discusses the above activities in detail.

2.5.1 Feasibility Study

The feasibility assessment is designed to develop information that addresses the following information (Bouse and Kamas, 1987):

- a) Employee/public relations
- b) Waste availability and characteristics
- c) Engineering and economic assessment
- d) Regulatory assessments

a) Employee/public relations

Employee and public relations can be the most important feature of overall waste fuel program success. Bouse and Kamas (1987) summarizes some principles and guidelines that have been followed in other successful waste fuel public relation programs and are listed below.

- a) Keep the public informed from the initial announcement of the waste fuel project and throughout its implementation.

- b) Invite public input to the project (i.e. meetings with community leaders and concerned citizens) and keep the communication channels open.
- c) Do not mislead or deceive the public about the project.
- d) Be willing to adjust the waste fuel program design and/or operation to respond to issues of public concern.

Ravishankar (1990) suggests that a specific Reference Steering Group with appointed representatives of different ministers, cement associations, cement and other industries, environmental groups, reporters, and international agencies such as those who have supported the incineration of wastes in cement kilns and public representative groups should be involved right from the planning stage. As the experiences in Canada have shown, without the public and employee co-operation, incineration of wastes in cement kilns is not likely to succeed in spite of all its technical capabilities.

Coles (1988) describes the project development aspects of firing refuse derived fuel in a cement kiln at St. Lawrence cement company in Canada. In his paper, Coles describes that it was St. Lawrence cement's goal from the outset of the project that the local community be completely involved in the development of the project. To achieve this, a unique organisation structure for the evaluation of the project was established. The organisation consisted of three main groups, namely the project steering committee, community liaison committee and project study group.

The function of the project steering committee was to develop and review all the technical information required for the project, as well as the strategy required for the progress of the project. The community liaison committee comprising of local citizen groups, local environmental groups and local citizens interested in the project was involved in providing feedback from the community at large. The project study group was charged with the responsibility of providing recommendations with respect to the development of the overall project. These recommendations were then

received and reviewed by the St. Lawrence cement company.

b) Waste availability and characteristics

The waste availability survey develops information on candidate sources of waste that can be entered in to the waste fuel program. Specific information of interest for each waste source includes the following:

- a) Identifying source data
- b) Waste quantities available.
- c) Waste characteristics
- d) Current methods of disposal and likely disposal cost.

Long term waste availability is an important issue addressed in the waste survey. Projections for on-going waste generation and competition for these wastes are therefore required (Bouse and Kamas, 1987).

c) Engineering and economic assessment

The engineering and economic assessment develops information in four basic areas (Bouse and Kamas, 1987).

1) Cement plant suitability for firing waste fuel

Engineering analyses are performed to determine flame stability, change in kiln's volatile balance, emission control device performance, and the effects on refractory components of the kiln. Modifications of plant design and operation to accommodate waste fuel firing are identified. Waste fuel limits such as heating value, halogen content, solids concentration etc. and waste fuel substitution rate are established.

2) New construction

New construction required to implement the waste fuel program are established. These could include waste fuel unloading terminal, waste fuel storage/blending

tanks, an analytical laboratory and offices. These facilities are sized and specified.

3) Estimated cost and profitability

Capital and operating costs for the total project are established. Waste fuel program profitability projections are prepared as a function of waste fuel substitution rate, waste fuel disposal fees and capital and operating cost sensitivities.

4) Emissions estimates

Emission changes resulting from waste fuel facility operation and waste fuel firing in the kiln are estimated. Air emissions include storage/blend tank losses, fugitive leaks and stack emissions. The changes in kiln dust rate and composition are estimated along with the changes in clinker product.

d) Regulatory assessment

The objective of the regulatory assessment is to evaluate major site-specific environmental and regulatory issues associated with waste fuel project's construction and operation, to develop a permitting strategy for complying with applicable environmental laws and regulations and to address issues of employee/public concern. The regulatory assessment should provide an insight in to expected environmental constraints.

2.5.2 Facility Design

Facility design is completed in two stages, namely the preliminary stage and detail design stage. The preliminary design stage includes process flowsheet, major equipment sizing and specification, process and instrumentation diagrams and material and energy balances. Preliminary design should be carefully integrated with the permitting activities.

The detail design stage is undertaken while the permit application is being processed by regulatory agencies and involves development of structural, mechanical and electrical drawings and specifications that will facilitate equipment procurement, shop fabrication and field erection.

2.5.3 Permitting Requirements

Permitting is one of the most critical steps in implementing a waste fuel program as there can be no project if the permits cannot be obtained and also because it can take longer time to complete than any other step of the program.

Gorman (1989) provides a detail description of the permitting process used in the United States. In the United States all hazardous waste incinerators are required by the US EPA to submit a Part B Permit Application under the authority of Resource Conservation and Recovery Act (RCRA). One section of this application is a trial burn plan. After the trial burn plan has been approved by the US EPA and other state agencies, the actual trial burn must be conducted and results reported before the operating permit is issued. Gorman describes important aspects in preparing a trial burn plan and in conducting the actual trial burn.

Burton (1990) emphasizes that destruction and removal efficiency requirements specified by US EPA are very high and these were not set on the basis of actual health risks assessments. The widespread availability of cement kilns and the lack of alternative disposal methods in many countries might justify their use even if the cement kilns fail to meet the US standard. Burton suggests that in many cases mini burns may be adequate to establish satisfactory procedure and performance criteria resulting in substantial cost savings.

2.6 PRESENT EXPERIENCE AND PRACTICE IN MANAGING WASTES IN CEMENT KILNS

The author surveyed all the major cement plants in North, Central and South America, Africa, Middle East, Asia and Eastern and Western Europe to obtain information on the use of solid and hazardous wastes as supplementary fuel or raw material substitutes and their operational experiences. This section of the thesis describes the information received from the above survey.

2.6.1 American Experience

A summary of cement plants in North, Central and South America managing solid and hazardous wastes is given in Table 2.12 below:

TABLE 2.12 SUMMARY OF CEMENT PLANTS IN NORTH, CENTRAL AND SOUTH AMERICA MANAGING SOLID AND HAZARDOUS WASTES

CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
Arizona Portland	Rillito, Arizona, USA	waste tyres
Ash Grove Cement	Durkee, Oregon, USA	waste tyres
Ash Grove Cement	Foreman, Arkansas, USA	hazardous waste
Ash Grove Cement	Chanute, Kansas, USA	hazardous waste
Ash Grove Cement	Louisville, Nebraska, USA	hazardous waste
Calaveras Cement	Redding, California, USA	waste tyres
Continental Cement	Hannibal, Missouri, USA	hazardous waste
Essroc Corporation	Frederick, Maryland, USA	waste tyres

CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
Essroc Corporation	Logansport, Indiana, USA	hazardous waste
Essroc - San Juan	San Juan, Puerto Rico	hazardous waste
Giant Cement	Harleyville, S.Carolina,USA	hazardous waste
Hawaiian Cement	Oahu, Hawaii	waste tyres
Heartland Cement	Independence, Kansas, USA	hazardous waste
Holnam Inc.	Clarksville, Missouri, USA	hazardous waste
Holnam Inc.	Holly Hill, S.Carolina, USA	hazardous waste
Holnam Inc.	Seattle, Washington, USA	waste tyres
Holnam Inc.	Devils Slide, Utah, USA	waste tyres
Inland Cement	Edmonton, Alberta, Canada	waste tyres and oil
Keystone Cement	Bath, Pennsylvania, USA	hazardous waste
Lafarge Corporation	Demopolis, Alabama, USA	hazardous waste
Lafarge Corporation	Fredonia, Kansas, USA	hazardous waste
Lafarge Corporation	Alpena, Michigan, USA	hazardous waste
Lafarge Corporation	Paulding, Ohio, USA	hazardous waste
Lafarge Corporation	St.Constant, Quebec,Canada	waste tyres
Lehigh Portland Cement	Leeds, Alabama, USA	waste tyres
Lone Star Industries	Greencastle, Indiana, USA	hazardous waste
Lone Star Industries	CapeGirardeau,Indiana,USA	hazardous waste
Medusa Cement	Wampum,Pennsylvania,USA	hazardous waste

CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
Medusa Cement	Clinchfield, Georgia, USA	waste tyres
Monarch Cement	Humbolt, Kansas, USA	waste tyres
National Cement	Lebec, California, USA	hazardous waste
National Cement	Ragland, Alabama, USA	waste tyres
North Texas Cement	Midlothian, Texas, USA	hazardous waste
River Cement	Festus, Missouri, USA	hazardous waste
Southwestern Portland	Fairborn, Ohio, USA	hazardous waste
Southwestern Portland	Lyons, Colorado, USA	waste tyres
Southwestern Portland	Victorville, California, USA	waste tyres
Dixie Cement	Knoxville, Tennessee, USA	hazardous waste
Texas Industries	Midlothian, Texas, USA	hazardous waste
Tibury Cement	Delta, BC, Canada	waste tyres

The following sections of the thesis will demonstrate a few examples of cement kilns in America using solid and hazardous wastes as supplemental fuel or raw material substitutes.

a) Calaveras Cement, Redding, California, USA.
(Siemering et al., 1991)

The Calaveras cement company has burnt a variety of waste fuel, including combinations of coal, natural gas, wood waste, rice hulls, almond shells, petroleum coke and tyre derived fuel (TDF). The company started experimenting with TDF in 1982/83 and by 1986 TDF made up about 5% of total fuel used. In 1988, after

perfecting some equipment, the company used about 14% TDF increasing to 20% in 1990.

The system used by Calaveras is simple, consisting of a feed hopper with variable speed screw and conveyor belt feeding in to the bucket elevator. The elevator discharges into a pipe that drops TDF down into a riser. Although, the TDF was initially produced by shredding tyres, in January 1991 Calaveras company installed a system to feed whole used tyres.

Calaveras discovered many economic factors to be involved in the burning of waste tyres. The net heat content of the tyres was determined as 29,000 KJ/kg (12,500 Btu/lb). Although the number of tonnes of tyre that can be loaded on to a truck depends on several factors, the normal truck freight is about \$0.85/km. It obviously helps to shred the tyres, but this is costly. Shredding tyres up to 50mm particles costs about \$23/Mg (\$25/ton). The approximate estimate of production of waste tyres in a given area is one tyre per person per year and the tyre dealers will pay \$0.25 to \$0.80 per tyre to have their waste tyres hauled away. With these economic factors taken into account, Calaveras estimates that their fuel cost in 1991 should be about 42% of the 1981 costs, prior to using TDF.

b) Medusa Cement, Wampum, Pennsylvania, USA.
(Siemering et al., 1991)

Medusa cement company currently burns chlorinated spent solvents in all three of their kilns at the Wampum plant. Initially in 1985 Medusa cement was issued with a permit for kiln no. 3 to burn spent solvents directly from tank trucks, but later in 1985 a waste fuel plant was constructed to receive and process waste derived liquid fuel (WDLF). Using this facility 875,000 litres of WDLF were burnt in 1985. Permits were also issued for other two kilns and Medusa began using WDLF in kiln no. 1 on June 15, 1990 and in kiln no. 2 on July 17, 1990.

During the early period of operation several technical problems were encountered. For example, positioning of WDLF injection lance was a problem. Many times the lance was not supported properly as it was deformed by heat. This problem was solved by inserting the lance in a pipe to protect it from radiant heat. Another problem was that the circulating load of chlorides affecting the efficiency of ESP by coating the wires and building up deposits of sticky chlorides in the hopper of precipitator sections. This problem was solved by designing a system to extract a portion of cement kiln dust, convey it, and store it for eventual loadout.

The use of waste derived liquid fuels each year at the Wampum plant is shown in Table 2.13 below:

TABLE 2.13 ANNUAL CONSUMPTION OF WASTE FUELS AT MEDUSA
WAMPUM PLANT (Thousand litres)

YEAR	ANNUAL CONSUMPTION
1985	875
1986	4044
1987	5174
1988	5904
1989	6536
1990	13365

Presently, the Wampum plant operates without any problems destroying about 10 million litres/year of WDLF. The company plans to destroy and recover the energy from WDLF at a rate of 3.5 million litres/month or greater by combining its three kilns.

In the Medusa cement's Clinchfield, Georgia preheater cement plant tyre derived fuel is being used as a partial substitute for its regular fuel. The plant began using whole scrap tyres in July, 1990, using a mechanical system of introduction into the riser duct above the feed shelf prior to stage four. The plant was replacing 15% of the coal fuel with used tyres during 1990.

**c) North Texas Cement, Midlothian, Texas, USA.
(Siemering et al., 1991).**

In 1985, North Texas cement applied and received a permit to use waste derived fuel (WDF) as a replacement for up to 60% of the conventional fuel burnt in the Midlothian kiln. This equates to about 250,000 litres/day of WDF, a substance that is composed of hazardous and non-hazardous waste oils, spent solvents, paint thinners, still bottoms, petrochemical and refinery wastes, off specification industrial products and other organic matter.

The Midlothian plant presently has three waste fuel storage tanks that are contained within an epoxy-coated concrete containment area. The tanks operate under a slight pressure to minimize vapour emissions. The tanks are constructed of mild steel and equipped with agitators to keep the fuel stirred. During the burning operation, the fuel is pumped from storage tanks to a manifold on the burner floor of the kiln building. The fuel carrying pipes are double walled to prevent any leaks. The Midlothian plant has been operating for the last four years without any incident.

**d) Lafarge Corporation, Fredonia, Kansas, USA
(Douvre, 1992 and Peters, 1990)**

Lafarge Corporation operates a wet process cement plant in Fredonia, Kansas. The plant initially built with a capacity of 136,000 tonnes of clinker, was expanded to 363,000 tonnes by adding a second wet kiln. In 1988 this plant was burning primarily bulk liquid waste fuels. During the years 1988 -1990, the plant installed a container management facility, a pyrolyzer to convert non pumpable wastes into

a combustible gas and started to process drummed wastes on a commercial basis. During 1990, the plant also installed a system to receive and feed dry combustible solids such as refinery wastes and plastic chips, and started to receive nonhazardous raw material substitutes. The key activities of the plant are shown in Table 2.14 below:

TABLE 2.14 USE OF WASTE FUELS AND RAW MATERIAL SUBSTITUTES
AT LAFARGE CORPORATION FREDONIA PLANT

WASTE TYPE	1988	1989	1990	1991
Bulk liquids (gallons)	14,043,257	16,545,068	20,678,300	18,304,909
Containerized waste (gallons)	39,165	519,606	992,436	1,279,186
Pyrolyzer material (drums)	-	80	2,068	2,770
Dry solids (tonnes)	-	-	645	4,440
Raw material substitutes (tonnes)	-	-	1,150	1,798
Total waste substitution	47%	60.0%	74.5%	82.7%
Co-processing revenues (US\$)	\$3,403,176	\$5,192,708	\$8,175,372	\$10,763,093

Lafarge Corporations's Fredonia plant plans to achieve optimum co-processing capabilities during 1993/94. These optimum conditions are expected to generate up to US\$25,000,000 in co-processing revenues annually.

The waste fuel operation at this plant generated public concern during the initial stages. However, the approach since has been to be very open and to address all issues raised by the community. Some of the activities at this plant includes organizing an open house every other year to attract over 500 visitors, starting a community advisory panel consisting of cross section of the local community and plant management and the plant getting involved in all kind of community programs

which include disposal of glass collected in the city, programs to support science classes in local high schools and donations to many community organisations. Thus, Fredonia plant could be treated as an excellent case study on the change from an old, somewhat, inefficient wet process cement plant to full co-processing facility.

2.6.2 European Experience

A summary of cement plants in Europe managing solid and hazardous waste is given in Table 2.15 below:

TABLE 2.15 SUMMARY OF CEMENT PLANTS IN EUROPE MANAGING SOLID AND HAZARDOUS WASTES

COUNTRY	CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
Austria	Gmundner Zement	Gmunden	waste tyres and oil
Austria	Perlmooser Zement	Rodaun	waste tyres
Austria	Perlmooser Zement	Retznei	waste tyres
Belgium	Ciments d'Obourg	Obourg	hazardous waste, RDF
Denmark	Nordecement	Hardeggen	landfill gas
Denmark	Nordecement	Hover	waste tyres
Denmark	Alsen Breitenburg	Lagerdorf	waste oil
Denmark	Aalborg Portland	Aalborg	flyash
England	Castle Cement	Bedfordshire	hazardous waste
France	Ciments d'Origny	Altkirch	solvents, waste oil
France	Ciments d'Origny	Origny	waste oil

COUNTRY	CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
France	Ciments d'Origny	Lumbres	solvents, waste oil
France	SCORI	22 kilns	hazardous waste
Germany	Portlandzementwerk	Wittekind	municipal waste
Germany	Rohrbach-Zement	Dotternhaus	waste tyres
Germany	Dyckerhoff-Zement	Wiesbaden	waste tyres
Italy	Cementeria Merone	Merone	waste oil
Norway	Norcen Cement	Dalen,Brevik	hazardous waste,
Sweden	Cementa	Degerhamn	residual paint, solvents
Sweden	Cementa	Skovde	acid sludge, graphite
Switzerland	Bundner Cementwerke	Untervaz	waste oil, sewage sludge
Switzerland	Holderbank	Rekingen	waste timber
Switzerland	Vigier Cement	Reuchenette	waste oil, solvents
Switzerland	Ciments de Betons	Eclepens	tyres, RDF, sawdust
Switzerland	Ciments de Betons	Roche	spent solvents
Switzerland	Jura Cement	Wildeggen	waste tyres
Switzerland	Port.cementwerke	Siggenthal	waste tyres

Out of all the European countries, France claims to be the leader in the treatment of industrial wastes in cement kilns. A company named SCORI (a subsidiary of French cement producers Ciments Lafarge, Societe des Ciments Francais and Societe des Ciments Vicat) specialises in this area and claims to be the world specialist in cement kiln incineration. The company has 16 cement plants having 22 cement kilns with a production capacity of 600,000 tonnes, all burning industrial wastes. During 1990 alone SCORI has burnt over 1,000,000 tonnes of industrial wastes saving over 100,000 tonnes of crude oil per year. Unfortunately, the complete details of their operations are not available.

Kirsch (1992) reports the results of a brief survey carried out by the German Cement Works Association to determine the quantities of waste residues disposed as secondary fuels in German cement plants. The results are summarized in Table 2.16 below:

TABLE 2.16 USE OF SECONDARY FUELS IN GERMAN CEMENT INDUSTRY

TYPE OF FUEL	QUANTITY (tonnes/year)	COAL REPLACEMENT (tonnes of coal/year)
Waste tyres/rubber	230,000	213,500
Used oil/solvents	141,500	155,500
RDF/industrial residues	92,500	51,000
TOTAL	464,000	420,000

According to the above survey, one sixth of the total fuel requirement in the German cement industry was covered by the secondary fuels. It was also noted that almost half the primary energy replaced was accounted for by the use of tyres and rubber

waste, which constitutes about one quarter of the amount of tyres and waste rubber generated in Germany.

Obrist (1992) summarises the present activities in Switzerland on the use of alternative fuels in Swiss cement industry. According to Obrist, the cement plants in Switzerland have sporadically used small quantities of alternative fuels, mainly waste oils, before 1980's. However, the most important event was the testing of burning sewage sludge in one of the plants, influencing and giving encouragement to other plants to use alternative fuels. At present 7 large cement plants in Switzerland are involved in alternative fuels. A summary of their operations is given in Table 2.17.

TABLE 2.17 USE OF ALTERNATIVE FUELS IN SWITZERLAND

Cement Company	Plant Location	Alternative Fuel	Quantity (tpy)	Fuel Substitution
Bundner Cementwerke	Untervaz	waste oil	15000	28%
		sewage sludge	2100	0.6%
Vigier Cement	Reuchenete	waste oil	25000	54%
		spent solvents	5450	9%
Ciments et Betons	Eclepens	waste tyres	7200	11%
		RDF, saw dust	3000	3.9%
Ciments Betons	Roche	spent solvents	2200	10.2%
Jura Cement	Wildeg	waste tyres	5300	11%

During 1991, the entire Swiss cement industry replaced 14.7% of its total fuel consumption by waste materials as follows:

Waste tyres	12500 tonnes/year
Waste oils	37000 tonnes/year
Spent solvents	8000 tonnes/year
Dried sewage sludge	2100 tonnes/year

The following sections of the thesis will demonstrate some description of cement plants in Europe using solid and hazardous wastes as supplemental fuel or raw material substitutes

a) Rohrbach-Zement, Dotternhausen, Germany
(Weislehner, 1983)

Based on the initial trials to use waste tyres as supplemental fuel in the Rohrbach Zement's Dotternhausen cement plant, full commercial operations commenced in 1982. The method developed by this company is characterized by the following features: The tyres are shredded into pieces about 200 mm in size. The tyre shreds are then fed via a slot-bunker scraper with attached weigh-belt feeder at a satisfactorily uniform rate and are introduced into the precalcining loop of the preheater kiln. Although shredding of the tyres requires some labour, the feeding system is fully automatic.

b) Portland Zementwerke, Wittekind
(Maury, 1988)

In the early 1980s, as a result of rising energy prices and site shortages for waste disposal. Portland Zementwerke Wittekind, began to study and develop methods for using the combustible parts of general household waste as supplemental fuel. The development of the project included introduction of a waste classifying system, crushing equipment and from this, the production of an alternative fuel suitable for blowing into the kiln.

During the initial stages of the project, problems were encountered due to the chlorines and PVC in the household waste causing preheater blockages and corresponding plant shut downs. However, a new by-pass system was later installed to overcome these problems. The sequence of operations for producing fuel from household waste at this plant can be identified in the following steps:

- 1) a delivery and interim storage of rubbish and waste in bundles
- 2) breaking down bales and sorting out bulky incombustible parts on a rotary screen
- 3) direct crushing of the fuel out of the waste or pressing of the combustible parts, baling and interim storage followed by the cutting of the bales and crushing
- 5) interim storage of waste fuel
- 6) transport of this fuel to the rotary kiln

The details of the complete process are as follows:

The delivered rubbish and waste is unloaded and stored in the rubbish supply shed. From here it goes to the feeding bin and a belt conveyor to the pre-screening section for the separation of bulky parts. In the rotary screen the waste bundles are undone and the incombustible parts are separated. The combustible portion is then passed onto the crushing unit where the waste is crushed to less than 30 mm in size.

c) Norcem Cement, Dalen, Norway
(NORCEM, 1992)

Norcem Cement Engineering (Norcem) has developed an innovative technology that saves fuel costs by utilizing a wide range of organic liquid wastes as supplementary fuel in cement kilns. This technology is utilized at Norcem's cement plant in Norway and has resulted in reducing fuel costs up to 48%.

Norcem operates three basic systems to complement the facilities existing fuel system. System one is based on receiving waste for direct incineration in the kiln without blending. System two can handle a wide variety of wastes by blending with the fuel from system one. System three is capable of incinerating toxic and

hazardous liquid wastes or highly corrosive wastes by introducing a separate fuel line in the system.

Norcem's cement plant in Brevik is burning around 5000 tonnes of liquid hazardous wastes annually. The plant is now permitted to burn following hazardous waste types:

- Waste oil
- Oil containing residues
- Oil emulsions
- Organic solvents
- Paints, adhesives, varnish etc
- Distillation residue
- Tar
- Waste with mercury and cadmium
- Water soluble heavy metal compounds
- Waste containing cyanides
- Pesticides
- Waste containing PCBs

Norcem's experience shows an investment payback period of only one year. The waste burning system has been in operation since early 1987 and daily fuel savings from using waste fuel ranges from \$2100 to \$3800 depending on the percentage of waste fuel used. One of the interesting economic factors in the project is the average fee of \$50/Mg paid by the waste suppliers, when they utilize the cement kiln as a disposal system.

d) Ciments d'Obourg, Obourg, Belgium
(Degre, 1992)

Ciments d'Obourg produces 1,360,000 tonnes of clinker per year at its Obourg plant. The production in this plant is by wet process. In Belgium, the industrial installations of Ciments d'Obourg are approved as a centre for the destruction, neutralization or disposal of toxic waste. The main types of waste fuel presently used at this plant include solvents from chemical processes, paint, varnish and ink industries, oils and hydrocarbon products from metallurgy of ferrous and non ferrous metals and petroleum industry and the waste water. The waste water, injected directly into the burning zone, is obtained from the following sources:

- cutting fluids from metal machining processes
- water from rinsing and washing processes
- waste water from paint shops
- waste water from textile industry
- oily liquid wastes
- waste from organic synthesis processes
- waste from water cleaning and treatment processes

The quantities of the waste materials presently used by the plant are shown in Table 2.18 below:

TABLE 2.18 WASTE QUANTITIES PRESENTLY USED AT OBOURG CEMENT PLANT

TONS/YEAR	1990	1991	1992
Total liquid fuel substitute	8,000	15,000	35,000
Total solid fuel substitute	85,000	100,000	120,000
Household waste	2,000	2,000	2,000

TONS/YEAR	1990	1991	1992
Waste water	10,000	15,000	15,000
TOTAL FUEL USED	105,000	132,000	172,000
% substitution	17%	22%	30%

The plant has planned to increase the waste fuel substitution rate to reach 50% by the end of 1994.

2.6.3 Asian Experience

A summary of Asian cement plants managing solid and hazardous is given in Table 2.19 below:

TABLE 2.19 SUMMARY OF ASIAN CEMENT PLANTS MANAGING SOLID AND HAZARDOUS WASTES

COUNTRY	CEMENT COMPANY	PLANT LOCATION	WASTE TYPE
Japan	Tosoh Corp.	Tokyo	waste tyres
Japan	Mitsubishi Corp.	Tokyo	waste tyres, ash, slag
Japan	Tokuyama Soda Co	Yamaguchi	waste tyres, ash, slag
Japan	Nihon Cement	Tokyo	waste tyres
Japan	Onoda Cement	Tokyo	waste tyres, waste oil, ash, sludge

The experience with waste fuel in Asian cement industry is mainly confined to Japanese operations. According to a report by the Japan Automobile Tyre Manufacturers Association (JATMA), the cement industry in Japan has consumed 137 000 tonnes (ie 18%) of the waste tyres generated in Japan.

2.7 SUMMARY

Test burns conducted to date demonstrate that properly operated cement kilns can achieve DREs equal to or better than DREs achieved by well designed and operated commercial hazardous waste incinerators. DREs exceeding 99.99% and reaching up to 99.9999% were reached in most of the test burns even for the most difficult to incinerate organic substances such as PCBs and PAHs. The actual DREs may have been much higher than those reported in the test burns if the results were corrected for baseline conditions and background contamination.

Although some low molecular weight PIC emissions were recorded in a few test burns, these compounds were generally present in both test conditions, i.e. baseline and waste burn conditions. The fact that none of the high molecular weight organics were detected in the emissions suggest that these low molecular weight PICs are not materials that escaped destruction. Two possible explanations are that these compounds originated from feed water used to blend the clinker or a mechanism exists by which these compounds are formed in the cooler end of the kiln. When the cement kilns were operating properly, none of the PCDDs or PCDFs were detected during most of the test burns. However, when these compounds were detected in some test burns, their concentration in the stack gas when hazardous waste fuel is burnt was similar to their concentration in the stack gas when no hazardous waste is burnt.

The test results for particulate matter indicate that particulate emissions from chlorinated waste combustion can be controlled by properly operating control devices

and limiting the chloride loading. The kilns equipped with ESPs encountered increased particulate emissions when high amounts of chlorine were fed into the kiln and specially if ESP hopper dust was recirculated to kiln. It is possible to reduce the particulate emissions in these cases by discarding a portion of ESP hopper dust and also by adjusting the ESP to compensate for the change in dust's resistivity due to addition of chlorides. Apparently, the kilns equipped with baghouse type dust control are not affected by the chlorine content of the waste.

Burning chlorinated wastes generally increase HCl emissions. However, test burns indicate that up to 95 - 99% of chlorine entering the kiln is retained by the process solids (i.e. cement clinker and cement kiln dust) reducing any risk of HCl emissions to the atmosphere. As most of the additional chlorides is removed with waste dust, high HCl removal efficiencies can be obtained by increasing the waste dust discard rate and optimizing the chloride cycle. Test results also indicate that chlorine can be added to the kiln up to 0.7% of clinker weight without causing any upsets to the kiln operation or cement quality.

Test results indicate that cement kilns have a large potential for retaining metals such as lead entering with the waste fuel. This is a definite advantage considering the fact that most hazardous waste fuels contain high concentration of lead. Tests indicate that over 99% of the lead in the waste fuel is retained in the process solids. Although the distribution of lead within the process solids is not clearly understood, it appears that more of the lead is removed by the waste dust.

A decrease in SO₂ emissions is noted during the test burns when waste fuel containing little sulphur replaces sulphur containing fossil fuel. The NO_x emissions are not significantly affected by waste fuel combustion. Test results clearly demonstrate that emissions of SO₂ and NO_x are more dependent on operational parameters rather than the waste combustion. The test results for THC emissions indicate that kiln operation may effect THC emissions more than the waste fuel does.

Public and employee co-operation is extremely vital in the implementation of a waste fuel project for a cement kiln. Public should be kept informed about the project from the initial announcement and throughout its implementation and every possible communication channel should be kept open. The other important factors to be considered in implementation of a waste fuel project include waste availability and characteristics, engineering and economic assessment, regulatory assessment and permitting.

Presently several cement plants in the United States and Europe are successfully burning solid and hazardous wastes to achieve significant economic advantages. Thus, incineration of hazardous wastes in cement kilns would benefit both the public and the cement industry. Public would benefit as society's solid and hazardous wastes would be destroyed in an environmentally safe manner. Cement industry would benefit from utilizing the fuel value of these waste materials.

CHAPTER 3

CONCERNS IN MANAGING WASTES IN CEMENT KILNS

3.1 INTRODUCTION

As discussed in the previous section, the cement kilns offer an excellent alternative for completely and safely destroying solid and hazardous wastes, while simultaneously recovering their energy and material values for the use in cement manufacture. However, nearly 19 years have now passed since PCBs were successfully destroyed in a Canadian cement kiln and this technically innovative and sound technology is not implemented to the extent one would expect in many countries including Australia. Its introduction has often been delayed or prevented by the public, politicians and environmental groups. As a technical professional in the cement industry, Coles (1992) has observed the process of implementing this technology for the last 19 years and lists some of the events that have happened in many different locations when cement plants have attempted to obtain approvals or have commenced to use waste fuels:

- * neighbours who have lived co-operatively with the plant for many years become alarmed and often protest and become adversaries of the plant
- * environmental groups arrive in the area and fan the flames of discontent
- * strangers arrive and chain themselves to trucks, gates, climb stacks or use other obstructive techniques
- * politicians take a negative attitude to a plant operation that they have previously supported
- * legislation is passed that prevents the use of waste as fuel or that puts undue pressure on the plant operation to meet the regulatory requirements
- * the profile of the plant in the community is raised and generally presented in a negative light where previously it was regarded as a positive contributor to the community

- * employees begin to question the motives of the plant management
- * personal criticism of the plant management occurs in the media

Coles (1992) concludes that in order to overcome the above negative aspects of implementing this technology, it is important to consider all aspects of its development. This will include addressing not only the technical aspects of the project, but also the communications, public relations and political aspects of the project as well. As an initial step towards achieving these objectives, this section of the thesis will attempt to identify some of the technical, environmental and social concerns in managing solid and hazardous wastes in cement kilns. These concerns will be then addressed in detail in the following chapters of the thesis.

3.2 TECHNICAL CONCERNS

The use of solid and hazardous waste as supplementary fuel or as raw material substitutes is seen by many public and environmental groups as a leading contributor to the degradation of human and environmental health. The critics say that this technology is proposed, advocated and mandated because it frees waste generators of their responsibility for the effects of these wastes and if its proliferation is not immediately stopped, the dispersal of toxic and persistent poisons will have a dramatic impact on the global environment and human health. One of the main arguments of these critics is that the cement kilns are originally not designed to handle solid and hazardous wastes and their unsuitability for such purpose would lead to several technical concerns among the general public. The technical concerns identified in this section are the temperature and combustion upsets during hazardous waste burning, alkalinity in cement kilns and the efficiency of pollution control devices.

3.2.1 Temperature and Combustion Upsets

Kleppinger and Carnes (1990) report that the single most important issue with regard to cement kilns acting as hazardous waste incinerators is that the fundamental design of a cement kiln is not compatible with the conditions necessary for the destruction of hazardous wastes. Their main concern is that a cement kiln operator would try to operate at zero excess air since the energy penalty for having excess oxygen and its associated nitrogen, assuming the air is ambient supply, would be much greater than the additional energy reclaimed by more waste combustion. Therefore, they argue that although the temperatures in cement kilns are higher than those generally experienced in incinerators, the lower concentrations of oxygen can cause lower destruction of organics as the amount of oxygen is directly related to the degree of destruction of organic molecules. Greenpeace (1989) also reports that even if high temperatures and consistent combustion conditions are perfectly maintained in a cement kiln burning hazardous wastes, toxic emissions could still occur. The metals will be emitted at any temperature as they are not destroyed and products of incomplete combustion such as dioxins and furans have been shown to form not in the kiln itself but at lower temperatures in other parts of the process such as kiln stacks, pollution control devices and ambient air outside the kiln.

The combustion upsets in cement kilns are considered to be the major technical concern in using cement kilns for waste disposal. According to Kleppinger and Carnes (1990), it is generally recognised that combustion upsets in any combustion device can lead to the possibility of fugitive emissions being released that contain the original hazardous waste components along with the products of incomplete combustion, release of large amounts of particulate matter containing organic compounds along with high levels of heavy metals, release of unscrubbed acid gases into the environment and degrades the performance of air pollution control devices such as ESPs which are very sensitive to flow ratios.

According to Mix and Murphy (1984), one of the most common types of upsets in a cement kiln is due to a rapid movement of clinker down the kiln and into the clinker cooler. The main causes for these upsets result from a sudden release of solids held up in the chains in the drying section of the kiln and the formation and sudden breaching of a ring of fused solids at the interface between the calcining and clinkering zones of the kiln. In the latter case, the calcining solids which are fluidized by the carbon dioxide evolution and which have built up behind the ring of fused solids, which acts as a dam, are suddenly released by the breaching in the ring dam. These solids then fall down the kiln toward the lower firing end and constituting an avalanche. Due to solids movement towards the firing end, the kiln gases will be pushed ahead of the solids and will be pushed out of the firing end of the kiln into the atmosphere outside the kiln (and not through the main stack) and also into the clinker cooler as well. During such an upset, the emission of these gases is usually evident from the dust cloud which accompanies their release. According to Mix and Murphy (1984), in a very severe upset, the flame at the firing end of the kiln can be extinguished and these upsets are not uncommon. The kiln they studied averaged three upsets a month according to the plant manager.

A major concern with the burning of hazardous waste in any device is the possible release of incompletely combusted toxic compounds into the atmosphere during upset conditions. The release of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) is of highest concern during such an upset. According to Mix and Murphy (1984), in the kiln region behind the flame front, the conditions present appear ideally suited for generating complex chemical reactions and a wide variety of products of incomplete combustion including PCDDs and PCDFs. During an upset while burning chlorinated waste fuel, these compounds would be emitted to the atmosphere.

The cement kiln operation can also be interrupted when the hazardous wastes fed to the hot end of the kiln as homogenized mixtures of liquids give rise to large gas pressure increases as the water, while absorbing heat energy, expands into steam, greatly increasing gas volume, and decreasing the temperature (Kleppinger and Carnes, 1990).

3.2.2 Alkalinity in Cement Kilns

The cement kilns are well known to naturally remove acid gas emissions through neutralization by the alkaline raw materials in the kiln. Kleppinger and Carnes (1990) argue that if dry scrubbing is considered to be natural then wet scrubbing must be considered unnatural. They point out that although dry scrubbing can be effective, it is limited in its capacity to absorb the acid products of combustion. Further, it increases particulate loading to the gas cleaning equipment as well.

Greenpeace (1989) states that some advocates of hazardous waste incineration in cement kilns argue that the formation of PCDDs, PCDFs and other chlorinated PICs is prevented by the unavailability of chlorine in organochlorine wastes which is dechlorinated by the alkaline materials in the kiln. According to this report, the fact that dioxins and furans are regularly found in kiln emissions suggests that alkalinity does not prevent the formation of PCDDs and PCDFs even under optimal operating conditions. The report further suggests that the presence of chlorine, even converted into its inorganic form, makes the formation of dioxins and furans likely. Therefore, the possibility that alkalies in a cement kiln might convert organically bound chlorine to inorganic chloride bears little relevance to the formation of dioxin, furans and other complex organochlorines.

3.2.3 Efficiency of Pollution Control Devices

Greenpeace (1989) states that pollution control devices which filter stack emissions from the cement kiln before they are emitted to the atmosphere do not prevent the dispersal of metals and toxic combustion products to the environment. These devices are not capable of capturing 100% of the pollutants and any chemicals and metals captured eventually present yet another hazardous waste disposal problem. The report further states that baghouse type cloth filters are designed to catch large particles only. Thus, they are not effective in capturing dioxins and furans which are attached to the smallest particles or are in vapour phase. Furthermore, many of the most common semivolatile pollutants such as dioxins, furans, lead, mercury, cadmium and zinc preferentially attach themselves to the smallest, hardest to filter particulates of less than 2 microns. These particulates may carry up to 90% of the particulate borne metals and elevated levels of PCDDs and PCDFs (Greenpeace, 1989).

There are concerns about the electrostatic precipitators (ESPs) as well, which are now commonly used in many cement kilns. The efficiency of these devices can be very sensitive to changes in gas velocity and particulate resistivity. As burning of hazardous wastes will result in variations in both of these parameters, hazardous waste disposal in cement kilns degrades the efficiency of ESPs (Kleppinger and Carnes, 1990).

3.3 ENVIRONMENTAL CONCERNS

The critics of using cement kilns in waste management argue that although the proponents of this technology refer to it as a proven technology, existing data demonstrate that cement kilns burning hazardous waste release three dangerous groups of emissions to the environment via stack gas emissions and cement kiln dust particles. These groups are:

- * Unburnt toxic chemicals released to air from stack and kiln dust
- * Products of Incomplete Combustion (PICs)
- * Metals

This section will attempt to identify the social concerns of each of these three groups.

3.3.1 Release of Unburnt Wastes

Unburnt wastes from cement kiln incineration can be released to the environment with the stack gases (both as vapours and deposited on particulates), as fugitive emissions during transport and storage, in pollution control effluents such as cement kiln dust and as constituents of the solid residues that are incorporated into cement products. The quantities of unburnt hazardous wastes that are released into the environment via these routes varies with the combustion conditions in the kiln.

Greenpeace (1989) argues that since the Destruction and Removal Efficiency (DRE), which is a measure of the ability of a combustion process to dispose of hazardous waste, is determined by comparing the quantity of a specified chemical in the waste with the quantity of that same chemical found in the stack gases, a DRE of 99.99 % does not mean that 99.99 % of that particular chemical was actually destroyed; it means that 0.01 % of that chemical was identified in stack gases after passing through the combustion zone and any pollution control devices. The report further notes that a US EPA review of test burns in eight cement kilns found DREs for variety of chemicals varying from 91.043 % to 99.9999 % with an overall average of 99.53 %. The report further notes that the United States that year burnt about 1.4 billion kg per year of hazardous wastes in cement kilns with an average DRE value of 99.53%. This resulted in over 6 million kg per year of unburnt hazardous wastes being released to atmosphere.

It is further argued that values of DREs do not reflect the deposition of unburnt wastes on captured or released cement kiln dust or in the solid residues that are incorporated into cement products as DREs are based only on the analyses of stack gases of selected organics.

Another route of unburnt wastes that can be released to the environment is through fugitive emissions during the transport, storage and processing of hazardous wastes. Greenpeace (1989) reports that at a Systech/Lafarge cement kiln the United States burning hazardous wastes, the total amount of fugitive emissions were reported to be 9,100 kg per year. These emissions included 27 chemicals out of which 12 were reported to be carcinogens. The report further finds that at a plant in Kansas, United States, the fugitive emissions amounted to approximately 0.04 % of the quantity of hazardous wastes burnt in the kiln. From this data the report concludes that if the fugitive emissions are released at the same rate from all other hazardous waste burning cement kilns, then the total fugitive emissions from all waste burning cement kilns in the United States would amount to approximately 0.5 million kg per year.

3.3.2 Products of Incomplete Combustion

Any compound which was not identified from the analysis of the kiln feed stream but is found in the kiln off-gas is considered a Product of Incomplete Combustion (PIC). The PICs occur when parts of partially burnt waste chemicals recombine within the kiln, stack or pollution control devices to form several new chemical compounds, which are more complex than the original waste chemicals and sometimes more toxic than the parent compound. PICs can also result from the compounds introduced from sources other than the waste fuel (ie. coal, oil and gas) and from the compounds present in the waste but not identified due to very low concentration. Independent of its origin, the PICs are released in the kiln stack gases, cement kiln dust, effluents of pollution control devices, cement

products and "puffs" that escape the firing end of the kiln during upsets (Greenpeace, 1989).

Out of possible sources for PIC emissions, PICs in stack gas emissions are of greatest concern to society. According to Greenpeace (1989), a US EPA Science Advisory Board study has found that in a dedicated commercial hazardous waste incinerator, as much as 1% of the mass of waste feed could exit an incinerator as compounds other than carbon dioxide, carbon monoxide, water and hydrogen chloride. The report further finds that PIC emissions from the burning of hazardous wastes in cement kilns would range from 0.5 to 5 times the emission rates of unburnt waste chemicals. Using these data and calculated emissions of 135,000 to 14 million kg per year of unburnt wastes, the PIC emissions from the United States cement kilns would range from 67,500 to 70 million kg per year (Greenpeace, 1989).

The stack emissions of chlorinated dioxins and furans are of greatest concern due to their well known properties of extreme toxicity, persistence and tendency to bioaccumulate. In order to highlight the publicity given by the environmental groups on the emissions of these compounds during the burning of hazardous wastes, the following findings were extracted from a report by Greepeace(1991):

- * In the United States, 46% of the wastes currently burnt in incinerators are halogenated, with an average halogen content of 33.2%.
- * USEPA researchers have identified that the formation of dioxins is generally understood to occur as a result of burning organic material with chlorine containing material.
- * Of the approximately 100 PICs identified in the literature on operating hazardous waste incinerators, 46 are organohalogens.
- * In the United Kingdom, comprehensive tests have established that all waste incinerators, independent of type of incinerator or waste

composition, are likely to produce all of the possible 75 PCDD and 135 PCDF isomers and congeners as well as other organic compounds.

- * PCDDs and PCDFs have been detected in air emissions, ash and liquid residues of many hazardous waste incinerators.
- * The USEPA's National Dioxin Study listed hazardous waste incinerators as important sources of PCDDs and PCDFs in the environment. The total dioxin and furan emissions were found to average 80.9 ng/m³ at two rotary kiln hazardous waste incinerators.
- * The same study found that one hazardous waste incinerator to be emitting 2,3,7,8 tetrachlorodibenzo-p-dioxin (TCDD) equivalents at the rate of 7.4 ng/m³. Assuming an average stack flow rate of 250 m³/min and an annual operating time of 7,000 hours, that incinerator was releasing TCDD-equivalent dioxin and furans at the rate of 778 million ng/year.

(It should be noted here that above reference to hazardous waste incinerators does not include the cement kilns burning hazardous wastes, a matter which will be discussed in detail later).

Greenpeace (1989) also reports on two cases of PCDD and PCDF emissions from cement kilns burning hazardous wastes. The first case reports that in 1988, the National Cement's hazardous waste burning cement kiln in Lebec, California, United States was violating its permitted emission limits for chlorinated dioxins and furans. The kiln was releasing dioxins and furans at a rate of 1.65×10^{-8} kg per hour of equivalent 2,3,7,8 TCDD. In the second case, at another cement plant burning hazardous wastes, several species of dioxins and furans were detected in the air emissions at a total concentration of 44.8 ng/m³.

Apart from the PIC releases in stack emissions, PICs in cement kiln dust are also considered to be of greatest concern when burning hazardous wastes in cement kilns. The cement kiln dust consists of small particles of material formed during

the combustion. A portion of this dust is captured by pollution control devices and the remainder escapes into the environment. Some portion or total of captured dust is recycled back to the kiln. According to Mix and Murphy (1984), a cement kiln burning about 80,000 kg of hazardous waste per day was found to produce cement kiln dust at the rate of 200 tonnes per day. Greenpeace (1989) estimates from this data that in the United States where about 1.4 billion kg of hazardous wastes are burnt annually, the expected production of cement dust would be around 3 billion kg per year. The report also states that dioxins and furans at levels as high as 180 parts per trillion (ppt) were detected in the fly ash from a cement kiln burning chlorinated wastes.

3.3.3 Burning of Metal Containing Wastes

The metallic compounds present in solid and hazardous waste fuels are not destroyed by the combustion process in the kiln. The cement kiln will redistribute any metals in the waste by releasing them in stack gas emissions, cement kiln dust or in the cement product. According to Greenpeace (1989), the metal concentration in hazardous wastes burnt in cement kilns could be as much as 1.35 %, thus releasing up to 18 million kg per year of metals into the environment via all the routes mentioned above.

As the metals are not destroyed, any metal in the waste stream burnt in cement kilns is of concern to the general public and other interest groups. Out of these metals, however, those of most concern are the metals which are known or suspected to be carcinogens. These metals include lead, zinc, cadmium, chromium, nickel, thallium and mercury. The following sections will attempt to identify the concerns related to metal emissions with stack gases, metals in kiln dust and the metals incorporated in the cement product.

Out of all the avenues of heavy metal releases to the environment, the air emission of metals is of greatest concern due to the health risks resulting from this release. Greenpeace (1989) estimates that the total metal emissions to the air from burning hazardous wastes in cement kilns may be high as 5% of the wastes fed into the kiln and the total air emissions of metals from cement kilns burning hazardous wastes in the United States may be high as 1 million kg per year. Another Greenpeace (1991) reports that an average hazardous waste incinerator (32,000 tonnes per year), burning hazardous waste containing an average metal content of 1.5%, would release approximately 93 tonnes of heavy metals in its stack gases annually. The report also notes that in one study involving eight hazardous waste incinerators, the emissions of airborne lead were high as 2,700 kg per year, cadmium as high as 30.5 kg per year and nickel as high as 205.5 kg per year. All these data illustrate the attention given by the environmental groups to highlight the importance of metal emissions in stack gases when burning hazardous wastes.

The distribution of metals found in the waste stream, raw material feed and the natural fuels within the stack gases, kiln dust or cement product will largely depend on temperature, chlorine content of the waste and the efficiency of pollution control devices. The temperatures found in the kiln are sufficient to vaporise some of the metals such as lead, mercury, cadmium, nickel and zinc. These metals will be released in the vapour phase or attach themselves to the surface of kiln dust particles. The less volatile metals are incorporated in the cement product.

It is well known that metals bound to chlorine tend to be more volatile than the elemental metals or its oxides. Therefore, for the volatile metals mentioned above higher temperatures lead to greater volatilization, which results in higher metals concentrations in the stack gas and the kiln dust. Greenpeace (1991) reports of a kiln where the chlorine content of the waste was raised from zero to 8.3%. The

result was that overall percentage of metal partitioning to the kiln dust decreased from 81% to 63% and at the same time the air releases of metals increased by 700%.

Greenpeace (1989) highlights some examples of metals emissions from cement kilns burning hazardous wastes. According to the report, a waste burning cement kiln in Mohave, California, USA was releasing more than 6,800 kg per year of heavy metals which included arsenic, cadmium and chromium. Greenpeace (1989) also reports that in a test burn conducted at an Illinois cement kiln in the United States, air emissions of lead were 82% higher when burning hazardous wastes were burnt; chromium emissions were 167% higher; and zinc emissions were 662% higher.

The release of metals with cement kiln dust is also of great concern because, according to Greenpeace (1989), as much as 46% of metals entering the cement kiln could be distributed in the kiln dust. This means that the waste burning cement kilns in the United States could be releasing as much as 8.5 million kg of heavy metals to the environment via kiln dust annually. According to Mix and Murphy (1984), analyses of several cement kiln dust samples from cement kilns burning hazardous wastes have shown that as much as 75% of the lead entering the kiln could end up in the cement kiln dust.

Finally, the incorporation of metals in the cement product has also received much attention. Greenpeace (1991) states that the bottom residues from hazardous waste incinerators containing high concentrations of heavy metals and dozens of toxic chemicals are disposed of as a hazardous waste. However, bottom residues from cement kilns that burn hazardous wastes which can be presumed to contain the same types of contaminants end up in the cement product itself and sold to the public at a profit. Greenpeace (1991) further claims that although some of the heavy metals are chemically bound to the clinker product, the binding is neither

100% effective nor will it last forever. Therefore, over time trace quantities of heavy metals may potentially be released from the cement to the soils and groundwater and in the case of water pipelines manufactured using cement made from burning hazardous wastes, the heavy metals could end up in drinking water.

3.4 SOCIAL CONCERNS

Identifying and addressing the social concerns of burning hazardous wastes in cement kilns can be considered as one of the most important tasks in the implementation of such a program. According to a study on public perception to incinerating hazardous wastes completed by Petts (1992), the issues raised by the local action groups, local parish and district councillors and the individual members of the public on the incineration of hazardous wastes lead to the following four main areas of concern:

- * The health effects on incinerator emissions
- * Potential accidents involving toxic wastes
- * Adverse impact on the quality of life
- * The management of industrial waste

These concerns, if not properly identified and addressed, can be effectively used by the general public and especially the environmental groups to oppose the incineration of waste fuel in cement kilns, thereby depriving the implementation of a useful technology. In this section of the thesis, an attempt is made to identify some of the critical concerns such as potential effects to human health and the risks associated with the transport, storage and handling of hazardous wastes in cement kilns.

3.4.1 Potential Effects to Human Health

The Petts (1992) study has identified long term health effects and potential genetic effects as the main areas of public concerns for human health as a result of burning hazardous wastes. These concerns include threat to children, unseen and unknown hazards, lack of expert agreement on hazards and emissions, apparent evidence of adverse health effects in those living near plants, no opportunity for public control and specific fears of the unknowns such as dioxins, furans and PCBs.

According to Greenpeace (1989), the pollutants discharged from facilities burning hazardous wastes can be exposed to the humans by direct inhalation, absorption through skin, ingestion of contaminated dust and soils or by ingestion of contaminated food products. Greenpeace (1989) claims that significant human exposure to chemicals such as dioxins and other complex halogenated hydrocarbons and heavy metals can result from the ingestion of fish, seafood, meats and dairy products from area where hazardous waste incineration occurs. Greenpeace (1989) further reports that excess levels of cancer, birth effects, miscarriage and lung diseases are common among the residents of neighbourhoods adjacent to hazardous waste incineration. Greenpeace (1989) further reports that some pulmonary ailments near a hazardous waste burning cement kiln in Lebec, California, USA illustrate the local health impacts of such facilities.

Kelly and Beahler (1992) reports a statement made by an activist group in Midlothian ,Texas ,USA to oppose the waste fuel operations in Midlothian cement plants. The statement says " The Midlothian cement plants release tens of thousand of pounds of toxic waste into the air...toxicologists believe that it only takes a single particle of some of this waste, when not completely combusted, to cause serious health effects to humans... there are reports of infants getting sick

every time they visit relatives here, animals getting unusual diseases, and sickening fumes engulfing entire homes..".

The above selected statements seriously highlight the importance of identifying and addressing these issues. Segal (1992) highlights this critical situation by saying that the rationale for locals opposing the use of cement kilns for managing hazardous wastes seems to be a real concern for human health. However, such local opposition is often initiated, spurred onward, and maintained by a nationally coordinated opposition network with a possible political agenda beyond protection of human health and the environment.

3.4.2 Risks Associated with Transport, Storage and Handling of Wastes

Apart from the human health effects, the other main area of social concern on the use of cement kilns in waste management is the risks associated with the transport, storage and handling of hazardous wastes in cement kilns. Petts (1992) study identifies some of the social concerns in this category such as lack of trust in operators to control operation and mitigate accidents, lack of trust in regulatory agencies to monitor operations and to identify problems and specific fears such as transport accidents in nearby residential areas.

Greenpeace (1989) reports that the public is most concerned about those risks which are involuntary, uncontrolled, unfamiliar, immediate, manmade and catastrophic. Greenpeace argues that transportation of hazardous wastes possess many and sometimes all of these risks. The report also estimates that most hazardous waste and waste oils incinerated at cement plants are transported to these facilities in 20,000 litre capacity tanker trucks. Thus, for a cement plant burning 75 million litres of waste fuel annually, the number of trucks entering the premises would be approximately 70 to 75 per week.

Greenpeace (1991) estimates that an average incinerator burning 32,000 tonnes of hazardous waste annually will receive over 1500 tanker truck shipments of wastes per year, or more than 28 trucks per week. The report further states that the greater the traffic between a source and an incinerator, the more likely is the incidence of chemical spills and the likelihood of exposure will be influenced by the total annual amount of material incinerated in a region and the capacity of the transport vehicles. Greenpeace reports that a United States study has revealed that more than 78,000 incidents involving the release of hazardous materials during the transport have occurred in the years 1976 to 1984.

Mix and Murphy (1984) undertook a probability analysis of transport accidents during the transportation of hazardous wastes to cement plants in the United States. They assumed an average round trip transportation route length of 1,120 km and an average tanker accidents in the United States as 0.68 accidents per million km travelled. Based on these assumptions, Mix and Murphy (1984) concluded that operation of an average sized hazardous waste burning cement kiln was likely to result in one loaded tanker truck accident every five years.

Greenpeace (1992) reports some of the social concerns on the risks associated with storage and handling of hazardous wastes. According to the report, the treatment of toxic and reactive wastes in all kind of central plants involves a risk of accident such as fires, explosions or leakages of liquids and gases. These risks are unexpected and incalculable as the supply of the waste is from most varied waste producers with widely unknown composition and concentration. According to Greenpeace (1992), fires or other accidents are not uncommon in the practical operation of toxic waste incinerating plants. Such a plant in Germany reported eight serious accidents during two years of operation. Greenpeace (1992) states that the worst possible accident at a hazardous waste incinerating plant would without doubt be a fire in the drum storage.

The risks of hazardous waste transport, storage and handling are further emphasised by Greenpeace (1991). This report states that some typical hazardous chemicals fed to incinerators are extremely volatile. When exposed to air they escape to the atmosphere easily. This uncontrolled escape of fugitive emissions occur during the transport of hazardous wastes and also during loading/unloading and from spills, cracks, leaks, damaged drums and faulty valves around and within the plant.

As mentioned above, Petts (1992) study also identified the management of hazardous wastes and adverse impact on the quality of life as the remaining two main public concerns apart from the potential health effects and risks associated with the incineration process. These social concerns include the following:

- * No local benefit from operations
- * Concern about being a dumping ground for imports
- * Concern about the generation of toxic wastes by industry
- * Conflicting perceptions of how to manage hazardous wastes
- * Waste management industry seen as lacking in professionalism
- * Waste materials less well handled than product materials
- * Concern over property values
- * Concern over loss of local amenity.

3.5 SUMMARY

In summary this section of thesis has identified three major social concerns regarding the use of cement kilns in solid and hazardous waste management. They are as follows:

- * Unburnt chemicals are emitted in the stack gases
- * Products of Incomplete Combustion such as chlorinated dioxins and furans

are formed in the combustion process and emitted in the stack gases and deposited in the cement kiln dust

- * Metals are not destroyed during the combustion process and are often released in forms that are more dangerous than the original wastes.

The above discussion has also clearly identified the approach taken by the main environmental groups such as Greenpeace towards the use of this innovative technology. From the several reports cited by the author, it is very much clear that the groups such as Greenpeace are using whatever available information/emission data from commercial hazardous waste incinerators to energise the local activists and to prevent or delay the implementation of this technology. Therefore, it is important to address the social concerns in the context of cement kilns using hazardous waste as fuel compared to using commercial hazardous waste incinerators to dispose such wastes.

The chapters 4, 5 and 6 of the thesis will attempt to address the above mentioned three major social concerns in detail as well as the other technical, environmental and social concern mentioned in this section of the thesis.

CHAPTER FOUR

ASSESSMENT OF ENVIRONMENTAL CONCERNS

4.1 INTRODUCTION

This chapter will describe the assessment made on the environmental concerns in managing solid and hazardous wastes in cement kilns. The most of the environmental concerns described in Chapter 3 of the thesis will be addressed using the most recent data available from test burns in cement kilns burning solid and hazardous wastes. This chapter will initially address the environmental concerns in burning metal containing wastes in cement kilns followed by the issue of destruction of organics and emissions of products of incomplete combustion (PICs) when burning hazardous wastes in cement kilns.

4.2 BURNING OF METAL CONTAINING WASTES

Cement plants planning to manage solid and hazardous wastes in their kilns typically are encountered with two main concerns from the general public and environmental groups. These groups would like to obtain assurances from the plant management with regard to emissions of metals and hazardous organic compounds as a result of burning hazardous wastes in the cement kiln. This section of the thesis will address some of the environmental concerns of metal emissions by analysing a database covering a wide range of kilns with different metal input rates.

Since metals are not destroyed during the combustion process, the mass of all metals introduced into a cement kiln should be equal to the metal mass exiting the kiln. The metals mainly enter with natural fuel (coal, oil etc.), raw material feed or the waste derived fuels. The metals generally exit with the cement clinker, cement kiln dust or as stack emissions. As described in section 3.3.3 of the

thesis, the main environmental concerns in burning metal bearing wastes in cement kilns are concentrated around the metals in stack gas emissions and the metals exiting with cement kiln dust.

The first part of this section will describe the general behaviour of metals in a cement kiln followed up with a section determining the origin of the metals entering the cement kiln (ie. coal or raw material feed or waste derived fuel) and the distribution of metals within input streams. The following section of the thesis will address the most important question of metals in stack emissions. This section will analyse the comprehensive database to reveal valuable information on stack gas emissions of metals which can be used effectively by the cement plant management for public education and consultation. Finally, similar findings to stack gas emissions will be made regarding the distribution of metals in the cement kiln dust and cement clinker.

4.2.1 General Behaviour of Metals in Cement Kilns

Since cement kilns derive their process materials from the earth's crust, the kilns already have the operational experience with metals even prior to burning metal bearing wastes. Generally, depending on their melting and boiling temperatures, the metal compounds in a cement kiln are classified into three major areas:

- * Highly volatile metal compounds having the potential to exit the cement kiln system in the vapour phase
eg. mercury and thallium

- * Semi-volatile metal compounds having a high potential to concentrate in the cement kiln dust
eg. cadmium, lead, antimony and selenium

- * Refractory metal compounds which are compounds passing through the cement kiln system and incorporating in the cement clinker
eg. silver, arsenic, barium, beryllium, chromium and nickel

The volatile metals and their compounds may easily vaporise at the conditions experienced in the cement production process. Therefore, the metals such as mercury and thallium have the potential of escaping the air pollution control devices independent of burning wastes or not. The semi volatile metal compounds tend to vaporise in the burning zone of the kiln and then condense in the cooler regions and concentrate in cement kiln dust. The cement kilns are well prepared to manage these semi volatile emissions. Since the raw material feed is ground to very fine consistency, the cement kilns are well equipped with very efficient air pollution control devices to trap limestone and clay particles from exhaust gas. The refractory metals and their compounds are those which are not easily vaporised at the conditions in the cement kiln process. These metals are absorbed into the forming minerals of cement product or form new crystalline compounds and are stabilised. Because of the large amounts of raw materials being processed in cement kilns, the effect of refractory metals are insignificant in the cement product.

4.2.2 Construction of the Database for Metals

The most of the environmental concerns on metal emissions described in the section 3.3.3 of the thesis are based on the results of test burns conducted in cement kilns during the 1970s and early 1980s. However, the technology of cement manufacture and precision of scientific equipment used in the testing and analysis of process streams in a test burn have developed much during the late 1980s and early 1990s. Therefore, the author surveyed all the major cement plants using or planning to use solid and hazardous wastes in their cement kilns to obtain recent data on test burns conducted in cement kilns. Based on the results

of this survey, the following database shown in Table 4.1 was constructed:

TABLE 4.1 DATABASE OF CEMENT KILNS USING WASTE DERIVED FUELS

TEST REFERENCE	TYPE OF KILN	TEST CONDITION
A1 to A2	Wet process	Liquid waste
B1	Dry process precalciner	Baseline coal only
B2 to B3	Dry process precalciner	Liquid and solid waste
C1	Wet process	Liquid and solid waste
D1	Wet process	Liquid waste
E1	Wet process	Liquid and solid waste
F1 to F4	Wet process	Baseline coal only
F5 to F9	Wet process	Liquid waste
G1 to G2	Dry process	Baseline coal only
G3 to G5	Dry Process	Liquid waste
H1 to H3	Dry process	Liquid waste
I1 to I2	Dry process preheater	Liquid waste
J1 to J3	Wet process	Liquid waste
K1 to K3	Dry process preheater	Liquid waste
L1 to L3	Dry process	Liquid waste
M1 to M6	Wet process	Liquid waste
N1 to N2	Wet process	Liquid and solid waste

TEST REFERENCE	TYPE OF KILN	TEST CONDITION
P1	Semi dry process	Liquid and solid waste
P2	Dry process precalciner	Liquid and solid waste
Q1 to Q2	Wet process	Liquid and solid waste

4.2.3 Overall Metal Material Balance

The overall metal material balance is performed by monitoring the mass metal rates for all inputs and outputs of the cement kiln. The percentage of mass closure is then determined for each metal by dividing the total output metal rate by total input metal rate and presented as a percentage. Due to the conservation of metals in the combustion process, theoretically, the percentage of mass closure should be in the vicinity of 100%. However, the accurate monitoring of input and output streams is complicated due to factors such as low concentrations of the trace elements with values close to or below detection limits, inability to maintain constant input and output flows throughout the test burn and the inability to capture volatile species such as mercury in the sampling system. Furthermore, the measurements are made more difficult since the test burns are conducted as full scale experiments in actual cement kilns. The Table 4.2 illustrates some of the percent closure values for selected test runs.

TABLE 4.2 PERCENTAGE OF MASS CLOSURE FOR SELECTED TESTS

METAL	Test A1	Test A2	Test C1	Test D1	Test E1	Test F2	Test F6
Arsenic	107%	111%	109%	118%	121%	108%	73%
Beryllium	102%	99%	64%	69%	104%		
Cadmium	101%	88%	74%	87%	95%	197%	161%
Chromium	99%	106%	97%	96%	93%	54%	61%
Lead	99%	95%	81%	116%	108%	83%	101%
Barium	85%	123%	149%	92%	102%	92%	96%
Mercury	92%	60%	43%	75%	100%	59%	37%
Silver	55%	75%	68%	50%	66%		
Antimony	134%	99%	73%	52%	83%		
Thallium	47%	29%	39%	19%	54%		
Nickel	66%	80%				62%	51%
Selenium	144%	13%				39%	61%
Vanadium						63%	72%
Zinc						108%	180%

A significant portion of above data is within the 30% of mass closure even with the difficulties of measurement described above. The largest errors are found for highly volatile metals such as mercury and thallium. Therefore, the uncertainty of test data for mercury and thallium could be a possibility. The detailed metal material balances for each of the metals for all the kilns in database are given in Tables B1 to B49 in Appendix B.

4.2.3.1 Metal Distribution in Input Streams

This section of the thesis will determine the total metal input and the distribution of metals in the input stream during the baseline (coal only) operations and waste fuel operations. It will also determine the increase in metal input attributed to the use of waste derived fuels. In determining these observations care was taken to select data from test burns where the metal spiking was not practised. Thus, the results are typical of cement kilns burning hazardous fuel waste.

The total metal input to the kiln and its distribution within input streams during the baseline test run F2 are shown in Figs. 4.1 and 4.2.

As shown, the metal with highest input rate is barium, closely followed by lead and zinc. According to Fig. 4.2, it is interesting to note that the fraction of the metals added with coal is very low for all the metals except for selenium and zinc. Approximately 90% of the metals arsenic, cadmium, chromium, lead, barium, mercury, nickel and vanadium is added by the raw material feed.

The Figs. 4.3 to 4.5 show the total metal input, the distribution of metals in input and the factor of increase in metal input during the waste fuel test F5. As shown, the metals lead and barium recorded high input rates. According to Fig. 4.4, more than 50% of the metals arsenic, chromium, lead, barium, mercury and vanadium are still added by the raw feed even after waste fuel substitution. However, about 95% of selenium was added with waste fuel.

The Fig. 4.5 places the increase in metal input due to waste addition in perspective. As shown, metals cadmium, lead, nickel and selenium recorded approximately two fold increase in input rate due to fuel substitution. The metals arsenic, chromium, barium and mercury showed little change whereas metals vanadium and zinc showed a decrease in input due to waste substitution.

Figure 4.1 Total metal input during baseline test F2

Figure 4.2 Distribution of metal input during baseline test F2

Figure 4.3 Total metal input during waste fuel test F5

Figure 4.4 Distribution of metals in input during waste fuel test F5

Figure 4.5 Factor of increase in metal input during test F5

Figure 4.6 Total metal input during baseline test G1

The analysis similar to above conducted for other test runs F6 to F9 showed similar results together with a reduction of barium due to waste fuel substitution. The corresponding figures for this analysis are given in Figs. B1 to B12 in Appendix B.

The total metal input to the kiln and its distribution within input streams during the baseline test run G1 are shown in Figs. 4.6 and 4.7.

As shown, metals barium, nickel, lead and vanadium have high input rates during baseline conditions. The distribution of the metals in input stream shows again that the fraction of metals added by coal is very low except for nickel and selenium.

The Figs. 4.8 to 4.10 show the total metal input, the distribution of metals in input and the factor of increase in metal input during waste fuel run G3.

As shown, the metals nickel, lead, barium and chromium showed high input rates in this case. According to Fig. 4.9, approximately 80% of metals arsenic, barium, mercury, vanadium and zinc were added with raw material feed even with waste fuel substitution. The Fig. 4.10 shows that the metals cadmium, chromium, lead and nickel recorded increased inputs due to waste fuel substitution and the metals barium, selenium, vanadium and zinc recorded decreases in input rates. Similar analysis performed for test runs G4 and G5 showed identical results. The corresponding figures for these analysis are given in Figs. B13 to B18 in Appendix B.

The above analyses of metal input for different kiln systems illustrates that the metal compounds are fed into the kiln with the raw materials, regular fuels such as coal and waste derived fuels. For most elements studied, the raw material feed is the principal source of metal compounds in the total feed to the kiln.

Figure 4.7 Distribution of metals in input during baseline test G1

Figure 4.8 Total metal input during waste fuel test G3

Figure 4.9 Distribution of metal input during test G3

Figure 4.10 Factor of increase in metal input during test G3

The metal compounds which may be attributed to coal include arsenic, barium, mercury, vanadium and zinc. These compounds experienced a decrease in input when waste fuel substitution was made. The metals for which waste derived fuels may be the principal source include cadmium, chromium, lead and nickel. The analysis also highlights the importance of characterising the metal distribution in the total kiln feed prior to any conclusion being made on the metal emissions.

4.2.3.2 Air Emissions of Metals

Due to the number of concerns by the public and environmental groups on the metal emissions in cement kilns resulting from the use of waste derived fuels, this section can be regarded as one of the high priority sections in the thesis. The data from the compiled database was used again to determine which metals are most prevalent in the stack gas stream during normal operations and when burning waste fuel. The Fig. 4.11 shows the total metal emissions during the baseline test F2. As shown, the high emissions during the baseline conditions were recorded for lead, nickel, selenium and zinc. The Fig. 4.12 shows the factor of increase in metal emissions during the waste fuel test run F7. As shown, lead and mercury showed clear increase in metal emissions while zinc and selenium showed a reduction in emissions. The factor of increase in metal emissions for waste fuel test runs F5, F6, F8 and F9 showed similar results. The corresponding graphs for such analysis is given in Figs. B19 to B22 in Appendix B.

During most of the test burns reported in the database, metal spiking with the waste derived fuel was practised in order to test the worst case scenarios. Thus, the input metal concentrations in waste feed is very much higher for spiked metals than the typical concentration of the same metal in regular waste derived fuels. Therefore, any conclusions made purely on the stack emissions without any consideration to the metal input could be misleading. Therefore, in all the metal analyses concentration of metal input was taken into account.

Figure 4.11 Stack emissions of metals during baseline test F2

Figure 4.12 Factor of increase in metal emissions during waste fuel test F7

Impact of Metal Input Rate on Metal Emissions

It is generally believed that the metal emissions increase with any increase in metal input. The comprehensive sets of data available in the database for the most concerned metals such as lead, chromium, cadmium, beryllium and arsenic provide an excellent opportunity to examine this in further detail to investigate whether there will be any correlation between the input and the emissions of metals.

This section reports the results of statistical analysis conducted on the relationships between metal emissions, metal input rates and the corresponding chlorine input rates for metals arsenic, beryllium, cadmium, chromium and lead. The Table 4.3 shows the input rate, emission rate and the chlorine input rate for these metals at different test burns. The Table 4.4 shows the results of the statistical analysis performed on these metals. The output of the regression analysis results from metal input versus metal output and chlorine input versus metal output were examined for any statistical significance.

The procedure used to perform the statistical analysis of the data and to interpret the results is as follows:

The variables used in this analysis are a) the metal input rate and b) the chlorine input rate. The dependant variable used is the metal emission rate. A linear regression was performed separately for the two variables to investigate whether there is any linear relationship between metal emissions and metal input rate and between the metal emissions and chlorine input rate. The results of this regression analyses are shown in Table 4.4. The initial interpretation of the results was made by evaluating the value of "R Squared" in the Table for each linear regression analysis. The value of "R Squared" , known as the sample correlation coefficient, gives an assessment of the adequacy of the linear fit and is interpreted as the proportion of total variability which is attributed to the

Test	Arsenic		Arsenic		Beryllium		Beryllium		Cadmium		Chromium		Chromium		Lead		Lead		Chlorine	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
A1	2.00E+00	4.72E-04	8.42E-01	5.40E-04	2.47E+00	3.22E-02	2.69E+01	2.61E-03	2.35E+01	2.73E-01	1.84E+02									
A2	2.78E+00	2.90E-04	1.56E+00	2.17E-04	4.46E+00	6.85E-03	4.80E+01	1.66E-03	4.06E+01	8.71E-02	2.47E+02									
C1	1.05E+01	7.76E-04	1.43E+00	5.03E-04	8.02E+00	5.17E-02	5.14E+01	2.44E-02	5.24E+01	3.54E-01	5.66E+02									
D1	4.54E+00	1.41E-03	3.24E+00	4.54E-04	7.60E+00	3.18E-02	6.49E+01	1.54E-03	9.10E+01	4.26E-01	1.28E+03									
E1	5.65E+00	7.39E-04	1.70E+00	2.96E-04	4.75E+00	5.85E-02	4.93E+01	1.65E-02	3.31E+01	1.56E-01	2.17E+02									
H1	2.15E+01	5.40E-04	2.38E-01	3.00E-05	5.43E-01	3.30E-04	4.00E+00	7.00E-04	7.85E+00	1.51E-03	1.47E+02									
H2	2.96E+01	8.80E-04	3.84E-01	3.00E-05	5.67E-01	5.90E-04	6.81E+00	8.10E-04	1.71E+01	3.73E-03	1.59E+02									
H3	2.01E+01	7.50E-04	3.42E-01	3.00E-05	7.71E-01	5.40E-04	7.21E+00	6.40E-04	9.53E+00	2.45E-03	1.54E+02									
I1	3.85E-03	4.56E-07	1.34E-04	4.19E-08	2.11E-03	4.20E-06	3.12E-02	8.39E-06	1.97E-02	8.39E-06	1.29E-01									
I2	2.89E-03	4.17E-07	1.25E-04	4.17E-07	1.55E-03	4.17E-07	3.22E-02	8.08E-06	2.01E-02	8.08E-06	1.84E-01									
I3	2.24E-03	4.10E-07	9.25E-05	4.10E-07	1.24E-04	4.10E-06	1.50E-02	8.19E-06	2.32E-03	8.19E-06	8.35E-02									
J1	3.59E+00	2.00E-04	2.46E-01	3.00E-05	2.04E+00	4.70E-03	1.22E+01	9.00E-04	2.61E+01	5.20E-02	2.13E+02									
J2	3.18E+00	5.00E-04	2.40E-01	5.00E-05	2.07E+00	1.20E-02	1.11E+01	2.00E-03	3.11E+01	2.48E-01	2.03E+02									
J3	3.70E+00	2.00E-04	2.62E-01	3.00E-05	2.34E+00	8.40E-03	1.13E+01	1.00E-03	2.91E+01	6.40E-02	1.99E+02									
K1	4.30E+00	1.00E-04	7.10E-01	3.00E-05	1.11E+00	2.00E-04	1.92E+01	4.00E-04	2.58E+01	5.60E-03	2.10E+02									
K2	5.40E+00	3.00E-04	6.40E-01	3.00E-05	1.20E+00	4.00E-04	1.84E+01	1.90E-03	2.50E+01	1.02E-02	2.14E+02									
K3	5.10E+00	1.00E-04	8.10E-01	3.00E-05	1.01E+00	1.00E-04	1.86E+01	3.00E-04	2.58E+01	1.40E-03	2.07E+02									
L1	7.44E+00	3.50E-04	1.17E+00	1.20E-04	1.39E+00	9.40E-04	4.51E+00	6.30E-04	1.12E+01	1.39E-03	1.78E+02									
L2	7.42E+00	1.30E-04	1.10E+00	9.00E-05	1.39E+00	8.00E-05	3.65E+00	7.90E-04	1.11E+01	7.50E-04	1.56E+02									
L3	8.46E+00	3.30E-04	1.29E+00	1.20E-04	4.79E+00	8.00E-05	3.71E+00	7.10E-04	1.14E+01	8.40E-04	1.61E+02									
M1	5.98E+00	3.00E-04	2.71E-01	2.00E-05	6.82E-01	7.00E-04	7.56E+00	6.00E-04	1.20E+01	1.02E-02	2.46E+02									
M2	5.62E+00	7.00E-04	3.01E-01	2.00E-05	8.96E-01	9.00E-04	7.90E+00	9.00E-04	1.03E+01	1.12E-02	2.42E+02									
M3	6.95E+00	7.00E-04	3.28E-01	2.00E-05	8.39E-01	1.30E-03	9.05E+00	1.10E-03	9.25E+00	1.24E-02	2.28E+02									
M4	6.42E+00	1.10E-03	5.86E-01	1.00E-04	1.17E+00	2.30E-03	1.37E+01	2.30E-03	1.86E+01	8.30E-02	3.55E+02									
M5	3.38E+00	1.20E-03	4.88E-01	1.00E-04	1.19E+00	4.40E-03	1.07E+01	3.00E-03	1.56E+01	6.60E-02	3.16E+02									
M6	8.61E+00	4.10E-03	4.47E-01	1.00E-04	1.04E+00	9.80E-03	1.58E+01	5.40E-03	1.57E+01	1.22E-01	3.34E+02									
N1	3.22E-01	1.29E-03	1.36E-02	4.54E-04	3.72E-01	2.09E-03	3.92E+00	3.65E-03	7.83E+00	3.51E-02	4.26E+02									
N2	8.77E+00	1.23E-03	1.36E-02	4.72E-04	7.76E-01	3.41E-03	1.43E+01	1.36E-03	2.29E+01	8.80E-02	3.79E+02									
P1	6.26E+00	4.94E-03	5.03E-01	1.74E-04	1.13E+00	4.81E-03	1.67E+01	9.66E-04	1.96E+01	6.99E-02	1.94E+02									
P2	2.81E+00	1.42E-03	5.90E-02	4.54E-05	2.90E-01	3.56E-03	1.37E+01	3.65E-03	7.02E+00	9.62E-02	2.12E+02									
Q1	6.29E+00	2.63E-03	6.35E-02	2.08E-04	3.36E-01	2.62E-03	1.41E+01	8.21E-04	1.58E+01	1.26E-01	2.56E+02									
Q2	7.33E+00	2.24E-03	9.53E-02	1.22E-04	1.19E+00	6.21E-04	2.63E+01	6.71E-04	1.46E+01	9.34E-03	3.67E+02									

TABLE 4.3 INPUT AND EMISSION RATES OF METALS AND INPUT RATE OF CHLORINE (kg/hr)

Regression Output: Arsenic Input/Arsenic Output		Regression Output: Beryllium Input/Beryllium Output	
Constant	0.000081	Constant	0.000002
Std Err of Y Est	0.000166	Std Err of Y Est	0.000105
R Squared	0.030536	R Squared	0.294247
No. of Observations	25	No. of Observations	22
Degrees of Freedom	23	Degrees of Freedom	20
X Coefficient(s)	0.0000132522	X Coefficient(s)	0.0001488301
Std Err of Coef.	0.0000155698	Std Err of Coef.	0.0000515401
Regression Output: Chlorine Input/Chlorine Output		Regression Output: Chlorine Input/Beryllium Output	
Constant	0.000033	Constant	0.000107
Std Err of Y Est	0.000141	Std Err of Y Est	0.000125
R Squared	0.034173	R Squared	0.000225
No. of Observations	23	No. of Observations	22
Degrees of Freedom	21	Degrees of Freedom	20
X Coefficient(s)	0.0000003967	X Coefficient(s)	-0.0000000322
Std Err of Coef.	0.0000004602	Std Err of Coef.	0.0000004799
Regression Output: Cadmium Input/Cadmium Output		Regression Output: Chlorine Input/Cadmium Output	
Constant	-0.003331	Constant	0.008017
Std Err of Y Est	0.010922	Std Err of Y Est	0.013327
R Squared	0.329316	R Squared	0.001391
No. of Observations	24	No. of Observations	24
Degrees of Freedom	22	Degrees of Freedom	22
X Coefficient(s)	0.0058799401	X Coefficient(s)	-0.0000069463
Std Err of Coef.	0.0017890119	Std Err of Coef.	0.0000396671

TABLE 4.4 REGRESSION OUTPUT FOR METAL INPUT, METAL OUTPUT AND CHLORINE INPUT

Regression Output: Chromium Input/Chromium Output		Regression Output:Lead Input/Lead Output	
Constant	0.001185	Constant	-0.008745
Std Err of Y Est	0.001285	Std Err of Y Est	0.066941
R Squared	0.019720	R Squared	0.206715
No. of Observations	25	No. of Observations	27
Degrees of Freedom	23	Degrees of Freedom	25
X Coefficient(s)	0.000027	X Coefficient(s)	0.003765
Std Err of Coef.	0.000039	Std Err of Coef.	0.001475
Regression Output:Chlorine Input/Chromium Output		Regression Output:Chlorine Input/Lead Output	
Constant	-0.000381	Constant	0.038939
Std Err of Y Est	0.001127	Std Err of Y Est	0.074822
R Squared	0.246419	R Squared	0.008945
No. of Observations	25	No. of Observations	27
Degrees of Freedom	23	Degrees of Freedom	25
X Coefficient(s)	0.000007	X Coefficient(s)	0.000091
Std Err of Coef.	0.000002	Std Err of Coef.	0.000192

TABLE 4.4 REGRESSION OUTPUT FOR METAL INPUT, METAL OUTPUT AND CHLORINE INPUT (CONT.)

variations in independent variables. Once the initial assessment was made with "R Squared" value, the slope of the regression line (X coefficient in the regression results in Table 4.4) was statistically tested using the null hypothesis test to investigate whether any of the independent variables, metal input and chlorine input, explains a significant amount of the variation in metal emissions. If the relationship satisfied the null hypothesis test, then it was confirmed that there is no correlation between the variables whereas if the relationship rejected the null hypothesis test then a correlation was confirmed and the relevant correlation derived. The confidence level used in this analysis is 95%. The interpretation of the above regression analysis results are discussed separately under individual metals below.

Arsenic

The impact on arsenic emissions due to variations in arsenic input and chlorine input are shown in Figs. 4.13 and 4.14. According to these figures it is obvious that the arsenic emissions are not much effected by an increase in arsenic input or chlorine input. This observation is further confirmed by the regression results reported for arsenic in Table 4.4. According to these results, based on the 95% confidence level, only 3% of the variation in arsenic emissions can be explained by the increase in arsenic input and only 3.4% of the variation in arsenic emissions can be explained by the chlorine input increase. At the 95% confidence level both of the above correlation coefficients satisfy the null hypothesis test, thus statistically confirming that there is no correlation between arsenic emissions and arsenic input rate and chlorine input rate respectively.

Beryllium

The Figs. 4.15 and 4.16 show the relationship between beryllium emissions and beryllium input and the relationship between beryllium emissions and chlorine input respectively. According to Fig. 4.15, there is some evidence of correlation between beryllium emissions and beryllium input.

Figure 4.13 Arsenic emissions as a function of arsenic input

Figure 4.14 Arsenic emissions as a function of chlorine input

Figure 4.15 Beryllium emissions as a function of beryllium input

Figure 4.16 Beryllium emissions as a function of chlorine input

The regression results reported in Table 4.4 confirms this observation where by about 29% of total variation in beryllium emissions can be explained by the increase in beryllium input. This relationship rejects the null hypothesis test at 95% confidence level, thus statistically the following correlation exists between beryllium emissions and beryllium input:

$$\begin{aligned} * \quad & \text{Beryllium Emissions (kg/hr)} = (1.48\text{E-}04) \text{ Beryllium Input (kg/hr)} + \\ & (2.00\text{E-}06) \end{aligned}$$

The Fig. 4.16 does not show an existence of correlation between beryllium emissions and chlorine input. This observation is statistically confirmed by the regression results reported in Table 4.4. According to these results, no percentage of the total variation in beryllium emissions can be explained by a variation of chlorine input and the relationship satisfies the null hypothesis test based on 95% confidence level confirming that there is no correlation between the beryllium emissions and chlorine input.

Cadmium

The impact on cadmium emissions due to variations in cadmium input and chlorine input is shown in Figs. 4.17 and 4.18. The Fig. 4.17 clearly illustrates a correlation between the cadmium emissions and cadmium input. According to the regression results in Table 4.4, nearly 33% of the variation in the cadmium emissions can be explained by the variation in cadmium input. This relationship rejects the null hypothesis test based on 95% confidence level, thus confirming a statistical correlation. According to the regression results, the correlation between the cadmium emissions and cadmium input can be expressed as follows:

$$\begin{aligned} * \quad & \text{Cadmium Emissions (kg/hr)} = (5.88\text{E-}03) \text{ Cadmium Input(kg/hr)} - \\ & (3.33\text{E-}03) \end{aligned}$$

The Fig. 4.18 clearly shows that the cadmium emissions are not increased when the chlorine input is increased. This observation is statistically confirmed by the regression results reported in Table 4.4. According to these results, no percentage of the variation in cadmium emissions can be explained by the variation in chlorine input. Furthermore, this relationship satisfies the null hypothesis test based on 95% confidence level confirming that there is no correlation between the cadmium emissions and chlorine input.

Chromium

The Figs. 4.19 and 4.20 illustrate the relationship between the chromium output and the chromium input and chlorine input respectively. The Fig. 4.19 does not show any clear increase in chromium emissions for most of the test burns when the chromium input is increased. In order to explain this observation, the regression results in Table 4.4 for chromium was used. According to these results, only about 2% of the variation in chromium emissions can be explained by the variation in chromium input. This relationship satisfied the null hypothesis test at 95% confidence level, thus confirming the non-existence of a correlation between the chromium emissions and chromium input.

The Fig. 4.20 illustrates that some relationship could exist between chromium emissions and chlorine input as the chromium emissions increase when chlorine input is increased. This observation was tested statistically using the regression results in Table 4.4. According to these results about 24% of the variation in chromium emissions can be explained by the variation in chlorine input. This relationship failed to satisfy the null hypothesis test at 95% confidence level, thus confirming some correlation. The statistical correlation between the chromium emissions and chlorine input is as follows:

$$\begin{aligned} * \quad & \text{Chromium Emissions (kg/hr)} = (7.00\text{E-}06) \text{ Chlorine Input (kg/hr)} - \\ & (3.81\text{E-}04) \end{aligned}$$

Figure 4.19 Chromium emissions as a function of chromium input

Figure 4.20 Chromium emissions as a function of chlorine input

Lead

The relationship between lead emissions and lead input is shown in Fig. 4.21. According to the figure, there is strong evidence of increase in lead emissions due to an increase in lead input. This observation was tested statistically using the regression data in Table 4.4 for lead. According to these results, nearly 21% of the variation in lead emissions can be explained by the variation in lead input. This relationship rejected the null hypothesis at 95% confidence level confirming a correlation. The statistical correlation between the lead emissions and lead input is as follows:

$$* \quad \text{Lead Emissions (kg/hr)} = (3.77\text{E-}03) \text{ Lead Input (kg/hr)} - (8.74\text{E-}04)$$

The Fig. 4.22 shows the variation in lead emissions due to the variation in chlorine input.

The figure does not show any clear increase in lead emissions when the chlorine input is increased. The regression results in Table 4.4 for lead confirms this observation. According to these results, only about 1% of the variation in lead emissions can be explained by the variation in chlorine input. This relationship satisfied the null hypothesis test at 95% confidence level, thus confirming that no correlation exists between the chlorine input and lead emissions.

According to the above analysis, the metals arsenic and chromium show no correlation between their input and emissions, whereas the metals beryllium, cadmium and lead show a moderate correlation between their input and emissions. All the metals studied in the above section show no correlation between their emissions and chlorine input except for chromium, where a moderate correlation is noted.

Figure 4.21 Lead emissions as a function of lead input

Figure 4.22 Lead emissions as a function of chlorine input

The above statistical analysis of arsenic, beryllium and chromium emissions under various metal and chlorine input rates has confirmed that emissions of refractory metals are not increased by any increase in their inputs. This observation was derived from considering the results of refractory metals arsenic and chromium. The analysis also confirmed that emissions of semi volatile metals are moderately correlated with the metal input. The results of lead and cadmium were used to derive this observation. Thus for semi volatile metals, a correlation can be assumed between the metal emissions and metal input to extrapolate the data to different metal inputs. The above analysis further confirmed that the metal emissions are not affected by any increase in chlorine input except for chromium.

Percent of Metal Input Emitted with Stack Gas

One of the most useful measures of determining the potential for release of metal compounds by a cement kiln when burning waste derived fuels is to give the percent of the input metal that is emitted with stack gas. This section of the thesis reports the results of such analysis carried out using the compiled database. The percent of input emitted for these test runs was determined by dividing the total stack output by the total metal input and expressing as a percentage.

The Table 4.5 shows the total metal input data for 39 test runs with different metal input rates. The Table 4.6 shows the results of percentage of input metal determinations carried out for above mentioned test runs. The graphical representations of percentage of input metal for each individual metal are shown in Figs. B23 to B36 in Appendix B. The Table 4.7 and Fig. 4.23 summaries the metal input rates and the mean value of the percentage metal input emitted and the percentage of metals retained by process solids in the kiln system for that range.

Test	Arsenic	Beryllium	Cadmium	Chromium	Lead	Barium	Mercury	Silver	Antimony	Thallium	Nickel	Selenium	Vanadium	Zinc
A1	2.00E+00	8.42E-01	2.47E+00	2.69E+01	2.35E+01	1.75E+01	1.38E-02	2.35E-01	7.31E+00	1.14E-01	3.76E+00	1.15E-01		
A2	2.78E+00	1.56E+00	4.46E+00	4.80E+01	4.06E+01	2.33E+01	2.88E-02	3.01E-01	1.27E+01	2.53E-01	8.47E+00	1.63E+00		
B2	2.12E+00	1.68E-01	3.03E+00	1.15E+01	9.51E+00	1.13E+01	1.32E-01	1.38E-01	1.87E-01	9.07E-01				3.16E+01
B3	2.09E+00	1.44E-01	3.48E+00	1.10E+01	7.63E+00	1.24E+01	1.15E-01	1.92E-01	2.60E-01	1.09E+00				1.37E+01
C1	1.05E+01	1.43E+00	8.02E+00	5.14E+01	5.24E+01	1.80E+01	2.01E-02	2.72E-01	5.36E-01	1.94E-01				
F1	1.58E+00		3.30E-02	1.44E+00	7.50E+00	9.80E+00	5.50E-03				1.52E+00	7.00E-03	2.15E+00	3.84E+00
F2	2.02E+00		3.30E-02	2.30E+00	6.01E+00	6.88E+00	5.23E-03				1.50E+00	8.50E-03	2.48E+00	4.22E+00
F3	2.23E+00		3.30E-02	3.36E+00	2.57E+00	9.18E+00	5.30E-03				1.58E+00	6.40E-03	1.49E+00	2.58E+00
F4	2.60E+00		3.30E-02	1.54E+00	2.70E+00	9.82E+00	5.90E-03				1.38E+00	7.00E-03	1.80E+00	3.77E+00
F5	2.57E+00		1.31E-01	1.51E+00	4.64E+00	9.91E+00	6.80E-03				3.29E+00	8.45E-02	1.47E+00	2.48E+00
F6	2.68E+00		8.18E-02	2.36E+00	7.64E+00	5.59E+00	1.16E-02				1.82E+00	1.73E-02	1.53E+00	2.24E+00
F7	2.71E+00		5.65E-02	2.33E+00	5.29E+00	6.90E+00	7.50E-03				1.77E+00	1.66E-02	1.80E+00	6.35E+00
F8	2.60E+00		3.30E-02	1.54E+00	2.70E+00	9.82E+00	5.90E-03				1.38E+00	7.00E-03	1.80E+00	3.77E+00
F9	3.35E+00		2.71E-01	1.97E+00	9.08E+00	6.61E+00	3.77E-02				2.49E+00	2.06E-01	1.67E+00	3.31E+00
H1	2.15E+01	2.38E-01	5.43E-01	4.00E+00	7.85E+00	2.99E+01	2.01E-01	7.78E-02	1.05E+00	6.65E-01				
H2	2.96E+01	3.84E-01	5.67E-01	6.81E+00	1.71E+01	3.27E+01	1.18E+00	7.94E-02	1.90E+00	6.70E-01				
H3	2.01E+01	3.42E-01	7.71E-01	7.21E+00	9.53E+00	2.83E+01	8.23E-01	7.94E-02	2.10E+00	6.57E-01				
I1	3.85E-03	1.34E-04	2.11E-03	3.12E-02	1.97E-02									
I2	2.89E-03	1.25E-04	1.55E-03	3.22E-02	2.01E-02									
I3	2.24E-03	9.25E-05	1.24E-04	1.50E-02	2.32E-03									
J1	3.59E+00	2.46E-01	2.04E+00	1.22E+01	2.61E+01									
J2	3.18E+00	2.40E-01	2.07E+00	1.11E+01	3.11E+01									
J3	3.70E+00	2.62E-01	2.34E+00	1.13E+01	2.91E+01									
K1	4.30E+00	7.10E-01	1.11E+00	1.92E+01	2.58E+01									
K2	5.40E+00	6.40E-01	1.20E+00	1.84E+01	2.50E+01									
K3	5.10E+00	8.10E-01	1.01E+00	1.86E+01	2.58E+01									

TABLE 4.5 TOTAL METAL INPUT RATE (kg/hr)

Test	Arsenic	Beryllium	Cadmium	Chromium	Lead	Barium	Mercury	Silver	Antimony	Thallium	Nickel	Selenium	Vanadium	Zinc
L1	7.44E+00	1.17E+00	1.39E+00	4.51E+00	1.12E+01									
L2	7.42E+00	1.10E+00	1.39E+00	3.65E+00	1.11E+01									
M1	5.98E+00	2.71E-01	6.82E-01	7.56E+00	1.20E+01									
M2	5.62E+00	3.01E-01	8.96E-01	7.90E+00	1.03E+01									
M3	6.95E+00	3.28E-01	8.39E-01	9.05E+00	9.25E+00									
M4	6.42E+00	5.86E-01	1.17E+00	1.37E+01	1.86E+01									
M5	3.38E+00	4.88E-01	1.19E+00	1.07E+01	1.56E+01									
M6	8.61E+00	4.47E-01	1.04E+00	1.58E+01	1.57E+01									
P1	6.26E+00	5.03E-01	1.13E+00	1.67E+01	1.96E+01	1.52E+01	9.07E-03	7.08E-01	3.30E+00	4.27E+00				
P2	2.81E+00	5.90E-02	2.90E-01	1.37E+01	7.02E+00	6.51E+00	1.36E-02	2.61E+00	5.17E-01	5.90E-01				
Q1	6.29E+00	6.35E-02	3.36E-01	1.41E+01	1.58E+01	8.82E+00	9.07E-03	4.08E-02	3.45E+00	3.22E-01				
Q2	7.33E+00	9.53E-02	1.19E+00	2.63E+01	1.46E+01	1.42E+01	9.07E-03	8.16E-02	4.63E-01	5.13E-01				
Minimum	0.0022	0.0001	0.0001	0.0150	0.0023	5.5900	0.0052	0.0408	0.1870	0.1140	1.3800	0.0064	1.4700	2.2400
Maximum	29.6000	1.5600	8.0200	51.4000	52.4000	32.7000	1.1800	2.6100	12.7000	4.2700	8.4700	1.8300	2.4800	31.6000
Average	5.6005	0.4630	1.1938	11.0452	14.2095	13.9352	0.1260	0.4013	2.8144	0.8538	2.6327	0.1914	1.7989	7.0782
Std. Dev.	5.9435	0.4151	1.5302	11.5152	11.4006	7.9729	0.2937	0.6882	3.5644	1.0665	1.9993	0.4590	0.3126	8.3406

TABLE 4.5 TOTAL METAL INPUT RATE (kg/hr) CONT.

Test	Arsenic	Beryllium	Cadmium	Chromium	Lead	Barium	Mercury	Silver	Antimony	Thallium	Nickel	Selenium	Vanadium	Zinc
A1	0.024	0.064	1.305	0.01	1.161	0.082	55.459	0.064	0.015	1.768	0.041	5.059		
A2	0.01	0.014	0.154	0.003	0.215	0.015	23.435	0.083	0.005	0.489	0.01	0.045		
B2	0	0	0.002	0	0.001	0	0.124	0	0	0				0
B3	0	0	0	0	0.001	0	0.158	0	0	0				0.001
C1	0.007	0.035	0.645	0.048	0.675	0.071	0.266	0.084	0.02	1.774				
D1	0.031	0.014	0.418	0.002	0.468	0.095	28.087	0.263	0.137	0.277				
F1	0		0	0	0.16	0	2				0.061	71.429	0.011	0.146
F2	0.002		0	0	0.067	0	0.516				0.127	21.176	0	0.036
F3	0		0	0	0.093	0	0				0.032	3.125	0.001	0.054
F4	0		0	0	0.126	0	0				0	8.571	0	0.042
F5	0.001		2.977	0	0.028	0	1.25				0.013	3.905	0	0.069
F6	0.004		2.567	0	0.537	0	2.845				0	4.046	0	0.129
F7	0		0.832	0	0.246	0	0.573				0	1.265	0	0.01
F8	0		0.583	0	0.409	0	2.15				0	1.097	0	0.025
F9	0.001		1.253	0	0.562	0	4.244				0	28	0	0.057
H1	0.003	0.013	0.061	0.017	0.019	0.011	93.871	2.16	0.093	0.032				
H2	0.003	0.008	0.104	0.012	0.022	0.017	55.219	1.952	0.051	0.317				
H3	0.004	0.009	0.07	0.009	0.026	0.014	98.611	0.542	0.044	0.078				
I1	0.012	0.031	0.199	0.027	0.043									
I2	0.014	0.333	0.027	0.025	0.04									
I3	0.018	0.443	3.309	0.055	0.353									
J1	0.006	0.012	0.231	0.007	0.199									
J2	0.016	0.021	0.581	0.018	0.797									
J3	0.005	0.011	0.358	0.009	0.22									
K1	0.002	0.004	0.018	0.002	0.022									
K2	0.006	0.005	0.033	0.01	0.041									
K3	0.002	0.004	0.01	0.002	0.005									
L1	0.005	0.01	0.067	0.014	0.012									
L2	0.002	0.008	0.006	0.022	0.007									
L3	0.004	0.009	0.002	0.019	0.007									
M1	0.005	0.007	0.103	0.008	0.085									
M3	0.01	0.006	0.155	0.012	0.134									

TABLE 4.6 PERCENTAGE OF INPUT METAL THAT IS EMITTED (%)

Test	Arsenic	Beryllium	Cadmium	Chromium	Lead	Barium	Mercury	Silver	Antimony	Thallium	Nickel	Selenium	Vanadium	Zinc
M4	0.017	0.017	0.197	0.017	0.447									
M5	0.036	0.02	0.371	0.028	0.422									
P1	0.079	0.035	0.424	0.006	0.356	0.761	9.55	0.172	0.438	0.022				
P2	0.05	0.077	1.225	0.027	1.37	0.631	13.267	0.158	4.053	2.331				
Q1	0.042	0.328	0.78	0.006	0.795	0.311	12	1.289	0.461	1.008				
Q2	0.031	0.128	0.052	0.003	0.064	0.114	8.4	0.689	4.206	0.542				
Minimum	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.000	0.000
Maximum	0.079	0.443	3.309	0.056	1.370	0.761	98.611	2.160	4.206	2.331	0.127	71.429	0.011	0.146
Average	0.012	0.057	0.503	0.011	0.269	0.096	18.728	0.574	0.733	0.664	0.026	13.429	0.001	0.052
Std. Dev.	0.017	0.110	0.808	0.013	0.328	0.203	29.233	0.722	1.457	0.770	0.038	20.213	0.003	0.046

TABLE 4.6 PERCENTAGE OF INPUT METAL THAT IS EMITTED (%) CONT.

TABLE 4.7 SUMMARY OF INPUT METAL EMITTED (%)

METAL	INPUT (kg/hr)	% OF INPUT EMITTED	% OF INPUT RETAINED
Antimony	0.1870 to 12.7000	0.733 %	99.267
Thallium	0.1140 to 4.2700	0.664 %	99.336
Silver	0.0408 to 2.6100	0.574 %	99.426
Cadmium	0.0001 to 8.0200	0.503 %	99.496
Lead	0.0023 to 52.4000	0.269 %	99.722
Barium	5.5900 to 32.7000	0.096 %	99.904
Beryllium	0.0001 to 1.5600	0.057 %	99.945
Zinc	2.2400 to 31.6000	0.052 %	99.948
Arsenic	0.0022 to 29.6000	0.012 %	99.987
Chromium	0.0150 to 51.4000	0.011 %	99.988
Vanadium	1.4700 to 2.4800	0.001 %	99.999
Nickel	1.3800 to 8.4700	0.026%	99.974

Note: Mercury and selenium were excluded from this analysis due to the uncertainty of data.

Figure 4.23 Percentage of input metal emitted (%)

According to the above analysis, the percentage of input metal emitted for all the refractory metals (arsenic, beryllium, chromium, barium, vanadium, nickel and silver) is below 0.1% confirming that more than 99.9% of these metals are retained by the cement kiln process solids. The percent of input emitted for volatile and semi volatile metals (cadmium, lead, antimony and thallium) is below 0.75% confirming that more than 99.25 % of these metals are retained by the cement kiln process solids. Thus it can be concluded that for any metal added to the cement kiln with raw materials or waste derived fuels, less than 1% of the input will appear in the stack gas stream whilst more than 99% of the input will be retained by the cement kiln process solids.

Since the database used for above analysis consists of different kiln types with varying input rates, the above percentage of metal input results could be used to predict the metal output within the above mentioned input ranges knowing the metal input rate.

4.2.3.3 Distribution of Metals in Process Solids

The issues related to metals in process solids, cement clinker and cement kiln dust (CKD), are twofold. One issue is the concentration of metals in CKD and cement clinker and the second issue is the potential of the metals to leach from the CKD and cement product. The second issue is addressed in detail by the Portland Cement Association of the United States during a recent study (PCA, 1992). Extensive tests for trace metals in CKD and finished cement from 97 kiln systems throughout North America were carried out in this study to confirm that the results for leachability of metals from the CKD and cement product obtained for cement kilns burning only conventional fuel as opposed to those obtained for kilns using hazardous waste are not significant. It should be noted here that this study was undertaken to update and expand upon a study completed by the United States Bureau of Mines in 1982 (Haynes and Kramer, 1982) with similar

findings. Since the database compiled for the present study does not include the data on the potential of the metals to leach from CKD and cement clinker, the issue of leachability of metals will not be further addressed in this section. However, the first issue of metal concentrations in the CKD and cement clinker will be discussed in detail in the following section of the thesis.

The distribution of metals in the cement clinker and CKD is of some concern to those who oppose using cement kilns for waste management. In order to study this distribution, the database compiled in this study was used to determine the percentage of each metal in the cement clinker and CKD and to determine the CKD Metals/Clinker Metals ratio for the database. The CKD Metals/Clinker Metals ratio was determined by dividing the metal output rate (measured in kg/hr) in CKD by the metal output rate (measured in kg/hr) in the cement clinker. The results of this analysis is given in Table 4.8. The graphical representations of CKD Metals/Clinker Metals ratio for each metal under different tests are given in Figs. B37 to B50 in Appendix B. The average CKD Metals/Clinker Metals ratios are summarised in Table 4.9.

Test	Arsenic	Beryllium	Cadmium	Chromium	Lead	Barium	Mercury	Silver	Antimony	Thallium	Nickel	Selenium	Vanadium	Zinc
A1	0.296	0.256	25.366	0.237	72.069	0.346	0.283	1.309	0.3	0.617	0.246	4.046		
A2	0.29	0.268	10.635	0.213	61.778	0.247	0.257	0.157	0.298	0.325	0.16	2.762		
B1	0.18	0.05	0.07	0.02	0.27	0.07	0.72	0.21	0.13	40.26				0.08
B2	0.02	0.04	0.18	0.05	0.22	0.04	1.51	0.17	0.13	60.33				0.06
B3	0.02	0.04	0.17	0.03	0.13	0.04	1.11	0.11	0.11	43.16				0.04
C1	0.305	0.192	38.182	0.185	38.475	0.171	0.234	0.052	0.217	0.519				
D1	0.301	0.343	36.154	0.314	82.374	0.505	0.359	0.274	1.139	1.123				
E1	0.096	0.054	43.08	0.065	29.531	0.051	0.094	0.28	0.113	0.107				
F1	0.065		0.1	0.041	0.454	0.079	0.1				0.095	0.267	0.069	0.118
F2	0.058		0.083	0.078	0.302	0.055	0.096				0.409	0.093	0.076	0.06
F3	0.075		0.12	0.05	0.528	0.123	0.107				0.09	6	0.113	0.078
F4	0.054		0.112	0.045	0.234	0.067	0.104				0.051	2.357	0.19	0.158
F5	0.136		8.4	0.166	1.536	0.124	0.5				0.19	26.154	0.153	0.241
F6	0.089		1.6	0.066	1.026	0.2	0.481				0.134	6	0.222	0.222
F7	0.072		1.4	0.139	2.005	0.101	0.144				0.049	6.538	0.095	0.203
F8	0.2		1.8	0.162	3.09	0.055	1.25				0.271	47.5	0.161	0.478
G1	0.01		0.2	0.01	0.32	0.03	0.01				0.01	0.07	0.02	0.04
G2	0.01		0.2	0.01	0.25	0.01	0.01				0.01	0.07	0.01	0.01
G3	0.007		1	0.002	1.438	0.003	0.008				0.005	0.087	0.003	0.002
G4	0.068		11	0.022	6.746	0.051	0.064				0.063	0.857	0.086	0.093
G5	0.006		0.667	0.003	1.051	0.007	0.009				0.005	0.042	0.008	0.01
Minimum	0.006	0.040	0.070	0.002	0.130	0.003	0.008	0.052	0.110	0.107	0.005	0.042	0.003	0.002
Maximum	0.305	0.343	43.080	0.314	82.374	0.505	1.510	1.309	1.139	60.330	0.409	47.500	0.222	0.478
Average	0.112	0.155	8.596	0.091	14.468	0.113	0.355	0.320	0.305	18.305	0.119	6.855	0.093	0.118
Std. Dev.	0.104	0.116	13.847	0.087	26.653	0.121	0.427	0.381	0.324	23.571	0.114	12.597	0.070	0.118

TABLE 4.8 SUMMARY OF CKD METALS/CLINKER METALS RATIOS

TABLE 4.9 AVERAGE CKD METALS/CLINKER METALS RATIOS
METALS

Metal	Average	Std. Dev
Thallium	18.305	24.578
Lead	14.468	25.653
Cadmium	8.596	13.847
Selenium	6.856	12.597
Mercury	0.355	0.427
Silver	0.320	0.381
Antimony	0.305	0.381
Beryllium	0.155	0.116
Nickel	0.119	0.114
Zinc	0.118	0.118
Barium	0.113	0.121
Arsenic	0.112	0.104
Vanadium	0.093	0.070
Chromium	0.091	0.087

According to the above table, the volatile metals such as cadmium, lead, thallium and selenium tend to accumulate mostly in the CKD. However all the other refractory metals are incorporated mostly in the cement clinker.

Although the above results confirm that metals such as lead and cadmium concentrate more in the CKD, it is essential to investigate whether this

observation is attributed to the cement kilns burning waste derived fuels or whether this observation is true even under baseline conditions. In order to investigate this, the relevant data from test runs B1, B2 and B3 were extracted from the database. The test run B1 was conducted under baseline conditions while the test runs B2 and B3 were conducted using hazardous waste fuel and used tyres. The Figs. 4.24 and 4.25 illustrate that the metal concentrations in the CKD during the baseline conditions do not differ substantially from the metal concentrations in CKD when burning waste derived fuels (the waste/baseline metal ratios for metals arsenic, beryllium, lead, barium, silver and zinc are 0.11, 0.80, 0.48, 0.57, 0.52 and 0.50 respectively). The Figs. 4.26 and 4.27 show similar results for the metal concentrations for cement clinker. It should be noted that the high variation in zinc concentration is due to the use of waste tyres. Furthermore, the Figs. 4.28 and 4.29 illustrate that the CKD Metals/Clinker Metals ratio does not differ substantially from baseline conditions to waste fuel conditions. Therefore, it can be concluded that the use of solid and hazardous waste derived fuels in a cement kiln is not the determining factor in the metal concentrations of the CKD and cement clinker.

Figure 4.24 Comparison of metals in CKD during baseline test B1 and waste fuel test B2

Figure 4.25 Comparison of metal in CKD between baseline test B1 and waste fuel test B3

Figure 4.26 Comparison of metals in cement clinker between baseline test B1 and waste fuel test B2.

Figure 4.27 Comparison of metals in cement clinker between baseline test B1 and waste fuel test B3.

Figure 4.28 Comparison of CKD Metals/Clinker Metals ratio between baseline test B1 and waste fuel test B2

Figure 4.29 Comparison of CKD Metals/Clinker Metals ratio between baseline test B1 and waste fuel test B3

4.3 Destruction of Organics and Emissions of Products of Incomplete Combustion (PICs)

This section of the thesis will address the issue of destruction of organics and the emissions of PICs when burning solid and hazardous waste in cement kilns. In contrast to metals, which are limited in number and whose individual masses are conserved, the fate of organics fed into any combustion device could be very much more complex. The reason for this complexity is that many organic compounds fed into the kiln may react to form hundreds of species quite different in chemical structure from the original compound. However, with the available data, this section will attempt to address the main issues such as the destruction and removal efficiency (DRE) of organic compounds and the emissions of PICs, especially the emissions of dioxins and furans.

4.3.1 Construction of the Database for Organics

As with the concerns on metal emissions, much of the environmental concerns on the destruction of organics and emissions of PICs described in section 3.3.1 and 3.3.2 of the thesis are based on the results of test burns conducted in cement kilns during the 1970s and early 1980s. In order to make use of the improved technologies in cement production and the increased precision of scientific measurements during the late 1980s and early 1990s, the author surveyed all the major cement plants burning or planning to burn solid and hazardous wastes to obtain most recent data on the destruction of organics and the emissions of PICs. As a result of this survey, the following database shown in Table 4.10 was constructed:

TABLE 4.10 DATABASE OF CEMENT KILNS USING WASTE DERIVED FUELS (DESTRUCTION OF ORGANICS AND EMISSIONS OF PICs)

TEST	TYPE OF KILN	TEST CONDITION
A1 to A2	Wet process	Liquid waste
A3 to A4	Wet process	Baseline coal only
C1	Wet process	Liquid and solid waste
D1	Wet process	Liquid waste
D2	Wet process	Baseline coal only
E1	Wet process	Liquid and solid waste
E2	Wet process	Baseline coal only
H1	Dry process	Liquid waste
I1	Dry process preheater	Liquid waste
I2	Dry process preheater	Baseline coal only
L1 TO L3	Dry process	Liquid and solid waste
M1 TO M6	Wet process	Liquid waste
N1 TO N2	Wet process	Liquid and solid waste
P1	Semi dry process	Liquid and solid waste
P2	Dry process preheater	Liquid and solid waste
Q1 TO Q3	Wet process	Liquid and solid waste

4.3.2 Destruction of Organics

The determination of destruction and removal efficiency (DRE) is one of the criteria developed to assess the total destruction of organic compounds fed into any combustion device. The definition of DRE is given in section 2.4.2.1 of the thesis. The idea of DRE was initially developed to measure the destruction of organic hazardous wastes burnt in hazardous waste incinerators. The waste feed provides the main input of organic wastes for these incinerators. However, in a cement kiln organic compounds are present not only in the hazardous waste entering the kiln, but also in the kiln raw feed and the natural fuel. The values of DRE determined for cement kilns according to the definition of DRE do not take into account any contribution of organic compounds from the raw material feed. Since the raw materials enter the kiln at the cooler end additional amounts of volatile organics are more likely to be volatilised rather than destroyed. Therefore, the calculated DRE would be lower as a result of greater concentration of the organic compound in the stack gas. Therefore, extreme care should be taken when deciding on the principal organic hazardous constituents (POHCs) to determine the DRE values. Any organic material present in the raw material feed or the natural fuel should not be used as a POHC. The DRE values less than 99.99% recorded for the test burns conducted in the 1970s and 1980s could be attributed to above mentioned problem of DRE determination in cement kilns.

The Table 4.11 shows some DRE values extracted from the test burns conducted in the early 1990s.

TABLE 4.11 DESTRUCTION AND REMOVAL EFFICIENCIES FOR POHCs
(as percent)

TEST	1,1,1 trichloroethane	1,2,4 trichlorobenzene	Perchloroethylene
N1	99.99997	99.99996	99.99994
N2	99.99996	99.99996	99.99995
P1	99.996	99.99996	99.9995
P2	99.9996	99.99996	99.99993
Q1	99.9998	99.9999	99.99997
Q2	99.99995	99.99999	99.9998
Q3	99.9998	99.9998	99.9991

As shown, the DRE values reported are well in excess of 99.99% regulatory requirement for POHCs and even reaching excess of 99.9999% in most cases. It should also be noted that perchloroethylene and 1,1,1 trichloroethane in the above tests were pumped into the liquid waste derived fuel feed line prior to the burner pipe and 1,2,4 trichlorobenzene was added to cans containing inert substances and fed into the burning zone of the kiln along with the containers of solid hazardous waste fuel. Therefore, the above data illustrate that independent of the type of kiln and method of waste injection, the cement kilns can achieve greater than 99.99% DRE for most stable organic compounds. Thus, the argument put forward by the critics that organics are not destroyed properly in a cement kiln due to the deficiency of oxygen in the kiln cannot be justified from the above analysis. The extreme combustion conditions, high turbulence and long residence times in a cement kiln readily overcome any deficiencies in oxygen concentration to achieve DREs much greater than 99.99%.

4.3.3 Emissions of Products of Incomplete Combustion (PICs)

This section of the thesis will initially analyse the compiled database for the emissions of PICs other than chlorinated dibenzodioxins (PCDDs) and chlorinated dibenzofurans (PCDFs). The emissions of PCDDs and PCDFs will be addressed in detail in the subsequent section.

4.3.3.1 Emissions of PICs

There is very limited data in the compiled database for the emissions of PICs other than chlorinated dioxins and furans. The organic emissions in the database for PICs other than chlorinated dioxins and furans are divided into two major categories, namely the semi-volatile organic compounds and volatile organic compounds. The emissions of both categories during the waste burn test conditions and baseline coal only conditions are shown in Tables 4.12 and 4.13 below:

TABLE 4.12 EMISSIONS OF VOLATILE ORGANIC COMPOUNDS (g/hr)

Compound	Test D Base	Test D Waste	Ratio W/B	Test E Base	Test E Waste	Ratio W/B
Acetone	65.84	36.70	0.56	4.61	6.32	1.37
Carbon disulphide	542.33	596.85	1.10	54.01	46.37	0.86
Benzene	543.75	374.52	0.69	312.58	389.42	1.25
Toluene	536.11	236.57	0.44	89.42	84.95	0.95
Ethylbenzene	200.67	121.69	0.61	6.69	10.25	1.53

TABLE 4.13 EMISSIONS OF SEMI-VOLATILE ORGANIC COMPOUNDS
(g/hr)

COMPOUND	Test D Base	Test D Waste	Ratio W/B	Test E Base	Test E Waste	Ratio W/B
Pyridine	43.15	41.58	0.96	11.48	23.83	2.08
Phenol	618.39	749.11	1.21	43.45	73.22	1.69
Benzyl alcohol	22.16	13.15	0.59	1.08	1.06	0.98
Acetophenone	32.61	38.07	1.17	4.12	4.82	1.17
Benzoic acid	132.47	72.23	0.55	24.85	12.36	0.50
Naphthalene	194.99	195.85	1.00	23.95	21.02	0.88
2-methylnaphthalene	203.72	232.82	1.14	4.40	5.02	1.14
Dibenzofuran	73.24	77.29	1.06	6.25	10.92	1.75
Pyrene	32.53	24.23	0.74	0.61	1.34	2.20

As shown in Tables 4.12 and 4.13, the ratio of waste emissions/baseline emissions (W/B) was determined for each compound to investigate effect of waste combustion. The Figs. 4.30 and 4.31 show the W/B ratio for volatile organic compounds and semi-volatile compounds respectively. As shown, the volatile and semi-volatile compounds detected during waste burns were also detected during the coal only baseline operations. Noticeably, the volatile compounds benzene and toluene showed reduction in emissions when waste derived fuel was substituted for coal. This is an expected results as it is well known that benzene and toluene are PICs mainly from coal combustion. The results of Waste/Baseline ratio for volatile and semi-volatile organic compounds illustrate that the cement kilns burning waste derived fuel do not emit greater quantities of these PICs than the cement kilns burning only natural fuel such as coal. Thus, the

Figure 4.30 Waste/Baseline emissions ratio for volatile organic compounds

Figure 4.31 Waste/Baseline emissions ratio for semi-volatile organic compounds

waste derived fuel is not a contributing factor to the emissions of PICs other than chlorinated dioxins and furans.

4.3.3.2 Emissions of Chlorinated Dioxins and Furans

This section of the thesis will analyse the large database on the emissions of chlorinated dioxins and furans during 25 different test runs. These test runs include data from all the kiln types as well as data from waste burns and coal only baseline operations. As described in section 2.4.2.3 of the thesis, based on the number and position of chlorine atoms on the ring structure, it is possible to have 75 isomers of dibenzodioxins and 135 isomers of dibenzofurans. Of all these isomers 2,3,7,8-tetrachlorodibenzo-p-dioxin, commonly known as 2,3,7,8 TCDD, is the isomer of most concern. In order to assess the risks posed by isomers of dioxins and furans other than 2,3,7,8 TCDD isomer, a method was developed to convert all these isomers into an equivalent concentration of 2,3,7,8 TCDD. These equivalent factors of dioxin and furan isomers, known as "Toxicity Equivalent Factors (TEFs)" will be used in the data analysis of this section.

The Table 4.14 shows the emissions of chlorinated dioxins and furans converted to equivalent 2,3,7,8 TCDD emissions (referred to as "dioxins" in the subsequent sections) for different test runs against the waste input rate, chlorine input rate, emissions of carbon monoxide and total hydrocarbons and the kiln exit (or air pollution control device inlet) temperature. The database shown in Table 4.14 has following properties:

- * The data for dioxin emissions contains data from different types of kilns, different types and input rates of waste derived fuels and different chlorine input rates and kiln exit temperatures.

Test	Klin	Wastes	Rate t/d	Dioxins ng/dscm	Dioxins g/s	Chlorine kg/hr	CO ppm	THC ppm	O ₂ %	Temp deg C
A1	wet	L	5.44	0.0465	2.26E-09	110	140	18		244
A2		L	10.43	2.2457	1.59E-07	228	175	20		276
A3		base	0.00	0.0277	1.35E-09	12	140	17		243
A4		base	0.00	0.0600	4.28E-09	225	115	8		232
D1	wet	L	19.05	0.6710	8.29E-08	883	316	321	4.4	314
D2	wet	base	0.00	1.3734	1.76E-07	84	434	188	4.9	314
E1	wet	L+S	11.40	4.7159	2.83E-07	984	300	50	1.4	270
E2	wet	base	0.00	0.1750	1.01E-08	220	160	25	1.4	270
H1	dry	L	4.57	0.0570	2.86E-09	159	11	20		288
I1	dry/ph	L	3.20	0.5730	6.23E-08	83	156	25		264
I2	dry/ph	base	0.00	0.6880	7.21E-08	40	143	22		263
L1	dry	L+S	5.35	0.0550	8.33E-09	160	1966	98	6.9	266
L2	dry	L+S	5.35	0.0320	5.55E-09	190	2121	101	7.6	265
L3	dry	L+S	5.35	0.0880	1.38E-08	178	2098	101	9.4	260
M1	wet	L	4.89	6.5855	1.28E-07	289	748	6		282
M2	wet	L	4.71	2.9362	5.83E-08	248	751	6		285
M3	wet	L	4.80	3.0128	5.83E-08	208	850	6		282
M4	wet	L	7.70	3.9784	9.16E-08	301	573	11		256
M6	wet	L	7.80	2.7811	6.67E-08	355	384	9		260
Q1	wet	L+S	6.90	0.0036	1.07E-10	256				
Q2	wet	L+S	8.47	0.7199	1.93E-08	219				
Q3	wet	L+S	8.80	0.0046	2.01E-11	368				
P2	dry/pc	L+S	6.30	0.7000	3.15E-08	194				
Minimum			0.00	0.00	2.01E-11	12.00	11.00	6.00	1.40	232.00
Maximum			19.05	6.59	2.83E-07	984.00	2121.00	321.00	9.40	314.00
Average			5.67	1.37	5.82E-08	260.61	609.53	55.37	5.14	270.21

TABLE 4.14 DIOXIN EMISSIONS IN STACK GASES AS TOXICITY EQUIVALENT FACTORS

Note: ng/dscm = nanogram/dry standard cubic meter

- * The data for dioxin emissions were obtained from test burns conducted under worst case conditions and not from normal operational conditions. Therefore, the dioxin emissions recorded are as a result of maximum waste input rates, highest allowable chlorine input rates and maximum temperature that would be encountered in the air pollution control device.

The database for dioxins was initially investigated for the dioxin emissions from each test run (Fig. 4.32) and for a comparison of dioxin emissions between waste burn conditions and coal only baseline conditions (Fig. 4.33).

According to the database, the range of dioxin emissions recorded under worst case scenario is 0.0036 to 6.58 ng/dscm with an average value of 1.37 ng/dscm. The Table 4.15 compares these values with the dioxin emission data from other waste combustion systems.

TABLE 4.15 DIOXIN EMISSIONS FROM THERMAL DESTRUCTION FACILITIES (ng/dscm)

FACILITY TYPE	MINIMUM	MAXIMUM
Municipal waste incinerator	9.07	2628.9
Medical waste incinerator	7.59	435.18
Hazardous waste incinerator	0.30	17.7
Cement Kiln (worst case scenario)	0.0036	6.58

Source: Modified Dempsey and Oppelt (1993) Table XXII

According to the above table, the maximum dioxin rate recorded under worst case scenario for a cement kiln burning hazardous wastes is even lower than the minimum recorded for normally operated municipal waste incinerators and medical waste incinerators. Furthermore, the maximum value recorded is about

Figure 4.32 Emissions of dioxins for each test run

Figure 4.33 Dioxin emissions during waste burn and baseline tests

half of the maximum value recorded for a normally operating hazardous waste incinerator. Therefore, it is clearly evident that the emissions of dioxins from cement kilns burning wastes may be several orders of magnitude less than those typically reported for other waste combustion facilities.

According to the Fig. 4.33, the comparison of dioxin emissions from baseline coal only operations and waste fuel burn operations does not show any conclusive evidence that dioxin emissions increase during waste burn operations. Two test runs showed noticeable reductions in dioxin emissions when burning hazardous wastes while two other tests showed noticeable increases. The emissions for one test run showed no noticeable difference to baseline conditions when burning hazardous wastes. The initial assessment, therefore, from this figure is that burning hazardous waste is not a contributing factor to dioxin emissions. This observation will be further tested in the next section when a correlation between dioxin emissions and waste input rate will be examined.

Statistical Analysis of Dioxin Emissions

This section of the thesis reports and discusses the results of statistical analysis conducted on the correlation between dioxin emissions and kiln exit temperature, chlorine input rate, waste input rate, carbon monoxide emissions, total hydrocarbon emissions and oxygen concentration. The database shown in Table 4.14 was again used for this analysis. The procedure used to perform this statistical analysis is similar to the procedure used for metal emissions 4.2.3.2 of the thesis. As with the metal emissions, linear regression analysis was performed between the dioxin emissions and above mentioned variables. The output of the regression analysis results were then examined using null hypothesis test for any statistical significance. The Table 4.16 shows the results of the above regression analysis. The interpretation of the regression results shown in Table 4.16 for each variable is given below.

Regression Output:Dioxins/Temperature		Regression Output:Dioxins/Chlorine Input	
Constant	-3.753698	Constant	0.635600
Std Err of Y Est	1.943275	Std Err of Y Est	1.899899
R Squared	0.046995	R Squared	0.117202
No. of Observations	19	No. of Observations	19
Degrees of Freedom	17	Degrees of Freedom	17
X Coefficient(s)	0.019751	X Coefficient(s)	0.002904
Std Err of Coef.	0.021571	Std Err of Coef.	0.001933
Regression Output:Dioxins/ln(Temperature)		Regression Output:Dioxins/ln(Chlorine Input)	
Constant	-11.37912	Constant	-2.162297
Std Err of Y Est	1.812961	Std Err of Y Est	2.313596
R Squared	0.182322	R Squared	0.098707
No. of Observations	19	No. of Observations	19
Degrees of Freedom	17	Degrees of Freedom	17
X Coefficient(s)	0.039182	X Coefficient(s)	0.003212
Std Err of Coef.	0.020125	Std Err of Coef.	0.002354
Regression Output:log(Dioxins)/log(Temperature)		Regression Output:log(Dioxins)/log(Chlorine Input)	
Constant	-27.23400	Constant	-9.835071
Std Err of Y Est	0.781398	Std Err of Y Est	2.279130
R Squared	0.194855	R Squared	0.125360
No. of Observations	19	No. of Observations	19
Degrees of Freedom	17	Degrees of Freedom	17
X Coefficient(s)	11.06388	X Coefficient(s)	3.590233
Std Err of Coef.	5.458089	Std Err of Coef.	2.300020

TABLE 4.16 REGRESSION OUTPUT FOR DIOXIN EMISSIONS, TEMPERATURE, WASTE, CHLORINE, OXYGEN, THC AND CO

Regression Output:Dioxins/Waste Input		Regression Output:Dioxins/CO	
Constant	1.466364	Constant	-0.024779
Std Err of Y Est	2.033731	Std Err of Y Est	1.430165
R Squared	0.001571	R Squared	0.521543
No. of Observations	18	No. of Observations	15
Degrees of Freedom	16	Degrees of Freedom	13
X Coefficient(s)	0.021390	X Coefficient(s)	0.005612
Std Err of Coef.	0.134772	Std Err of Coef.	0.001490
Regression Output:Dioxins/ln(Waste Input)		Regression Output:Dioxins/ln(CO)	
Constant	-1.708709	Constant	-1.983519
Std Err of Y Est	2.449007	Std Err of Y Est	1.331876
R Squared	0.020387	R Squared	0.488621
No. of Observations	18	No. of Observations	15
Degrees of Freedom	16	Degrees of Freedom	13
X Coefficient(s)	0.093652	X Coefficient(s)	0.004893
Std Err of Coef.	0.162292	Std Err of Coef.	0.001388
Regression Output:log(Dioxins)/log(Waste Input)		Regression Output:log(Dioxins)/log(CO)	
Constant	-0.994098	Constant	-4.942958
Std Err of Y Est	1.067352	Std Err of Y Est	0.503695
R Squared	0.013445	R Squared	0.612223
No. of Observations	18	No. of Observations	15
Degrees of Freedom	16	Degrees of Freedom	13
X Coefficient(s)	0.666358	X Coefficient(s)	1.975483
Std Err of Coef.	1.426966	Std Err of Coef.	0.436051

TABLE 4.16 REGRESSION OUTPUT FOR DIOXIN EMISSIONS, TEMPERATURE, WASTE, CHLORINE, OXYGEN, THC AND CO CONT.

Regression Output:Dioxins/Oxygen		Regression Output:Dioxins/THC	
Constant	4.402819	Constant	2.205106
Std Err of Y Est	1.004788	Std Err of Y Est	2.177811
R Squared	0.756305	R Squared	0.004833
No. of Observations	6	No. of Observations	14
Degrees of Freedom	4	Degrees of Freedom	12
X Coefficient(s)	-0.563052	X Coefficient(s)	-0.012381
Std Err of Coef.	0.159805	Std Err of Coef.	0.051285
Regression Output:Dioxins/ln(Oxygen)		Regression Output:Dioxins/ln(THC)	
Constant	2.419256	Constant	-0.327093
Std Err of Y Est	1.027184	Std Err of Y Est	2.061593
R Squared	0.788361	R Squared	0.001541
No. of Observations	6	No. of Observations	14
Degrees of Freedom	4	Degrees of Freedom	12
X Coefficient(s)	-0.630611	X Coefficient(s)	-0.006608
Std Err of Coef.	0.163367	Std Err of Coef.	0.048548
Regression Output:log(Dioxins)/log(Oxygen)		Regression Output:log(Dioxins)/log(THC)	
Constant	1.243879	Constant	0.692405
Std Err of Y Est	0.480985	Std Err of Y Est	0.866889
R Squared	0.753966	R Squared	0.063985
No. of Observations	6	No. of Observations	14
Degrees of Freedom	4	Degrees of Freedom	12
X Coefficient(s)	-2.548838	X Coefficient(s)	-0.766166
Std Err of Coef.	0.728002	Std Err of Coef.	0.845928

TABLE 4.16 REGRESSION OUTPUT FOR DIOXIN EMISSIONS, TEMPERATURE, WASTE, CHLORINE, OXYGEN, THC AND CO CONT.

Effect of Kiln Exit Temperature

The impact on dioxin emissions due to variations in kiln exit temperature (ie. air pollution control device inlet temperature) is shown in Fig. 4.34. According to this figure, there is no clear correlation between the dioxin emissions and kiln exit temperature. This observation is further confirmed by the regression results in Table 4.16. According to these results only 4% of the variation in dioxin emissions can be explained by the increase in kiln exit temperature. At 95% confidence level the above correlation satisfied the null hypothesis test, statistically confirming that there is no correlation between the dioxin emissions and kiln exit temperature.

Although the data indicate no simple correlation exists between the kiln exit temperature and the dioxin emissions, the Fig. 4.34 shows an important observation. According to Fig. 4.34 the dioxin emissions decreases remarkably when the kiln exit temperature falls below 250°C and the kiln exit temperature exceeds 310°C. This observation is in agreement with the generally accepted theory that dioxins could reform at the temperature of 250 - 350°C, in the presence of chlorides, carbon compounds, fly ash and oxygen with a sufficiently long reaction times (Reimann, 1992). Therefore, if the kiln exit temperature or the temperature in the air pollution control device can be controlled below 250°C, it will be possible to reduce the dioxin emissions to levels even much lower than those recorded in the database.

Effect of Chlorine Input

The Fig. 4.35 shows the impact on dioxin emissions due to the variations in the chlorine input. According to this figure, there seems to be no relationship between the dioxin emissions and the chlorine input. In order to examine this further, the regression results reported in Table 4.16 was used. According to these results, only 1% of the variation in dioxin emissions can be explained by any increase in chlorine input. Furthermore, based on 95% confidence level, the

Figure 4.34 Correlation between the dioxin emissions and kiln exit temperature

Figure 4.35 Correlation between dioxin emissions and chlorine input

above correlation satisfy the null hypothesis test, thus confirming that there is no statistical correlation between the chlorine input and the dioxin emissions.

Effect of Waste Derived Fuel Input

The Fig. 4.36 shows the relationship between the dioxin emissions and waste fuel input. The figure does not indicate any firm correlation between the waste input and dioxin emissions. The regression results reported in Table 4.16 for this relationship confirms this observation. According to these results, no percentage of variation in dioxin emissions can be explained by any increase in waste fuel input, strengthening the previous observation that waste fuel substitution in a cement kiln is not a contributing factor to dioxin emissions. Based on 95% confidence level, the above relationship satisfied the null hypothesis test, thus confirming that there is no correlation between the dioxin emissions and waste fuel input.

Effect of Carbon Monoxide (CO)

The relationship between CO emissions and dioxin emissions is shown in Fig. 4.37. As shown, there is a clear relationship between the CO emissions and dioxin emissions. This observation was statistically tested using the regression results in Table 4.16. According to these results, nearly 50% of the variation in dioxin emissions can be explained by the increase in CO emissions. Based on the 95% confidence level, this relationship rejected the null hypothesis test, thus confirming a correlation between the CO emissions and dioxin emissions. The derived relationship is as follows:

*
$$\text{Dioxin Emissions (ng/dscm)} = (5.61\text{E-}03) \text{ CO Emissions (ppm)} - (0.025)$$

Figure 4.36 Correlation between dioxin emissions and waste input rate

Figure 4.37 Correlation between dioxin emissions and CO emissions

Effect of Total Hydrocarbon (THC) Emissions

The Fig. 4.38 shows the relationship between the dioxin emissions and THC emissions. The figure does not indicate any correlation between dioxin emissions and THC emissions. This observation was statistically tested using the regression results in Table 4.16. According to these results, no percentage of the variation in dioxin emissions can be explained by any increase in THC emissions. Based on the 95% level of confidence, the above relationship satisfied the null hypothesis test, thus confirming no correlation between the dioxin emissions and THC emissions.

Effect of Oxygen Concentration

The relationship between dioxin emissions and kiln oxygen concentrations is shown in Fig. 4.39. The figure shows a clear decrease in dioxin emissions when the oxygen concentration are high. This observation was statistically tested using the regression results in Table 4.16. According to these results about 75% of the total variation in dioxin emissions can be explained by the oxygen concentration. Based on 95% confidence level, the above relationship rejected the null hypothesis test confirming a negative correlation between dioxin emissions and oxygen concentration.

The foregoing analysis clearly illustrates that the dioxin emissions correlate only with the combustion conditions (such as CO emissions and oxygen concentration) in the kiln and not with the parameters such as chlorine input and waste fuel input. Thus, the completeness of combustion has a major influence on dioxin emissions rather than the type of cement kiln or the type of fuel used in the cement production process.

Figure 4.38 Correlation between dioxin emissions and THC emissions

Figure 4.39 Correlation between dioxin emissions and kiln oxygen concentration

4.4 SUMMARY

The metal analysis of input process streams (ie. raw material feed, natural fuel such as coal and waste derived fuel) has identified three types of metals entering the cement kiln. They are highly volatile metals such as mercury and thallium, semi-volatile metals such as cadmium, lead, antimony and selenium and refractory or non-volatile metals such as silver, arsenic, barium, beryllium, chromium and nickel. The above analysis also identified that the raw material feed as the principal source of metals input to the kiln. The metals input which may be attributed to natural fuel such as coal was identified to be arsenic, barium, mercury, vanadium and zinc. The metals which may be attributed to waste derived fuels were identified to be cadmium, chromium, lead and nickel. As the metal composition of kiln input streams could vary from plant to plant, the study highlighted the importance of characterising the metal distribution in kiln input streams prior to any conclusion made on the metal emissions.

From the available data, this section of the thesis has identified that the correlation of metal input and metal emissions will largely depend on the type of metal under considerations. For refractory metals, the metal emissions are not increased by any increase in their inputs. Thus, no correlation was found between the refractory metal emissions and refractory metal inputs. However, for semi-volatile metals a moderate correlation was found between the input and the emissions. The semi-volatile metal emissions tend to increase linearly with the increase in metal input. The study also confirmed that there is no correlation between the chlorine input and the metal emissions.

The database of metal emissions was analysed to determine the percent of metal input that is emitted with stack gas stream. The emissions of refractory metals were found to be less than 0.1%, thus indicating that more than 99.9% of these metals are retained by the cement kiln. The analysis for semi-volatile metals

indicated that the emissions were less than 0.75%, thus confirming that more than 99.25% of the semi-volatile metals are retained by the cement kiln. These data confirm that for any metal added to the cement kiln via raw materials, natural fuels or waste derived fuels, only less than 1% of the input will appear in the stack gases while over 99% of the input is retained by the cement kiln.

The analysis of metal concentrations in cement clinker and cement kiln dust indicated that although the semi-volatile metals such as lead and cadmium tend to concentrate more on the cement kiln dust rather than cement clinker, the use of waste derived fuels in a cement kiln is not the determining factor for high metal concentrations in the cement kiln dust. The analysis also indicated that all the refractory metals are incorporated mostly in the cement clinker.

The analysis of the database for the destruction of organics found that cement kilns can achieve DRE values well in excess of 99.99% regulatory requirement and even reaching 99.9999% in most cases. It was noted that extreme combustion conditions in cement kiln combined with high turbulence and long residence times readily overcome any oxygen deficiencies to achieve very high destruction levels even for the most stable organics.

The database for organic compounds was analysed in detail for the emissions of products of incomplete combustion (PICs), specially for chlorinated dioxins and furans. The analysis of PICs other than dioxins and furans indicated that waste derived fuel is not a contributing factor to the emissions of such PICs. The emissions recorded for dioxins/furans from cement kilns burning waste derived fuels under worst case scenarios were very much lower than the dioxin/furan emissions from municipal solid waste incinerators, medical waste incinerators or hazardous waste incinerators. The study also found that burning hazardous wastes in a cement kiln is not a contributing factor to dioxin/furan emissions. It was shown that the completeness of combustion has a major influence in dioxin/furan

emissions and not the type of cement kiln or the substitution natural fuel by waste derived fuels.

CHAPTER FIVE

ASSESSMENT OF SOCIAL CONCERNS

5.1 INTRODUCTION

The assessment of social concerns is one of the most important segments of a successful implementation of any project. It is important to address the social concerns of using cement kilns for managing hazardous waste fuel as most of the neighbours around the cement plants have lived co-operatively with the plant management for many years. Any negligence of social concerns may tarnish this well earned reputation. Two of the main public concerns on using cement kilns for hazardous waste management is the potential effects to human health and the risks associated with the transport of such wastes to the plant. In this section of the thesis, both of these social concerns will be addressed in detail. Having addressed the social concerns with valid scientific data, the next major task is to convey this information to the general public. The final section of this chapter will describe the techniques that can be used to get the public involved in the implementation of the project.

5.2 POTENTIAL EFFECTS TO HUMAN HEALTH

The potential effects to human health due to any industrial process is of major concern to the general public as persons exposed to high concentrations of air emissions or industrial products can experience adverse health effects. The potential effects to human health due to cement production process may occur as a result of human exposure to cement plant emissions. In addition, humans may also be exposed to hazardous chemicals during the transportation of hazardous wastes to the cement kiln.

5.2.1 Cement Plant Emissions

The potential health effects due to cement plant emissions may occur from both the emissions from kiln stack and the fugitive emissions around the plant. The components of cement kiln stack emissions that may cause human health effects can be broadly categorised as organic chemicals, metals and particulates. The organic compounds include products of incomplete combustion such as dioxins and furans and volatile organic compounds (VOCs). The metals of concern include arsenic, beryllium, cadmium and chromium which are considered as potential carcinogens and antimony, barium, lead, mercury, silver and thallium which are considered as toxic noncarcinogens. From these metals, lead is considered to be the metal of most concern from the public point of view. The emissions of particulates through the cement kiln stack is also of public health concern due its harmful effects from excessive inhalation and also due to the toxic metals and organic chemicals which may get adsorbed to dust particles.

Kelly (1992) notes that despite decades of operations and extensive public exposure to cement plant emissions, the evidence of problems with local public health has not been sufficient enough to initiate any major studies to examine the effects on public health of burning either conventional or hazardous waste fuel. Kelly (1992) also observes that the lack of initiation to conduct such major health studies may be partly due to the low rate of occupational illness in the cement industry in the United States (24.8 incidences of occupational illness per 10,000 workers) compared to average incidences of occupational illness rate of 108.3 per 10,000 workers for all the other types of manufacturing industry. However, with the increased use of hazardous waste fuels in cement kilns, the public is very much concerned about the potential effects to human health due to chemicals and metals emitted from cement kilns burning hazardous waste as supplementary fuel. The main assumption made in this renewed concern is that cement plants burning

hazardous waste emit much greater amounts of potentially toxic chemicals than those using only conventional fuel. In order to investigate the validity of this assumption, the author surveyed all the major cement plants presently burning or planning to burn hazardous wastes to obtain any information on the human health risk assessment studies conducted in their kilns. The information gained from this survey is described below:

a) Human Health Risk Assessment for the Southdown, Inc., Cement Kiln, Fairborn, Ohio, USA.

This assessment evaluates human health risks associated with the operating conditions involving coal only and coal supplemented with hazardous waste fuel at the Southwestern Portland Cement's (SWPC) Fairborn cement kiln, which is capable of treating 29,000,000 litres of hazardous waste fuel annually. The human health risk assessment was conducted in four stages as described below:

- Stage 1 Determination of the nature and amount of toxic chemicals that could potentially be released during waste fuel use at the SWPC facility, and selection of those chemicals of greatest concern to human health.

- Stage 2 Identification of health effects potentially associated with the chemicals of potential concern and determination of relationships between exposure to the chemicals and the expected human health effects.

- Stage 3 Mathematical modelling to determine the amounts of chemicals released to which individual humans may be exposed. The pathways selected for exposure included inhalation, incidental ingestion of outdoor soil, ingestion of locally produced agricultural products and ingestion of drinking water.

Stage 4 This final step involves calculation of the probability that an adverse health effect may result from exposure to the chemicals of potential concern

The risk assessment reported here was conducted according to the United States regulatory guidelines using conservative assumptions. The purpose of using conservative assumptions is to ensure that data gaps in the exposure and toxicology do not lead to an underestimation of health risks. Therefore, the final risk estimates presented in this assessment overestimate the exposures and risk, and in fact, are near to or higher than the upper end of the range of actual exposure and risks.

The human health risk assessment in this study relied primarily on the guidelines developed by the United States Environmental Protection Agency. According to these guidelines, the emission testing and dispersion modelling conducted in a facility must ensure that the hypothetical maximum exposed individual (MEI) is not subjected to a chemical concentration that would result in a lifetime cancer risk greater than 1 in 100,000 (1×10^{-5}). The MEI in this case is assumed to reside at the location of maximum possible exposure for 24 hours per day, 365 days per year over a 70 year lifetime.

In this risk assessment, the individual lifetime excess cancer risks for stack emissions (coal supplemented with hazardous waste fuel) ranged from 1 in 100 billion (1×10^{-11}) for groundwater ingestion to 2 in 1 million (2×10^{-6}) for inhalation. The individual lifetime cancer risk for inhalation of fugitive emissions from the plant associated with hazardous waste fuel storage and handling was 9 in 100 million (9×10^{-8}). In summary, this risk assessment revealed that the individual excess lifetime cancer risk for stack emissions associated with exposures to all potential carcinogens via all pathways combined was 2 in 10 million (2×10^{-7}) for coal only baseline operations and 3 in 10 million (3×10^{-7})

for coal with hazardous fuel operations. The assessment estimated that these overall risks are less than the risk of lung cancer associated with smoking two cigarettes over a 70 year lifetime.

b) Health Risk Assessment for Continental Cement Kiln, Hannibal, Missouri, USA.

In this study, the United States Environmental Protection Agency conducted a health risk assessment for the emissions of dioxins from the Continental Cement Kiln in Hannibal, Missouri. The evaluation was based on dioxin stack analysis from four different test runs where different materials were burnt in the kiln. The first and fifth runs represented baseline where coal and coal/diesel fuel, respectively, were used. In the third and fourth runs (the second run was aborted), hazardous waste fuel was used. The procedure used for the health risk assessment was similar to the procedure described for the previous study.

Based on the conservative assumptions, the study found that the lifetime cancer risks exceeded 1 in 1,000,000 only at the MEI and one of the elevated terrain locations for any of the runs. The MEI baseline cancer risks for a coal only run were 0.67 in 1,000,000 and were 2.3 in 1,000,000 for the coal and diesel fuel run. The risks to the MEI for the two kiln runs where hazardous waste fuel was burnt were approximately 2 to 4 in 1,000,000.

The above health risk assessment studies clearly indicate that the public's risk of developing cancer from cement kiln emissions, irrespective of burning hazardous wastes or conventional fuel, is less than 3 in 1,000,000. The United States Environmental Protection Agency and many other regulatory agencies usually consider any health risk near or below 1 in 1,000,000 as below the level of concern for any regulation. These risk levels have not been regulated and even health risks up to 1 in 10,000 are seldomly regulated. Therefore, the human

health risks from cement kiln emissions during the burning of hazardous wastes are considerably below the levels of acceptable risk by most regulatory standards. Furthermore, the above analysis indicates that the potential health effects from cement kilns using hazardous wastes as supplementary fuel are not expected to be different from those that could be confronted from burning conventional fuel only.

5.2.2 Health Risks Associated with Transportation of Waste

The activities involving hazardous wastes always involve some health risk that such wastes will be released to the environment. These risks are the same types of risks that are involved in the transportation of chemicals and conventional fuels to the commercial and domestic activities. According to Mantus (1991), the data available in the United States do not support the claim that use of hazardous waste fuel in cement kilns will significantly increase the health risks to local residents due to transportation spills and accidents. The statistics provided by the United States Department of Transportation for the 10 year period ending in 1990 has indicated that hazardous wastes accounted for only 2.9% of all hazardous materials releases (hazardous materials include all the hazardous wastes as well as hazardous materials consumed by industry and the conventional fuel such as gasoline), 2.3% of the damages and most importantly only 0.8% of all the deaths and injuries attributed to transportation of hazardous materials. These statistics further indicate that there was only one accident reported due to interstate hazardous waste incidents during the above 10 year period. The two main reasons given by Mantus (1991) for this low incidence rate due to transportation accidents involving hazardous wastes are a) hazardous wastes are generally spent or diluted byproducts and not concentrated raw materials, which make them inherently less hazardous than most hazardous materials spilled and b) hazardous waste transport is more highly regulated than normal hazardous materials such as gasoline. Therefore, it is very much evident that health risks are unlikely to increase due to

the transportation of hazardous wastes to cement kilns since these kilns are already accepting shipments of commercial fuel which are designated as hazardous materials.

5.3 PUBLIC INVOLVEMENT

The chapters four and five of this thesis address the environmental and social concerns of managing solid and hazardous wastes in cement kilns. The evidence indicated by both of these chapters from analysing valid scientific data is that properly operated cement kilns do not pose a greater risk to the environment and public health when conventional fuel is supplemented by hazardous waste fuels. Such evidence alone is not sufficient to successfully implement this technology unless these findings are conveyed to the general public in an effective way. As seen in chapter 3 of the thesis, the environmental interest groups such as Greenpeace are constantly providing the public with misleading information on the use of cement kilns in waste management by drawing parallels with commercially operated waste incinerators (refer to Greenpeace, 1989). Therefore, if the plant management anticipate implementing this technology in their cement kilns, it is essential to convey the genuine scientific facts on cement kiln incineration to the general public, politicians and interest groups and involving them in the entire implementation process. This section of the thesis will address the techniques of getting public involved and how to communicate risks of using cement kilns in waste management to the general public effectively.

5.3.1 Public Education

Public involvement for any process is a two way communication that involves both providing information to the public (public education) and getting information such as ideas, issues and concerns back from the public (public consultation). The public described here is not a single entity but includes general

public, politicians and many interest groups that make up various segments of the public. Therefore, one of the initial steps in public involvement process is to define the public who will be affected by or having an interest on the use of hazardous waste fuels in cement kilns.

The majority of the public who will get involved in the above process will be the people who live in the immediate vicinity of the cement plant. This group will be very much interested in the public involvement process because they sense using hazardous waste fuel in their vicinity as a threat to the neighbourhood through factors such as depreciating property values, increased noise and air pollution and possible health risks. The second major group of public who will get involved in the process may be local and national environmental groups. This group is mainly interested on the health risks associated with the stack emissions as well as on the impact of using cement kilns for managing solid hazardous wastes on the waste minimisation and recycling programs. The third major group who will be interested in the process is the government officials at local, state and national level. The fourth and one of the most vital groups to be involved in the public consultation process is the media. Above the general interest shown by the media to get involved in the public consultation process, there are several advantages to the plant management by getting the media involved in the entire process of the implementation. In addition to these four major public groups various other interest groups and associations ranging from business and industry organisations to residents should also be considered for the public involvement process. Once a decision is made on the composition of the public to be involved in the process, then it is necessary to develop techniques for the public involvement.

As described above, the public education process is the first part of public involvement process. In this process the actual scientific facts on the use of

cement kilns for managing solid and hazardous wastes are conveyed to the public using different techniques. This section will describe some of the techniques that can be used in the public education process. One of the initial steps that can be undertaken in this regard is to brief key government officials or group leaders to announce the decision of the plant management to investigate the use of hazardous waste fuel in their cement kiln. This can be achieved through a personal visit or a telephone call. This initial step has the advantage of alerting key personal to issues that may affect them and more importantly it will enable the plant management to determine the initial reactions prior to going public. This initial step will also avoid any bitterness developing between the key officials, politicians in particular, and the plant management by not creating any situation where the key officials are informed about the proposal through newspapers or local residents. Once the real facts are conveyed to the key officials and regulatory agencies, they are in a position to answer the questions raised by the environmental groups and general community.

Once the key officials and group leaders have been informed about the intention of the project, it is now necessary to make contact with the media. A media person should be invited to the plant and should be briefed on the technology and the future plans to use this technology in the cement plant. One of the most effective ways of educating the media personnel on the technology is provide a media kit. The media kit should contain all the relevant facts such as cement manufacturing process, technology and benefits of using cement kilns in waste management, the environmental and social issues such as fate of pollutants and potential health risks and the present experience with this technology elsewhere. Apart from inviting media personnel to the plant, it is also wise idea to identify other reporters or editors who will be interested in the project and arrange to drop in at their office and hand deliver the press kit and also answer any questions on the spot. It is vital to inform and educate the media during the initial stages of the public involvement process before the environmental groups supply

the media with misleading data. If the reporters are given the press kit during the initial stages they will also be in a position to answer any queries made by the community in an authoritative way. The ideal result of this exercise is to motivate media personal to write a feature article on the proposed project which will stimulate interest in the general public or to provide the plant management with an opportunity to participate in a news conference which will reach the general public via the national radio or television.

Once the key officials in the government and regulatory agencies and media have been informed about the project, it will be now necessary to reach the most actively involved citizens in the community to brief them about the project. This can be achieved by mailing out key scientific reports to the leaders of organised groups and interests, including business, environmental or neighbourhood organisations. At this stage it is also necessary to establish an organisational structure to address the issues going to be raised by the public. The public education can be further strengthened by making visual presentations (such as slide or video demonstrations) to groups such as community groups and environmental groups on a regular basis. Establishment of a newsletter is an another step to educate the most interested people on a continuous basis.

5.3.2 Public Consultation

Once the necessary steps have been taken to educate the public on the project, the next step in the public involvement process is to provide opportunities for the public to express their feelings and concerns on the project.

Coles (1988) reports of an ideal makeup of an organisational structure used at the St. Lawrence Cement plant in Mississauga, Ontario, Canada for the public involvement process. The structure consists of three main groups and the full organisational structure is ultimately responsible to the St. Lawrence Cement

Company. The three groups are as follows:

- * Project Steering Committee
- * Community Liaison Committee
- * Project Study Group

Each group mentioned above has a key function in the development of the project. The project steering committee mainly consisting of the officials from cement company, consulting engineers, research organisations, lawyers, media and communication personnel develops and reviews the technical information required for the project as well as the strategy required for the progress of the project. The community liaison committee is comprised of representatives of local citizen groups, the local environmental groups and local citizens who have an interest in the project. The prime function of this group is to communicate with community at large. This committee receives all the information with respect to the progress of the project and in return the committee provides the feedback from the community. The community liaison committee can nominate 3 representatives to sit on the project study group. The project study group consists of representatives from cement company, community liaison committee and local and regional municipal staff and is chaired by an independent but knowledgeable chairperson. This group is charged with the responsibility of producing recommendations with respect to the development of the overall project. The project study group reviews the details of all documentation that is prepared, recommends other studies to be undertaken and reviews all reports that are prepared. This group has the decision making power and their recommendations with respect to the project will be received and reviewed by the company.

There are other techniques as well to obtain feed back from the public. One of them is the formation of focus groups. These groups are small discussion groups

established to give the typical reactions of the community at large. Ideally the focus group should be conducted by a trained facilitator who is capable of drawing out people's reactions to the project. Another technique to gather public opinion is to organise an open house at the plant. This open house may consist of an afternoon of free food and soft drinks, plant tours and an opportunity for the public to meet and ask questions from the plant management and plant employees. The plant tour should be an ideal finale for the public who attended the slide and video presentations as they are able to obtain first information on the plant operation. One very important factor to consider prior to organising any plant tours or open houses is that all the employees at the plant should be well briefed on the project. This has the added benefit of giving an opportunity to plant employees to air their views and concerns on the project which in turn could be used to fine tune the process before going public.

A widely advertised phone number (hotline) may also be useful in obtaining in the public involvement process. This phone number can act as a two way communication tool. By dialling this number, the public will be able ask questions as well as convey their comments on the project. The key to the success of this method will depend on the knowledge of the person receiving the calls on all aspects of the project. One of the other popular method of getting public involved in the project is to conduct public hearings. These are formal meetings where public gather in a certain location and present their views on the project. Alternatively, less formal public meetings could be held enabling all the individuals present to express their views. Conducting fact-to-face interviews with key public officials, interest group leaders or key individuals from the community may also be effectively used to obtain the public opinion. Although these interviews cannot be substituted for the meetings mentioned above, most of the time face-to-face interviews could produce valuable information which is difficult to obtain from other methods.

The above section described several options for public education and public participation in the implementation of a project. The success of a public involvement process, however, will largely depend on how these may be combined to prepare a successful public involvement plan. It is important for the plant management to allocate all the necessary resources for this public involvement process since an unsuccessful public involvement process will definitely lead to a termination of the project.

5.4 SUMMARY

In summary, the analysis of health risks associated with the use of hazardous waste fuel as supplementary fuel in the cement industry has shown that the lifetime cancer risk of an individual assumed to reside at the location of maximum possible exposure for 24 hours per day, 365 days per year over a 70 year lifetime is only few in a million. This risk was noted to be less than the risk of lung cancer associated with smoking two cigarettes over 70 year lifetime. The analysis of data on risks involved in transportation of hazardous waste to cement plants has revealed that transportation of hazardous materials such as hazardous chemical consumed by the industry and conventional fuel such as gasoline pose far greater risk to the human health than transporting hazardous wastes.

The public involvement was identified as a vital component in addressing the public concerns of using cement kilns for managing hazardous waste fuel. It was noted that the public education and public consultation should be combined to form a successful public involvement process. There are several techniques available for public education and public consultation. However, the plant management should carefully review all these techniques and select the most effective combinations to suit its needs.

CHAPTER SIX

ASPECTS OF IMPLEMENTATION IN AUSTRALIA

6.1 INTRODUCTION

The technology of using cement kilns to manage solid and hazardous is being studiously ignored in Australia as several aspects of its implementation are not being addressed at present. This chapter will address some of the aspects of implementing this technology in Australia. The first section of the chapter will address the problem of estimating the solid and hazardous waste generation in Australia followed by the structure of the cement industry in Australia. The final sections of the chapter will attempt to identify and present suggestions to overcome the constraints related to the implementation of this technology in Australia.

6.2 WASTE GENERATION IN AUSTRALIA

6.2.1 Solid Wastes

The principal sources of solid wastes can be broadly classified as domestic, commercial and industrial, demolition and council solid wastes. The domestic solid wastes include normal household wastes such as kitchen waste, garden wastes and some hazardous wastes such as mercury batteries and pesticides. The commercial and industrial wastes include solid wastes such as food scraps and paper packaging generated from shops, offices, hotels and restaurants. The demolition solid wastes are generally demolition rubble and offcuts from building construction activities. The sources of council wastes include street sweepings and tree prunings. The special wastes such as waste tyres are also categorised as solid wastes.

Australia's Solid Waste Problem

In the recent years, the increasing quantity of solid wastes generated by our consumer based society has caused increased concern to local councils, government departments dealing with the environment and the community in general. The decreasing capacities of presently used landfills have added more to these concerns. According to an Industry Commission (1990) report, Australia generates 12.8 million tonnes of solid wastes annually, which is equivalent to about 800 kg per person per year of solid wastes. According to this report, Australia relies heavily on landfill for disposal of its solid wastes. Approximately 96% of the solid wastes generated in Australia are currently landfilled and the remaining 3% being recycled and 1% being incinerated.

Australia is not yet facing a critical shortage of landfill space but the Industry Commission (1990) notes that the provision for future landfill capacity is inadequate. The report estimates that Australia has about 12 years of capacity remaining in present landfills which is equivalent to about 190 million tonnes of solid wastes. The report also notes that the capacities remaining in major capital cities may be much lower. For example, Melbourne has only five years of landfill capacity at the present generation rate of solid wastes. Therefore, the problem of solid waste disposal in Australia is an inescapable problem.

Solid Waste Generation in Australia

The data available for solid waste generation in Australia is not fully consistent or reliable. The reason for this situation is that solid waste data has been recorded only recently in some areas because most of the landfill sites were not equipped with weighbridges and therefore had no method of accumulating waste data. Furthermore, the solid waste data available for a particular state mainly consists of solid waste generated in capital cities as most states do not collect comprehensive data for the whole state. However, some estimates of solid wastes generated in individual states and capital cities are currently available.

Quantities of Solid Wastes

Industry Commission (1990) reports that New South Wales produced 6.9 million tonnes of solid wastes in 1988. In 1989, there were some 3.4 million tonnes of solid waste generated in the Sydney region alone at a rate of 1.13 tonnes per person. The Waste Management Authority of New South Wales (1990) notes that solid waste quantities are increasing, both in total terms and per capita basis, that if the present rates are allowed to continue the annual solid wastes generated in Sydney region would increase to 5.5 million tonnes by year 2001 and 7.1 million tonnes by year 2011. According to Pym and Perram (1992), Sydney is rapidly consuming its available landfill capacity. They estimate that all the approved solid waste landfill sites in the Sydney region could be full in approximately six years.

The solid wastes generated in other major capitals are estimated in different studies. A study undertaken by Sinclair Knight Consulting Engineers (1991) to estimate the solid wastes generated in Perth reports that in 1991 Perth metropolitan area produced about 1 million tonne of solid wastes at a rate of 0.93 tonnes per person. The Department of Environment and Land Management of South Australia (1993) estimates that during 1992 Adelaide metropolitan area produced 1.14 million tonnes of solid wastes at a rate of 1.08 tonnes per person. During 1988, the Brisbane City Council conducted a detailed study of the Brisbane metropolitan waste stream characteristics by surveying over 70% of the Brisbane metropolitan area. Durkin and Davis (1989) reports from this study that Brisbane City Council collected 0.6 million tonnes of solid wastes in 1988 at a rate of 0.8 tonnes per person. Hubick (1991) reports that solid wastes generated in Melbourne during 1991 was 4.1 million tonnes at a rate of 0.8 tonnes per person. A summary of these solid waste data is given in Table 6.1.

**TABLE 6.1 GENERATION OF SOLID WASTES IN MAJOR
CAPITAL CITIES IN AUSTRALIA**

City	Quantity (t/y)	Rate (t/y/p)	Study year
Sydney	3.4	1.13	1989
Melbourne	4.1	0.8	1991
Brisbane	0.6	0.8	1988
Adelaide	1.14	1.08	1992
Perth	1.0	0.93	1991

Note: t/y = tonnes/year and t/y/p = tonnes per year per person

According to the above data, the average per capita production of solid wastes in Australian major capital cities is approximately 0.9 tonnes per year per capita or 900 kg per person annually.

In addition to the amounts of solid wastes mentioned above, disposal of used tyres also adds to the problem of solid wastes in Australia. According to Australian and New Zealand Environmental Council (1991), Australia generates about 14 million used tyres annually which is equivalent to one used tyre per person per year. At present, over 90% of the used tyres generated in Australia are deposited (stored) in landfills.

Composition of Solid Wastes

The composition of solid wastes in Australia is periodically monitored by sampling the solid wastes in waste bins. The Table 6.2 indicates composition of solid wastes for different capital cities in Australia.

TABLE 6.2 COMPOSITION OF SOLID WASTES IN CAPITAL CITIES IN AUSTRALIA (as percent weight)

(Source: Hubick, 1991)

City	Putrescible	Paper	Glass	Plastic	Metals	Other
Adelaide (1986)	40%	27%	13%	9%	6%	5%
Adelaide (1991)	47%	24%	8%	7%	5%	9%
Perth (1989)	56%	23%	7%	9%	4%	2%
Canberra (1989)	44%	19%	14%	10%	5%	7%
Brisbane (1989)	42%	30%	7%	12%	6%	3%
Melbourne (1975)	45%	26%	15%	3%	8%	3%
Melbourne (1985)	43%	21%	16%	10%	6%	4%
Sydney (1989)	48%	21%	9%	8%	6%	8%
AVERAGE	46%	24%	11%	8%	6%	5%

According to the above data, the major components in solid waste generated in capital cities are putrescible wastes and paper products, which make up about 70% of the solid waste.

The study conducted by the Brisbane City Council and reported by Durkin and Davis (1989) included an analysis of combustibility of the solid waste stream. The study concluded that 77.7% of the solid waste stream is combustible.

6.2.2 Hazardous Wastes

Hazardous wastes may arise from many areas including industrial and manufacturing processes, hospitals and research establishments. The hazardous waste streams could include wastes such as chlorinated organic wastes, including polychlorinated biphenyls (PCBs) and related compounds, mineral oils from oil processing industry, toxic metals and cyanides from various metal treating and fabrication industries, arsenic bearing wastes from the smelting and refining of some ores, distillation wastes, solvents, pharmaceutical, hospital and research wastes and pesticides. The hazardous wastes generated by the industrial and manufacturing processes is by far the largest source of generation.

Although it is not easy to define hazardous wastes in a simple and yet comprehensive way, in general they exhibit characteristics of corrosivity, flammability, explosivity or toxicity and if disposed of untreated to land, water or atmosphere may have harmful effects to the humans and the environment. Therefore, the hazardous wastes are unsuitable for disposal to the sewerage system or to the solid waste landfills and needs special management systems to protect the human health and the environment from the effects of improper disposal of these wastes.

Australia's Hazardous Waste Problem

The safe management of hazardous wastes is becoming a serious problem not only in Australia but also in much of the developed and third world. The concern over the safe disposal of hazardous wastes has originated due to the public's increased understanding and concern for the value and fragility of our environment and steady growth of industrial activities giving rise to more and more hazardous wastes requiring proper disposal.

In Australia, the chemical wastes can be generally classified into three groups. They are a) hazardous wastes, b) intractable wastes and c) non-BAT wastes. The hazardous wastes are defined as any wastes containing significant quantities of substances dangerous to the life or health of living organisms when released to the environment or to the safety of humans or equipment if incorrectly handled (Joint Task Force, 1990). The intractable wastes (now renamed as "scheduled wastes") are a subset of hazardous wastes for which there are at present no environmentally acceptable (to the public) disposal facilities in Australia. These wastes include all the chlorinated organic wastes such as organochlorine pesticides, PCBs, hexachlorobenzenes (HCBs), chlorofluorocarbons (CFCs) and halons. These scheduled wastes are currently being stockpiled awaiting safe destruction. The last group, non-BAT wastes, are principally those hazardous organic wastes currently being landfilled. These wastes include paint and resin residues, organic solvents, non organochlorine pesticides and some other organic chemicals. Since these hazardous wastes are not presently disposed using the "best available technology" (BAT), these wastes are classified as non-BAT wastes. However, it would be preferable to permanently destroy these hazardous wastes rather than sending to landfills. It is clear from the above description that Australia's hazardous waste problem is far worse than the hazardous waste problems in other developed world where facilities exist for safe disposal of such wastes. Presently, Australian industry generates large amounts of hazardous wastes for which there is no proper disposal facilities. Furthermore, Australia has a large amount of hazardous wastes stockpiled around the country awaiting destruction. Storing these hazardous without permanently destroying them represents an unacceptable risk to the Australian society, either through the danger of food chain contamination or the risk of uncontrolled warehouse fires. Therefore, the most critical hazardous waste problem faced by Australia is to find a suitable method to permanently destroy the hazardous wastes stockpiled around the country and the hazardous wastes that are generated daily by the industry. So far most of the attempts by the Australian government to find a solution to this

problem have gained little success. A proposal to construct a high temperature incinerator in Corowa, New South Wales was abandoned due to overwhelming public opposition (McDonell, 1991). There are number of innovative techniques such as biological and chemical treatment of hazardous wastes which are being tested at the moment. However, none of these processes have been adequately developed for large scale use. All these emerging technologies may take many years before they are ready for full scale operation. Furthermore, most of the emerging technologies also suffer from a disadvantage in that they are currently tested for simple and pure chemicals such as pure liquid PCBs. Once in full scale operation, these technologies would have to deal with highly complex mixtures of wastes from the real industry. Therefore, while there is some uncertainty of the successful operation of some of the emerging technologies during full scale operations, Australia's hazardous waste storage keeps increasing daily posing increased risk to the humans and the environment.

Quantities of Hazardous Wastes

The real quantities of hazardous wastes generated in Australia are not widely available due to the low priority given to such wastes in the past. The statistics for hazardous wastes in Australia should include the quantities of hazardous wastes that are presently stockpiled and the quantities that are generated on daily basis. Due to the increased attention given by the Australian government to the management of intractable wastes during last 3-4 years, most of the data available are for such wastes.

According to findings by the "Independent Panel on Intractable Wastes" (1992), the earlier estimates available of intractable wastes dispersed throughout Australia are unreliable and the real quantities of intractable wastes have been underestimated. Earlier, the Joint Task Force (1990) estimated the following quantities of intractable wastes in Australia:

- * Approximately 1,800 tonnes of PCBs are in use or storage throughout New South Wales and Victoria.
- * Approximately 10,500 tonnes of hexachlorobenzenes (HCBs) are in storage at ICI's chemical plant at Botany, New South Wales.
- * Approximately 1,800 tonnes of organochlorine pesticides (OCPs) are in storage throughout Australia, mainly in New South Wales and Victoria.
- * Approximately 80,000 tonnes of chlorofluorocarbons (CFCs) are in use throughout Australia.

The Joint Task Force estimated that the total quantity of known intractable wastes in Australia in 1990, either in use or storage, is approximately 94,100 tonnes with an annual generation rate of 402 tonnes.

The Independent Panel on Intractable Wastes made the following estimates for intractable wastes in Australia:

- * The best estimate of the total quantity of intractable wastes in New South Wales is about 102,000 tonnes, the great majority of which is the gross mass of PCB contaminated equipment. The gross mass of PCB intractable waste in New South Wales is about 24,000 tonnes with a net PCB content of about 6,800 tonnes.
- * An estimated 1,485 tonnes of packaged organochlorine pesticides (mainly DDT, dieldrin and aldrin) are stockpiled in New South Wales.
- * More than 87,000 tonnes of soil in New South Wales and several million tonnes Australia wide may have been contaminated through use of organochlorine pesticides on agricultural crops.
- * Currently, an estimated 4,600 tonnes of chlorofluorocarbons (CFCs) are in use in Australia. Also an estimated 1,300 tons of halons (which are CFCs that also contain bromine) are in use in Australia.

- * An estimated 9,329 tonnes of hexachlorobenzenes (HCBs) remains to be managed at the ICI plant in Sydney.

The quantities of hazardous waste described above mainly belong to the intractable waste category. In addition, there are large quantities of solid and liquid industrial wastes that are generated daily by the Australian manufacturing industry. Again, no accurate data on such wastes are widely available. It is estimated that the production of solid hazardous wastes could include the millions of tonnes of mine tailings and toxic sludges that results from mining operations annually (Hubick, 1991). It is also estimated that in Sydney alone, the amount of solid hazardous industrial wastes generated annually amounts to about one million tonnes each year (State Pollution Control Commission, 1987).

Although an accurate assessment of the quantities of industrial hazardous generated in Australia is not widely available, it is possible to gain an indication of the order of magnitude of the problem by making use of the relationship between production of certain goods and the generation of hazardous wastes. The main industry groupings known to be mostly responsible for the production of hazardous wastes in Australia are described below.

The main manufacturing industries that contribute to the hazardous waste stream in Australia are as follows:

- * Food industry which includes meat products, milk products, fruit and vegetable products, flour and cereal food products, beverages and malt products and tobacco products.
 - * Textile industry which includes textile fibres, yarns, woven fabrics and other textile products.
 - * Clothing industry which includes knitting mills, clothing and footwear products.
-

- * Wood industry which includes wood and wood products, furniture and mattress production.
- * Paper industry which includes paper and paper products, printing, publishing and allied industries
- * Chemical industry which includes basic chemicals and other chemical products, petroleum refining products, petroleum and coal products.
- * Non metal industry which includes glass and glass products, clay products and refractories, cement and concrete products and other non metallic products.
- * Basic metal industry which includes basic iron and steel, basic non ferrous metals and non ferrous metal basic products.
- * Fabricated metal industry which includes structural and metal products, sheet metal products and other fabricated metal products.
- * Transport industry which includes motor vehicles and parts and other transport equipment.
- * Other machinery industry which includes photographic equipment, scientific equipment, appliances and electrical equipment and industrial machinery and equipment.
- * Miscellaneous manufacturing industry which includes leather and leather products, rubber products, plastic and related products and other manufacturing products.

The Bureau of Statistics (1991) has compiled data on the number of establishments of above industries and their annual turnover on a State by State basis. These basic data were used in this section to determine the percentage of distribution of above industries on a State by State basis. Since the number of establishments of above industries are not directly correlated to the amount of hazardous wastes generated, due to their difference in output capacities, the percentages determined in this section considered their annual turnover as well. The Tables 6.3 and 6.4 show the determined percentages for each State. The

data shown in Tables 6.3 and 6.4 were used in this section to estimate the amount of hazardous wastes potentially generated by the Australian manufacturing industry.

The Victorian Environmental Protection Agency (1985) conducted a comprehensive survey of the amounts of hazardous wastes generated by the Victorian manufacturing industry. The study concluded that Victorian industry produces about 100,000 m³ of potentially hazardous wastes which is equivalent to 25 kg of industrial hazardous wastes per person annually. The study also determined the breakdown of type and origin of the industrial hazardous waste stream as shown in Table 6.5.

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	1074 27.0%	1159 29.2%	762 19.2%	413 10.4%	382 9.6%	138 3.5%	20 0.5%	24 0.6%	3972 100.0%
Textiles	283 29.5%	387 40.3%	122 12.7%	71 7.4%	73 7.6%	19 2.0%	4 0.4%	1 0.1%	960 100.0%
Clothing	902 35.3%	1144 44.7%	271 10.6%	132 5.2%	93 3.6%	11 0.4%	1 0.0%	3 0.1%	2557 100.0%
Wood	2045 30.4%	1920 28.6%	1251 18.6%	537 8.0%	669 9.9%	228 3.4%	30 0.4%	45 0.7%	6725 100.0%
Paper	1844 39.3%	1457 31.0%	592 12.6%	299 6.4%	348 7.4%	71 1.5%	24 0.5%	59 1.3%	4694 100.0%
Chemicals	444 39.3%	370 32.7%	141 12.5%	73 6.5%	86 7.6%	16 1.4%	1 0.1%	0 0.0%	1131 100.0%
Non Metals	539 32.0%	462 27.4%	285 16.9%	148 8.8%	178 10.6%	40 2.4%	18 1.1%	17 1.0%	1687 100.0%
Basic Metals	280 34.6%	266 32.9%	120 14.8%	61 7.5%	58 7.2%	17 2.1%	5 0.6%	2 0.2%	809 100.0%
Fabricated Metals	2461 37.1%	1813 27.4%	1049 15.8%	516 7.8%	591 8.9%	131 2.0%	47 0.7%	20 0.3%	6628 100.0%
Transport	583 28.9%	578 28.6%	400 19.8%	174 8.6%	227 11.2%	35 1.7%	12 0.6%	9 0.4%	2018 100.0%
Other Machinery	2106 36.8%	1814 31.7%	657 11.5%	468 8.2%	537 9.4%	91 1.6%	17 0.3%	27 0.5%	5717 100.0%
Misc. Manufacturing	1335 35.6%	1194 31.8%	581 15.5%	293 7.8%	264 7.0%	54 1.4%	19 0.5%	15 0.4%	3755 100.0%
TOTAL	13896 34.2%	12584 30.9%	6231 15.3%	3185 7.8%	3506 8.6%	851 2.1%	198 0.5%	222 0.5%	40653 100.0%

TABLE 6.3 DISTRIBUTION OF INDUSTRIES IN AUSTRALIA ACCORDING TO NUMBER OF ESTABLISHMENTS (No)
Source: Australian Bureau of Statistics (1991)

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	10518 30.1%	10532 30.1%	7289 20.8%	2813 8.0%	2502 7.2%	1149 3.3%	100 0.3%	69 0.2%	34972 100.0%
Textiles	1213 30.0%	1952 48.3%	168 4.2%	402 9.9%	160 4.0%	149 3.7%			4044 100.0%
Clothing	1807 36.4%	2438 49.2%	301 6.1%	317 6.4%	71 1.4%	26 0.5%			4960 100.0%
Wood	2553 32.6%	1977 25.3%	1312 16.8%	727 9.3%	717 9.2%	462 5.9%	17 0.2%	62 0.8%	7827 100.0%
Paper	5743 38.8%	4977 33.6%	1578 10.7%	867 5.9%	708 4.8%	804 5.4%	28 0.2%	87 0.6%	14792 100.0%
Chemicals	8517 36.6%	8179 35.1%	2833 12.2%	1425 6.1%	2333 10.0%				23287 100.0%
Non Metals	2670 35.5%	1890 25.1%	1438 19.1%	550 7.3%	710 9.4%	151 2.0%	45 0.6%	61 0.8%	7515 100.0%
Basic Metals	7835 38.5%	3661 18.0%	3975 19.5%	1516 7.4%	3384 16.6%				20371 100.0%
Fabricated Metals	4389 34.9%	3898 31.0%	1941 15.5%	851 6.8%	965 7.7%	155 1.2%	360 2.9%		12559 100.0%
Transport	2575 16.5%	7556 48.4%	828 5.3%	4137 26.5%	363 2.3%	118 0.8%	12 0.1%	8 0.1%	15597 100.0%
Other Machinery	6966 42.6%	5644 34.6%	1137 7.0%	1636 10.0%	820 5.0%	75 0.5%	8 0.0%	48 0.3%	16334 100.0%
Misc. Manufacturing	3036 35.6%	3429 40.2%	756 8.9%	849 9.9%	407 4.8%	50 0.6%	7 0.1%	5 0.1%	8539 100.0%
TOTAL	57822 33.9%	56133 32.9%	23556 13.8%	16090 9.4%	13140 7.7%	3139 1.8%	577 0.3%	340 0.2%	170797 100.0%

TABLE 6.4 DISTRIBUTION OF INDUSTRIES IN AUSTRALIA ACCORDING TO ANNUAL TURNOVER (\$ MILLION)

Source: Australian Bureau of Statistics (1991)

TABLE 6.5 DISTRIBUTION OF HAZARDOUS WASTES BY INDUSTRY TYPE

Source: Environment Protection Authority of Victoria (1985)

Type of Industry	Hazardous Wastes (%)
Fabricated Metal Products	34.2%
Chemicals, Petroleum and Coal Products	16.9%
Paper, Paper Products, Printing and Publishing	14.3%
Food, Beverages and Tobacco	11.7%
Textiles	10.5%
Basic Metal Products	7.5%
Transport Equipment	3.8%
Miscellaneous Manufacturing	0.4%
Other Machinery and Equipment	0.3%
Wood, Wood Products and Furniture	0.2%
Non-metallic Mineral Products	0.1%
Clothing and Footwear	0.1%

The basic information contained in the above Tables was used in the present study to determine the percentage of hazardous wastes generated by the Australian industry on a State by State basis and then to estimate the amount of hazardous wastes generated by each industry. The Tables 6.6 and 6.7 show the distribution of industrial hazardous wastes produced by each state determined as a percentage of total industrial hazardous wastes generated in Australia and based on number of establishments and annual turnover respectively.

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	3.2%	3.4%	2.2%	1.2%	1.1%	0.4%	0.1%	0.1%	11.7%
Textiles	3.1%	4.2%	1.3%	0.8%	0.8%	0.2%	0.0%	0.0%	10.5%
Clothing	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Wood	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Paper	5.6%	4.4%	1.8%	0.9%	1.1%	0.2%	0.1%	0.2%	14.3%
Chemicals	6.6%	5.5%	2.1%	1.1%	1.3%	0.2%	0.0%	0.0%	16.9%
Non Metals	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Basic Metals	2.6%	2.5%	1.1%	0.6%	0.5%	0.2%	0.0%	0.0%	7.5%
Fabricated Metals	12.7%	9.4%	5.4%	2.7%	3.0%	0.7%	0.2%	0.1%	34.2%
Transport	1.1%	1.1%	0.8%	0.3%	0.4%	0.1%	0.0%	0.0%	3.8%
Other Machinery	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Misc. Manufacturing	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
TOTAL	35.3%	30.9%	14.9%	7.6%	8.4%	2.0%	0.5%	0.4%	100.0%

TABLE 6.6 DISTRIBUTION OF INDUSTRIAL HAZARDOUS WASTES PRODUCED BY EACH STATE AND AUSTRALIA
(as a percentage of total industrial hazardous wastes in Australia and based on number of establishments)

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	3.5%	3.5%	2.4%	0.9%	0.8%	0.4%	0.4%	0.0%	11.7%
Textiles	3.1%	5.1%	0.4%	1.0%	0.4%	0.4%	0.0%	0.0%	10.5%
Clothing	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Wood	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Paper	5.6%	4.8%	1.5%	0.8%	0.7%	0.8%	0.0%	0.1%	14.3%
Chemicals	6.2%	5.9%	2.1%	1.0%	1.7%	0.0%	0.0%	0.0%	16.9%
Non Metals	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
Basic Metals	2.9%	1.3%	1.5%	0.6%	1.2%	0.0%	0.0%	0.0%	7.5%
Fabricated Metals	12.0%	10.6%	5.3%	2.3%	2.6%	0.4%	1.0%	0.0%	34.2%
Transport	0.6%	1.8%	0.2%	1.0%	0.1%	0.0%	0.0%	0.0%	3.8%
Other Machinery	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
Misc. Manufacturing	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
TOTAL	34.3%	33.5%	13.5%	7.8%	7.7%	2.0%	1.0%	0.1%	100.0%

TABLE 6.7 DISTRIBUTION OF INDUSTRIAL HAZARDOUS WASTES PRODUCED BY EACH STATE AND AUSTRALIA
(as a percentage of total industrial hazardous wastes in Australia and based on turnover)

The Tables 6.8 and 6.9 show the estimated generation of industrial hazardous waste by each state and in Australia based on number of establishments and annual turnover respectively. The Figs. 6.1 and 6.2 illustrate the distribution and amount of industrial hazardous wastes generated by each state and Australia. According to this analysis, the total estimated industrial hazardous wastes generated in Australia is 400,000 tonnes per year.

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	12654	13656	8978	4866	4501	1626	236	283	46800
Textiles	12381	16931	5337	3108	3194	831	175	44	42000
Clothing	141	179	42	21	15	2	0	0	400
Wood	243	228	149	64	80	27	4	5	800
Paper	22471	17755	7214	3844	4241	865	292	719	57200
Chemicals	26538	22115	8428	4363	5140	956	60	0	67600
Non Metals	128	110	68	35	42	9	4	4	400
Basic Metals	10383	9864	4450	2262	2151	630	185	74	30000
Fabricated Metals	50794	37420	21651	10650	12198	2704	970	413	136800
Transport	4391	4354	3013	1311	1710	264	90	68	15200
Other Machinery	295	254	92	65	75	13	2	4	800
Misc. Manufacturing	711	636	309	156	141	29	10	8	2000
TOTAL	141131	123501	59731	30543	33486	7956	2029	1622	400000

TABLE 6.8 ESTIMATED GENERATION OF INDUSTRIAL HAZARDOUS WASTES IN EACH STATE AND AUSTRALIA (tonnes)
(based on number of establishments)

Description	NSW	VIC	QLD	SA	WA	TA	NT	ACT	AUSTRALIA
Food	14075	14094	9754	3764	3348	1538	134	92	46800
Textiles	12598	20273	1745	4175	1662	1547	0	0	42000
Clothing	146	197	24	26	6	2	0	0	400
Wood	261	202	134	74	73	47	2	6	800
Paper	22208	19246	6102	3353	2738	3109	108	336	57200
Chemicals	24724	23743	8224	4137	6772	0	0	0	67600
Non Metals	142	101	77	29	38	8	2	3	400
Basic Metals	11538	5391	5854	2233	4984	0	0	0	30000
Fabricated Metals	47808	42459	21143	9270	10511	1688	3921	0	136800
Transport	2509	7364	807	4032	354	115	12	8	15200
Other Machinery	341	276	56	80	40	4	0	2	800
Misc. Manufacturing	711	803	177	199	95	12	2	1	2000
TOTAL	137062	134149	54096	31371	30621	8070	4181	450	400000

TABLE 6.9 ESTIMATED GENERATION OF INDUSTRIAL HAZARDOUS WASTES IN EACH STATE AND AUSTRALIA (tonnes)
(based on annual turnover)

Figure 6.1 Percentage of industrial hazardous wastes generated by each state

Figure 6.2 Estimated generation of industrial hazardous wastes in each state and Australia

Further to the hazardous waste types described above, the disposal of waste lubricating oil without alteration or treatment to the land, sea or other waterways is regarded as environmentally hazardous to some degree. The waste lubricating oil is generated from variety of applications including motor vehicle engines, transmissions, bearings and hydraulics, cutting and polishing, heat transmission and electrical equipment such as transformers. According to Australian and New Zealand Environmental Council (1991), an estimated 262 megalitres of waste oil is generated annually in Australia from which the industry collects about 91 megalitres (ie. about 35%) of this quantity and the remainder is disposed by the generator.

6.3 CEMENT INDUSTRY IN AUSTRALIA

The first Australian cement was produced in 1882 near Brighton, South Australia. Since then, the several other cement plants were established around Australia where easy access to raw materials, fuel and market to cement product were available. Since major market areas in Australia have always been the capital cities where the population has been concentrated, most of the Australian cement kilns are located near capital cities. At present there are 12 cement producing plants scattered around Australia operating a total of 22 cement kilns. Each State in Australia has at least one cement plant with larger States having two or more. The distribution of cement plants around Australia is shown in Fig. 6.3.

Based on a recent survey conducted by the Bureau of Industry Economics (1992), the cement production in Australia peaked during 1989-90 period with an annual production reaching 7 million tonnes. The cement production in Australia has fallen since then to about 5.6 million tonnes at present. The Table 6.10 shows the State by State distribution of the cement plants and their locations, rated capacity of cement clinker production, the number of kilns and the process used. The Fig. 6.4 illustrates the distribution of cement plant capacities in Australia.

TABLE 6.10 STATE BY STATE DISTRIBUTION OF CEMENT PLANTS
AND THEIR PRODUCTION CAPACITIES

Source: Bureau of Industry Economics (1988 and 1992)

State	Plant Location	Capacity ('000 tonnes)	No. of Kilns	Process
NSW	Berrima	1180	2	Dry & Wet
	Kandos	400	2	Dry
	Maldon	300	1	Wet
Victoria	Waurm Ponds	500	1	Dry
	Geelong	640	3	Wet
Queensland	Darra	270	1	Wet
	Gladstone	550	1	Semi Dry
S. Australia	Angaston	250	2	Wet
	Birkenhead	480	1	Dry
W. Australia	Rivervale	260	3	Wet
	Coogee	310	4	Wet
Tasmania	Railton	550	1	Dry

Figure 6.4 The State by State distribution of cement plant capacities (Bureau of Industry Economics, 1992)

6.3.1 Opportunities for Managing Wastes

The cement manufacturing process and the technology related to managing solid and hazardous wastes in cement kilns were described in detail in the sections 2.2 and 2.3 of the thesis. This section of the thesis will investigate the opportunities in Australia to manage wastes in cement kilns.

According to the previous section of the thesis, there are twenty two (22) cement kilns in Australia presently under operation of which seven (7) are dry process kilns and fifteen (15) are wet process kilns. The wet process kilns require more fuel energy than the dry process kilns. The wet process kilns typically require about 6.0 gigajoules (GJ) of fuel energy per one tonne of clinker produced whereas the dry cement kilns require only about 4.5 GJ/tonne of clinker. Based on these information, the total annual fuel energy demand by the Australian

cement industry to produce 5.6 million tonnes of cement clinker is approximately 29.3 million gigajoules. This energy demand is equivalent to about 1 million tonne of coal per year assuming an energy content of coal about 30.2 GJ/tonne of coal.

According to section 6.2.2 of the thesis, the total estimated hazardous wastes generated by the Australian industry is about 400,000 tonnes per annum. The energy content of these industrial wastes vary according to the source, but typically the energy content exceeds 10,000 BTU/pound (23.27 GJ/tonnes) for all the industrial hazardous wastes. Therefore, the lower estimate of the energy available from the Australian industrial hazardous waste is approximately 9.2 million gigajoules. Therefore, if the cement industry in Australia replaced 31% of its conventional fuels with hazardous wastes it could have disposed of 100% of the industrial hazardous wastes generated by the Australian manufacturing industry. Furthermore, the cement industry would have also saved about 300,000 tonnes of coal.

The distribution of cement kiln fuel demand in each State of Australia and the energy content available from the industrial hazardous wastes in each State (based on the estimated industrial hazardous wastes generated by each State in Table 6.9 of section 6.2.2 of the thesis) are shown in Fig. 6.5.

Figure 6.5 The State by State distribution of cement kiln fuel energy demand and energy available from industrial hazardous waste

6.4 CONSTRAINTS FOR IMPLEMENTATION

This section of the thesis will attempt to identify some of the constraints for implementation of cement kiln technology to manage solid and hazardous wastes in Australia. The section will initially identify the constraints followed by some suggestions to overcome the same.

6.4.1 Identification of Constraints

In Australia, most of the constraints that exist for implementation of cement kiln technology to manage wastes are similar to the constraints encountered during an implementation of any incineration process to dispose solid and hazardous wastes. Some of these constraints are listed below:

- * The general public and the environmental groups consider using cement kilns for managing solid and hazardous wastes is similar in every aspect to commercial incineration of such wastes in Australia.
- * Although there are some estimates of the quantities of solid and hazardous wastes generated in Australia, the complete profile of such wastes including the waste characteristics is not yet available.
- * The cement companies may consider managing hazardous wastes in their kiln could pose additional responsibility on the company and the cement product would be affected due to managing hazardous wastes. These concerns may initially inhibit the implementation of this technology.
- * At present there are no regulations imposed by an organisation like the Commonwealth Environmental Protection Agency to manage solid and hazardous wastes in cement kilns.

From the constraints described above, the constraints due to public perception should be considered having top priority. Unless the general public, the politicians and the environmental groups are totally convinced about the benefits of this technology, it will be nearly impossible to implement this technology. The next section of the thesis will attempt to address the constraints mentioned above.

6.4.2 Overcoming the Constraints

Public Perception

Addressing the public concerns prior to implementation of any project involving cement kilns and waste management should be regarded as an essential component rather than an option in the implementation process. The public, politicians and the environmental groups consider incineration as an unclean process producing majority of the offensive chemicals that are deteriorating the environment and human health. Furthermore, it is common practice by the above groups to draw parallels between the commercial incineration process and the

process of managing wastes in cement kilns because both processes utilise high temperature to burn the wastes. In addition to all these factors, the public has a great fear of burning wastes based mainly on the misinformation provided by the environmental groups and general media. Thus overcoming these deep rooted thoughts within the public and the environmental groups is an enormous task under any standards.

One of initial steps that should be taken to transform the public perception on cement kiln incineration is to educate the public, politicians and environmental groups on the whole process of manufacturing cement and how the cement kilns could be used to manage the wastes in our society. A clear message should be given that there are fundamental differences between managing wastes in cement kilns and commercial incinerators. There are several ways to conduct this education process. One of the most effective ways to generate interest among the public, politicians and the environmental groups is to organise an international conference to bring together the world's experience on this technology and provide an opportunity to the above groups to participate in an open forum. The KILNBURN'92 conference is a perfect example of such an exercise.

The KILNBURN'92 - An international conference on the role of cement kilns in waste management was held on September 10-11, 1992 in Brisbane, Australia. The conference conceived and planned by Professor Philip H Jones, Head of Environmental Engineering at Griffith University, was organised by the Waste Management Research Unit of Griffith University with support from the Cement Industry Federation of Australia. The conference attracted speakers and attendees from over 13 countries with the total registrations numbering up to 165. The author performed an active role in the planning and organisation of the conference being in the organising committee.

The objectives of the KILNBURN'92 conference were as follows:

- * Creation of a climate favourable to the introduction of using cement kilns for waste management in Australia.
- * Provide evidence to the public, media and the politicians in Australia that there are inexpensive, safe, environmentally sound and proven technologies available to solve Australia's waste problems.
- * To bring together the world's experts in using cement kilns for waste management to describe their routine use of wastes as supplementary fuels.
- * Promote media exposure to this technology and encourage their assistance with the change of community perceptions necessary prior to the introduction of this technology in Australia.

The conference was thoughtfully organised to include experiences from different parts of the world and also to attract representatives from all the vital groups of society who will be interested and affected by introducing this technology. The conference program was organised in the following sessions:

- * Introduction to the Conference included a formal introduction, a keynote address and a presentation on introduction to cement manufacture.
- * Session on European Experience included presentations from Belgium, Norway and Switzerland.
- * Session on North American Experience included several presentations from the United States from the cement industry, waste management industry and most importantly from the Environmental Protection Agency of United States.
- * Session on Pacific Rim Experience included presentations from Australia and New Zealand on their very limited experience to date.

- * Panel Session and Workshop which followed the main technical sessions involved representatives from the Queensland Department of Environment and Heritage, Queensland Conservation Council, Environment Management Industry Association of Australia, Waste Recycling and Processing Service of New South Wales, Brisbane City Council and Cement Industry Federation.
- * Free Public Session which followed all the above sessions was moderated by a media person and included several overseas speakers to directly answer the public's questions.

The following organisations, media and public groups were selected to receive special invitations to the conference keeping in mind the objectives of the conference:

- * Commonwealth Environmental Protection Agency of Australia
- * Australian States' Environment and Industry Ministries
- * Local Government Representatives
- * Local and National Newspaper Journalists
- * Radio and National Television Journalists
- * National and Local Conservation Groups
- * Cement Industry
- * Waste Management Industry
- * Community Representatives
- * Local Residents' Associations

In addition to sending special invitations to the above groups, the conference management developed several innovative events considering public education and participation as a vital component of the conference. A media briefing and a luncheon was held a day before the conference to brief the media on the use of this technology and to present the objectives of the conference. A detailed

information booklet, providing the detailed conference program, the bio data of the speakers and the synopses of the presentations to be made and the details of this technology was handed over to all the participants of the media briefing. This event proved very useful and resulted in extensive coverage given by the media. The other innovative events developed by the conference management include the free public information session following the main conference, participation in national radio live to air interviews, national news, current affairs and talkback programmes to describe the potential of this technology to solve our waste problems, the provision of newspaper editorials describing the objectives of the conference and finally the production of the edited video proceedings of the conference. These innovative events were proved to be highly successful and should be included in a program of any conference of this nature.

The KILNBURN'92 conference was applauded by the speakers and the delegates of the conference as one of the most highly successful, informative conferences they have attended. The immediate achievements of the conference were as follows:

- * Demonstration that the technology of using cement kilns in solid and hazardous waste management as an established and internationally accepted practice.
- * An independent panel established to review the disposal options for hazardous wastes in Australia recommended the use of cement kilns to manage hazardous wastes as an appropriate and available technology.
- * Increased confidence and awareness within the cement industry in Australia to implement this technology.

Once the public has been introduced to the actual facts of this technology through conferences and public forums such as above, the public education process should continue with the techniques described in section 5.3 of this thesis.

Overcoming other Constraints

With the advent of Commonwealth Environmental Protection Agency of Australia most of the constraints related to the amounts and characteristics of wastes generated in Australia should gradually be solved. The same organisation can be entrusted with the task to formulate a set of guidelines for the use of cement kilns to manage wastes in Australia. The guidelines formulated by the United States Environmental Protection Agency and the European Economic Commission may be used as models for such an exercise. Furthermore, the cement companies should arrange for one of their officials to visit some overseas plants successfully managing wastes in cement kilns. In addition to the knowledge gained through conferences such as KILNBURN'92, the cement plant management will gain added confidence by seeing these plants managing wastes successfully without any detrimental effects to their cement product. Finally, formation of a group with appointed representations from organisations such as various environmental and related ministries, cement associations, waste industries, environmental groups, public representative groups and media groups right from the planning stage could contribute to a large extent in overcoming most of the constraints in using this technology.

6.5 SUMMARY

In summary, the Australians generate about 12.8 million tonnes of solid wastes each year, which is equivalent to about 800 kg of solid wastes per person per annum. Currently over 96% of these solid wastes are sent to landfills. On average Australian solid wastes consist of 46% putrescibles, 24% paper, 11% glass, 8% plastics, 6% metals and 5% other materials. A study undertaken in Brisbane showed that 77.7% of the total solid waste stream is suitable for combustion.

The estimates for hazardous wastes generated in Australia are not widely available. The present study estimated that the Australian manufacturing industry generates about 400,000 tonnes of industrial hazardous wastes each year. The estimates for intractable (schedule) wastes, which are a subset of hazardous wastes, reveal that there is over 100,000 tonnes of such wastes either stockpiled or presently in use in Australia.

There are 22 cement kilns scattered around Australia which are presently in operation. These kilns consumed about 1 million tonne of coal to produce 5.6 million tonnes of cement clinker in 1993. These kilns are located near the urban centres where most of the industrial hazardous wastes are generated. The present study estimated that if the Australian cement kilns could replace 31% of its thermal energy requirement by hazardous wastes, then it would dispose the total amount of industrial hazardous wastes generated annually in Australia.

The main constraint to implement this technology in Australia was identified as the public perception. The other constraints identified include incomplete waste profile in Australia and lack of regulatory guidelines. Educating the public of this technology is seen as a vital component in the implementation process and it was pointed out that conferences such as KILNBURN'92 could be used effectively to overcome the public perception constraints.

CHAPTER SEVEN

USE OF ALUM SLUDGE AS A RAW MATERIAL SUBSTITUTE IN CEMENT MANUFACTURE - A CASE STUDY IN AUSTRALIA

7.1 INTRODUCTION

Water treatment plants, once concerned almost exclusively with finished water quality, are increasingly aware of the importance of managing the by-products of water treatment practice. The water treatment commonly involves addition of alum or ferric chloride for coagulation and the removal of suspended solids present in raw water. The sludges produced during water treatment consist primarily of the precipitated hydroxide of the coagulant along with material removed from raw water. In the past, the standard disposal procedure for these sludges involved direct discharge to a water course. In most cases, however, this practice is no longer permissible. Sanitary landfilling is becoming increasingly difficult, expensive and unattractive in view of the potential liability for landfill cleanup. The co-disposal of water treatment sludge with the municipal sewage sludge is a possibility, but requires a nearby sewage treatment facility with the capacity and willingness to accept the water treatment sludges. Thus, the reclamation of water treatment sludge and the use in other processes should be considered as an important option in water treatment sludge management.

The manufacture of cement requires the use of a tremendous amount of raw materials, while employing operating conditions conducive to the management and destruction of society's waste materials. The appropriate wastes are those which have energy value as a substitute fuel, or material value (calcium, silica, aluminium or iron) as a substitute for portions of mined raw material feed. As the mining operations are expensive, any raw material substitution with waste materials provides significant economic advantages.

The suitability of substituting waste alum sludge as a raw material in cement manufacture will largely depend on the chemical composition of the sludge and whether it will cause any excessive emissions from the stack. Sources for potable water supplies should represent the purest water available at reasonable cost. This generally means that toxic organics and pathogens are not concentrated in raw waters and therefore not important constituents of water treatment sludges. The toxic metals, however, are common contaminants of raw water and certain water treatment chemicals. As a result, most water treatment sludges contain measurable quantities of heavy metals. Since heavy metals are of great concern to the cement industry as well as the general public, any proposal to substitute raw materials with water treatment plant sludges needs to be evaluated in detail.

The aim of this case study is to conduct a comprehensive test program to evaluate the substitution of raw materials used at the Darra Cement Plant in Brisbane, Australia by the alum sludges generated by Brisbane City Council's water treatment plant at Mt. Crosby. The study specifically addressed the environmental concerns posed by the metal impurities in the water treatment sludge.

This chapter describes the test program of the above case study in detail and then analyses the results obtained for the baseline (coal only) study and the alum sludge study. The analysis of the results specifically examines whether there is any difference in metal emissions and the metal distribution within the cement clinker and cement kiln dust due to alum sludge.

7.2 ALUM SLUDGE

Alum sludge is predominantly aluminium hydroxide with some iron, calcium, magnesium and manganese hydroxides. Small quantities of a variety of other metals are also present but typically these make up less than 1% of the total composition. Once dewatered to greater than 15% w/w solids, the alum sludge behaves as a solid

and it becomes increasingly stable as it dries further.

A typical analysis for the metals in dried alum sludge taken from Sydney Water Board's Nepean Dam Water Treatment Plant is shown in Table 7.1 below.

Table 7.1 TYPICAL CONCENTRATIONS OF METALS IN DRIED ALUM SLUDGE

ELEMENT	CONCENTRATION (ppm)
Aluminium	60,000
Iron	5,800
Manganese	1,400
Magnesium	1,300
Calcium	1,620
Sodium	240
Potassium	360
Nickel	40
Copper	20
Zinc	30
Lead	10
Chromium	10
Total Phosphorus	2,600
Total Nitrogen	2,060

7.3 TEST PROGRAM

7.3.1 Project Location and Test Objectives

A comprehensive test program was planned at the Darra Cement Plant in Brisbane to obtain data to evaluate the use of waste alum sludge as a raw material substitute in cement manufacture. The test program was designed to evaluate the metal emissions and to determine the fate and distribution of metals during the baseline and alum study. (The author wishes to acknowledge Mr. Chris Clunies-Ross for his assistance during this test program).

7.3.2 Test Schedule

The test program included 2 days of baseline testing (with regular raw materials) and 2 days of testing with alum sludge substitution. The dried alum sludge was mixed with coal for the introduction through the coal burner system. The Figures 7.1 and 7.2 illustrate the view of the cement plant used for the study and the alum sludge introduction to the kiln. The test schedule included the following observations:

- * Sampling and analysis of stack gas.
- * Sampling and analysis of process streams coal, raw feed, clinker and dust.
- * Obtaining detailed process data observations for the sampling period.

7.3.3 Sampling and Analysis Procedure

Exhaust Gas Velocity and Volume Flowrate

Velocity profiles were obtained across the stack using a calibrated S-type (Stausscheibe) pitot tube and an manometer supplied by Airflow Developments Ltd. The positions for velocity pressure measurements were determined by the equal area method. The total number of positions were chosen in accordance with the

Figure 7.1 View of the cement kiln used for the study

Figure 7.2 View of alum sludge introduction to the cement kiln

procedures outlined in the isokinetic sampling method, as specified in Schedule 2, Appendix A of the NSW Clean Air Act. The gas velocities and volume flow rates were calculated in accordance with the Victorian EPA Standard Analytical Procedure B4.

Temperature

Gas meter temperature was measured using a calibrated mercury in glass thermometer. The flue gas temperature was measured using a type K thermocouple and a calibrated Eirelec thermocouple indicator.

Moisture

A measured volume of air was bubbled through a series of impingers each containing 100 mls of chilled water. The total change in volume of water in the impingers was used to calculate the percentage of moisture in the stack.

Heavy Metals

Heavy metals were sampled according to the Regulation 20D as specified in Schedule 2, Appendix A of NSW Clean Air Act. A measured volume of air was withdrawn isokinetically through a glass probe and bubbled through a series of impingers containing chilled nitric acid solution. The probe was maintained at a sufficient temperature to prevent any condensation. The Figures 7.3 and 7.4 illustrate the equipment used for the heavy metals sampling. At the end of each run, the contents of the impingers were transferred to glass bottles along with the triplicate nitric acid rinses of the impingers and the connecting glassware. The analysis of heavy metals was done via Atomic Absorption Spectrometry.

Process Samples

Samples of various process streams were collected every 2 hours and composited into a single sample for each 2 test days. During the baseline study, the daily composites were made for raw material slurry feed, cement clinker, coal and cement

Figure 7.3 View of stack gas sampling during the study

Figure 7.4 View of stack gas sampling during the study

kiln dust and during the alum study, the composites were made for slurry, clinker, cement kiln dust and the coal/alum sludge blend. The slurry feed samples were taken from the sample valve on the discharge end of the slurry feed pump located between the tank and the kiln feed head tank. The coal samples were taken with cyclone sampler at a location between the pulveriser and the burner. The clinker samples and dust samples were taken from their corresponding drag chains. All the above samples were analysed for heavy metals using Atomic Absorption Spectrometry.

7.4 ANALYSIS OF RESULTS

7.4.1 Metal Emissions

The results of metal analysis for slurry feed, coal, coal/alum sludge, cement clinker, cement kiln dust and the stack emissions are shown in Tables 7.2 and 7.3 under different test conditions. The Table 7.4 and the Fig. 7.5 present the summary of metal emissions in the stack gas during the baseline test and the alum sludge test. In the Table 7.3, these emissions are compared with the permissible metal emission levels in the European Economic Community (EEC), Germany and New South Wales (NSW), Australia.

TABLE 7.2 METALS IN PROCESS SAMPLES DURING BASELINE STUDY

Metal	Slurry (% dry)	Coal (% dry)	Clinker (% dry)	Dust (% dry)	Stack (mg/cu.m)
Aluminium	1.09	0.34	2.6	1	0.4419
Arsenic	0.003	0.02	0.01	0.01	0.093
Calcium	33.7	0.65	52	27	8.2558
Cadmium	0.0002	0.002	0.001	0.001	0.0116
Cobalt	0.001	0.002	0.001	0.001	0.0116
Chromium	0.005	0.002	0.005	0.002	0.0116
Copper	0.004	0.002	0.004	0.003	0.0016
Iron	2.01	0.69	2.5	1	0.4419
Potassium	0.22	0.09	0.07	3.7	13.953
Magnesium	1.39	0.11	0.92	0.54	0.2209
Manganese	0.02	0.004	0.023	0.01	0.0069
Molybdenum	0.0003	0.002	0.001	0.001	0.0016
Sodium	0.61	0.089	0.51	3.9	12.791
Nickel	0.003	0.003	0.002	0.002	0.0232
Lead	0.001	0.02	0.01	0.01	0.093
Silicon	2.06	0.08	2.1	0.05	0.6977
Tin	0.0008	0.003	0.002	0.002	0.0233
Strontium	0.61	0.009	0.8	0.41	0.1395
Zinc	0.002	0.006	0.006	0.005	0.0698

TABLE 7.3 METALS IN PROCESS SAMPLES DURING ALUM STUDY

Metal	Slurry (% dry)	Coal (% dry)	Clinker (% dry)	Dust (% dry)	Stack (mg/cu.m)
Aluminium	1.03	1	2.4	0.69	0.2888
Arsenic	0.005	0.01	0.01	0.01	0.0693
Calcium	30.15	0.57	51	23	4.7361
Cadmium	0.0002	0.001	0.001	0.001	0.0116
Cobalt	0.001	0.001	0.001	0.001	0.0116
Chromium	0.006	0.001	0.005	0.001	0.0116
Copper	0.003	0.001	0.003	0.003	0.0016
Iron	2.27	0.96	2.5	0.58	0.2657
Potassium	0.21	0.08	0.06	4.4	13.862
Magnesium	1.21	0.13	0.88	0.5	0.1386
Manganese	0.02	0.01	0.025	0.007	0.0046
Molybdenum	0.0005	0.001	0.001	0.001	0.0016
Sodium	0.34	0.089	0.48	4.4	13.862
Nickel	0.003	0.003	0.002	0.002	0.0116
Lead	0.001	0.01	0.01	0.01	0.0693
Silicon	2.14	0.07	2.1	0.05	0.3927
Tin	0.001	0.003	0.002	0.002	0.0116
Strontium	0.56	0.007	0.7	0.37	0.0925
Zinc	0.002	0.007	0.005	0.005	0.0578

Table 7.4 STACK EMISSIONS OF METALS (mg/m³)

Metal	Baseline Emissions	Alum Study Emissions	Permissible EEC	Permissible Germany	Permissible NSW
Aluminium	0.4419	0.2888			
Arsenic	0.093	0.0693	1.0	1.0	
Calcium	8.2558	4.7361			
Cadmium	0.0116	0.0116	0.1	0.1	3.0
Cobalt	0.0116	0.0116	1.0	1.0	
Chromium	0.0116	0.0116	1.0	1.0	
Copper	0.0016	0.0016	1.0	1.0	
Iron	0.4419	0.2657			
Potassium	13.953	13.862			
Magnesium	0.2209	0.1386			
Manganese	0.0069	0.0046	1.0	1.0	
Molybdenum	0.0016	0.0016			
Sodium	12.791	13.862			
Nickel	0.0232	0.0116	1.0	1.0	
Lead	0.093	0.0693	1.0	1.0	10.0
Silicon	0.6977	0.3927			
Tin	0.0233	0.0116	1.0	1.0	
Strontium	0.1395	0.0925			
Zinc	0.0698	0.0578

Figure 7.5 Stack emissions of metals during baseline and alum study

Figure 7.6 Factor of increase in metal emissions due to alum use

As shown, the stack gas metal emissions are similar during the baseline study and the alum study. More importantly, the emissions of key elements such as arsenic, lead, cadmium and chromium which are considered to be a potential risk to the environment and human health from both tests are many orders below the permissible levels in the EEC, Germany and NSW, Australia. The Fig. 7.6, which illustrates the factor of increase in metal emissions due to the addition of alum sludge, further confirms that the metal emissions do not increase and sometimes reduce due to the addition of alum sludge.

7.4.2 Metals Material Balance

The various process streams were sampled and analysed for their metal content in order to conduct a metal materials material balance during the baseline study and alum study. The major inlet streams are the slurry, coal and coal/waste (coal combined with alum sludge). The major outlet streams include the cement clinker, cement kiln dust and stack gases. The mass flow rates of inlet and outlet process streams, obtained during the baseline and alum study from the plant operational data, are shown in Table 7.5.

Table 7.5 MASS FLOW RATES OF PROCESS STREAMS (kg/hr)

Process Stream	Baseline Study	Alum Study
Slurry (dry)	64,833	65,500
Coal	10,542	10,333
Alum Sludge	nil	1,000
Cement Clinker	40,750	40.958
Cement Kiln Dust	2,500	2,583

The concentration of each metal element in the process stream was determined using the above process flow rates. The "percentage of closure" value for each element was determined by dividing the total output by total input of the element and expressing as a percentage. The results of above analysis are shown in Tables 7.6 and 7.7.

The percentage of closure of an element in a material balance calculation is known to give evidence for the consistency of data collected during the experiment. Due to many difficulties encountered in sampling procedure during a full scale experiment, it is commonly agreed that the percentage of closure value within 30% of closure (ie. between 70% and 130%) would be sufficient enough to confirm the consistency of data. The percentage closure values for the baseline study and the alum study are shown in Table 7.8 and Fig. 7.7.

TABLE 7.6 METAL MATERIALS BALANCE FOR BASELINE STUDY (kg/hr)

Metal	Slurry	Percent	Coal	Percent	Total In	Clinker	Percent	Dust	Percent	Stack	Percent	Total Out
Aluminium	706.68	95.2%	35.84	4.8%	742.52	1059.50	97.7%	25.00	2.3%	0.051	0.005%	1084.55
Arsenic	1.94	48.0%	2.11	52.0%	4.05	4.08	94.0%	0.25	5.8%	0.011	0.246%	4.34
Calcium	21848.72	99.7%	68.52	0.3%	21917.24	21190.00	96.9%	675.00	3.1%	0.946	0.004%	21865.95
Cadmium	0.13	38.1%	0.21	61.9%	0.34	0.41	93.9%	0.03	5.8%	0.001	0.306%	0.43
Cobalt	0.65	75.5%	0.21	24.5%	0.86	0.41	93.9%	0.03	5.8%	0.001	0.306%	0.43
Chromium	3.24	93.9%	0.21	6.1%	3.45	2.04	97.5%	0.05	2.4%	0.001	0.064%	2.09
Copper	2.59	92.5%	0.21	7.5%	2.80	1.63	95.6%	0.08	4.4%	0.000	0.011%	1.71
Iron	1303.14	94.7%	72.74	5.3%	1375.88	1018.75	97.6%	25.00	2.4%	0.051	0.005%	1043.80
Potassium	142.63	93.8%	9.49	6.2%	152.12	28.53	23.3%	92.50	75.4%	1.599	1.304%	122.62
Magnesium	287.21	96.1%	11.60	3.9%	298.81	374.90	96.5%	13.50	3.5%	0.025	0.007%	388.43
Manganese	12.97	96.9%	0.42	3.1%	13.39	9.37	97.4%	0.25	2.6%	0.001	0.008%	9.62
Molybdenum	0.19	48.0%	0.21	52.0%	0.41	0.41	94.2%	0.03	5.8%	0.000	0.042%	0.43
Sodium	395.48	97.7%	9.38	2.3%	404.86	207.83	67.7%	97.50	31.8%	1.466	0.478%	306.79
Nickel	0.52	62.1%	0.32	37.9%	0.83	0.82	93.9%	0.05	5.8%	0.003	0.306%	0.87
Lead	1.30	38.1%	2.11	61.9%	3.41	4.08	94.0%	0.25	5.8%	0.011	0.246%	4.34
Silicon	1335.56	99.4%	8.43	0.6%	1343.99	855.75	99.8%	1.25	0.1%	0.080	0.009%	857.08
Tin	0.52	62.1%	0.32	37.9%	0.83	0.82	93.9%	0.05	5.8%	0.003	0.308%	0.87
Strontium	395.48	99.8%	0.95	0.2%	396.43	326.00	96.9%	10.25	3.0%	0.016	0.005%	336.27
Zinc	1.30	67.2%	0.63	32.8%	1.93	2.45	94.8%	0.13	4.8%	0.008	0.310%	2.58

TABLE 7.7 METAL MATERIALS BALANCE FOR ALUM STUDY (kg/hr)

Metal	Slurry	Percent	Coal	Percent	Total In	Clinker	Percent	Dust	Percent	Stack	Percent	Total Out
Aluminium	674.65	85.6%	113.33	14.4%	787.98	982.99	98.2%	17.82	1.8%	0.033	0.003%	1000.85
Arsenic	3.28	74.3%	1.13	25.7%	4.41	4.10	93.9%	0.26	5.9%	0.008	0.182%	4.36
Calcium	19748.25	99.7%	64.60	0.3%	19812.85	20888.58	97.2%	594.09	2.8%	0.543	0.003%	21483.21
Cadmium	0.20	63.4%	0.11	36.6%	0.31	0.41	93.8%	0.03	5.9%	0.001	0.304%	0.44
Cobalt	0.66	85.2%	0.11	14.8%	0.77	0.41	93.8%	0.03	5.9%	0.001	0.304%	0.44
Chromium	3.93	97.2%	0.11	2.8%	4.04	2.05	98.7%	0.03	1.2%	0.001	0.064%	2.08
Copper	1.97	94.5%	0.11	5.5%	2.08	1.23	94.1%	0.08	5.9%	0.000	0.014%	1.31
Iron	1486.85	93.2%	108.80	6.8%	1595.65	1023.95	98.6%	14.98	1.4%	0.030	0.003%	1038.96
Potassium	137.55	93.8%	9.07	6.2%	146.62	24.57	17.6%	113.65	81.3%	1.589	1.136%	139.82
Magnesium	236.45	94.1%	14.73	5.9%	251.19	360.43	96.5%	12.92	3.5%	0.016	0.004%	373.36
Manganese	13.10	92.0%	1.13	8.0%	14.23	10.24	98.3%	0.18	1.7%	0.001	0.005%	10.42
Molybdenum	0.33	74.3%	0.11	25.7%	0.44	0.41	94.0%	0.03	5.9%	0.000	0.042%	0.44
Sodium	222.70	95.7%	10.09	4.3%	232.79	196.60	63.0%	113.65	36.4%	1.589	0.509%	311.84
Nickel	0.66	65.8%	0.34	34.2%	0.99	0.82	93.9%	0.05	5.9%	0.001	0.152%	0.87
Lead	1.97	63.4%	1.13	36.6%	3.10	4.10	93.9%	0.26	5.9%	0.008	0.182%	4.36
Silicon	1401.70	99.4%	7.93	0.6%	1409.63	860.12	99.8%	1.29	0.1%	0.045	0.005%	861.45
Tin	0.66	65.8%	0.34	34.2%	0.99	0.82	93.9%	0.05	5.9%	0.001	0.152%	0.87
Strontium	366.80	99.8%	0.79	0.2%	367.59	286.71	96.8%	9.56	3.2%	0.011	0.004%	296.27
Zinc	1.31	62.3%	0.79	37.7%	2.10	2.05	93.8%	0.13	5.9%	0.007	0.303%	2.18

Table 7.8 PERCENTAGE OF CLOSURE FOR METALS

Metal	Baseline Study (%)	Alum Study (%)
Aluminium	146.1	127.0
Arsenic	107.0	99.0
Calcium	99.8	108.4
Cadmium	127.4	141.0
Cobalt	50.5	56.8
Chromium	60.5	51.3
Copper	60.8	62.8
Iron	75.9	65.1
Potassium	80.6	95.4
Magnesium	130.0	148.6
Manganese	71.9	73.2
Molybdenum	106.7	98.8
Sodium	75.8	134.0
Nickel	103.9	87.7
Lead	127.3	140.8
Silicon	63.8	61.1
Tin	103.9	87.7
Strontium	84.8	80.6
Zinc	133.6	103.8

Figure 7.7 Percentage of closure for metals during baseline and alum study

As shown, the percentage closure values for majority of the metals during the baseline study and alum study are within 30% of closure. Furthermore, the Fig. 7.7 illustrates that the percentage closure values are similar during the baseline and alum study confirming the a similar consistency of data during both experiments. The data were then analysed to determine the percentage of metal emitted with stack gas and the distribution of metals in the process solids, ie. cement clinker and cement kiln dust.

Percent of Metal Input Emitted with Stack Gas

One of the most useful measures of determining the potential release of metal components by a cement kiln burning waste materials is to determine the percent of the input metal that is emitted with stack gas. This measure is very useful when comparing metals between experiments with different metal input rates. The Table 7.9 and Fig. 7.8 show the percentage of metals that is emitted with stack gas during

the baseline study and alum study.

TABLE 7.9 PERCENT OF INPUT METAL EMITTED WITH STACK GAS

Element	Baseline Study (%)	Alum Study (%)
Aluminium	0.007	0.004
Arsenic	0.263	0.180
Calcium	0.004	0.003
Cadmium	0.390	0.429
Cobalt	0.155	0.173
Chromium	0.039	0.033
Copper	0.007	0.009
Iron	0.004	0.002
Potassium	1.051	1.083
Magnesium	0.008	0.006
Manganese	0.006	0.004
Molybdenum	0.045	0.042
Sodium	0.362	0.682
Nickel	0.318	0.134
Lead	0.313	0.256
Silicon	0.006	0.003
Tin	0.320	0.134
Strontium	0.004	0.003
Zinc	0.415	0.315

Figure 7.8 Percentage of input metal emitted during baseline and alum study

As shown in the Table 7.9 and Fig 7.8, all the values for percent of input metal emitted are below 0.011%, confirming that over 99.9% of metal input for all the metals during the baseline study and alum study are retained by the process solids in the cement kiln. Therefore, there is no environmental or human health risk posed by the metal emissions due to the use of alum sludge as a raw material substitute. The distribution of metals within the process solids is discussed in the next section.

Distribution of Metals in Process Solids

This section of the thesis will attempt to determine whether there will be difference to the distribution of metals within the cement clinker and cement kiln dust (CKD) due to the use of alum sludge as a raw material substitute. The Figs. 7.9 and 7.10 illustrate the distribution of metals in the output during the baseline study and the alum study respectively.

Figure 7.9 Distribution of metals in the output during baseline study

Figure 7.10 Distribution of metals in output during alum study

As shown, on average over 95% of the metal output is retained by the cement clinker for the majority of metals. The Figs. 7.11 and 7.12 illustrate the factor of increase in metal content of cement clinker and CKD due to the use of alum sludge. As shown, there is no indication that metal concentrations in the cement clinker or CKD increased during the use of alum sludge. Thus, the behaviour of metals in the process solids was not affected by the use of alum sludge.

7.5 CONCLUSIONS

The analysis of metals in the process streams during the baseline (coal only) study and the alum study indicates that the use of water treatment alum sludge as a raw material substitute in the cement manufacture does not effect the emission levels of toxic metals in the exhaust stack gases. The emission levels of key elements such as arsenic, cadmium, chromium and lead are within the permissible limits during the normal operations and with alum sludge substitution. The analysis also indicate that the distribution of metals between the cement clinker and cement kiln dust is not effected by the use of alum sludge. Based on the results of this investigation it can therefore be concluded that the alum sludge can be safely used as a raw material substitute in the cement manufacture without any adverse effects to the metal emissions or the metal distribution within the process solids.

Figure 7.11 Factor of increase in clinker metals due to use of alum

Figure 7.12 Factor of increase in CKD metals due to use of alum

CHAPTER EIGHT

CONCLUSIONS

Based on the research completed on the use of cement kilns in managing solid and hazardous wastes, it can be concluded that:

1. The metals that enter the cement kiln via waste derived fuels and raw material feed can be grouped into three categories based on their volatilities. They are a) highly volatile metals such as mercury and thallium, b) semi-volatile metals such as cadmium, lead, antimony and selenium and c) refractory or non-volatile metals such as silver, arsenic, barium, beryllium, chromium and nickel.
2. The principal source of metal input to a cement kiln is the raw material feed. Coal feed is the major source for metals such as arsenic, barium, vanadium and zinc. Thus, any substitution of coal by waste derived fuels decreases the input of these metals. Waste derived fuel is the major source of metals such as cadmium, chromium, lead and nickel.
3. Emissions of refractory metals are not increased by any increase in the input of these metals. However, a moderate correlation exists between the semi-volatile metal emissions and their input. The metal emissions are not affected by any increase in the chlorine input.
4. Emissions of refractory metals are less than 0.1% of their total input, indicating that over 99.9% of these metals are retained by the cement kiln. The emissions of semi-volatile metals are less than 0.75% of their total input, indicating that more than 99.25% of these metals are retained by the cement kiln. In overall, out of the metals added to a cement kiln via

any route only less than 1% will appear in stack gas emissions whereas over 99% of the total input is retained by the cement kiln. Thus, the metal emissions estimated by Greenpeace as high as 5% of the metal input is grossly overestimated.

5. Using Greenpeaces' upper end estimate of metal concentration in hazardous wastes burnt in cement kilns as 1.35%, the total metal content of the 400,000 tonnes of hazardous wastes generated annually by the Australian manufacturing industry is 5400 tonnes. Using the findings of this study that less than 1% of the total metal input is emitted to the atmosphere, the total metal emission from burning 400,000 tonnes of above wastes in cement kilns is less than 54 tonnes per year. According to Australian Environmental Council, the total lead emissions in Australia from motor vehicles alone in 1988 was about 3700 tonnes. Thus, the total metal emissions from cement kilns(which includes lead and all other metals in hazardous wastes generated by Australian industry) are only about 1.5% of the total lead emissions from motor vehicle emissions.
6. Semi-volatile metals such as lead and cadmium tend to concentrate more in the cement kiln dust than the cement clinker. However, the use of waste derived fuels is not the determining factor for this distribution as the same distribution exists even when the kiln is using normal fuel. All the refractory metals are mostly incorporated in the cement clinker.
7. Extreme high combustion conditions in a cement kiln combined with high turbulence and long residence times readily overcome any oxygen deficiencies inside the kiln to achieve very high destruction levels for most stable organics. Thus, the argument that fundamental design of a cement kiln is not compatible with the conditions necessary for the destruction of organics is not valid. A cement kiln can achieve destruction efficiencies

well exceeding the 99.99% requirement and reaching excess of 99.9999% in most cases.

8. The emissions of dioxins and furans from a cement kiln burning hazardous waste derived fuels under worst case scenarios are very much lower than the dioxin/furan emissions from a municipal solid waste incinerator, medical waste incinerator or hazardous waste incinerator.
9. Dioxin/furan emissions in a cement kiln, irrespective of burning wastes or not, decreases remarkably when the kiln exit temperatures fall below 250°C. Therefore, if the cement kiln operators can control the kiln exit temperatures below 250°C, it will be possible to reduce the dioxin/furan emissions to even lower levels.
10. There is no statistical correlation between the dioxin/furan emissions and the chlorine input or the waste fuel input. However, there is a strong statistical correlation between the dioxin/furan emissions and the carbon monoxide emissions. Since carbon monoxide emissions result from incomplete combustion, it can be concluded that completeness of combustion has a major influence on dioxin/furan emissions rather than the type of cement kiln or the type of fuel used in the cement production process.
11. Potential health effects from cement kilns burning hazardous wastes as supplementary fuel are not different from those health effects that could be confronted from burning conventional fuel only. The lifetime cancer risk of an individual assumed to reside at a location of maximum possible exposure to cement plant emissions for 24 hours per day, 365 days per year over a 70 year lifetime is about 1 in 1,000,000. This is equivalent to risk of lung cancer associated with smoking two cigarettes over a 70 year

lifetime.

12. Transportation of hazardous materials such as hazardous chemicals used by the manufacturing industry and conventional fuel such as gasoline pose far greater risk to the human health than transporting hazardous wastes to cement kilns.
13. Public involvement is the most important component of a program to address the public concerns of using cement kilns for managing hazardous waste fuel. Public involvement involves both providing information to the public (public education) and obtaining information such as concerns and ideas from the public (public consultation).
14. Public education involves educating the general public, politicians, environmental groups and other interest groups on the benefits of using this technology to solve society's hazardous waste problem. One of the most important groups that should be contacted and utilised to achieve public education goals is the media. The most effective way to get media involved is to provide them with a detailed media kit. The media kit should include all the relevant facts such as cement manufacturing process, technology and benefits of managing wastes in cement kilns, the environmental and social issues such as fate of metals and organics and potential risks to human health and the present experience with this technology elsewhere.
15. International conferences such as KILNBURN'92 involving experts from around the world would enhance the public education process considerably. A free session to the public and interest groups in the presence of experts could further assist the public education process. Public education can be further strengthened by making visual

presentations, such as video or slide presentations, to community groups and environmental groups on a regular basis and also by establishing a regular newsletter.

16. Public consultation can be effected by the formation of a group with appointed representations from organisations such as Commonwealth Environmental Protection Agency, related environmental ministries, cement associations, waste industries, environmental groups, public representative groups and media groups right from the inception of the project. These representatives can be grouped into several committees or task forces having well defined responsibilities or tasks.
17. Australia produces about 12.8 million tonnes of solid wastes each year, which is equivalent to about 800 kg of solid wastes per person per year. Over 75% of these solid wastes are suitable for combustion.
18. Australian manufacturing industry generates about 400,000 tonnes of industrial hazardous wastes each year. In addition, over 100,000 tonnes of scheduled wastes are stockpiled or presently in use in Australia.
19. There are 22 cement kilns in Australia burning about 1 million tonne of coal to produce 5.6 million tonnes of cement clinker each year. If the Australian cement kilns could replace 31% of its thermal energy requirement by hazardous wastes, then it would dispose the total amount of industrial hazardous wastes generated in Australia each year.
20. The main constraints to implement this technology in Australia are public perception, incomplete waste profiles and lack of regulatory guidelines. The cement kilns should collaborate with the Commonwealth Environmental Protection Agency to construct complete waste profiles in

Australia and also to formulate necessary regulatory guidelines. The cement plant management may use the techniques discussed in this thesis to address the constraint of public perception.

21. Waste alum sludge from water treatment plants can be safely used in the cement manufacture as a raw material substitute without any adverse effects to the metal emissions or the metal distribution within the cement clinker and cement kiln dust.
22. The organic and metal emissions from a properly operated cement kiln burning hazardous wastes are not significantly different from the emissions of a cement kiln burning conventional fuel only. Furthermore, there are no adverse effects to the properties of cement kiln dust and the cement product as a result of burning hazardous wastes. However, if a cement company is planning to implement this technology in their cement kilns, proper attention should be given to inform the public about the actual scientific facts of this technology. Although the technical superiority of using cement kilns for managing wastes can be easily illustrated by conducting comprehensive test burns, an unsuccessful public involvement process will definitely lead to the final termination of the project. Therefore, the cement plant management should allocate all the necessary resources to the public involvement process rather than allocating all the available resources to conducting a test burn, as done in the past.

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APPENDIX A DETAILS OF TEST BURNS CONDUCTED IN CEMENT KILNS

A.1 St Lawrence Cement Company, Ontario, Canada (Berry et al., 1975)

Test Date: March, 1974 to May, 1974

Kiln Type: The plant used for this test burn is a dry process kiln with suspension preheaters and equipped with an alkali by-pass system. The kiln is 5m in diameter, 85m in length and is equipped with an electrostatic precipitator (ESP). The alkali by-pass is used to reduce the build up of chlorides and alkalis in the system by by-passing a fraction of exhaust gas through a conditioning tower. The particulate matter is divided into two fractions at the conditioning tower, where the high alkali fraction is collected in the ESP and discarded and the low alkali fraction is recycled back to the raw feed.

Waste Characteristics:

The used lubricating oil utilised for this test burn originated from automotive crankcase drainings. The range of properties of used oil is given in Table A.1

TABLE A.1 COMPOSITION OF USED OIL USED AT ST. LAWRENCE PLANT

PROPERTY	MINIMUM VALUE	MAXIMUM VALUE
Gravity, API at 60°F	20.7	27.9
Specific Gravity	0.887	0.934
Density lb/US gal	7.4	7.78
Viscosity, centistokes	17.3	180.6
Flash Point deg F	75	415
Heating Value, BTU/lb	13571	19300

Appendix A: Details of Test Burns Conducted in Cement Kilns

PROPERTY	MINIMUM VALUE	MAXIMUM VALUE
Silicon ppm	10	875
Calcium ppm	700	3000
Sodium ppm	16	300
Iron ppm	50	2000
Magnesium ppm	10	1108
Lead ppm	800	21700
Vanadium ppm	3	39
Copper ppm	5	348
Barium ppm	10	2000
Zinc ppm	300	3000
Phosphorus ppm	500	2000
Tin ppm	5	112
Chromium ppm	8	50
Beryllium ppm	6	6
Manganese ppm	5	10
Nickel ppm	3	30
Cadmium ppm	4	4
Silver ppm	1	1
Strontium ppm	10	30
Aluminium ppm	10	800
Boron ppm	3	20
Molybdenum ppm	2	3
Titanium ppm	5	30

Those elements reported in the above table with minimum contamination concentration greater than 100 ppm were initially selected for the study. After rejecting those elements already present in large quantities in cement manufacture (ie. Ca, Si, Al, Fe and S), Lead, Zinc and Phosphorus were selected for study.

Summary of Results:

Three sets of data are available from the study as described below:

Set 1 - Data prior to burning oil ie. baseline conditions

Set 2 - Data during the waste oil burn

Set 3 - Data collected after the elapse of oil burn

TABLE A.2 STACK EMISSION RESULTS AT ST. LAWRENCE PLANT

Stack	Set	Particulates	Lead	Zinc	Bromium	Phosphorus
		lb/hr	lb/hr	lb/hr	lb/hr	lb/hr
NW	1	73.5	0.0104	0.0062	0.0180	0.0278
NE	1	38.7	0.0034	0.0042	0.0090	0.0125
SE	1	3.42	0.0011	0	0.0210	0
TOTAL		115.6	0.0149	0.0104	0.0480	0.0393
NW	2	56.6	0.0067	0.0060	0.0561	0.0178
NE	2	25	0.0032	0.0027	0.0199	0.0071
SE	2	1.72	0.0032	0.0007	0.0243	0
TOTAL		83.3	0.0131	0.0094	0.1003	0.0249
NW	3	18.8	.0048	0.0021	0.0087	0.0048
NE	3	128.3	0.0118	0.0134	0.0391	0.0392
SE	3	14.4	0.0068	0.0001	0.0639	0
TOTAL		161.5	0.0234	0.0156	0.1117	0.0440

A.2 St. Lawrence Cement Company, Ontario, Canada
(MacDonald et al., 1977)

Test Date: October 1975 to January 1976

Kiln Type: The above test burn was conducted in an oil fired wet process kiln. The kiln is 120m long and 3.5m in diameter and has a production capacity of 950 Mg/day (1050 tons/day). The kiln exhaust gases are cleaned by an ESP which collects up to 450 Mg/day (500 tons/day) of dust and recycles about 320 Mg/day (350 tons/day back to the kiln.

Waste Characteristics:

The typical heating values of the wastes used were 22-28 MJ/kg (9,300-11,900 Btu/lb). The fuel replacement level achieved was 12%.

The wastes used for the test burns included a variety of hydrocarbons in a series of program phases designed to progress from easily combusted chlorinated hydrocarbons to those which are combusted only with difficulty, as described below:

- Test 1 Chlorinated aliphatics (WBA)
 - Test 2 WBA + Chlorinated Aromatics (WBB)
 - Test 3 WBB + Polychlorinated biphenyls (WBC)
- (Waste Stream WBC consisted of 50% PCBs)

A detail composition of the above wastes is described in Table A.3 below:

TABLE A.3 COMPOSITION OF WASTES USED AT ST. LAWRENCE PLANT

Waste Stream	Waste Contents	Percentage
Chlorinated Aliphatics	chloropropane & propane	17.4
(WBA)	ethylchloride & dichloromethane	1.4

Appendix A: Details of Test Burns Conducted in Cement Kilns

Waste Stream	Waste Contents	Percentage
	chlorobutane & butene	5.5
	1,2, dichloroethane	16.5
	carbon tetrachloride	7.6
	1,1,2 trichloroethane	11.5
	dichloropropanes	4.7
	tetrachloroethylene	2.4
	tetrachloroethane	7.3
	chlorobenzene	15.6
	multichlorinated butanes, butenes, hexanes, hexenes	11.3
Chlorinated Aliphatics +	chloropropane	2.2
Chlorinated Aromatics	chloroform	1.4
(WBB)	1,2 dichloroethane	1.5
	carbon tetrachloride	5
	1,1,2 trichloroethane	3.3
	chlorobenzene	1
	chlorotoluene	52.6
	hexachlorocyclopentadiene	6.3
	heptachlorocyclopentene	2.8
	pentachlorobenzene	1
	octachlorocyclopentene	8.5
	hexachlorocyclopentadiene	12.6

Waste Stream	Waste Contents	Percentage
Chlorinated Aliphatics +	chloropropane	3.7
Chlorinated Aromatics +	1,1 dichloroethane	1.4
PCBs (WBC)	carbon tetrachloride	2.1
	1,1,2 trichloroethane	4.4
	chlorotoluene	28.7
	hexachlorocyclopentadiene	6.4
	dichlorobiphenyl	5.5
	trichlorobiphenyl	16
	tetrachlorobiphenyl	23.3
	pentachlorobiphenyl	9.1

Summary of Results:

Kiln emissions were sampled before the test burns (BLA), during the test burns (WBA, WBB, WBC) and after the test burns (BLB). The results of combustion efficiencies and particulate matter are summarised in the Tables A.4 and A.5 respectively.

TABLE A.4 ESTIMATED MINIMUM COMBUSTION EFFICIENCIES FOR EACH WASTE BURN AT ST. LAWRENCE PLANT

Waste Stream	Minimum Combustion Efficiency %
Chlorinated Aliphatics (WBA)	99.990
Chlorinated Aromatics (WBB)	99.989
Chlorinated Aromatics & PCBs (WBC)	99.986

TABLE A.5 SUMMARY OF PARTICULATE TEST DATA AT ST. LAWRENCE PLANT

Test Number	Particulate Emissions (lb/hr)	Test Number	Particulate Emissions (lb/hr)
1 BLA	20.8	1 WBC	45.3
2 BLA	25.4	2 WBC	34.5
3 BLA	19.6	3 WBC	52.2
AVERAGE	21.9		44.0
1 WBA	83.9	1 BLB	23.9
2 WBA	84.6	2 BLB	21.0
3 WBA	200.0	3 BLB	14.6
AVERAGE	122.8		19.8
1 WBB	40.3		
2 WBB	40.5		
3 WBB	55.0		
AVERAGE	45.3		

**A.3 Peerless Cement Company, Detroit, Michigan, USA
(Swanson Environmental Inc., 1976)**

Test Date: December 1976

Kiln Type: The cement kiln used for this test burn is a coal fired wet process plant having a production capacity of 1960 Mg/day (2160 tons/day). The kiln is 6m in diameter and 175m in length. The emission control is provided by an ESP.

Waste Characteristics:

The waste used for this test burn contained 40% PCB Arochlor 1260 from utility transformers.

Summary of Results:

Table A.6 shows the summary of PCB results from the test burn.

TABLE A.6 PCB TEST RESULTS AT PEERLESS PLANT

Description	Run 1	Run 2	Run 3	Run 4
PCB in fuel ($\mu\text{g}/\text{min}$)	0	5.66E08	1.7E09	0
PCB out ($\mu\text{g}/\text{min}$)	5864	7763	33212	44930
PCB in feed ($\mu\text{g}/\text{min}$)	8.3E04	6.0E04	7.2E04	8.3E04
DRE (%)	NA	99.9986	99.9981	NA

Note: The DRE calculations are based only on PCB in fuel with no correction for baseline or for PCBs in slurry water.

A.4 Stora Vika Cement Plant, Sweden (Ahling, 1979 ; Ahling, 1978)

Test Date: February, 1978 and April-July 1978

Kiln Type: The kiln utilised for these tests is a coal fired wet process kiln with production capacity of 560 Mg/day (620 tons/day). The plant is equipped with an ESP for controlling dust emissions.

Waste Characteristics:

The test program involved experiments with four different types of chlorinated hydrocarbons.

- a) Chlorinated aliphatics
- b) Chlorinated aromatics (PCBs)
- c) Chlorophenols and phenoxy acids
- d) Trichlorotrifluoroethane (Freon)

The detail composition of above wastes is given in Table A.7.

TABLE A.7 COMPOSITION OF WASTES USED AT STORA VIKÅ PLANT

Waste Type	Waste Contents	%
Chlorinated Aliphatics	methylene chloride	28
	trichloroethylene	2
	2-propanol	70
Chlorinated Aromatics	PCB Arochlor with oil	
Chlorophenols & Phenoxy Acids	xylene	94
	2-(2-methyl-4-chlorophenoxy)-propionic acid	2
	2-methyl-4-chlorophenoxyacetic acid	2
	chlorophenols and phenoxy acids	2
Trichlorotrifluoroethane	Freon	100

Summary of Results:

The DREs and emission rates for major organic constituents in the waste are summarised in Table A.8. The emissions of particulate matter during the test burn are shown in Table A.9.

TABLE A.8 DRE AND EMISSION TEST RESULTS AT STORA VIKA PLANT

Chemical Compound	Waste Burn Emission (mg/s)	Destruction Efficiency (%)
methylene chloride	<7.3	>99.995
trichloroethylene	<0.3	>99.9998
PCBs	<0.04	>99.99998
chlorophenols	<0.025	>99.99999
Freon 113	0.03	>99.99986
Phenoxy acids	<0.05	>9.99998
chlorinated hydrocarbons	NA	>99.99998

TABLE A.9 EMISSIONS OF PARTICULATE MATTER DURING AT STORA VIKA PLANT

Test Condition	Particulate Emissions (lb/h)	Chlorine (kg/Mg clinker)
Aliphatics	21	4.4
Baseline	4.7	0
PCBs	12.7	3.6
Baseline	5.9	0
Chlorophenols	30.9	0.95
Baseline	7.7	0
Freon 113	33.3	1.7
Baseline	11.7	0

A.5 Lehigh Portland Cement Company, Maryland, USA
(Willey and Weinberger, 1985)

Test Date: November 1979 - December 1979

Kiln Type: The test burn used a 700 tpd capacity cement kiln.

Waste Characteristics:

The waste used in this test burn is refuse derived fuel (RDF) from a nearby County Council. The average values of the results of analysis of RDF samples are as follows:

Heat Value	6440 BTU/lb
Moisture Content	20.45 %
Ash Content	11.8%

Summary of Results:

The stack emissions were sampled and analyses for particulates, chlorine, sulfur dioxides and nitrogen oxides. The results of the above are summarised in Table A.10

Table A.10 STACK EMISSION RESULTS AT LEHIGH PORTLAND PLANT

Description	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Fuel Type	Coal only	Coal only	Coal only	Coal + RDF	Coal + RDF	Coal + RDF
Particulates, grain/DSCF	0.0128	0.0221	0.0331	0.0474	0.0801	0.0495
Chloride as HCl, ppm	7.47	192	77.8	155	223	242
Sulfur dioxide, ppm	19.7	34.3	235	1050	353	444
Sulfur trioxide, ppm	3.0	2.5	9.3	4.1	25.4	7.1
Nitrogen oxides, ppm	135	295	112	72	130	160

A.6 Marquette Cement Plant, Oglesby, Illinois, USA
(Higgins and Helmstetter, 1983)

Test Date: October 1981

Kiln Type: The kiln used for the test burn is a coal fired dry process kiln with a production capacity of 1190 Mg/day (1200 tons/day). The kiln is 160m in length, 4.6m in diameter and is equipped with an ESP which collects about 210 Mg/day (230 tons/day) of dust and recycles about 90% back to the kiln.

Waste Characteristics:

The liquid waste fuel used for these experiments was high energy, low chlorine waste solvents from ink and paint manufacturing processes. The liquid waste had a mean heating value of 29 MJ/kg (12,350 Btu/lb) and a mean chlorine content of 4.54%. The primary metallic constituent of the waste was lead, with a mean concentration of 1800 ppm, followed by zinc and chromium.

No PCBs were detected in the waste. The following compounds were designated as Principal Organic Hazardous Constituents (POHCs) for these test burns, which comprised an average 24.7% of the liquid waste.

- a) Methylene chloride
- b) Methyl ethyl ketone
- c) 1,1,1-trichloroethane
- d) Toluene

The detail composition of wastes used is given in Table A.11 below:

TABLE A.11 COMPOSITION OF WASTES USED AT MARQUETTE PLANT

Waste Description	Test 1	Test 2	Test 3
Chloride (%)	3.56	4.28	5.8
Sulphur (%)	0.09	0.09	0.06
Nitrogen (%)	0.13	0.10	0.2
Metals in ppm			
Cadmium	3	2	1
Chromium	725	565	446
Copper	195	167	177
Lead	2520	1820	1050
Manganese	47	35	42
Mercury	0.076	0.104	0.032
Nickel	52	42	107
Zinc	1770	1290	905
Quantified Organics (%)			
methylene chloride	2.72	2.94	6.27
1,1,1-trichloroethane	1.86	1.63	1.97
methyl ethyl ketone	7.51	8.9	8.18
toluene	11.79	8.54	11.84
PCBs	ND	ND	ND
Other Organics (%)	53.29	59.87	53.09
methanol			
ethanol			
2-propanol			

Waste Description	Test 1	Test 2	Test 3
acetone			
methyl acetate			
ethylene chloride			
2-ethoxy-ethyl acetate			
methyl isobutyl ketone			
butyl acetate			
4-hydroxy-4-methyl-2-pentanone			
benzene			
ethyl benzene			
styrene			
alkyl benzenes			

The total chlorine input ranged from 0.11-0.22% relative to the clinker weight.

Summary of Results:

The summaries of DRE results, stack emissions and metal emissions at Marquette Cement plant are shown in Tables A.12, A.13 and A.14 respectively below:

TABLE A.12 DRE RESULTS FOR MARQUETTE PLANT

ORGANIC CONSTITUENT	TEST 1	TEST 2	TEST 3	AVERAGE
methylene chloride	99.869	99.851	99.917	99.879
methyl ethyl ketone	99.960	99.959	99.961	99.960
1,1,1-trichloroethane	99.718	99.604	99.710	99.677
toluene	99.968	99.947	99.968	99.961

TABLE A.13 EMISSION TEST RESULTS AT MARQUETTE PLANT

RUN NO	% WASTE	POHCs ppm	TGNMO ppm	Particle lb/hr	SO ₂ lb/hr	NO _x lb/hr	HCl lb/hr
1 Waste	14	ND	220	63.8	25.3	162.5	137
2 Waste	11.2	ND	800	58.7	5.3	280.4	89
3 Waste	12.8	ND	390	52.7	3.9	328	119
4 Base	NA	ND	1350	42.9	27.7	402.9	196
5 Base	NA	ND	670	50.1	40.5	350.2	145
6 Base	NA	ND	1740	55.7	103.2	458.7	230

Note: POHCs are methylene chloride, toluene, methyl ethyl ketone and 1,1,1 trichloroethane. TGNMO refers to total gaseous nonmethane organics.

TABLE A.14 METAL EMISSION TEST RESULTS AT MARQUETTE (lb/hr)

RUN	1	2	3	AVERAGE	4	5	6	AVERAGE
Cd	.003	.001	.001	.002	.002	.003	.002	.002
Cr	.075	.030	.054	.053	.02	-	-	.020
Cu	-	-	-	-	-	-	-	-
Pb	.105	.060	.052	.072	.042	.036	.043	.040
Mn	.007	.004	.003	.005	.003	.002	.003	.003
Hg	.0002	.0002	.0001	.002	.0003	.0003	.0003	.003
Ni	.160	.061	.065	.095	.044	.018	.032	.031
Zn	.049	.005	.001	.018	.002	.002	-	.002

A.7 Slemmestad Cement Works, , Norway
(Trovaag, 1983 ; Viken and Waage, 1983)

Test Date: 1981

Kiln Type: The kiln used for this test burn is a wet process kiln, 5m in diameter and 170m in length, with a production capacity of 770 Mg/day (850 tons/day).

Waste Characteristics:

Two test burns were conducted using following waste types:

- a) Tar containing alkanes, alkylbenzenes and polychlorinated hydrocarbons (PAHs)
- b) PCB containing about 40% chlorine

Summary of Results:

The summary of stack emissions during the test burn is given in Table A.15 below:

TABLE A.15 STACK EMISSION RESULTS AT SLEMMESTAD PLANT

ORGANIC COMPOUND	BASELINE (mg/h)	TAR (mg/h)	PCB (mg/hr)
C2-Alkylbenzenes	-	10200	2300
C3-Alkylbenzenes	-	7760	500-700
C4-Alkylbenzenes	90	3300	800
Alkanes	1270	15500	4800-5400
PAHs	1270	1360	200
Thiophenes	635	775	100
Ketones	545	2230	400-700
Aldehydes	365	9310	600-2200

ORGANIC COMPOUND	BASELINE (mg/h)	TAR (mg/h)	PCB (mg/hr)
Phenol	-	1940	-
Organic Acids	-	2910	-
Alcohols	-	1460	-
Chloroform	-	-	87-118
Carbontetrachloride	-	-	40-122
Trichloroethylene	-	-	30-91
Tetrachloroethylene	-	-	40-121
PCBs	4	-	8-17
Chlorobenzene	89	-	290-930

A.8 San Juan Cement Company, Dorado, Puerto Rico
(Peters et al., 1983; Peters et al., 1984)

Test Date: October 1981 to February 1982

Kiln Type: The test burn was conducted in a wet process kiln, 135m long and 3m in diameter, fired by No 6 oil. The production capacity of the kiln is 760 Mg/day (840 tons/day) and it is equipped with a baghouse type dust collector.

Waste Characteristics:

Six different waste batches were experimented in the trial burns. A seventh batch tested was a mixture of batches 4 and 5. The POHCs chosen for these test burns were methylene chloride, chloroform and carbon tetrachloride. The detail composition of the waste batches is given in Table A.16.

TABLE A.16 COMPOSITION OF WASTES BATCHES USED AT SAN JUAN PLANT
(VOL %)

COMPOUND	No 1	No 2	No 3	No 4	No 5	No 6
Water	1.0	4.1	4.3	8.9	23.0	2.0
Methanol	10.4	7.1	13.9	6.2	10.9	ND
Ethanol	0.8	3.2	8.6	4.7	16.8	5.6
Acetone	14.2	12.2	11.2	10.5	4.6	2.2
2-propanol	4.7	5.2	5.3	4.5	3.1	1.6
methylene chloride	24.4	16.9	12.0	12.1	1.4	5.0
hexane isomers	3.9	3.2	1.8	1.5	ND	1.5
3-methyl pentane	5.4	4.6	2.7	3.2	ND	3.6
hexane	19.4	17.3	7.2	8.5	5.9	15
chloroform	1.0	0.6	3.4	5.4	4.0	0.1
ethyl acetate	4.0	14.0	9.0	6.6	3.5	22
methyl acetate	ND	NA	0.4	1.0	ND	ND
carbon tetrachloride	0.8	0.6	1.4	10.2	7.8	0.01
benzene	0.4	0.4	0.2	0.3	0.1	0.05
hexamethyl disiloxane	0.1	ND	ND	NA	NA	NA
toluene	0.2	0.1	0.02	0.5	ND	ND
acrylonitrile	ND	1.0	1.1	0.7	1.0	ND
methyl ethyl ketone	NA	NA	0.08	1.1	NA	NA
C5-benzene isomer	NA	NA	1.33	0.5	0.9	2.2
C6-benzene isomer	NA	NA	ND	NA	ND	23
Sec-butyl ethylbenzene	NA	NA	1.23	1.7	NA	NA
Xylene isomers	NA	NA	0.24	NA	NA	ND

COMPOUND	No 1	No 2	No 3	No 4	No 5	No 6
Dimethylphenol isomers	NA	NA	0.04	NA	ND	ND
PCBs (ppm)	50	100	100	100	100	100
Pesticides (ppm)	100	100	100	100	100	100
Chlorine (w/w)	32.0	22.9	21.4	35.1	18.7	6.5

Note: ND = Not Detected
 NA = Not Analysed

Summary of Results:

The DRE values of POHCs used, POHC emission results and stack gas emission results are summarised in Tables A.17, A.18 and A.19 respectively.

TABLE A.17 DESTRUCTION EFFICIENCIES OF POHCs AT SAN JUAN PLANT (%)

RUN NUMBER	METHYLENE CHLORIDE	CHLOROFORM	CARBON TETRACHLORIDE
W1-2	> 99.997	> 99.842	99.309
W2-1	99.995	> 99.859	> 99.996
W3-1	> 99.991	99.887	91.043
W3-2	99.960	99.932	96.864
W3-3	99.659	> 99.960	98.977
W4-1	98.237	98.592	97.732
W4-2	99.418	99.470	98.122
W4-3	99.461	99.283	99.142
W4-4	99.984	98.975	99.684
W4-5	99.335	99.950	99.069

RUN NUMBER	METHYLENE CHLORIDE	CHLOROFORM	CARBON TETRACHLORIDE
W5-1	93.292	98.388	99.553
W5-2	96.663	96.099	99.460
W6-1	99.223	-	-
W4/6-1	99.760	95.617	94.129
W4/6-2	99.668	92.171	99.324
W4/6-3	99.564	98.703	94.512
W4/6-4	99.133	>99.737	92.253
W4/6-5	99.474	97.515	95.873

TABLE A.18 EMISSIONS OF POHCs AT SAN JUAN PLANT

POHCs	Baseline Emissions (mg/s)	Waste Burn Emissions (mg/s)
Methylene chloride	1.4	94 (<1.
Chloroform	11	
Carbon tetrachloride	71	

TABLE A.19 RESULTS OF STACK EMISSIONS AT SAN JUAN PLANT

POLLUTANT	BASELINE EMISSION (lb/hr)	WASTE EMISSION (lb/hr)
Particulate Matter	22.4	21.7
Nitrogen Oxides	31.3	60.4
Sulphur Dioxide	264	170
Total Hydrocarbons (ppm)	8.3	12.7
Hydrogen Chloride	0.79	<0.19

A.9 Alpha Cement Company, Cementon, New York, USA
(Nesslebeck, 1982)

Test Date: 1983

Kiln Type: The kiln used for this test burn is a wet process kiln with a production capacity of 1180 Mg/day (300 tons/day). The kiln is equipped with an ESP for pollution control.

Waste Characteristics:

The tests were conducted under baseline conditions (ie. coal only) and with waste solvents cofired with the coal.

Summary of Results:

The emission testing mainly focussed on particulate matter, hydrogen chloride, sulphur dioxide and metal emissions. These results are summarised in Table A.20.

TABLE A.20 EMISSIONS RESULTS AT ALPHA CEMENT PLANT

EMISSION PARAMETER	BASELINE EMISSIONS (lb/hr)	WASTE BURN EMISSIONS (lb/hr)
Particulates	53	44
Hydrogen Chloride	2.4	5.8
Sulphur Dioxide	138	58.5
Lead (mg/s)	4	17

A.10 General Portland Cement, Los Robles, California, USA
(Jenkins 1985; Jenkins et al., 1983)

Test Date: August 1984

Kiln Type: The kiln used for the test burn is a dry process kiln having a production capacity of 1590 Mg/day (750 tons/day). The kiln is equipped with a bag house type pollution control device which collects up to 60 Mg/day (70 tons/day) of dust and recycles about 95 % back to the kiln.

Waste Characteristics:

Four different types of fuel mixes were utilised for this test burn. They were nominated as Baseline, 25 % Waste, Spiked 25 % and Spiked 40 %. The definitions of these wastes were:

- a) Baseline - The kiln was operated using coke for approximately 90% of the energy needs and natural gas for remainder.
- b) 25 % Waste - The kiln was operated using a representative blend of wastes for 25% of its energy needs and using coal for the remainder. No surrogate compounds were added.
- c) Spike 25% - The kiln operated using waste fuel spiked with surrogate compounds for 25% of its energy needs and using coke for the remainder. Freon 113, carbon tetrachloride, trichlorobenzene were added as surrogate compounds
- d) Spike 40% - The kiln was operated under same conditions as in c) above, but with lower level of chlorine.

The detail composition of waste used is given in Table A.21 below.

TABLE A.21 COMPOSITION OF WASTES USED AT GENERAL PORTLAND LOS
ROBLES PLANT (g/ml x 100)

COMPOUND	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Freon 113	0.55	1.95	15.80	11.50	3.19	0.44
Methylene chloride	0.65	0.67	0.25	0.21	0.81	0.12
1,1,1-trichloroethane	2.50	1.44	0.83	1.13	0.40	0.79
Carbon tetrachloride	4.00	4.00	3.22	2.62	0.75	1.16
Benzene	ND	ND	ND	ND	ND	ND
Toluene	8.01	14.30	29.10	21.50	6.79	3.82
Ethyl benzene	3.00	3.00	3.00	3.00	3.00	3.00
Xylenes	5.94	23.00	28.50	28.80	16.60	9.56
Chlorobenzenes	ND	ND	0.15	0.12	0.07	0.09
Trimethylbenzene	0.84	2.95	3.64	2.28	0.52	0.37
Trichlorobenzene	0.08	0.84	2.73	3.03	0.56	0.80

Note:

- Test 1 - 25% Waste
- Test 2 - 25% Waste
- Test 3 - 25% Spiked Waste
- Test 4 - 25% Spiked Waste
- Test 5 - 40% Spiked Waste
- Test 6 - Low BTU Blend

Summary of Results:

The DRE and stack emission results are summarised in Table A.22 below:

TABLE A.22 DREs AND EMISSIONS RESULTS AT LOS ROBLES PLANT

COMPOUND	Baseline lb/day	25%Waste lb/day	25%Spike lb/day	40%Spike lb/day	DRE %
Dichloromethane	0.054	0.220	0.162	0.063	99.951
1,1,1 trichloroethane	0.008	0.010	0.009	0.008	99.999
Carbon tetrachloride	0.006	0.017	0.006	0.007	99.999
Freon 113	0.442	0.689	1.410	0.221	99.993
Benzene	14.497	4.984	7.020	9.357	-
Toluene	2.798	2.816	0.805	1.743	99.998
Ethylbenzene	4.522	0.255	0.603	1.457	99.998
Trichlorobenzene	0.007	0.004	0.007	0.011	99.999
Hydrogen Chloride	32.03	13.32	30.77	68.83	-
Hydrocarbons,ppm	10	6	7	9	-
NO ₂ , ppm	1000	1165	1030	650	-
SO ₂ , ppm	54	70	70	50	-
Dioxins, mg/hr	3.196	0.186	-	0.041	-
Furans , mg/hr	0.133	0.24	-	-	-

**A.11 General Portland Cement, Paulding, Ohio, USA
(Branscome and Bolstad, 1985)**

Test Date: October 1983

Kiln Type: The kiln used for this purpose is a wet process kiln 128m in length and 3.4m in diameter and having a production capacity of 650 Mg/day (720 tons/day). An ESP is used for dust collection where dust is collected at a rate of

150 Mg/day (170 tons/day) and is recycled at a rate of 72-95 Mg/day (80-105 tons/day).

Waste Characteristics:

The waste fuel composed primarily of hydrocarbon solvents (eg. toluene, xylene), a wide range of other minor organic components, and some resins and other solids typical of paint wastes. The composition of waste fuel components is given in Table A.23 below.

TABLE A.23 COMPOSITION OF WASTES USED AT GENERAL PORTLAND PAULDING PLANT (g/l)

COMPOUND	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5
Methylene chloride	10.6	5.57	3.43	16.4	24.0
Freon 113	0.133	0.018	1.22	8.09	13.2
2-Butanone	8.56	3.08	6.80	7.64	15.7
1,1,1-Trichloroethane	0.614	1.03	9.86	8.00	11.7
Toluene	13.0	6.37	18.7	16.6	36.0
Styrene	19.1	9.23	17.8	19.6	13.8
Ethylbenzene	14.2	9.62	12.1	15.3	11.6
O-Xylene	18.7	13.2	18.3	19.5	16.4
Chloroform	0.37	0.88	0.085	0.027	0.159
Benzene	0.119	0.163	0.057	0.142	0.122
Trichloroethylene	0.737	1.25	0.407	5.05	3.72
Tetrachloroethylene	2.06	3.37	3.13	31.6	19.9
Benzaldehyde	21.2	15.4	26.4	26.3	19.3
C11 aliphatics	0.001	0.111	0.810	0.393	0.051

COMPOUND	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5
C3 benzenes	0.473	6.52	1.66	2.41	6.64
C4 benzenes	0.479	6.97	0.655	1.86	4.08
C6 benzenes	0.0008	0.055	0.0006	0.011	0.026
Biphenyl	0.007	0.769	0.0006	0.077	0.062
Diethylphthalate	0.00005	0.014	0.0007	0.05	0.009
Naphthalene	0.067	0.800	0.059	0.772	0.655
Methyl Naphthalanes	0.012	0.605	0.008	0.207	0.185

The POHCs selected for the test burn are as follows:

- a) Methylene Chloride
- b) 1,1,1-trichloroethane
- c) Methyl ethyl ketone
- d) Toluene
- e) Freon 113

Summary of Results:

The test schedule used is given in Table A.24

TABLE A.24 TEST CONDITIONS AT GENERAL PORTLAND PAULDING PLANT

TEST RUN	TYPE	COAL %	WASTE %	CHLORINE %
1	Baseline	100	0	0.08
2	Baseline	100	0	0.13
3	Baseline	100	0	0.09
4	Baseline	100	0	0.08
NA	Changeover	-	-	NA

TEST RUN	TYPE	COAL %	WASTE %	CHLORINE %
5	Waste Fuel	41	59	0.90
6	Waste Fuel	57	43	0.59
7	Waste Fuel	39	61	0.99
8	Waste Fuel	61	39	3.75
9	Waste Fuel	42	58	3.91

The DRE results of POHCs used, results of products of incomplete combustion, results of stack gas emissions and metal emissions are summarised in Tables A.25, A.26, A.27 and A.28 respectively below:

TABLE A.25 DREs OF POHCs AT GENERAL PORTLAND PAULDING PLANT

COMPOUND	Day 5	Day 6	Day 7	Day 8	Day 9	Average
Methylene Chloride	99.998	99.995	99.956	99.978	99.993	99.984
Freon 113	-	-	-	99.999	99.999	99.999
1,1,1 Trichloroethane	99.991	99.991	99.997	99.996	99.999	99.995
Methyl ethyl ketone	99.992	99.984	99.992	99.983	99.987	99.990
Toluene	99.953	99.942	99.974	99.951	99.988	99.962

TABLE A.26 EMISSIONS OF PRODUCTS OF INCOMPLETE COMBUSTION AT GENERAL PORTLAND PAULDING PLANT (mg/s)

COMPOUND	Day 1	Day 3	Day 4	Day 5	Day 7	Day 8	Day 9
Styrene	9.9	1.7	3.0	8.5	5.1	3.9	6.9
Ethylbenzenes	1.3	0.69	0.48	1.3	0.83	0.63	0.88
Xylene	7.2	0.25	1.3	4.1	1.2	1.3	1.4

COMPOUND	Day 1	Day 3	Day 4	Day 5	Day 7	Day 8	Day 9
n-undecane	ND	2.7	0.67	ND	ND	0.39	ND
C3-benzenes	6.3	2.0	9.0	ND	3.1	0.96	41
C4-benzenes	5.2	2.4	7.9	6.8	3.7	3.2	2.2
C5-benzenes	0.90	0.68	0.42	0.51	0.78	0.61	0.33
C6-benzenes	0.43	0.29	0.06	0.88	ND	0.21	0.06
Biphenyl	6.4	0.28	0.82	1.2	1.2	0.77	0.88
Phthalates	42	115	49	9.9	13	25	3.1
Naphthalene	26	2.8	8.1	16	11	6.3	15
Methylnaphthalene	19	1.7	4.3	5.6	6.9	3.0	2.4

TABLE A.27 EMISSIONS OF PARTICULATES, HYDROGEN CHLORIDE, NITROGEN OXIDES, SULPHUR DIOXIDE, HYDROCARBONS AND CARBON MONOXIDE AT PAULDING PLANT (kg/hr)

TEST DAY	PARTICULATE	HCl	NO _x	SO ₂	THC	CO
1	11.83	0.73	68.4	327	2.05	74.7
2	8.47	0.41	63.3	256	0.67	21.8
3	6.24	0.64	59.8	167	0.54	18.5
4	9.16	0.48	63.0	204	0.60	25.4
Baseline Average	8.93	0.57	63.6	239	0.97	35.1
5	6.99	0.27	56.6	39.2	2.63	21.3
6	9.80	1.0	56.4	68.1	1.53	24.1
7	7.70	1.5	63.4	96.0	2.15	51.7
8	7.45	2.3	99.1	135.2	1.72	28.4

9	11.08	5.4	121.1	130.9	1.34	22.4
Waste Average	8.60	2.1	79.3	93.9	1.87	29.6

TABLE A.28 METAL EMISSIONS AT GENERAL PORTLAND PAULDING PLANT
(mg/hr)

TEST DAY	Cd	Cu	Hg	Ni	Pb	Se
1	<5.83	<233	106	693	11660	4950
2	<4.29	<172	26.9	1240	4010	1810
3	<2.77	<111	ND	255	2360	201
4	<4.63	<185	ND	185	3350	595
Base Average	<4.38	<175	<66.5	593	5350	1890
5	3850	465	85.2	<175	1244	3250
6	2060	438	328	<180	41070	696
7	463	<148	43.3	<148	13360	213
8	1030	286	658	<144	18530	1680
9	3390	1700	1550	<224	50240	57290
Waste Average	2160	<608	533	<174	24890	12630

A.12 Lone Star Industries, Oglesby, Illinois, USA
(Branscome and Bolstad, 1984)

Test Date: 1983

Kiln Type: The kiln used for the test burn is a dry process kiln, 160m in length and 4.6m in diameter, having a production capacity of 1090 Mg/day (1200 tons/day). The kiln is equipped with an ESP which collects 210 Mg/day (230

tons/day) of dust and recycles 90% back to the kiln.

Waste Characteristics:

The test burn used waste paint solvents composed of chlorinated aliphatics, methyl ethyl ketone and toluene. In addition, the waste fuel was spiked with freon. The chlorine input rate ranged from 0.11-0.22% relative to clinker weight. The composition of wastes used in this test burn is given in Table A.29.

TABLE A.29 COMPOSITION OF WASTES USED AT LONE STAR INDUSTRIES
PLANT (g/l)

COMPOUND	TEST 1	TEST 2
Methylene chloride	3.7	3.77
Freon 113	8.26	6.28
Butanone	8.89	21.0
1,1,1-Trichloroethane	9.58	13.9
Toluene	21.6	40.8
Styrene	10.0	15.0
Ethylbenzene	7.41	15.4
O-Xylene	9.07	20.9
Chloroform	0.021	0.02
Benzene	0.206	0.193
Trichloroethylene	16.2	23.4
Tetrachloroethylene	10.4	13.5
Benzaldehyde	14.2	23.2
C11 aliphatics	0.335	1.13
C3 benzenes	0.399	1.22

COMPOUND	TEST 1	TEST 2
C4 benzenes	0.308	1.36
C6 benzenes	0.001	0.01
Biphenyl	0.0009	0.007
Diethylphthalate	0.003	0.02
Naphthalene	0.066	0.231
Methyl Naphthalanes	0.012	0.081

The POHCs selected for the test burn are as follows:

- a) Methylene Chloride
- b) 1,1,1-trichloroethane
- c) Methyl ethyl ketone
- d) Toluene
- e) Freon 113

Summary of Results:

The test schedule used is given in Table A.30.

TABLE A.30 TEST CONDITIONS AT LONE STAR INDUSTRIES PLANT

TEST RUN	TYPE	COAL %	WASTE %
1	Baseline	100	0
2	Baseline	100	0
3	Waste	75	25
4	Waste	63	37
5	Waste	58	42

The DRE results of POHCs used, results of products of incomplete emissions, results of stack gas emissions and metal emissions are summarised in Tables A.31, A.32, A.33 and A.34 respectively below:

TABLE A.31 DREs OF POHCs AT LONE STAR INDUSTRIES PLANT

COMPOUND	Run 3-1	Run 3-2	Run 3-3	Run 4-1	Run4-2	Average
Methylene Chloride	99.90	99.98	99.98	99.99	99.99	99.97
Freon 113	99.998	99.999	99.999	99.999	99.999	99.999
1,1,1 Trichloroethane	99.999	99.999	99.999	99.999	99.999	99.999
Methyl ethyl ketone	99.996	99.998	99.998	99.999	99.999	99.998
Toluene	99.987	99.995	99.997	99.998	99.998	99.995

TABLE A.32 EMISSIONS OF PRODUCTS OF INCOMPLETE COMBUSTION AT LONE STAR INDUSTRIES PLANT ($\mu\text{g/s}$)

COMPOUND	Run 1	Run 2	Run 3	Run 4	Run 5
Styrene	16.1	11	42	30	12
Ethylbenzenes	8.1	11	42	30	12
Xylene	8	11	42	30	12
C3-benzenes	32	11	42	243	12
C4-benzenes	81	11	84	334	37
C6-benzenes	8.1	11	460	30	111
Biphenyl	56	33	84	91	86
Benzaldehyde	307	44	167	304	209
Naphthalene	290	55	627	698	271
Methylnaphthalene	40	22	84	121	49

TABLE A.33 EMISSIONS OF PARTICULATES, HYDROGEN CHLORIDE, NITROGEN OXIDES, SULPHUR DIOXIDE, HYDROCARBONS AND CARBON MONOXIDE AT LONE STAR PLANT

RUN NO	PARTICULATE (kg/hr)	HCl (kg/hr)	NO _x ppm	SO ₂ ppm	THC ppm	CO ppm
1	30.8	1.61	570	1.5	2.5	40
2	74.6	1.06	670	11.9	2.4	35
3	348	2.20	840	38	9.2	43
4	145	5.46	771	13	4.8	49
5	227	26.7	831	5	1	24
Base Ave	52.7	1.3	-	-	-	-
Waste Ave	240	11.5	-	-	-	-

TABLE A.34 METAL EMISSIONS AT LONE STAR INDUSTRIES PLANT (mg/s)

ELEMENT	Run 1	Run 2	Run 3	Run 4	Run 5	Baseline Average	Waste Average
Aluminium	52	138	95	ND	309	95	135
Arsenic	0.082	0.11	0.75	0.17	0.45	0.096	0.46
Calcium	1210	2410	5930	992	4980	1810	3970
Cadmium	0.22	0.43	7.5	1.0	3.1	0.33	3.87
Chromium	ND	1.9	ND	ND	ND	0.95	ND
Iron	92	162	415	83	334	127	277
Mercury	0.023	0.045	0.3	0.092	0.25	0.034	0.214
Magnesium	ND	11	ND	ND	68	6	23
Manganese	4.5	8.3	25.4	9.6	20.7	6.4	18.6

Nickel	ND	ND	ND	ND	ND	ND	ND
Lead	0.74	1.62	311	119	28.2	1.15	153
Selenium	0.74	1.56	1.53	0.48	0.91	1.15	0.97
Titanium	0.69	4.86	ND	0.21	0.78	2.78	0.33
Vanadium	ND	ND	1.58	ND	0.94	ND	0.84
Zinc	0.49	1.08	1.2	0.46	1.82	0.79	1.16

A.13 Dalen Cement Works, Norway
(Benestad, 1989)

Test Date: 1983

Kiln Type: The kiln used for this test burn is a dry cement process kiln with a production capacity of 1000 Mg/day (1100 tons/day) and equipped with an ESP.

Waste Characteristics:

Two types wastes were experimented in this test burn . They were a) typical hazardous wastes and b) waste oil containing chlorinated organic compounds

The typical hazardous wastes contained mainly hydrocarbons and fatty acid esters originating from organic solvents and emulsified paint residues. The waste oil contained chlorinated benzenes and PCB.

Summary of Results:

The stack emission results are summarised in Table A.35 below:

TABLE A.35 STACK GAS EMISSION RESULTS AT DALEN PLANT ($\mu\text{g}/\text{cu.m}$)

COMPOUNDS	COAL	WASTE	PCB
ALIPHATICS			
alkanes (C5-C7)	1.15	1.15	1.15
alkanes (>C7)	89	45	65
alkenes	120	7	190
alcohols, thiols	8	6	4
ketones	0.1	0.1	0.1
aldehydes	15	5	11
acids	0.06	0.04	0.05
esters	0.04	0.07	0.3
AROMATICS			
benzene	170	10	10
toluene	160	20	10
alkyl-, alkenyl-benzenes	185	50	60
phenols	0.2	ND	0.07
ketones	14	8	21
aldehydes	60	20	40
acids	0.2	0.1	0.5
nitrobenzenes	2	1	1
benzonitriles	10	4	10
BI-AND POLYCYCLIC COMPOUNDS			
naphthalene, alkylnaphthalenes	30	30	20
naphthalene-derivatives	ND	ND	ND

COMPOUNDS	COAL	WASTE	PCB
biphenyl, alkylbiphenyls	5	5	8
PAH	10	8	20
PAH derivatives	ND	ND	ND
indenes	10	6	3
kinolines	0.3	0.8	0.8
HALOGENATED COMPOUNDS			
alkanes, alkenes	30	<0.3	<0.3
benzenes	0.4	<0.3	<0.5
phenols	0.1	ND	ND
PCB	ND	ND	ND
PCDF	-	-	0.001
PCDD	-	-	0.004
2,3,7,8, TCDD	-	-	0.0001
TOC	4000	7000	4000
Particles (mg/cu.m)	81	112	74
Lead	-	82	-
Cadmium	-	-	-

A.14 Golden Bay Cement Company, Nelson, New Zealand 1983
(Holden et al., 1983; Pilgrim et al, 1990)

Test Date: 1983

Kiln Type: The rotary kiln used for this test burn is a semi dry process kiln, 48m in length and 3.2m in diameter and having a production capacity of 29 Mg/day

(32 tons/day). The kiln is equipped with an ESP.

Waste Characteristics:

PCB waste stored in twenty 200 litre drums were pumped directly into the feed pipe.

**A.15 Eclepens Cement Plant, Switzerland
(Obrist, 1987)**

Test Date: 1984

Kiln Type: The kiln used for this test burn is a four stage cyclone preheater having a production capacity of 1360 Mg/day (1500 tons/day).

Waste Characteristics:

The moisture content in sewage sludge is around 96%. Dewatering by mechanical means yields a product which still contains about 55-75% moisture. When sewage is dried by heat, the moisture content can be reduced to around 5-25%. Such dried sewage have a calorific value of 6-14 MJ/kg (about 1/3 of coal) and can be blown into the preheater. The experiment used dried sludge obtained from a sludge drying plant.

**A.16 Cement Lafarge Ltd., Ontario, Canada
(Robb, 1984)**

Test Date: August 1983 to October 1983

Kiln Type: The cement kiln used for this test burn is a wet process plant with a kiln diameter of 3.7 m and length of 137 m.

Waste Characteristics:

The waste fuel used for the test burn comprised of liquid industrial wastes from industries such as automotive, paint and coating, ink and printing, cosmetics and photographic industries.

Summary of Results:

The test program used in this experiment is shown in Table A.36.

TABLE A.36 KILN STACK TEST SCHEDULE AT CEMENT LAFARGE PLANT

TEST NUMBER	TEST DATE	TEST TYPE
1	30 August 1983	Baseline
2	2 September 1983	Baseline
3	3 September 1983	Baseline
4	12 October 1983	20% heat replacement
5	13 October 1983	20% heat replacement
6	18 October 1983	20% heat replacement
7	20 October 1983	40% heat replacement
8	21 October 1983	40% heat replacement
9	22 October 1983	40% heat replacement

The stack emission results, metal emissions and average stack emission results are summarised in Tables A.37, A.38 and A.39 respectively below:

TABLE A.37 STACK EMISSION RESULTS AT CEMENT LAFARGE PLANT (g/s)

TEST	Particles	THC	SO ₂	NO _x	Chloride	Dioxins μg/s	Furans μg/s
1	6.86	416	58.1	37.9	0.636	0.57	3.13
2	4.08	386	39.5	47.2	0.488	0.09	0.92
3	2.98	283	55.3	35.7	0.970	0.11	0.12
4	2.90	629	5.5	25.1	1.064	1.82	1.59
5	2.21	803	34.2	23.6	1.412	0.92	0.59
6	2.41	553	32.2	29.3	1.466	0.24	3.25
7	1.63	776	34.7	32.0	3.231	0.19	1.25
8	1.46	709	48.6	21.2	2.610	0.17	0.76
9	2.57	808	37.7	20.8	2.909	0.26	0.52

TABLE A.38 METAL EMISSION RESULTS AT LAFARGE CEMENT PLANT (mg/s)

LOCATION	TEST	Ba	Cd	Ca	Cr	Cu	Pb	Zn
Kiln Stack	1	0.5	0.31	1209.5	11.2	45.6	9.2	206.1
	2	0.3	0.17	607.2	11.2	17.6	4.7	54.6
	3	0.3	0.18	592.8	12.6	21.0	8.3	50.3
	4	0.4	0.15	375.7	12.7	20.6	12.2	1.2
	5	0.3	0.14	274.0	14.4	19.7	33.2	6.6
	6	1.8	0.16	584.0	13.8	19.6	19.4	4.1
	7	1.7	0.13	582.0	14.6	16.9	20.7	3.4
	8	1.6	0.17	487.9	12.6	11.7	18.9	1.3
	9	1.5	0.13	427.0	12.5	13.6	18.3	1.0

TABLE A.39 AVERAGE STACK EMISSIONS AT CEMENT LAFARGE PLANT

PARAMETER	UNIT	BASELINE	20% WASTE	40% WASTE
Particulate	g/s	4.64	2.51	1.89
Hydrogen Chloride	g/s	0.70	1.31	2.92
Chlorine	g/s	<0.51	<0.42	<0.46
Barium	mg/s	0.37	0.83	1.60
Cadmium	mg/s	0.22	0.15	0.14
Calcium	mg/s	803	411	499
Chromium	mg/s	11.6	13.6	13.2
Copper	mg/s	28.1	20.0	14.1
Lead	mg/s	7.4	21.6	19.3
Zinc	mg/s	103.7	4.0	1.9
Total Hydrocarbons	mg/s	362	662	764
Sulphur Dioxide	g/s	51.0	24.0	40.3
Nitrogen Oxides	g/s	40.3	26.0	24.7
Dioxins	µg/s	0.26	0.99	0.21
Furans	µg/s	1.39	1.81	0.84

**A.17 Unicem Guidonia Cement Plant, Rome, Italy
(De Zorzi, 1988)**

Test Date: 1983

Kiln Type: The kiln used for this test burn is a dry process kiln with four stage cyclone preheater. The kiln has a production capacity of 1340 tons/day.

Waste Characteristics:

The waste used in this experiment is municipal solid waste. The following groups of refuse derived fuel (RDF) were used during the test burn:

- * Low bulk density RDF sized up to 50mm and insufflated into kiln
- * RDF packed in cubes and fed directly into coal mill
- * RDF cubes wrapped with steel and plastic
- * High density RDF with minimum size of 30 mm

**A.18 Medusa Cement Company, Pennsylvania, USA
(TRC Environmental Consultants Inc., 1986)**

Test Date: October 1985

Waste Characteristics:

The POHCs used for this test burn included carbon tetrachloride, 1,1,1-trichloroethane and toluene.

Summary of Results:

The DRE results of POHCs and the results of stack emissions are summarised in Tables A.40 and A.41 respectively below:

TABLE A.40 DESTRUCTION EFFICIENCIES OF POHCs AT MEDUSA PLANT (%)

POHC	TEST 1	TEST 2	TEST 3	TEST 4
Carbon tetrachloride	99.994	99.998	99.996	99.995
1,1,1 Trichloroethane	> 99.999	> 99.999	> 99.999	> 99.999
Toluene	99.973	99.973	99.976	99.985

TABLE A.41 STACK EMISSION RESULTS AT MEDUSA CEMENT PLANT (lb/hr)

Item	Base Run 1	Base Run 2	Base Run 3	Base Run 4	Base Ave	Waste Run 5	Waste Run 6	Waste Run 7	Waste Ave
Particle	19.7	5.88	168	10.6	51.0	11.9	11.8	17.6	13.8
HCl	12.6	8.23	0.0	7.36	7.06	16.4	12.4	13.0	14.0
NO _x	1150	1060	645.2	800	913	415	323	708	482
SO ₂	304	52.9	598	140	274	51.7	54.5	82.5	62.9
THC	40.1	15.3	25.1	15.4	24.0	11.7	15.6	7.9	11.7
As	0.005	0.002	0.002	0.001	.002	0.001	0.001	0.001	0.001
Cd	0.006	0.003	0.006	0.006	.005	0.006	0.005	0.004	0.005
Cr	0.762	1.186	2.097	1.178	1.31	0.608	0.204	2.374	1.062
CrVI	0.044	0.024	0.038	0.033	.035	0.025	0.026	0.002	0.018
Pb	0.038	0.046	0.093	0.013	.048	0.134	0.093	0.049	0.092
Ni	1.065	0.787	1.097	0.727	.919	0.487	0.621	1.360	0.823

A.19 Dalen Cement Works, Norway
(Benestad, 1989)

Test Date: December 1987

Kiln Type: The kiln used for this test burn is a dry cement process kiln with a production capacity of 1000 Mg/day (1100 tons/day) and equipped with an ESP.

Waste Characteristics:

Two types wastes were experimented in this test burn . They were

- a) Typical hazardous wastes
- b) Waste oil containing chlorinated organic compounds
- c) Waste oil containing lead

The typical hazardous wastes contained mainly hydrocarbons and fatty acid esters originating from organic solvents and emulsified paint residues. The waste oil contained chlorinated benzenes and PCB. Some components of the waste used in this experiment is shown in Table A.42.

TABLE A.42 COMPOSITION OF WASTES USED AT DALEN PLANT

COMPOUND	COAL	WASTE	PCB	Pb OIL
EOCl (mg/g)	-	10	29	1
Chlorobenzenes (mg/g)	-	0.02	1.3	0.1
PCB (mg/g)	-	0.04	29	0.2
Lead ($\mu\text{g/g}$)	20	520	400	320
Cadmium ($\mu\text{g/g}$)	<0.3	0.7	0.2	0.4
Mercury ($\mu\text{g/g}$)	<0.05	0.07	0.14	0.06

Summary of Results:

The stack gas emission results of the test burn are summarised in Table A.43 below:

TABLE A.43 STACK GAS EMISSION RESULTS AT DALEN PLANT

COMPOUNDS	COAL	WASTE	PCB	Pb OIL
ALIPHATICS				
alkanes (C5-C7)	1300	3900	4600	3100
alkanes (>C7)	300	70	280	110
alkynes (>C7)	72	27	42	-
alcohols, thiols	4	0.8	0.3	5
ketones	4	0.2	ND	ND
aldehydes	22	1	47	21
acids	0.8	3	ND	ND
esters	2	0.4	0.7	0.4
AROMATICS				
benzene	70	20	50	30
toluene	10	<5	20	10
alkyl-, alkenyl-benzenes	280	4	230	70
phenols	ND	ND	ND	ND
ketones	ND	0.5	7	7
aldehydes	70	10	60	20
acids	ND	ND	ND	ND
nitrobenzenes	ND	ND	ND	ND
benzonitriles	20	5	30	10

Appendix A: Details of Test Burns Conducted in Cement Kilns

COMPOUNDS	COAL	WASTE	PCB	Pb OIL
BI-AND POLYCYCLIC COMPOUNDS				
naphthalene, alkylnaphthalenes	130	10	80	40
naphthalene-derivatives	20	1	0.5	3
biphenyl, alkylbiphenyls	30	4	9	8
PAH	80	20	10	20
PAH derivatives	20	6	3	6
indenes	30	1	20	10
kinolines	0.2	ND	ND	ND
HALOGENATED COMPOUNDS				
alkanes, alkenes	4	3	3	20
benzenes	10	ND	2	ND
phenols	4	ND	ND	ND
PCB	ND	ND	0.1	ND
PCDF	-	0.03	0.006	-
PCDD	-	0.01	0.007	-
2,3,7,8, TCDD	-	0.0001	ND	-
TOC	2000	8000	2000	2000
OTHER EMISSIONS				
Particles (mg/cu.m)	140	55	72	74
Hydrogen Chloride (mg/cu.m)	8.5	7.9	6.9	4.4
Lead	11	8	8	5
Cadmium	<0.4	<0.5	<0.4	<0.4

A.20 Ash Grove Cement Company, Louisville, Nebraska, USA
(Trenholm and Hlustick, 1990 and Garg, 1990)

Test Date: 1989

Kiln Type: The kiln used for this test burn is a dry process, precalciner kiln with a production capacity of 1630 Mg/day (1800 tons/day). The kiln is 50m in length and 3.8m in diameter and is equipped with an ESP for dust control. In this kiln, the containerised hazardous waste fuels can be fed at the upper end of the kiln together with precalcined raw materials.

Waste Characteristics:

The test program covered three operating conditions, distinguished by the type of fuel used in the kiln. The first condition was a baseline with coal as the only fuel. The second condition was the liquid organic waste providing all the fuel needs. The third condition was similar to the second except solid waste spiked with monochlorobenzene (MCB) replaced one third of the liquid waste. The solid waste was fed to gas exit end of the kiln while the liquid waste was fired at the clinker exit end of the kiln.

The average heating values and chlorine content of the waste feed were 25 MJ/kg and 0.15 % relative to clinker weight respectively.

Summary of Results:

The test protocol for this experiment is shown in Table A.44.

TABLE A.44 TEST MATRIX AT ASH GROVE LOUISVILLE PLANT

TEST	COAL	LIQUID ORGANIC WASTE	SOLID WASTE WITH MCB
1	Minimum	Yes	Yes
2	Minimal	Yes	Yes
3	Yes	No	No
4	Minimal	Yes	No
5	Minimal	Yes	No

Summary of Results:

The results of DREs for POHC used, the results of products of incomplete combustion emissions, results of dioxin and furan emissions and chloride emissions are summarised in Tables A.45, A.46, A.47 and A.48 respectively below:

TABLE A.45 DESTRUCTION EFFICIENCIES FOR MONOCHLOROBENZENE (MCB) AT ASH GROVE LOUISVILLE PLANT

DRE	TEST RUN 1	TEST RUN 2	AVERAGE
Minimum	99.993	99.984	99.989
Maximum	99.9994	99.9986	99.999
Best Estimate	99.9958	99.9914	99.9936

TABLE A.46 PRODUCTS OF INCOMPLETE COMBUSTION RESULTS AT ASH GROVE LOUISVILLE PLANT (ng/l)

COMPOUND	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
MAIN STACK					
Benzene	600	700	490	500	450
Bromoform	ND	1	ND	ND	ND
Ethylbenzene	100	130	74	85	77
Methylene Chloride	66	89	260	54	64
Monochlorobenzene	44	72	5	66	62
1,1,2,2-Tetrachloroethane	ND	1	ND	ND	ND
Tetrachloroethane	6	2	2	ND	ND
Toluene	580	650	470	420	440
Trichloroethane	1	ND	3	ND	ND
Trichlorofluoromethane	ND	ND	35	ND	ND
Anthracene	10	ND	ND	ND	ND
Bis(2-ethylhexyl)phthalate	16	15	62	45	92
Dibenzofuran	25	28	ND	ND	ND
Di-n-butyl phthalate	ND	6	ND	ND	ND
Diphenyl	11	11	ND	ND	ND
BY PASS STACK					
Acetone	ND	ND	61	ND	ND
Benzene	28	63	15	7	9
1,1-Dichloroethane	ND	ND	2	ND	ND
Ethylbenzene	2	3	1	ND	1
Methylene Chloride	1	2	17	4	8

COMPOUND	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5
Methyl ethyl ketone	68	ND	ND	ND	1
Monochlorobenzene	10	15	1	1	1
Tetrachloroethane	2	1	1	1	1
Toluene	22	21	6	5	8
1,1,1-Trichloroethane	ND	ND	1	ND	ND
Trichloroethane	2	1	ND	ND	ND
Trichlorofluoromethane	2	2	5	ND	1
Bis(2-ethylhexyl)phthalate	8	ND	130	92	ND

TABLE A.47 DIOXIN AND FURAN EMISSIONS AT ASH GROVE LOUISVILLE P L A N T
(ng/dscm)

COMPOUND	RUN 1 MAIN	RUN 3 MAIN	RUN 4 MAIN	RUN 1 BYPASS	RUN 3 BYPASS	RUN 4 BYPASS
DIOXINS						
TCDD	ND	ND	0.16	ND	ND	ND
PeCDD	0.007	ND	0.21	0.017	ND	ND
HxCDD	0.041	0.10	0.46	0.044	0.043	0.020
HpCDD	0.10	0.13	0.52	0.082	0.07	0.085
OCDD	0.260	0.21	0.48	0.17	0.25	0.27
Total Dioxins	0.41	0.44	1.8	0.31	0.37	0.38
FURANS						
TCDF	0.046	0.066	1.1	0.48	0.043	0.25
PeCDF	0.081	0.084	1.1	0.21	0.024	0.10

COMPOUND	RUN 1 MAIN	RUN 3 MAIN	RUN 4 MAIN	RUN 1 BYPASS	RUN 3 BYPASS	RUN 4 BYPASS
HxCDF	0.03	0.069	0.90	0.15	0.046	0.12
HpCDF	ND	0.10	0.71	0.04	0.04	0.069
OCDF	0.071	0.23	0.43	0.12	0.16	0.13
Total Furans	0.23	0.55	4.2	1.0	0.31	0.67

TABLE A.48 CHLORIDE EMISSIONS AND REMOVAL EFFICIENCIES AT ASH GROVE LOUISVILLE PLANT

PROCESS CONDITION	TEST	CHLORIDE INPUT (lb/h)	CHLORIDE EMISSION (lb/h)	CHLORIDE REMOVAL (%)
Liquid + Solid	1	194	1.1	99.4
Liquid + Solid	2	248	0.7	99.7
Coal Only	3	ND	0.5	-
Liquid Waste	4	217	2.3	98.9

**A.21 Ash Grove Cement Company, Louisville, Nebraska, USA
(Benoit, 1990)**

Test Date: 1989

Kiln Type: The kiln used for this test burn is preheater/precalciner kiln with 50m in length and 3.8m in diameter and having a production capacity of 1630 Mg/day (1800 tons/day). The kiln is equipped with an ESP for dust control.

Due to several limitations in solid wastes such as economic viability of converting these wastes into pumpable form and the possibility of unburnt fuel settling on the

product load near the kiln's exit, it was not favoured to feed the solid wastes via the firing hood using the conventional burner technology. Thus, in this experiment, mid-kiln injection of solid was studied in detail.

Waste Characteristics:

The POHC used for this experiment was 1,1,1-trichloromethane. Solid hazardous waste fuel comprised up to 20% of the fuel input with the balance being either coal, liquid hazardous waste or both. The lead and chlorine input for this experiment ranged from 7.4-19.3 kg/hr and 0.12-0.39% relative to clinker weight respectively.

Solid waste used for this experiment was processed to maximise the homogeneity of the waste and the waste was containerised to minimise its physical variability.

Summary of Results:

The stack emission results are summarised in Table A.49 below:

TABLE A.49 STACK EMISSION RESULTS AT ASH GROVE LOUISVILLE PLANT

ITEM	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6
Total hazardous waste(lb/h)	0	11200	10400	9600	10000	14400
Solid hazardous waste (lb/h)	3900	3900	3900	3900	3900	0
Lead input (lb/h)	30.8	42.7	39.8	39.8	42.5	16.3
Lead output (lb/h)	0.286	0.007	0.004	0.006	0.003	0.005
Chlorine input, lb/h	188.4	575.9	439.3	585.2	533.8	331.2
Hcl emission, lb/h	14.1	19.3	19.9	13.5	14.3	19.5
1,1,1-TCE in fuel	204.0	439.2	443.2	415.2	394.0	331.2

ITEM	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6
1,1,1-TCE emission (lb/h)	4.5E-05	6.3E-05	3.9E-05	1.2E-2	4.6E-05	3.7E-05
DRE	99.9999	99.9999	99.9999	99.997	99.9999	99.9999
HC (ppm)	7	25	9	6	5	22

Note: TCE = Trichloroethane

**A.22 Ash Grove Cement Company, Foreman, Arkansas, USA
(Benoit, 1990; Hansen, 1990)**

Test Date: 1989

Kiln Type: The kiln used for this test burn is a the wet process kiln.

Waste Characteristics:

The POHC used for this experiment was trichlorobenzene, as this compound is among the most thermally stable organic compounds. The solid hazardous waste was processed and containerised and charged to the kiln.

Summary of Results:

The results of stack gas emissions and metal emissions are summarised in Tables A.50 and A.51 respectively below:

TABLE A.50 STACK EMISSION RESULTS AT ASH GROVE FOREMAN PLANT

Run Number	Total HWF (lb/h)	Solid HWF (lb/h)	HCl (lb/h)	Hydrocarbons (lb/h)	DRE of TCB %
1	3900	3900	19.8	7	99.9999
2	3900	3900	28.4	12	99.9999

Run Number	Total HWF (lb/h)	Solid HWF (lb/h)	HCl (lb/h)	Hydrocarbons (lb/h)	DRE of TCB %
3	3900	3900	16.4	22	99.9999
4	15830	4030	17.2	6	99.9999
5	19610	4810	21.5	12	99.9999
6	18200	5200	19.7	7	99.9999
7	14875	4875	20.2	7	99.9999
8	15200	5200	22.2	9	99.9999

Note: TCB = Trichlorobenzene

TABLE A.51 METAL EMISSIONS AT ASH GROVE FOREMAN PLANT (lb/hr)

RUN	1	2	3	4	5	6	7	8
As	9.9E-5	9.6E-5	1.1E-4	2.0E-4	1.2E-4	2.3E-4	9.4E-5	3.1E-4
Be	4.0E-4	3.8E-4	4.0E-4	3.4E-4	3.2E-4	3.9E-4	3.7E-4	7.6E-4
Cd	4.7E-4	4.7E-4	2.6E-4	4.1E-3	1.1E-3	2.6E-3	5.1E-4	9.9E-4
Cr	0.05	0.061	0.019	0.019	0.034	0.026	0.021	0.031
Pb	0.027	0.021	0.012	0.187	0.077	0.209	0.035	0.069
Hg	3.0E-5	2.9E-5	9.8E-5	1.2E-4	2.4E-5	4.9E-5	2.8E-5	2.8E-5
Ag	9.8E-5	9.5E-5	9.8E-5	8.5E-5	8.1E-5	9.8E-5	9.3E-5	2.8E-4
Se	5.4E-4	3.3E-4	3.1E-4	6.6E-4	2.2E-4	2.1E-4	3.3E-4	8.5E-5
Th	9.8E-3	9.5E-3	9.8E-3	8.5E-3	8.1E-3	9.8E-3	9.3E-3	9.4E-3

A.23 D.G. Khan Cement Company, Pakistan
(Huden, 1990)

Test Date: 1989

Kiln Type: The kiln used for this test burn is a preheater dry process kiln with a production capacity of 1810 Mg/day (2000 tons/day).

Waste Characteristics:

Two types of pesticides, organophosphates and organochlorides, were used for this experiment. The detail composition of these wastes is given in Table A.52 below:

TABLE A.52 COMPOSITION OF WASTES USED AT DG KHAN CEMENT PLANT

COMPOUND	PERCENTAGE
ORGANOPHOSPHATES	
Nexion	55%
Fenitrothion	14%
Nuvacron	12%
Nogos (DDVP)	10%
Metasystox	5%
Dimethoate	2%
Gusathion	2%
ORGANOCHLORIDE	
Dieldrin	47%
Thiodan	3%
Kelthane	2%

COMPOUND	PERCENTAGE
Zolone	43 %
STAM F-34	5 %

Summary of Results:

The stack gas emission results are summarised in Table 53 below:

TABLE A.53 STACK EMISSION RESULTS AT DG KHAN PLANT (mg/cu.m)

RUN NO	PARTICLE	HCl	CHLORINE	SO _x	CO	OVERALL DRE
1	88.5	24	15.0	2.65	208	NA
2	89.7	40	12.0	1.54	137	NA
3	93.6	37	6.6	170.6	358	99.96
4	121.0	77	8.8	34.3	233	99.99
5	92.7	61	8.7	10.4	-	99.98
6	88.8	59	2.3	12.5	677	99.91

A.24 Texas Industries, Midlothian, Texas, USA (Hill and Daugherty, 1992)

Test Date: October 1990

Kiln Type: The kiln used for this test burn is wet process cement kiln with a production capacity of 1000 tons/day, 137 m in length and 4 m in diameter.

Waste Characteristics:

The waste used for this experiment is refuse derived fuel (RDF), which was cofired with coal. The composition of RDF used is shown in Table A.54.

TABLE A.54 COMPOSITION OF RDF USED AT TEXAS INDUSTRIES MIDLOTHIAN PLANT (%)

PARAMETER	AS RECEIVED	DRY BASIS
Total moisture	4.79	-
Ash	10.73	11.27
Fix carbon	12.29	12.91
Sulphur	0.34	0.36
BTU/lb	7008	7360
Volatile matter	72.19	75.82

Summary of Results:

The stack emission results are summarised in Table A.55 below:

TABLE A.55 STACK EMISSION RESULTS AT TEXAS INDUSTRIES MIDLOTHIAN PLANT (lb/hr)

POLLUTANT	BASELINE	TEST BURN
Sulphur Dioxides	460	370
Nitrogen Oxides	320	210
Hydrogen Chloride	7	25
Total Dioxins	8.55E-07	1.21E-06
Total Furans	1.02E-06	4.35E-07

**A.25 Continental Cement Company, Hannibal, Missouri, USA
(Garg, 1990)**

Test Date: 1990

Kiln Type: The kiln used for the test burn is a wet process kiln producing 1800 tons/day of cement clinker. The kiln is 189 m long and 5.5 m in diameter.

Waste Characteristics:

The waste fuel used in this test burn consisted of both liquid and solid (powdered) hazardous waste.

Summary of Results:

The test matrix used for this test burn is shown in Table A.56.

TABLE A.56 TEST MATRIX USED AT CONTINENTAL HANNIBAL PLANT

RUN	CONDITION
1	Baseline Coal only
2	Coal + Wastes (Liquid and Solid)
3	Coal + Wastes (Liquid and Solid)
4	Coal + Wastes (Liquid and Solid)
5	Baseline Coal + Diesel fuel
6	Baseline Coal + Diesel fuel
HCl Test	Coal + Wastes (Liquid only)

The results of products of incomplete emissions and dioxins and furans are summarised in Tables A.57 and A.58 respectively below:

TABLE A.57 EMISSIONS OF PRODUCTS OF INCOMPLETE COMBUSTION AT CONTINENTAL HANNIBAL PLANT (ng/l)

COMPOUND	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN6
Benzyl alcohol	700	600	500	400	600	400
Benzoic acid	1000	600	1000	1000	600	200
Phenol	ND	77	169	54	67	137
2-Chlorophenol	ND	ND	ND	9	ND	ND
2-Methylphenol	ND	ND	ND	ND	ND	15
4-Methylphenol	ND	52	53	61	62	56
Naphthalene	145	600	600	600	600	500
2-Methylnaphthalene	52	101	152	89	145	100
2.4.6-Trichlorophenol	ND	26	ND	32	ND	ND
Acenaphthalene	ND	95	117	72	106	86
Dibenzofuran	ND	101	146	94	129	91
Diethyl phthalate	ND	ND	ND	26	ND	ND
Fluorene	ND	26	29	ND	42	38
Phenanthrene	21	100	158	83	162	100
Anthracene	ND	13	15	ND	23	25
Fluoranthene	ND	46	47	ND	62	51
Pyrene	ND	29	28	ND	49	45
Benz(a)anthracene	ND	ND	ND	ND	ND	10
Chrysene	ND	23	22	ND	32	32
Bis(2-ethylhexyl)phthalate	ND	ND	ND	ND	53	27
Acrolein	160	240	87	130	750	570
1,1-Dichloroethane	ND	2.4	0.6	0.1	0.1	ND

Appendix A: Details of Test Burns Conducted in Cement Kilns

COMPOUND	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN6
Acetone	210	510	480	390	960	830
Methylene Chloride	72	260	12	10	14	4.1
Acrylonitrile	270	410	550	620	380	540
t-1,2-Dichloroethane	0.04	0.1	0.1	0.3	0.1	ND
1,1-Dichloroethane	0.2	2.6	ND	2.0	1.0	2.7
Methyl ethyl ketone	43	110	160	110	130	180
Chloroform	9.0	5.2	2.6	6.2	14	11
1,1,1-Trichloroethane	7.8	14	2.1	0.7	ND	ND
Carbon tetrachloride	0.5	2.3	ND	ND	ND	ND
Benzene	510	1800	2800	1400	2100	2100
1,2-Dichloropropane	3.5	16	38	ND	0.1	0.1
Trichloroethane	3.6	2.3	2.1	1.6	3.6	3.2
1,2-Dichloropropane	0.5	3.0	2.1	1.7	2.5	2.7
p-Dioxane	27	ND	ND	0.6	8.0	ND
Bromodichloromethane	5.1	2.5	2.4	2.3	4.0	0.6
Toluene	160	580	910	450	950	960
t-1,3-Dichloropropane	0.3	5.7	5.8	6.4	12	12
1,1,2-Trichloroethane	3.5	24	8.1	ND	2.1	5.7
Tetrachloroethane	1.8	0.74.5	2.3	0.4	0.3	nd
Dibromochloromethane	0.6	0.4	0.6	0.05	0.03	nd
Chlorobenzene	33	50	62	42	33	33
Ethylbenzene	26	170	190	75	200	200
1,1,2,2-Tetrachloroethane	10	18	12	14	14	14

TABLE A.58 EMISSIONS OF DIOXINS AND FURANS AT CONTINENTAL HANNIBAL PLANT (ng/dscm)

COMPOUND	RUN 1	RUN 3	RUN 4	RUN 5
DIOXINS				
TCDD	8.3	31.0	67.1	29.4
PeCDD	11.8	88.2	157.4	297
HxCDD	56.6	161.2	340.8	565
HpCDD	6.5	14.8	26.6	488.4
OCDD	3.7	9.9	10.8	88.4
Total Dioxins	86.9	305	603	951
FURANS				
TCDF	11.7	95.8	178.5	55.4
PeCDF	4.0	22.4	99.2	39.5
HxCDF	1.7	8.3	11.9	6.6
HpCDF	2.3	5.2	4.65	1.3
OCDF	<4.8E-03	<5.8E-03	<.015	<2.3E-03
Total Furans	19.8	131	294	103

A.26 Inland Cement Company, Alberta, Canada
(Alberta Environmental Protection, 1993)

Test Date: August 1991 and November 1992

Kiln Type: The kiln used for this test burn is a kiln consisting of a four stage preheat tower, a precalciner and a 59 m long and 3.8 m diameter rotary kiln.

Waste Characteristics:

The waste fuels used for the test burns were waste automobile tyres. The chemical composition and heavy metal content in the tyres used are shown in Table A.59.

TABLE A.59 AVERAGE COMPOSITION OF TYRES USED AT INLAND PLANT

CHEMICAL CONSTITUENT	PERCENTAGE (WEIGHT)
Carbon	70.0%
Hydrogen	7.0%
Zinc Oxide	1.2%
Sulphur	1.3% to 2.0%
Iron Oxide	15.0%
Others	5.0%
HEAVY METAL CONTENT	Parts Per Million (ppm)
Thallium	0.2
Cadmium	5 - 10
Lead	60 - 760
Nickel	77
Chromium	97

Summary of Results:

The results of stack emissions are summarised in Table A.60 Below:

TABLE A.60 STACK EMISSION RESULTS AT INLAND PLANT

PARAMETERS	UNITS	BASELINE	1991 TEST	1992 TEST
% Tyre derived fuel	%	0	10-12%	9-10%
Particulate matter	kg/h	16.7	9.7	16.7
Sulphur dioxide	kg/h	-	0.9	25.7
Hydrogen chloride	kg/h	0.9	-	-
Nitrogen oxides	kg/h	-	251	182.3
Zinc	g/h	-	-	40.84
Lead	g/h	-	<10	2.3
Cadmium	g/h	-	<10	3.44
Arsenic	g/h	-	<10	0.36
Chromium	g/h	-	10	9.31
PAHs	g/h	-	-	1.64
Dioxins and Furans	µg/h	-	12	3.17

APPENDIX B FATE OF METALS IN CEMENT KILNS

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	4.63E-03	0.2%	6.94E-01	34.8%	1.88E-02	0.9%	1.28E+00	0.9%	2.00E+00	0.00E+00	ERR
Beryllium	6.62E-03	0.8%	2.06E-01	24.5%	2.53E-02	3.0%	6.03E-01	3.0%	8.42E-01	0.00E+00	ERR
Cadmium	6.08E-02	2.5%	1.16E-01	4.7%	6.62E-04	0.0%	2.29E+00	0.0%	2.47E+00	0.00E+00	ERR
Chromium	8.44E-01	3.1%	5.40E+00	20.0%	4.81E-02	0.2%	2.06E+01	0.2%	2.69E+01	0.00E+00	ERR
Lead	2.75E+00	11.7%	9.16E-01	3.9%	4.03E-02	0.2%	1.98E+01	0.2%	2.35E+01	0.00E+00	ERR
Barium	4.81E+00	27.5%	1.24E+01	71.0%	2.79E-01	1.6%	0.00E+00	1.6%	1.75E+01	0.00E+00	ERR
Mercury	1.99E-03	14.4%	1.16E-02	83.7%	2.64E-04	1.9%	0.00E+00	1.9%	1.38E-02	0.00E+00	ERR
Silver	2.02E-02	8.6%	2.14E-01	91.1%	6.62E-04	0.3%	0.00E+00	0.3%	2.35E-01	0.00E+00	ERR
Antimony	2.72E-01	3.7%	1.44E-01	2.0%	4.16E-03	0.1%	6.89E+00	0.1%	7.31E+00	0.00E+00	ERR
Thallium	4.63E-02	40.7%	6.53E-02	57.5%	2.09E-03	1.8%	0.00E+00	1.8%	1.14E-01	0.00E+00	ERR
Nickel	1.95E-01	5.2%	2.94E+00	78.3%	6.21E-01	16.5%	0.00E+00	16.5%	3.76E+00	0.00E+00	ERR
Selenium	1.06E-02	9.2%	1.02E-01	88.9%	2.09E-03	1.8%	0.00E+00	1.8%	1.15E-01	0.00E+00	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	Out/In	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	ERR
Chlorine	1.68E+02	91.2%	1.16E+01	6.3%	4.63E+00	2.5%	0.00E+00	2.5%	1.84E+02	ERR	ERR

Metal	Clinker	Percent	CKD	Percent	Slack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Slack/In
Arsenic	1.64E+00	77.2%	4.85E-01	22.8%	4.72E-04	0.0%	2.13E+00	0.00E+00	ERR	1.07	0.296	0.024%
Beryllium	6.80E-01	79.6%	1.74E-01	20.4%	5.40E-04	0.1%	8.55E-01	0.00E+00	ERR	1.02	0.256	0.064%
Cadmium	9.30E-02	3.7%	2.36E+00	95.0%	3.22E-02	1.3%	2.48E+00	0.00E+00	ERR	1.01	25.366	1.305%
Chromium	2.16E+01	80.8%	5.13E+00	19.2%	2.61E-03	0.0%	2.68E+01	0.00E+00	ERR	0.99	0.237	0.010%
Lead	3.13E-01	1.4%	2.26E+01	97.5%	2.73E-01	1.2%	2.32E+01	0.00E+00	ERR	0.99	72.069	1.161%
Barium	1.11E+01	74.2%	3.85E+00	25.7%	1.43E-02	0.1%	1.50E+01	0.00E+00	ERR	0.85	0.346	0.082%
Mercury	3.97E-03	31.1%	1.12E-03	8.8%	7.67E-03	60.1%	1.28E-02	0.00E+00	ERR	0.92	0.283	55.459%
Silver	5.58E-02	43.3%	7.30E-02	56.6%	1.51E-04	0.1%	1.29E-01	0.00E+00	ERR	0.55	1.309	0.064%
Antimony	7.53E+00	76.9%	2.26E+00	23.1%	1.10E-03	0.0%	9.79E+00	0.00E+00	ERR	1.34	0.300	0.015%
Thallium	3.16E-02	59.5%	1.95E-02	36.7%	2.01E-03	3.8%	5.31E-02	0.00E+00	ERR	0.47	0.617	1.768%
Nickel	1.99E+00	80.2%	4.90E-01	19.7%	1.56E-03	0.1%	2.48E+00	0.00E+00	ERR	0.66	0.246	0.041%
Selenium	3.16E-02	19.1%	1.28E-01	77.4%	5.81E-03	3.5%	1.65E-01	0.00E+00	ERR	1.44	4.046	5.059%
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Chlorine	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	0.00	ERR	0.000%

TABLE B1 METAL MATERIAL BALANCE FOR TEST A1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	5.53E-03	0.2%	8.26E-01	29.7%	5.81E-02	2.1%	1.89E+00	68.0%	2.78E+00	0.00E+00	ERR
Beryllium	3.80E-03	0.2%	3.31E-01	21.2%	8.85E-02	5.7%	1.14E+00	72.9%	1.56E+00	0.00E+00	ERR
Cadmium	1.01E-01	2.3%	2.80E-01	6.3%	2.59E-03	0.1%	4.08E+00	91.4%	4.46E+00	0.00E+00	ERR
Chromium	8.66E-01	1.8%	9.39E+00	19.5%	1.38E-01	0.3%	3.76E+01	78.4%	4.80E+01	0.00E+00	ERR
Lead	2.93E+00	7.2%	2.05E+00	5.1%	6.62E-02	0.2%	3.55E+01	87.6%	4.06E+01	0.00E+00	ERR
Barium	6.03E+00	25.9%	1.65E+01	70.6%	8.30E-01	3.6%	0.00E+00	0.0%	2.33E+01	0.00E+00	ERR
Mercury	4.99E-03	17.3%	2.28E-02	79.1%	1.03E-03	3.6%	0.00E+00	0.0%	2.88E-02	0.00E+00	ERR
Silver	1.84E-02	6.1%	2.80E-01	93.0%	2.59E-03	0.9%	0.00E+00	0.0%	3.01E-01	0.00E+00	ERR
Antimony	3.31E-01	2.6%	3.13E-01	2.5%	1.19E-02	0.1%	1.21E+01	94.8%	1.27E+01	0.00E+00	ERR
Thallium	5.53E-03	2.2%	2.34E-01	92.4%	1.38E-02	5.5%	0.00E+00	0.0%	2.53E-01	0.00E+00	ERR
Nickel	3.81E-01	4.5%	5.58E+00	65.8%	2.51E+00	29.7%	0.00E+00	0.0%	8.47E+00	0.00E+00	ERR
Selenium	1.46E-02	0.9%	1.59E+00	97.7%	2.30E-02	1.4%	0.00E+00	0.0%	1.63E+00	0.00E+00	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	Out/In	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	ERR
Chlorine	2.16E+02	87.4%	2.28E+01	9.2%	8.21E+00	3.3%	0.00E+00	0.0%	2.47E+02	ERR	ERR

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	2.39E+00	77.5%	6.94E-01	22.5%	2.90E-04	0.0%	3.08E+00	0.00E+00	ERR	1.11	0.290	0.010%
Beryllium	1.22E+00	78.9%	3.25E-01	21.1%	2.17E-04	0.0%	1.54E+00	0.00E+00	ERR	0.99	0.268	0.014%
Cadmium	3.36E-01	8.6%	3.57E+00	91.2%	6.85E-03	0.2%	3.91E+00	0.00E+00	ERR	0.88	10.635	0.154%
Chromium	4.19E+01	82.4%	8.94E+00	17.6%	1.66E-03	0.0%	5.08E+01	0.00E+00	ERR	1.06	0.213	0.003%
Lead	6.12E-01	1.6%	3.78E+01	98.2%	8.71E-02	0.2%	3.85E+01	0.00E+00	ERR	0.95	61.778	0.215%
Barium	2.30E+01	80.2%	5.67E+00	19.8%	3.49E-03	0.0%	2.86E+01	0.00E+00	ERR	1.23	0.247	0.015%
Mercury	8.30E-03	48.3%	2.13E-03	12.4%	6.76E-03	39.3%	1.72E-02	0.00E+00	ERR	0.60	0.257	23.435%
Silver	1.96E-01	86.3%	3.07E-02	13.5%	2.50E-04	0.1%	2.26E-01	0.00E+00	ERR	0.75	0.157	0.083%
Antimony	9.75E+00	77.1%	2.90E+00	22.9%	5.99E-04	0.0%	1.27E+01	0.00E+00	ERR	0.99	0.298	0.005%
Thallium	5.53E-02	74.2%	1.80E-02	24.1%	1.24E-03	1.7%	7.46E-02	0.00E+00	ERR	0.29	0.325	0.489%
Nickel	5.85E+00	86.2%	9.39E-01	13.8%	8.44E-04	0.0%	6.79E+00	0.00E+00	ERR	0.80	0.160	0.010%
Selenium	5.53E-02	26.5%	1.53E-01	73.2%	7.30E-04	0.3%	2.09E-01	0.00E+00	ERR	0.13	2.762	0.045%
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Chlorine	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	0.00	ERR	0.000%

TABLE B2 METAL MATERIAL BALANCE FOR TEST A2

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In
Antimony	5.98E+00	5.3%	1.08E+02	94.7%	0.00E+00	0.0%	0.00E+00	0.0%	1.14E+02	1.14E+02
Arsenic	5.36E+01	15.8%	2.86E+02	84.2%	0.00E+00	0.0%	0.00E+00	0.0%	3.40E+02	3.40E+02
Barium	6.89E+02	13.1%	4.56E+03	86.9%	0.00E+00	0.0%	0.00E+00	0.0%	5.24E+03	5.24E+03
Beryllium	1.02E+01	35.2%	1.88E+01	64.8%	0.00E+00	0.0%	0.00E+00	0.0%	2.90E+01	2.90E+01
Cadmium	4.53E+01	24.1%	1.42E+02	75.9%	0.00E+00	0.0%	0.00E+00	0.0%	1.88E+02	1.88E+02
Chromium	1.65E+02	11.3%	1.30E+03	88.7%	0.00E+00	0.0%	0.00E+00	0.0%	1.47E+03	1.47E+03
Lead	1.92E+02	7.2%	2.47E+03	92.8%	0.00E+00	0.0%	0.00E+00	0.0%	2.66E+03	2.66E+03
Silver	1.58E+00	9.3%	1.55E+01	90.7%	0.00E+00	0.0%	0.00E+00	0.0%	1.71E+01	1.71E+01
Thallium	2.39E+00	1.3%	1.78E+02	98.7%	0.00E+00	0.0%	0.00E+00	0.0%	1.80E+02	1.80E+02
Zinc	8.50E+02	22.3%	2.96E+03	77.7%	0.00E+00	0.0%	0.00E+00	0.0%	3.81E+03	3.81E+03
Mercury	3.79E+00	5.8%	6.10E+01	94.2%	0.00E+00	0.0%	0.00E+00	0.0%	6.48E+01	6.48E+01

Metal	Clinker	Percent	CKD	Percent	BPD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In
Antimony	6.62E+01	88.5%	8.49E+00	11.3%	3.45E-01	0.5%	1.21E-01	0.2%	7.48E+01	7.48E+01		0.66
Arsenic	2.92E+02	84.8%	5.15E+01	15.0%	1.42E+00	0.4%	7.69E-01	0.2%	3.44E+02	3.44E+02		1.01
Barium	7.69E+03	93.2%	5.48E+02	6.6%	3.59E+01	0.4%	1.37E+01	0.2%	8.25E+03	8.25E+03		1.57
Beryllium	7.01E+01	94.0%	3.74E+00	5.0%	3.45E-01	0.5%	7.43E-01	1.0%	7.46E+01	7.46E+01		2.57
Cadmium	2.10E+02	93.1%	1.55E+01	6.9%	1.89E+00	0.8%	1.58E-01	0.1%	2.25E+02	2.25E+02		1.20
Chromium	6.85E+03	97.5%	1.65E+02	2.3%	1.73E+01	0.2%	7.18E+00	0.1%	7.02E+03	7.02E+03		4.79
Lead	1.84E+03	78.4%	5.01E+02	21.3%	6.04E+01	2.6%	5.69E+00	0.2%	2.35E+03	2.35E+03		0.88
Silver	1.32E+01	82.6%	2.73E+00	17.1%	4.14E-01	2.6%	4.40E-02	0.3%	1.60E+01	1.60E+01		0.93
Thallium	2.65E+01	2.4%	1.07E+03	97.5%	3.31E-01	0.0%	5.20E-01	0.0%	1.09E+03	1.09E+03		6.08
Zinc	3.55E+03	92.0%	2.89E+02	7.5%	1.89E+01	0.5%	1.92E+01	0.5%	3.86E+03	3.86E+03		1.01
Mercury	1.35E+01	53.7%	9.76E+00	38.8%	8.90E-02	0.4%	1.89E+00	7.5%	2.51E+01	2.51E+01		0.39

TABLE B3 METAL MATERIAL BALANCE FOR TEST B1

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In
Antimony	3.44E+00	1.8%	6.41E+01	34.4%	1.19E+02	63.8%	0.00E+00	0.0%	1.87E+02	1.14E+02
Arsenic	4.49E+01	2.1%	3.26E+02	15.4%	1.75E+03	82.5%	0.00E+00	0.0%	2.12E+03	3.40E+02
Barium	5.86E+02	5.2%	2.83E+03	25.1%	7.86E+03	69.7%	0.00E+00	0.0%	1.13E+04	5.24E+03
Beryllium	6.60E+00	3.9%	1.39E+02	82.4%	2.30E+01	13.7%	0.00E+00	0.0%	1.68E+02	2.90E+01
Cadmium	1.99E+00	0.1%	3.63E+02	12.0%	2.66E+03	88.0%	0.00E+00	0.0%	3.03E+03	1.88E+02
Chromium	1.79E+02	1.6%	4.65E+03	40.6%	5.81E+03	50.7%	8.26E+02	7.2%	1.15E+04	1.47E+03
Lead	6.36E+01	0.7%	3.33E+03	35.0%	5.81E+03	61.1%	3.03E+02	3.2%	9.51E+03	2.66E+03
Silver	6.21E+00	4.5%	9.37E+01	67.9%	3.81E+01	27.6%	0.00E+00	0.0%	1.38E+02	1.71E+01
Thallium	7.63E+00	0.8%	8.98E+02	99.0%	1.45E+00	0.2%	0.00E+00	0.0%	9.07E+02	1.80E+02
Zinc	5.25E+02	1.7%	4.77E+03	15.1%	2.63E+04	83.3%	0.00E+00	0.0%	3.16E+04	3.81E+03
Mercury	8.90E-01	0.7%	1.16E+02	88.2%	1.47E+01	11.2%	0.00E+00	0.0%	1.32E+02	6.48E+01

Metal	Clinker	Percent	CKD	Percent	BPD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In
Antimony	5.34E+01	88.9%	6.70E+00	11.1%	1.60E+00	2.66E-02	0.00E+00	0.0%	6.01E+01	7.48E+01	0.80	0.32
Arsenic	2.40E+03	97.7%	5.65E+01	2.3%	4.57E+01	1.86E-02	1.03E+00	0.0%	2.45E+03	3.44E+02	7.12	1.16
Barium	8.74E+03	96.2%	3.49E+02	3.8%	2.20E+02	2.42E-02	0.00E+00	0.0%	9.09E+03	8.25E+03	1.10	0.81
Beryllium	1.12E+02	95.7%	5.00E+00	4.3%	1.22E+00	1.04E-02	2.00E-02	0.0%	1.17E+02	7.46E+01	1.57	0.70
Cadmium	6.51E+02	84.2%	1.15E+02	14.8%	1.36E+03	1.77E+00	7.20E+00	0.9%	7.72E+02	2.25E+02	3.43	0.26
Chromium	4.79E+03	95.3%	2.37E+02	4.7%	1.05E+02	2.09E-02	2.00E-02	0.0%	5.03E+03	7.02E+03	0.72	0.44
Lead	2.16E+03	81.9%	4.72E+02	17.9%	2.89E+03	1.09E+00	5.64E+00	0.2%	2.64E+03	2.35E+03	1.12	0.28
Silver	6.45E+01	85.6%	1.08E+01	14.4%	1.16E+01	1.54E-01	0.00E+00	0.0%	7.53E+01	1.60E+01	4.72	0.55
Thallium	2.14E+01	1.6%	1.29E+03	98.4%	6.16E+00	4.70E-03	0.00E+00	0.0%	1.31E+03	1.09E+03	1.20	1.44
Zinc	1.23E+04	94.8%	6.82E+02	5.2%	3.48E+02	2.68E-02	2.00E-02	0.0%	1.30E+04	3.86E+03	3.37	0.41
Mercury	1.21E+01	25.8%	1.82E+01	39.0%	2.60E-01	5.57E-03	1.64E+01	35.2%	4.67E+01	2.51E+01	1.86	0.35

TABLE B4 METAL MATERIAL BALANCE FOR TEST B2

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In
Antimony	4.26E+00	1.6%	6.72E+01	25.8%	1.88E+02	72.2%	1.00E+00	0.4%	2.60E+02	1.14E+02
Arsenic	6.07E+01	2.9%	1.74E+02	8.3%	1.86E+03	88.8%	0.00E+00	0.0%	2.09E+03	3.40E+02
Barium	6.75E+02	5.4%	3.21E+03	25.9%	8.51E+03	68.7%	0.00E+00	0.0%	1.24E+04	5.24E+03
Beryllium	3.68E+00	2.6%	1.18E+02	81.9%	2.23E+01	15.5%	0.00E+00	0.0%	1.44E+02	2.90E+01
Cadmium	2.63E+00	0.1%	7.99E+02	22.9%	2.68E+03	77.0%	0.00E+00	0.0%	3.48E+03	1.88E+02
Chromium	1.84E+02	1.7%	4.26E+03	38.8%	5.71E+03	52.0%	8.26E+02	7.5%	1.10E+04	1.47E+03
Lead	7.00E+01	0.9%	2.02E+03	26.5%	5.54E+03	72.6%	0.00E+00	0.0%	7.63E+03	2.66E+03
Silver	5.43E+00	2.8%	1.51E+02	78.8%	3.54E+01	18.4%	0.00E+00	0.0%	1.92E+02	1.71E+01
Thallium	8.08E+00	0.7%	1.08E+03	99.2%	1.18E+00	0.1%	0.00E+00	0.0%	1.09E+03	1.80E+02
Zinc	5.94E+02	4.3%	4.62E+03	33.7%	8.50E+03	62.0%	0.00E+00	0.0%	1.37E+04	3.81E+03
Mercury	2.28E+00	2.0%	9.43E+01	82.0%	1.84E+01	16.0%	0.00E+00	0.0%	1.15E+02	6.48E+01

Metal	Clinker	Percent	CKD	Percent	BPD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In
Antimony	5.64E+01	90.0%	6.24E+00	10.0%	2.09E+00	3.34E-02	0.00E+00	0.0%	6.27E+01	7.48E+01	0.84	0.24
Arsenic	2.25E+03	97.8%	5.06E+01	2.2%	4.93E+01	2.14E-02	6.40E-01	0.0%	2.30E+03	3.44E+02	6.68	1.10
Barium	8.18E+03	96.1%	3.35E+02	3.9%	1.51E+02	1.77E-02	0.00E+00	0.0%	8.52E+03	8.25E+03	1.03	0.69
Beryllium	1.20E+02	96.2%	4.78E+00	3.8%	1.44E+00	1.15E-02	2.00E-02	0.0%	1.25E+02	7.46E+01	1.68	0.87
Cadmium	4.74E+02	85.0%	8.29E+01	14.9%	9.43E+02	1.69E+00	8.20E-01	0.1%	5.58E+02	2.25E+02	2.48	0.16
Chromium	5.76E+03	96.6%	1.95E+02	3.3%	8.77E+01	1.47E-02	5.47E+00	0.1%	5.96E+03	7.02E+03	0.85	0.54
Lead	3.45E+03	88.5%	4.42E+02	11.3%	1.87E+03	4.78E-01	6.34E+00	0.2%	3.90E+03	2.35E+03	1.66	0.51
Silver	7.83E+01	90.4%	8.29E+00	9.6%	6.86E+00	7.92E-02	0.00E+00	0.0%	8.66E+01	1.60E+01	5.43	0.45
Thallium	2.60E+01	2.3%	1.12E+03	97.7%	4.60E+00	4.01E-03	0.00E+00	0.0%	1.15E+03	1.09E+03	1.05	1.05
Zinc	1.35E+04	95.7%	5.99E+02	4.3%	3.08E+02	2.19E-02	1.29E+01	0.1%	1.41E+04	3.86E+03	3.65	1.03
Mercury	1.28E+01	28.3%	1.42E+01	31.5%	2.50E-01	5.55E-03	1.81E+01	40.2%	4.51E+01	2.51E+01	1.79	0.39

TABLE B5 METAL MATERIAL BALANCE FOR TEST B3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	2.47E-02	0.2%	1.10E-01	1.0%	1.04E-01	1.0%	1.03E+01	97.7%	1.05E+01	0.00E+00	ERR
Beryllium	1.49E-02	1.0%	9.84E-02	6.9%	1.61E-02	1.1%	1.30E+00	90.9%	1.43E+00	0.00E+00	ERR
Cadmium	1.31E-03	0.0%	1.94E-01	2.4%	9.07E-02	1.1%	7.73E+00	96.4%	8.02E+00	0.00E+00	ERR
Chromium	1.09E-01	0.2%	2.65E+00	5.2%	4.87E+00	9.5%	4.38E+01	85.2%	5.14E+01	0.00E+00	ERR
Lead	6.71E-02	0.1%	5.85E-01	1.1%	7.26E+00	13.8%	4.45E+01	84.9%	5.24E+01	0.00E+00	ERR
Barium	6.03E-01	3.3%	9.98E+00	55.4%	7.44E+00	41.3%	0.00E+00	0.0%	1.80E+01	0.00E+00	ERR
Mercury	5.22E-04	2.6%	1.83E-02	91.0%	1.29E-03	6.4%	0.00E+00	0.0%	2.01E-02	0.00E+00	ERR
Silver	1.31E-03	0.5%	1.94E-01	71.5%	7.61E-02	28.0%	0.00E+00	0.0%	2.72E-01	0.00E+00	ERR
Antimony	5.40E-03	1.0%	1.08E-01	20.2%	4.22E-01	78.8%	0.00E+00	0.0%	5.36E-01	0.00E+00	ERR
Thallium	3.75E-03	1.9%	1.10E-01	56.5%	8.09E-02	41.6%	0.00E+00	0.0%	1.94E-01	0.00E+00	ERR
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	Out/In	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	ERR
Chlorine	9.89E+00	1.7%	1.06E+02	18.7%	4.50E+02	79.5%	0.00E+00	0.0%	5.66E+02	ERR	ERR

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	8.80E+00	76.6%	2.68E+00	23.3%	7.76E-04	0.0%	1.15E+01	0.00E+00	ERR	1.09	0.305	0.007%
Beryllium	7.62E-01	83.8%	1.47E-01	16.1%	5.03E-04	0.1%	9.09E-01	0.00E+00	ERR	0.64	0.192	0.035%
Cadmium	1.50E-01	2.5%	5.72E+00	96.6%	5.17E-02	0.9%	5.92E+00	0.00E+00	ERR	0.74	38.182	0.645%
Chromium	4.20E+01	84.4%	7.76E+00	15.6%	2.44E-02	0.0%	4.98E+01	0.00E+00	ERR	0.97	0.185	0.048%
Lead	1.07E+00	2.5%	4.12E+01	96.7%	3.54E-01	0.8%	4.26E+01	0.00E+00	ERR	0.81	38.475	0.675%
Barium	2.30E+01	85.4%	3.92E+00	14.6%	1.29E-02	0.0%	2.69E+01	0.00E+00	ERR	1.49	0.171	0.071%
Mercury	6.94E-03	80.5%	1.62E-03	18.8%	5.35E-05	0.6%	8.62E-03	0.00E+00	ERR	0.43	0.234	0.266%
Silver	1.75E-01	94.9%	9.12E-03	5.0%	2.29E-04	0.1%	1.84E-01	0.00E+00	ERR	0.68	0.052	0.084%
Antimony	3.20E-01	82.1%	6.94E-02	17.8%	1.05E-04	0.0%	3.89E-01	0.00E+00	ERR	0.73	0.217	0.020%
Thallium	4.81E-02	62.9%	2.49E-02	32.6%	3.45E-03	4.5%	7.65E-02	0.00E+00	ERR	0.39	0.519	1.774%
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Chlorine	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	0.00	ERR	0.000%

TABLE B6 METAL MATERIAL BALANCE FOR TEST C1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spikes	Percent	Total In	Base In	I/P Incr
Arsenic	1.29E-02	0.3%	2.76E-01	6.1%	1.32E-02	0.3%	4.24E+00	93.3%	4.54E+00	0.00E+00	ERR
Beryllium	1.20E-01	3.7%	2.58E-01	8.0%	1.45E-02	0.4%	2.84E+00	87.9%	3.24E+00	0.00E+00	ERR
Cadmium	4.46E-03	0.1%	4.31E-01	5.7%	8.75E-02	1.2%	7.08E+00	93.1%	7.60E+00	0.00E+00	ERR
Chromium	2.93E-01	0.5%	6.40E+00	9.9%	2.85E+00	4.4%	5.53E+01	85.3%	6.49E+01	0.00E+00	ERR
Lead	4.94E-02	0.1%	1.43E+00	1.6%	7.44E+00	8.2%	8.21E+01	90.2%	9.10E+01	0.00E+00	ERR
Barium	3.39E-01	0.8%	2.44E+01	60.3%	1.57E+01	38.9%	0.00E+00	0.0%	4.05E+01	0.00E+00	ERR
Mercury	1.79E-03	4.1%	3.99E-02	91.5%	1.90E-03	4.4%	0.00E+00	0.0%	4.36E-02	0.00E+00	ERR
Silver	4.46E-03	1.0%	4.31E-01	96.0%	1.34E-02	3.0%	0.00E+00	0.0%	4.49E-01	0.00E+00	ERR
Antimony	1.28E-02	2.6%	2.73E-01	54.8%	2.12E-01	42.6%	0.00E+00	0.0%	4.98E-01	0.00E+00	ERR
Thallium	1.29E-02	0.9%	1.38E+00	98.1%	1.32E-02	0.9%	0.00E+00	0.0%	1.41E+00	0.00E+00	ERR
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	Out/In	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	ERR
Chlorine	1.43E+01	1.1%	6.67E+01	5.2%	1.20E+03	93.7%	0.00E+00	0.0%	1.28E+03	ERR	ERR

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	4.12E+00	76.8%	1.24E+00	23.2%	1.41E-03	0.0%	5.37E+00	0.00E+00	ERR	1.18	0.301	0.031%
Beryllium	1.66E+00	74.4%	5.72E-01	25.6%	4.54E-04	0.0%	2.24E+00	0.00E+00	ERR	0.69	0.343	0.014%
Cadmium	1.77E-01	2.7%	6.40E+00	96.8%	3.18E-02	0.5%	6.60E+00	0.00E+00	ERR	0.87	36.154	0.418%
Chromium	4.76E+01	76.1%	1.50E+01	23.9%	1.54E-03	0.0%	6.26E+01	0.00E+00	ERR	0.96	0.314	0.002%
Lead	1.26E+00	1.2%	1.04E+02	98.4%	4.26E-01	0.4%	1.06E+02	0.00E+00	ERR	1.16	82.374	0.468%
Barium	2.48E+01	66.4%	1.25E+01	33.5%	3.86E-02	0.1%	3.73E+01	0.00E+00	ERR	0.92	0.505	0.095%
Mercury	1.52E-02	46.1%	5.44E-03	16.6%	1.22E-02	37.3%	3.28E-02	0.00E+00	ERR	0.75	0.359	28.087%
Silver	1.77E-01	78.1%	4.85E-02	21.4%	1.18E-03	0.5%	2.27E-01	0.00E+00	ERR	0.50	0.274	0.263%
Antimony	1.21E-01	46.6%	1.37E-01	53.1%	6.80E-04	0.3%	2.59E-01	0.00E+00	ERR	0.52	1.139	0.137%
Thallium	1.22E-01	46.4%	1.37E-01	52.1%	3.90E-03	1.5%	2.63E-01	0.00E+00	ERR	0.19	1.123	0.277%
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Chlorine	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	0.00	ERR	0.000%

TABLE B7 METAL MATERIAL BALANCE FOR TEST D1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	7.80E-02	1.4%	1.11E-01	2.0%	1.64E-02	0.3%	5.44E+00	0.3%	5.65E+00	0.00E+00	ERR
Beryllium	1.94E-02	1.1%	1.17E-01	6.9%	1.14E-02	0.7%	1.55E+00	0.7%	1.70E+00	0.00E+00	ERR
Cadmium	1.09E-02	0.2%	2.01E-01	4.2%	5.02E-02	1.1%	4.49E+00	1.1%	4.75E+00	0.00E+00	ERR
Chromium	1.49E+00	3.0%	9.66E+00	19.6%	3.09E+00	6.3%	3.50E+01	6.3%	4.93E+01	0.00E+00	ERR
Lead	3.15E-02	0.1%	7.26E-01	2.2%	7.25E+00	21.9%	2.51E+01	21.9%	3.31E+01	0.00E+00	ERR
Barium	3.76E+00	12.5%	1.83E+01	60.8%	8.03E+00	26.7%	0.00E+00	26.7%	3.01E+01	0.00E+00	ERR
Mercury	8.03E-04	3.4%	1.99E-02	84.5%	2.85E-03	12.1%	0.00E+00	12.1%	2.35E-02	0.00E+00	ERR
Silver	1.09E-02	4.9%	1.96E-01	87.8%	1.64E-02	7.4%	0.00E+00	7.4%	2.23E-01	0.00E+00	ERR
Antimony	2.02E-02	4.5%	1.10E-01	24.5%	3.18E-01	71.0%	0.00E+00	71.0%	4.48E-01	0.00E+00	ERR
Thallium	6.17E-02	5.2%	1.11E+00	94.1%	7.85E-03	0.7%	0.00E+00	0.7%	1.18E+00	0.00E+00	ERR
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	Out/In	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	ERR
Chlorine	1.19E+01	5.5%	3.87E+01	17.8%	1.67E+02	76.7%	0.00E+00	76.7%	2.17E+02	ERR	ERR

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	6.21E+00	91.2%	5.99E-01	8.8%	7.39E-04	0.0%	6.81E+00	0.00E+00	ERR	1.21	0.096	0.013%
Beryllium	1.67E+00	94.9%	8.98E-02	5.1%	2.96E-04	0.0%	1.76E+00	0.00E+00	ERR	1.04	0.054	0.017%
Cadmium	1.02E-01	2.2%	4.38E+00	96.5%	5.85E-02	1.3%	4.54E+00	0.00E+00	ERR	0.95	43.080	1.231%
Chromium	4.30E+01	93.9%	2.78E+00	6.1%	1.65E-02	0.0%	4.58E+01	0.00E+00	ERR	0.93	0.065	0.033%
Lead	1.16E+00	3.3%	3.43E+01	96.3%	1.56E-01	0.4%	3.56E+01	0.00E+00	ERR	1.08	29.531	0.472%
Barium	2.93E+01	95.2%	1.48E+00	4.8%	4.27E-03	0.0%	3.07E+01	0.00E+00	ERR	1.02	0.051	0.014%
Mercury	7.89E-03	33.5%	7.39E-04	3.1%	1.49E-02	63.4%	2.36E-02	0.00E+00	ERR	1.00	0.094	63.452%
Silver	1.02E-01	69.0%	2.85E-02	19.3%	1.71E-02	11.6%	1.47E-01	0.00E+00	ERR	0.66	0.280	7.679%
Antimony	3.34E-01	89.7%	3.76E-02	10.1%	8.39E-04	0.2%	3.72E-01	0.00E+00	ERR	0.83	0.113	0.188%
Thallium	5.76E-01	90.2%	6.17E-02	9.7%	6.40E-04	0.1%	6.38E-01	0.00E+00	ERR	0.54	0.107	0.054%
Nickel	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Selenium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Vanadium	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Zinc	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	ERR	ERR	ERR
Chlorine	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	ERR	0.00E+00	0.00E+00	ERR	0.00	ERR	0.000%

TABLE B8 METAL MATERIAL BALANCE FOR TEST E1

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	3.00E-02	1.9%	1.55E+00	98.1%		0.0%		0.0%	1.58E+00	1.58E+00	
Cadmium	3.00E-03	9.1%	3.00E-02	90.9%		0.0%		0.0%	3.30E-02	3.30E-02	
Chromium	1.40E-01	9.7%	1.30E+00	90.3%		0.0%		0.0%	1.44E+00	1.44E+00	
Lead	2.60E-01	3.5%	7.24E+00	96.5%		0.0%		0.0%	7.50E+00	7.50E+00	
Barium	3.00E-01	3.1%	9.50E+00	96.9%		0.0%		0.0%	9.80E+00	9.80E+00	
Mercury	1.00E-03	18.2%	4.50E-03	81.8%		0.0%		0.0%	5.50E-03	5.50E-03	
Nickel	1.00E-01	6.6%	1.42E+00	93.4%		0.0%		0.0%	1.52E+00	1.52E+00	
Selenium	4.00E-03	57.1%	3.00E-03	42.9%		0.0%		0.0%	7.00E-03	7.00E-03	
Vanadium	1.50E-01	7.0%	2.00E+00	93.0%		0.0%		0.0%	2.15E+00	2.15E+00	
Zinc	4.20E-01	10.9%	3.42E+00	89.1%		0.0%		0.0%	3.84E+00	3.84E+00	
Chlorine	5.40E+00	29.5%	1.29E+01	70.5%		0.0%		0.0%	1.83E+01	1.83E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	2.94E+00	93.9%	1.90E-01	6.1%	ND	0.0%	3.13E+00	3.13E+00		1.98	0.065	0.000%
Cadmium	6.00E-02	90.9%	6.00E-03	9.1%	ND	0.0%	6.60E-02	6.60E-02		2.00	0.100	0.000%
Chromium	2.44E+00	96.1%	1.00E-01	3.9%	ND	0.0%	2.54E+00	2.54E+00		1.76	0.041	0.000%
Lead	3.70E+00	68.6%	1.68E+00	31.2%	1.20E-02	0.2%	5.39E+00	5.39E+00		0.72	0.454	0.160%
Barium	5.32E+00	92.7%	4.20E-01	7.3%	ND	0.0%	5.74E+00	5.74E+00		0.59	0.079	0.000%
Mercury	2.90E-03	87.9%	2.90E-04	8.8%	1.10E-04	3.3%	3.30E-03	3.30E-03		0.60	0.100	2.000%
Nickel	7.40E-01	91.3%	7.00E-02	8.6%	9.30E-04	0.1%	8.11E-01	8.11E-01		0.53	0.095	0.061%
Selenium	1.50E-03	21.7%	4.00E-04	5.8%	5.00E-03	72.5%	6.90E-03	6.90E-03		0.99	0.267	71.429%
Vanadium	1.44E+00	93.5%	1.00E-01	6.5%	2.40E-04	0.0%	1.54E+00	1.54E+00		0.72	0.069	0.011%
Zinc	3.73E+00	89.3%	4.40E-01	10.5%	5.60E-03	0.1%	4.18E+00	4.18E+00		1.09	0.118	0.146%
Chlorine	5.90E+00	53.5%	4.40E+00	39.9%	7.30E-01	6.6%	1.10E+01	1.10E+01		0.60	0.746	3.989%

TABLE B9 METAL MATERIAL BALANCE FOR TEST F1

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	2.00E-02	1.0%	2.00E+00	99.0%		0.0%		0.0%	2.02E+00	2.02E+00	
Cadmium	3.00E-03	9.1%	3.00E-02	90.9%		0.0%		0.0%	3.30E-02	3.30E-02	
Chromium	2.40E-01	10.4%	2.06E+00	89.6%		0.0%		0.0%	2.30E+00	2.30E+00	
Lead	2.20E-01	3.7%	5.79E+00	96.3%		0.0%		0.0%	6.01E+00	6.01E+00	
Barium	7.50E-01	10.9%	6.13E+00	89.1%		0.0%		0.0%	6.88E+00	6.88E+00	
Mercury	6.30E-04	12.0%	4.60E-03	88.0%		0.0%		0.0%	5.23E-03	5.23E-03	
Nickel	2.00E-01	13.3%	1.30E+00	86.7%		0.0%		0.0%	1.50E+00	1.50E+00	
Selenium	5.50E-03	64.7%	3.00E-03	35.3%		0.0%		0.0%	8.50E-03	8.50E-03	
Vanadium	2.20E-01	8.9%	2.26E+00	91.1%		0.0%		0.0%	2.48E+00	2.48E+00	
Zinc	1.96E+00	46.4%	2.26E+00	53.6%		0.0%		0.0%	4.22E+00	4.22E+00	
Chlorine	8.20E+00	38.1%	1.33E+01	61.9%		0.0%		0.0%	2.15E+01	2.15E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	2.07E+00	94.5%	1.20E-01	5.5%	4.30E-05	0.0%	2.19E+00	2.19E+00		1.08	0.058	0.002%
Cadmium	6.00E-02	92.3%	5.00E-03	7.7%	ND	0.0%	6.50E-02	6.50E-02		1.97	0.083	0.000%
Chromium	1.16E+00	92.8%	9.00E-02	7.2%	ND	0.0%	1.25E+00	1.25E+00		0.54	0.078	0.000%
Lead	3.81E+00	76.8%	1.15E+00	23.2%	4.00E-03	0.1%	4.96E+00	4.96E+00		0.83	0.302	0.067%
Barium	5.99E+00	94.8%	3.30E-01	5.2%	ND	0.0%	6.32E+00	6.32E+00		0.92	0.055	0.000%
Mercury	2.80E-03	90.4%	2.70E-04	8.7%	2.70E-05	0.9%	3.10E-03	3.10E-03		0.59	0.096	0.516%
Nickel	6.60E-01	70.8%	2.70E-01	29.0%	1.90E-03	0.2%	9.32E-01	9.32E-01		0.62	0.409	0.127%
Selenium	1.40E-03	42.0%	1.30E-04	3.9%	1.80E-03	54.1%	3.33E-03	3.33E-03		0.39	0.093	21.176%
Vanadium	1.44E+00	92.9%	1.10E-01	7.1%	ND	0.0%	1.55E+00	1.55E+00		0.63	0.076	0.000%
Zinc	4.31E+00	94.3%	2.60E-01	5.7%	1.50E-03	0.0%	4.57E+00	4.57E+00		1.08	0.060	0.036%
Chlorine	5.50E+00	60.4%	3.20E+00	35.1%	4.10E-01	4.5%	9.11E+00	9.11E+00		0.42	0.582	1.907%

TABLE B10 METAL MATERIAL BALANCE FOR TEST F2

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	2.70E-02	1.2%	2.20E+00	98.8%		0.0%		0.0%	2.23E+00	2.23E+00	
Cadmium	3.00E-03	9.1%	3.00E-02	90.9%		0.0%		0.0%	3.30E-02	3.30E-02	
Chromium	1.60E-01	4.8%	3.20E+00	95.2%		0.0%		0.0%	3.36E+00	3.36E+00	
Lead	1.80E-01	7.0%	2.39E+00	93.0%		0.0%		0.0%	2.57E+00	2.57E+00	
Barium	5.80E-01	6.3%	8.60E+00	93.7%		0.0%		0.0%	9.18E+00	9.18E+00	
Mercury	1.00E-03	18.9%	4.30E-03	81.1%		0.0%		0.0%	5.30E-03	5.30E-03	
Nickel	6.70E-02	4.2%	1.51E+00	95.8%		0.0%		0.0%	1.58E+00	1.58E+00	
Selenium	3.40E-03	53.1%	3.00E-03	46.9%		0.0%		0.0%	6.40E-03	6.40E-03	
Vanadium	1.70E-01	11.4%	1.32E+00	88.6%		0.0%		0.0%	1.49E+00	1.49E+00	
Zinc	4.40E-01	17.1%	2.14E+00	82.9%		0.0%		0.0%	2.58E+00	2.58E+00	
Chlorine	5.50E+00	30.4%	1.26E+01	69.6%		0.0%		0.0%	1.81E+01	1.81E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.60E+00	93.0%	1.20E-01	7.0%	ND	0.0%	1.72E+00	1.72E+00		0.77	0.075	0.000%
Cadmium	5.00E-02	89.3%	6.00E-03	10.7%	ND	0.0%	5.60E-02	5.60E-02		1.70	0.120	0.000%
Chromium	1.20E+00	95.2%	6.00E-02	4.8%	ND	0.0%	1.26E+00	1.26E+00		0.37	0.050	0.000%
Lead	1.76E+00	65.4%	9.30E-01	34.5%	2.40E-03	0.1%	2.69E+00	2.69E+00		1.05	0.528	0.093%
Barium	4.14E+00	89.0%	5.10E-01	11.0%	ND	0.0%	4.65E+00	4.65E+00		0.51	0.123	0.000%
Mercury	2.70E-03	90.3%	2.90E-04	9.7%	ND	0.0%	2.99E-03	2.99E-03		0.56	0.107	0.000%
Nickel	6.70E-01	91.7%	6.00E-02	8.2%	5.10E-04	0.1%	7.31E-01	7.31E-01		0.46	0.090	0.032%
Selenium	1.30E-03	14.0%	7.80E-03	83.9%	2.00E-04	2.2%	9.30E-03	9.30E-03		1.45	6.000	3.125%
Vanadium	1.15E+00	89.8%	1.30E-01	10.2%	9.40E-06	0.0%	1.28E+00	1.28E+00		0.86	0.113	0.001%
Zinc	2.94E+00	92.7%	2.30E-01	7.3%	1.40E-03	0.0%	3.17E+00	3.17E+00		1.23	0.078	0.054%
Chlorine	5.30E+00	56.1%	3.50E+00	37.1%	6.40E-01	6.8%	9.44E+00	9.44E+00		0.52	0.660	3.536%

TABLE B11 METAL MATERIAL BALANCE FOR TEST F3

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	3.00E-02	1.2%	2.57E+00	98.8%		0.0%		0.0%	2.60E+00	2.60E+00	
Cadmium	3.00E-03	9.1%	3.00E-02	90.9%		0.0%		0.0%	3.30E-02	3.30E-02	
Chromium	2.40E-01	15.6%	1.30E+00	84.4%		0.0%		0.0%	1.54E+00	1.54E+00	
Lead	2.00E-01	7.4%	2.50E+00	92.6%		0.0%		0.0%	2.70E+00	2.70E+00	
Barium	6.10E-01	6.2%	9.21E+00	93.8%		0.0%		0.0%	9.82E+00	9.82E+00	
Mercury	1.40E-03	23.7%	4.50E-03	76.3%		0.0%		0.0%	5.90E-03	5.90E-03	
Nickel	8.00E-02	5.8%	1.30E+00	94.2%		0.0%		0.0%	1.38E+00	1.38E+00	
Selenium	4.00E-03	57.1%	3.00E-03	42.9%		0.0%		0.0%	7.00E-03	7.00E-03	
Vanadium	2.20E-01	12.2%	1.58E+00	87.8%		0.0%		0.0%	1.80E+00	1.80E+00	
Zinc	4.80E-01	12.7%	3.29E+00	87.3%		0.0%		0.0%	3.77E+00	3.77E+00	
Chlorine	5.00E+00	27.5%	1.32E+01	72.5%		0.0%		0.0%	1.82E+01	1.82E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.86E+00	94.9%	1.00E-01	5.1%	4.60E-06	0.0%	1.96E+00	1.96E+00		0.75	0.054	0.000%
Cadmium	5.00E-02	89.9%	5.60E-03	10.1%	ND	0.0%	5.56E-02	5.56E-02		1.68	0.112	0.000%
Chromium	1.32E+00	95.7%	6.00E-02	4.3%	ND	0.0%	1.38E+00	1.38E+00		0.90	0.045	0.000%
Lead	2.99E+00	81.0%	7.00E-01	19.0%	3.40E-03	0.1%	3.69E+00	3.69E+00		1.37	0.234	0.126%
Barium	5.37E+00	93.7%	3.60E-01	6.3%	ND	0.0%	5.73E+00	5.73E+00		0.58	0.067	0.000%
Mercury	2.70E-03	90.6%	2.80E-04	9.4%	ND	0.0%	2.98E-03	2.98E-03		0.51	0.104	0.000%
Nickel	1.18E+00	95.2%	6.00E-02	4.8%	ND	0.0%	1.24E+00	1.24E+00		0.90	0.051	0.000%
Selenium	1.40E-03	26.4%	3.30E-03	62.3%	6.00E-04	11.3%	5.30E-03	5.30E-03		0.76	2.357	8.571%
Vanadium	7.90E-01	84.0%	1.50E-01	16.0%	ND	0.0%	9.40E-01	9.40E-01		0.52	0.190	0.000%
Zinc	1.84E+00	86.3%	2.90E-01	13.6%	1.60E-03	0.1%	2.13E+00	2.13E+00		0.57	0.158	0.042%
Chlorine	5.50E+00	47.5%	5.60E+00	48.4%	4.80E-01	4.1%	1.16E+01	1.16E+01		0.64	1.018	2.637%

TABLE B12 METAL MATERIAL BALANCE FOR TEST F4

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	1.00E-02	0.4%	2.56E+00	99.6%	1.70E-04	0.0%		0.0%	2.57E+00	2.60E+00	0.989
Cadmium	1.00E-03	0.8%	3.00E-02	22.9%	1.00E-01	76.3%		76.3%	1.31E-01	3.30E-02	3.970
Chromium	8.00E-02	5.3%	1.30E+00	86.1%	1.30E-01	8.6%		8.6%	1.51E+00	1.54E+00	0.981
Lead	1.00E-01	2.2%	4.04E+00	87.1%	5.00E-01	10.8%		10.8%	4.64E+00	2.70E+00	1.719
Barium	2.60E-01	2.6%	9.42E+00	95.1%	2.30E-01	2.3%		2.3%	9.91E+00	9.82E+00	1.009
Mercury	5.00E-04	7.4%	4.60E-03	67.6%	1.70E-03	25.0%		25.0%	6.80E-03	5.90E-03	1.153
Nickel	8.00E-02	2.4%	1.30E+00	39.5%	1.91E+00	58.1%		58.1%	3.29E+00	1.38E+00	2.384
Selenium	1.50E-03	1.8%	3.00E-03	3.6%	8.00E-02	94.7%		94.7%	8.45E-02	7.00E-03	12.071
Vanadium	1.00E-01	6.8%	1.30E+00	88.4%	7.00E-02	4.8%		4.8%	1.47E+00	1.80E+00	0.817
Zinc	3.40E-01	13.7%	1.30E+00	52.4%	8.40E-01	33.9%		33.9%	2.48E+00	3.77E+00	0.658
Chlorine	1.80E+00	4.0%	1.35E+01	29.7%	3.02E+01	66.4%		66.4%	4.55E+01	1.82E+01	2.500

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.62E+00	88.0%	2.20E-01	12.0%	2.50E-05	0.0%	1.84E+00	1.96E+00	0.939	0.72	0.136	0.001%
Cadmium	5.00E-02	10.6%	4.20E-01	88.6%	3.90E-03	0.8%	4.74E-01	5.56E-02	8.523	3.62	8.400	2.977%
Chromium	2.17E+00	85.8%	3.60E-01	14.2%	ND	0.0%	2.53E+00	1.38E+00	1.833	1.68	0.166	0.000%
Lead	2.91E+00	39.4%	4.47E+00	60.6%	1.30E-03	0.0%	7.38E+00	3.69E+00	1.999	1.59	1.536	0.028%
Barium	7.60E+00	89.0%	9.40E-01	11.0%	ND	0.0%	8.54E+00	5.73E+00	1.490	0.86	0.124	0.000%
Mercury	2.60E-03	65.2%	1.30E-03	32.6%	8.50E-05	2.1%	3.98E-03	2.98E-03	1.337	0.59	0.500	1.250%
Nickel	7.90E-01	84.0%	1.50E-01	16.0%	4.30E-04	0.0%	9.40E-01	1.24E+00	0.758	0.29	0.190	0.013%
Selenium	1.30E-03	3.4%	3.40E-02	88.1%	3.30E-03	8.5%	3.86E-02	5.30E-03	7.283	0.46	26.154	3.905%
Vanadium	1.31E+00	86.8%	2.00E-01	13.2%	ND	0.0%	1.51E+00	9.40E-01	1.606	1.03	0.153	0.000%
Zinc	2.49E+00	80.5%	6.00E-01	19.4%	1.70E-03	0.1%	3.09E+00	2.13E+00	1.450	1.25	0.241	0.069%
Chlorine	1.85E+01	40.9%	2.65E+01	58.5%	2.70E-01	0.6%	4.53E+01	1.16E+01	3.909	0.99	1.432	0.593%

TABLE B13 METAL MATERIAL BALANCE FOR TEST F5

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	1.00E-02	0.4%	2.67E+00	99.6%	1.50E-04	0.0%		0.0%	2.68E+00	2.60E+00	1.031
Cadmium	1.80E-03	2.2%	3.00E-02	36.7%	5.00E-02	61.1%			8.18E-02	3.30E-02	2.479
Chromium	6.20E-01	26.3%	1.64E+00	69.5%	1.00E-01	4.2%			2.36E+00	1.54E+00	1.532
Lead	2.20E-01	2.9%	6.09E+00	79.7%	1.33E+00	17.4%			7.64E+00	2.70E+00	2.830
Barium	2.80E-01	5.0%	5.13E+00	91.8%	1.80E-01	3.2%			5.59E+00	9.82E+00	0.569
Mercury	6.00E-04	5.2%	4.70E-03	40.5%	6.30E-03	54.3%			1.16E-02	5.90E-03	1.966
Nickel	3.30E-01	18.1%	1.40E+00	76.9%	9.00E-02	4.9%			1.82E+00	1.38E+00	1.319
Selenium	2.30E-03	13.3%	3.00E-03	17.3%	1.20E-02	69.4%			1.73E-02	7.00E-03	2.471
Vanadium	7.00E-02	4.6%	1.40E+00	91.5%	6.00E-02	3.9%			1.53E+00	1.80E+00	0.850
Zinc	7.00E-02	3.1%	1.44E+00	64.3%	7.30E-01	32.6%			2.24E+00	3.77E+00	0.594
Chlorine	3.20E+00	9.3%	1.37E+01	39.8%	1.75E+01	50.9%			3.44E+01	1.82E+01	1.890

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.80E+00	91.8%	1.60E-01	8.2%	1.20E-04	0.0%	1.96E+00	1.96E+00	1.000	0.73	0.089	0.004%
Cadmium	5.00E-02	37.9%	8.00E-02	60.6%	2.10E-03	1.6%	1.32E-01	5.56E-02	2.376	1.61	1.600	2.567%
Chromium	1.36E+00	93.8%	9.00E-02	6.2%	ND	0.0%	1.45E+00	1.38E+00	1.051	0.61	0.066	0.000%
Lead	3.78E+00	49.1%	3.88E+00	50.4%	4.10E-02	0.5%	7.70E+00	3.69E+00	2.085	1.01	1.026	0.537%
Barium	4.49E+00	83.3%	9.00E-01	16.7%	ND	0.0%	5.39E+00	5.73E+00	0.941	0.96	0.200	0.000%
Mercury	2.70E-03	62.4%	1.30E-03	30.0%	3.30E-04	7.6%	4.33E-03	2.98E-03	1.453	0.37	0.481	2.845%
Nickel	8.20E-01	88.2%	1.10E-01	11.8%	ND	0.0%	9.30E-01	1.24E+00	0.750	0.51	0.134	0.000%
Selenium	1.40E-03	13.3%	8.40E-03	80.0%	7.00E-04	6.7%	1.05E-02	5.30E-03	1.981	0.61	6.000	4.046%
Vanadium	9.00E-01	81.8%	2.00E-01	18.2%	ND	0.0%	1.10E+00	9.40E-01	1.170	0.72	0.222	0.000%
Zinc	3.29E+00	81.8%	7.30E-01	18.1%	2.90E-03	0.1%	4.02E+00	2.13E+00	1.887	1.80	0.222	0.129%
Chlorine	5.40E+00	14.6%	3.05E+01	82.7%	1.00E+00	2.7%	3.69E+01	1.16E+01	3.187	1.07	5.648	2.907%

TABLE B14 METAL MATERIAL BALANCE FOR TEST F6

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spikes	Percent	Total In	Base In	I/P Incr
Arsenic	1.00E-02	0.4%	2.70E+00	99.6%	1.90E-04	0.0%		0.0%	2.71E+00	2.60E+00	1.042
Cadmium	1.50E-03	2.7%	3.00E-02	53.1%	2.50E-02	44.2%		44.2%	5.65E-02	3.30E-02	1.712
Chromium	1.60E-01	6.9%	2.09E+00	89.7%	8.00E-02	3.4%		3.4%	2.33E+00	1.54E+00	1.513
Lead	1.70E-01	3.2%	4.18E+00	79.0%	9.40E-01	17.8%		17.8%	5.29E+00	2.70E+00	1.959
Barium	2.80E-01	4.1%	6.00E+00	87.0%	6.20E-01	9.0%		9.0%	6.90E+00	9.82E+00	0.703
Mercury	3.00E-04	4.0%	4.70E-03	62.7%	2.50E-03	33.3%		33.3%	7.50E-03	5.90E-03	1.271
Nickel	4.50E-02	2.5%	1.30E+00	73.7%	4.20E-01	23.8%		23.8%	1.77E+00	1.38E+00	1.279
Selenium	1.60E-03	9.6%	3.00E-03	18.1%	1.20E-02	72.3%		72.3%	1.66E-02	7.00E-03	2.371
Vanadium	1.00E-01	5.6%	1.62E+00	90.0%	8.00E-02	4.4%		4.4%	1.80E+00	1.80E+00	1.000
Zinc	2.90E-01	4.6%	3.24E+00	51.0%	2.82E+00	44.4%		44.4%	6.35E+00	3.77E+00	1.684
Chlorine	3.00E+00	5.6%	1.35E+01	25.0%	3.75E+01	69.4%		69.4%	5.40E+01	1.82E+01	2.967

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	2.21E+00	93.2%	1.60E-01	6.8%	ND	0.0%	2.37E+00	1.96E+00	1.209	0.87	0.072	0.000%
Cadmium	5.00E-02	41.5%	7.00E-02	58.1%	4.70E-04	0.4%	1.20E-01	5.56E-02	2.167	2.13	1.400	0.832%
Chromium	2.23E+00	87.8%	3.10E-01	12.2%	ND	0.0%	2.54E+00	1.38E+00	1.841	1.09	0.139	0.000%
Lead	3.85E+00	33.2%	7.72E+00	66.6%	1.30E-02	0.1%	1.16E+01	3.69E+00	3.136	2.19	2.005	0.246%
Barium	1.53E+01	90.8%	1.55E+00	9.2%	ND	0.0%	1.69E+01	5.73E+00	2.941	2.44	0.101	0.000%
Mercury	2.70E-03	86.2%	3.90E-04	12.4%	4.30E-05	1.4%	3.13E-03	2.98E-03	1.051	0.42	0.144	0.573%
Nickel	8.10E-01	95.3%	4.00E-02	4.7%	ND	0.0%	8.50E-01	1.24E+00	0.685	0.48	0.049	0.000%
Selenium	1.30E-03	13.0%	8.50E-03	84.9%	2.10E-04	2.1%	1.00E-02	5.30E-03	1.889	0.60	6.538	1.265%
Vanadium	1.05E+00	91.3%	1.00E-01	8.7%	ND	0.0%	1.15E+00	9.40E-01	1.223	0.64	0.095	0.000%
Zinc	3.85E+00	83.1%	7.80E-01	16.8%	6.50E-04	0.0%	4.63E+00	2.13E+00	2.172	0.73	0.203	0.010%
Chlorine	5.40E+00	16.3%	2.63E+01	79.2%	1.50E+00	4.5%	3.32E+01	1.16E+01	2.867	0.61	4.870	2.778%

TABLE B15 METAL MATERIAL BALANCE FOR TEST F7

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	2.00E-02	0.4%	4.70E+00	99.6%	1.00E-04	0.0%		0.0%	4.72E+00	2.60E+00	1.815
Cadmium	1.60E-03	0.9%	3.00E-02	17.5%	1.40E-01	81.6%		0.0%	1.72E-01	3.30E-02	5.200
Chromium	1.00E-01	7.2%	1.21E+00	87.1%	8.00E-02	5.8%		0.0%	1.39E+00	1.54E+00	0.903
Lead	2.40E-01	5.2%	2.83E+00	60.9%	1.58E+00	34.0%		0.0%	4.65E+00	2.70E+00	1.722
Barium	2.10E-01	3.3%	5.97E+00	94.9%	1.10E-01	1.7%		0.0%	6.29E+00	9.82E+00	0.641
Mercury	5.00E-04	1.6%	4.20E-03	13.7%	2.60E-02	84.7%		0.0%	3.07E-02	5.90E-03	5.203
Nickel	7.00E-02	5.0%	1.21E+00	87.1%	1.10E-01	7.9%		0.0%	1.39E+00	1.38E+00	1.007
Selenium	2.00E-03	1.3%	3.00E-03	1.9%	1.50E-01	96.8%		0.0%	1.55E-01	7.00E-03	22.143
Vanadium	1.70E-01	12.1%	1.20E+00	85.1%	4.00E-02	2.8%		0.0%	1.41E+00	1.80E+00	0.783
Zinc	1.04E+00	30.6%	1.75E+00	51.5%	6.10E-01	17.9%		0.0%	3.40E+00	3.77E+00	0.902
Chlorine	2.50E+00	3.0%	1.21E+01	14.4%	6.95E+01	82.6%		0.0%	8.41E+01	1.82E+01	4.621

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.40E+00	83.3%	2.80E-01	16.7%	6.60E-06	0.0%	1.68E+00	1.96E+00	0.857	0.36	0.200	0.000%
Cadmium	5.00E-02	35.5%	9.00E-02	63.8%	1.00E-03	0.7%	1.41E-01	5.56E-02	2.536	0.82	1.800	0.583%
Chromium	1.42E+00	86.1%	2.30E-01	13.9%	ND	0.0%	1.65E+00	1.38E+00	1.196	1.19	0.162	0.000%
Lead	2.22E+00	24.4%	6.86E+00	75.4%	1.90E-02	0.2%	9.10E+00	3.69E+00	2.464	1.96	3.090	0.409%
Barium	1.54E+01	94.8%	8.50E-01	5.2%	ND	0.0%	1.63E+01	5.73E+00	2.836	2.58	0.055	0.000%
Mercury	2.40E-03	39.6%	3.00E-03	49.5%	6.60E-04	10.9%	6.06E-03	2.98E-03	2.034	0.20	1.250	2.150%
Nickel	4.80E-01	78.7%	1.30E-01	21.3%	ND	0.0%	6.10E-01	1.24E+00	0.492	0.44	0.271	0.000%
Selenium	1.20E-03	2.0%	5.70E-02	95.2%	1.70E-03	2.8%	5.99E-02	5.30E-03	11.302	0.39	47.500	1.097%
Vanadium	1.18E+00	86.1%	1.90E-01	13.9%	ND	0.0%	1.37E+00	9.40E-01	1.457	0.97	0.161	0.000%
Zinc	1.78E+00	67.7%	8.50E-01	32.3%	8.60E-04	0.0%	2.63E+00	2.13E+00	1.234	0.77	0.478	0.025%
Chlorine	4.80E+00	9.7%	4.22E+01	85.6%	2.30E+00	4.7%	4.93E+01	1.16E+01	4.257	0.59	8.792	2.735%

TABLE B16 METAL MATERIAL BALANCE FOR TEST F8

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	1.00E-02	0.3%	3.34E+00	99.7%	1.60E-04	0.0%		0.0%	3.35E+00	2.60E+00	1.289
Cadmium	1.30E-03	0.5%	7.00E-02	25.8%	2.00E-01	73.7%		0.0%	2.71E-01	3.30E-02	8.221
Chromium	8.00E-02	4.1%	1.36E+00	69.0%	5.30E-01	26.9%		0.0%	1.97E+00	1.54E+00	1.279
Lead	1.50E-01	1.7%	6.30E+00	69.4%	2.63E+00	29.0%		0.0%	9.08E+00	2.70E+00	3.363
Barium	1.50E-01	2.3%	6.16E+00	93.2%	3.00E-01	4.5%		0.0%	6.61E+00	9.82E+00	0.673
Mercury	4.00E-03	10.6%	4.70E-03	12.5%	2.90E-02	76.9%		0.0%	3.77E-02	5.90E-03	6.390
Nickel	3.00E-02	1.2%	1.36E+00	54.6%	1.10E+00	44.2%		0.0%	2.49E+00	1.38E+00	1.804
Selenium	2.80E-03	1.4%	3.00E-03	1.5%	2.00E-01	97.2%		0.0%	2.06E-01	7.00E-03	29.400
Vanadium	8.00E-02	4.8%	1.53E+00	91.6%	6.00E-02	3.6%		0.0%	1.67E+00	1.80E+00	0.928
Zinc	2.30E-01	6.9%	2.04E+00	61.6%	1.04E+00	31.4%		0.0%	3.31E+00	3.77E+00	0.878
Chlorine	2.90E+00	2.0%	1.36E+01	9.6%	1.25E+02	88.3%		0.0%	1.42E+02	1.82E+01	7.775

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	2.05E+00	88.4%	2.70E-01	11.6%	2.70E-05	0.0%	2.32E+00	1.96E+00	1.184	0.69	0.132	0.001%
Cadmium	5.00E-02	22.4%	1.70E-01	76.1%	3.40E-03	1.5%	2.23E-01	5.56E-02	4.018	0.82	3.400	1.253%
Chromium	2.51E+00	95.8%	1.10E-01	4.2%	ND	0.0%	2.62E+00	1.38E+00	1.899	1.33	0.044	0.000%
Lead	3.63E+00	29.6%	8.57E+00	70.0%	5.10E-02	0.4%	1.23E+01	3.69E+00	3.317	1.35	2.361	0.562%
Barium	6.25E+00	88.4%	8.20E-01	11.6%	ND	0.0%	7.07E+00	5.73E+00	1.234	1.07	0.131	0.000%
Mercury	2.70E-03	23.9%	7.00E-03	61.9%	1.60E-03	14.2%	1.13E-02	2.98E-03	3.792	0.30	2.593	4.244%
Nickel	7.80E-01	89.7%	9.00E-02	10.3%	ND	0.0%	8.70E-01	1.24E+00	0.702	0.35	0.115	0.000%
Selenium	1.40E-03	0.4%	2.60E-01	81.5%	5.76E-02	18.1%	3.19E-01	5.30E-03	60.189	1.55	185.714	27.988%
Vanadium	8.60E-01	83.5%	1.70E-01	16.5%	ND	0.0%	1.03E+00	9.40E-01	1.096	0.62	0.198	0.000%
Zinc	2.97E+00	81.8%	6.60E-01	18.2%	1.90E-03	0.1%	3.63E+00	2.13E+00	1.704	1.10	0.222	0.057%
Chlorine	5.40E+00	6.3%	7.54E+01	87.5%	5.40E+00	6.3%	8.62E+01	1.16E+01	7.444	0.61	13.963	3.816%

TABLE B17 METAL MATERIAL BALANCE FOR TEST F9

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	5.00E-02	4.2%	1.15E+00	95.8%		0.0%		0.0%	1.20E+00	1.20E+00	
Cadmium	6.00E-03	9.1%	6.00E-02	90.9%		0.0%		0.0%	6.60E-02	6.60E-02	
Chromium	2.00E-01	8.6%	2.13E+00	91.4%		0.0%		0.0%	2.33E+00	2.33E+00	
Lead	1.20E-01	3.8%	3.08E+00	96.3%		0.0%		0.0%	3.20E+00	3.20E+00	
Barium	7.00E-02	0.9%	7.75E+00	99.1%		0.0%		0.0%	7.82E+00	7.82E+00	
Mercury	7.00E-03	6.0%	1.10E-01	94.0%		0.0%		0.0%	1.17E-01	1.17E-01	
Nickel	3.91E+00	69.7%	1.70E+00	30.3%		0.0%		0.0%	5.61E+00	5.61E+00	
Selenium	2.00E-02	69.0%	9.00E-03	31.0%		0.0%		0.0%	2.90E-02	2.90E-02	
Vanadium	4.00E-01	13.2%	2.64E+00	86.8%		0.0%		0.0%	3.04E+00	3.04E+00	
Zinc	2.30E-01	13.7%	1.45E+00	86.3%		0.0%		0.0%	1.68E+00	1.68E+00	
Chlorine	1.02E+01	48.8%	1.07E+01	51.2%		0.0%		0.0%	2.09E+01	2.09E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.27E+00	99.2%	1.00E-02	0.8%	ND	0.0%	1.28E+00	1.28E+00		1.07	0.01	0.00%
Cadmium	5.00E-02	82.2%	1.00E-02	16.4%	8.00E-04	1.3%	6.08E-02	6.08E-02		0.92	0.20	1.21%
Chromium	1.65E+00	98.8%	2.00E-02	1.2%	ND	0.0%	1.67E+00	1.67E+00		0.72	0.01	0.00%
Lead	2.80E-01	75.1%	9.00E-02	24.1%	3.00E-03	0.8%	3.73E-01	3.73E-01		0.12	0.32	0.09%
Barium	3.04E+00	97.4%	8.00E-02	2.6%	ND	0.0%	3.12E+00	3.12E+00		0.40	0.03	0.00%
Mercury	1.10E-01	99.3%	7.00E-04	0.6%	8.00E-05	0.1%	1.11E-01	1.11E-01		0.95	0.01	0.07%
Nickel	1.39E+00	98.6%	2.00E-02	1.4%	ND	0.0%	1.41E+00	1.41E+00		0.25	0.01	0.00%
Selenium	4.10E-02	87.2%	3.00E-03	6.4%	3.00E-03	6.4%	4.70E-02	4.70E-02		1.62	0.07	10.34%
Vanadium	1.60E+00	97.6%	4.00E-02	2.4%	ND	0.0%	1.64E+00	1.64E+00		0.54	0.02	0.00%
Zinc	5.20E-01	96.3%	2.00E-02	3.7%	ND	0.0%	5.40E-01	5.40E-01		0.32	0.04	0.00%
Chlorine	6.50E+00	19.5%	2.53E+01	75.7%	1.60E+00	4.8%	3.34E+01	3.34E+01		1.60	3.89	7.66%

TABLE B18 METAL MATERIAL BALANCE FOR TEST G1

Metal	Coal	Percent	Raw Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	5.00E-02	3.8%	1.26E+00	96.2%		0.0%		0.0%	1.31E+00	1.31E+00	
Cadmium	4.00E-03	6.3%	6.00E-02	93.8%		0.0%		0.0%	6.40E-02	6.40E-02	
Chromium	6.40E-01	26.2%	1.80E+00	73.8%		0.0%		0.0%	2.44E+00	2.44E+00	
Lead	1.50E-01	4.5%	3.21E+00	95.5%		0.0%		0.0%	3.36E+00	3.36E+00	
Barium	1.70E-01	2.0%	8.30E+00	98.0%		0.0%		0.0%	8.47E+00	8.47E+00	
Mercury	8.00E-03	5.4%	1.40E-01	94.6%		0.0%		0.0%	1.48E-01	1.48E-01	
Nickel	1.39E+00	43.6%	1.80E+00	56.4%		0.0%		0.0%	3.19E+00	3.19E+00	
Selenium	1.50E-02	62.5%	9.00E-03	37.5%		0.0%		0.0%	2.40E-02	2.40E-02	
Vanadium	9.60E-01	25.3%	2.83E+00	74.7%		0.0%		0.0%	3.79E+00	3.79E+00	
Zinc	3.00E-01	16.2%	1.55E+00	83.8%		0.0%		0.0%	1.85E+00	1.85E+00	
Chlorine	1.06E+01	48.2%	1.14E+01	51.8%		0.0%		0.0%	2.20E+01	2.20E+01	

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.65E+00	99.4%	1.00E-02	0.6%	ND	0.0%	1.66E+00	1.66E+00		1.27	0.01	0.000
Cadmium	5.00E-02	81.3%	1.00E-02	16.3%	*****	2.4%	6.15E-02	6.15E-02		0.96	0.20	0.023
Chromium	4.26E+00	99.1%	3.00E-02	0.7%	*****	0.2%	4.30E+00	4.30E+00		1.76	0.01	0.003
Lead	3.20E-01	78.8%	8.00E-02	19.7%	*****	1.5%	4.06E-01	4.06E-01		0.12	0.25	0.002
Barium	9.51E+00	99.0%	1.00E-01	1.0%	ND	0.0%	9.61E+00	9.61E+00		1.13	0.01	0.000
Mercury	1.20E-01	99.3%	7.00E-04	0.6%	*****	0.2%	1.21E-01	1.21E-01		0.82	0.01	0.001
Nickel	2.27E+00	99.1%	2.00E-02	0.9%	ND	0.0%	2.29E+00	2.29E+00		0.72	0.01	0.000
Selenium	6.10E-02	50.4%	4.00E-03	3.3%	*****	46.3%	1.21E-01	1.21E-01		5.04	0.07	2.333
Vanadium	3.87E+00	98.7%	5.00E-02	1.3%	ND	0.0%	3.92E+00	3.92E+00		1.03	0.01	0.000
Zinc	2.60E+00	98.9%	3.00E-02	1.1%	ND	0.0%	2.63E+00	2.63E+00		1.42	0.01	0.000
Chlorine	6.90E+00	21.2%	2.46E+01	75.7%	*****	3.1%	3.25E+01	3.25E+01		1.48	3.57	0.045

TABLE B19 METAL MATERIAL BALANCE FOR TEST G2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	4.00E-02	3.1%	1.26E+00	96.9%	3.00E-04	0.0%		0.0%	1.30E+00	1.31E+00	0.99
Cadmium	4.00E-03	4.8%	6.00E-02	71.4%	2.00E-02	23.8%		23.8%	8.40E-02	6.40E-02	1.31
Chromium	4.30E-01	16.0%	1.80E+00	66.9%	4.60E-01	17.1%		17.1%	2.69E+00	2.44E+00	1.10
Lead	1.00E-01	1.9%	3.76E+00	71.3%	1.41E+00	26.8%		26.8%	5.27E+00	3.36E+00	1.57
Barium	6.00E-02	2.0%	2.91E+00	98.0%	ND	0.0%		0.0%	2.97E+00	8.47E+00	0.35
Mercury	5.00E-03	3.4%	1.40E-01	96.2%	5.00E-04	0.3%		0.3%	1.46E-01	1.48E-01	0.98
Nickel	4.56E+00	47.0%	1.80E+00	18.5%	3.35E+00	34.5%		34.5%	9.71E+00	3.19E+00	3.04
Selenium	1.30E-02	58.6%	9.00E-03	40.5%	2.00E-04	0.9%		0.9%	2.22E-02	2.40E-02	0.92
Vanadium	3.40E-01	15.7%	1.80E+00	83.3%	2.00E-02	0.9%		0.9%	2.16E+00	3.79E+00	0.57
Zinc	1.50E-01	12.2%	8.80E-01	71.5%	2.00E-01	16.3%		16.3%	1.23E+00	1.85E+00	0.66
Chlorine	9.50E+00	13.4%	1.10E+01	15.5%	5.03E+01	71.0%		71.0%	7.08E+01	2.20E+01	3.22

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.41E+00	99.3%	1.00E-02	0.7%	ND	0.0%	1.42E+00	1.66E+00	0.855	1.09	0.007	0.000%
Cadmium	2.00E-02	29.9%	2.00E-02	29.9%	2.70E-02	40.3%	6.70E-02	6.15E-02	1.089	0.80	1.000	32.143%
Chromium	5.08E+00	99.8%	1.00E-02	0.2%	ND	0.0%	5.09E+00	4.30E+00	1.185	1.89	0.002	0.000%
Lead	8.90E-01	27.1%	1.28E+00	38.9%	1.12E+00	34.0%	3.29E+00	4.06E-01	8.103	0.62	1.438	21.252%
Barium	1.11E+01	99.7%	3.00E-02	0.3%	ND	0.0%	1.11E+01	9.61E+00	1.158	3.75	0.003	0.000%
Mercury	1.00E-01	98.1%	8.00E-04	0.8%	1.10E-03	1.1%	1.02E-01	1.21E-01	0.843	0.70	0.008	0.756%
Nickel	1.90E+00	99.5%	1.00E-02	0.5%	ND	0.0%	1.91E+00	2.29E+00	0.834	0.20	0.005	0.000%
Selenium	4.60E-02	82.9%	4.00E-03	7.2%	5.50E-03	9.9%	5.55E-02	1.21E-01	0.459	2.50	0.087	24.775%
Vanadium	2.94E+00	99.7%	1.00E-02	0.3%	ND	0.0%	2.95E+00	3.92E+00	0.753	1.37	0.003	0.000%
Zinc	3.00E+00	99.6%	7.00E-03	0.2%	4.00E-03	0.1%	3.01E+00	2.63E+00	1.145	2.45	0.002	0.325%
Chlorine	6.70E+00	13.5%	4.07E+01	82.2%	2.10E+00	4.2%	4.95E+01	3.25E+01	1.523	0.70	6.075	2.966%

TABLE B20 METAL MATERIAL BALANCE FOR TEST G3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	3.00E-02	2.2%	1.36E+00	97.7%	2.00E-03	0.1%		0.1%	1.39E+00	1.31E+00	1.063
Cadmium	6.00E-03	7.6%	6.00E-02	75.9%	1.30E-02	16.5%		16.5%	7.90E-02	6.40E-02	1.234
Chromium	1.06E+00	28.9%	1.80E+00	49.0%	8.10E-01	22.1%		22.1%	3.67E+00	2.44E+00	1.504
Lead	1.00E-01	1.2%	4.16E+00	48.0%	4.40E+00	50.8%		50.8%	8.66E+00	3.36E+00	2.577
Barium	3.00E-02	0.9%	3.33E+00	99.1%	ND	0.0%		0.0%	3.36E+00	8.47E+00	0.397
Mercury	5.00E-03	3.2%	1.50E-01	96.5%	4.00E-04	0.3%		0.3%	1.55E-01	1.48E-01	1.050
Nickel	2.20E+00	21.8%	4.80E+00	47.5%	3.10E+00	30.7%		30.7%	1.01E+01	3.19E+00	3.166
Selenium	1.70E-02	64.6%	9.00E-03	34.2%	3.00E-04	1.1%		1.1%	2.63E-02	2.40E-02	1.096
Vanadium	2.10E-01	10.3%	1.80E+00	88.2%	3.00E-02	1.5%		1.5%	2.04E+00	3.79E+00	0.538
Zinc	1.50E-01	9.6%	9.00E-01	57.7%	5.10E-01	32.7%		32.7%	1.56E+00	1.85E+00	0.843
Chlorine	7.40E+00	9.0%	1.16E+01	14.1%	6.33E+01	76.9%		76.9%	8.23E+01	2.20E+01	3.741

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.18E+00	93.7%	8.00E-02	6.3%	ND	0.0%	1.26E+00	1.66E+00	0.759	0.91	0.068	0.000%
Cadmium	2.00E-02	8.2%	2.20E-01	90.2%	4.00E-03	1.6%	2.44E-01	0.00E+00	ERR	3.09	11.000	5.063%
Chromium	6.72E+00	97.8%	1.50E-01	2.2%	ND	0.0%	6.87E+00	0.00E+00	ERR	1.87	0.022	0.000%
Lead	2.52E+00	12.6%	1.70E+01	85.2%	4.30E-01	2.2%	1.99E+01	0.00E+00	ERR	2.30	6.746	4.965%
Barium	1.29E+01	95.1%	6.60E-01	4.9%	ND	0.0%	1.36E+01	0.00E+00	ERR	4.04	0.051	0.000%
Mercury	1.10E-01	93.8%	7.00E-03	6.0%	3.30E-04	0.3%	1.17E-01	0.00E+00	ERR	0.76	0.064	0.212%
Nickel	1.90E+00	94.1%	1.20E-01	5.9%	ND	0.0%	2.02E+00	0.00E+00	ERR	0.20	0.063	0.000%
Selenium	4.20E-02	52.7%	3.60E-02	45.2%	1.70E-03	2.1%	7.97E-02	0.00E+00	ERR	3.03	0.857	6.464%
Vanadium	3.14E+00	92.1%	2.70E-01	7.9%	ND	0.0%	3.41E+00	0.00E+00	ERR	1.67	0.086	0.000%
Zinc	3.02E+00	91.5%	2.80E-01	8.5%	ND	0.0%	3.30E+00	0.00E+00	ERR	2.12	0.093	0.000%
Chlorine	7.00E+00	12.1%	4.55E+01	78.7%	5.30E+00	9.2%	5.78E+01	0.00E+00	ERR	0.70	6.500	6.440%

TABLE B21 METAL MATERIAL BALANCE FOR TEST G4

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Base In	I/P Incr
Arsenic	3.00E-02	2.4%	1.22E+00	97.4%	3.00E-03	0.2%		0.0%	1.25E+00	1.31E+00	0.956
Cadmium	3.00E-03	4.5%	5.00E-02	74.6%	1.40E-02	20.9%		0.0%	6.70E-02	6.40E-02	1.047
Chromium	1.02E+00	29.3%	2.19E+00	62.9%	2.70E-01	7.8%		0.0%	3.48E+00	2.44E+00	1.426
Lead	8.00E-02	0.7%	3.92E+00	36.4%	6.76E+00	62.8%		0.0%	1.08E+01	3.36E+00	3.202
Barium	5.00E-02	0.6%	8.57E+00	99.4%	ND	0.0%		0.0%	8.62E+00	8.47E+00	1.018
Mercury	4.00E-03	2.4%	1.60E-01	97.1%	8.00E-04	0.5%		0.0%	1.65E-01	1.48E-01	1.114
Nickel	5.10E+00	71.3%	1.80E+00	25.2%	2.50E-01	3.5%		0.0%	7.15E+00	3.19E+00	2.241
Selenium	1.10E-02	49.1%	1.10E-02	49.1%	4.00E-04	1.8%		0.0%	2.24E-02	2.40E-02	0.933
Vanadium	2.90E-01	8.9%	2.92E+00	89.8%	4.00E-02	1.2%		0.0%	3.25E+00	3.79E+00	0.858
Zinc	1.50E-01	5.8%	1.82E+00	70.8%	6.00E-01	23.3%		0.0%	2.57E+00	1.85E+00	1.389
Chlorine	6.80E+00	8.1%	1.14E+01	13.6%	6.56E+01	78.3%		0.0%	8.38E+01	2.20E+01	3.809

Metal	Clinker	Percent	CKD	Percent	Stack	Percent	Total Out	Base Out	O/P Incr	Out/In	CKD/Clin	Stack/In
Arsenic	1.56E+00	99.4%	1.00E-02	0.6%	ND	0.0%	1.57E+00	1.66E+00	0.946	1.25	0.006	0.000%
Cadmium	3.00E-02	49.2%	2.00E-02	32.8%	1.10E-02	18.0%	6.10E-02	6.15E-02	0.992	0.91	0.667	16.418%
Chromium	6.36E+00	99.7%	2.00E-02	0.3%	ND	0.0%	6.38E+00	4.30E+00	1.485	1.83	0.003	0.000%
Lead	2.36E+00	47.8%	2.48E+00	50.2%	1.00E-01	2.0%	4.94E+00	4.06E-01	12.167	0.46	1.051	0.929%
Barium	1.27E+01	99.3%	9.00E-02	0.7%	ND	0.0%	1.28E+01	9.61E+00	1.331	1.48	0.007	0.000%
Mercury	1.10E-01	98.3%	1.00E-03	0.9%	9.00E-04	0.8%	1.12E-01	1.21E-01	0.926	0.68	0.009	0.546%
Nickel	2.00E+00	99.5%	1.00E-02	0.5%	ND	0.0%	2.01E+00	2.29E+00	0.878	0.28	0.005	0.000%
Selenium	7.10E-02	91.8%	3.00E-03	3.9%	3.30E-03	4.3%	7.73E-02	1.21E-01	0.639	3.45	0.042	14.732%
Vanadium	3.71E+00	99.2%	3.00E-02	0.8%	ND	0.0%	3.74E+00	3.92E+00	0.954	1.15	0.008	0.000%
Zinc	3.82E+00	99.0%	4.00E-02	1.0%	ND	0.0%	3.86E+00	2.63E+00	1.468	1.50	0.010	0.000%
Chlorine	2.10E+01	19.7%	5.96E+01	56.0%	2.59E+01	24.3%	1.07E+02	3.25E+01	3.277	1.27	2.838	30.907%

TABLE B22 METAL MATERIAL BALANCE FOR TEST G5

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	9.10E-04	0.0%	3.81E+00	17.7%	1.18E-02	0.1%	1.77E+01	82.3%	2.15E+01	5.40E-04	0.003%
Beryllium	1.36E-03	0.6%	3.08E-02	12.9%	2.27E-03	1.0%	2.04E-01	85.6%	2.38E-01	3.00E-05	0.013%
Cadmium	1.36E-03	0.3%	3.08E-02	5.7%	5.81E-02	10.7%	4.53E-01	83.4%	5.43E-01	3.30E-04	0.061%
Chromium	3.13E-02	0.8%	1.18E+00	29.4%	3.56E-01	8.9%	2.44E+00	60.9%	4.00E+00	7.00E-04	0.017%
Lead	7.71E-03	0.1%	2.21E+00	28.1%	7.03E-01	9.0%	4.93E+00	62.8%	7.85E+00	1.51E-03	0.019%
Antimony	3.13E-02	3.0%	6.13E-01	58.5%	4.13E-02	3.9%	3.63E-01	34.6%	1.05E+00	9.80E-04	0.093%
Barium	6.26E-02	0.2%	2.82E+00	9.4%	1.03E+00	3.5%	2.60E+01	86.9%	2.99E+01	3.32E-03	0.011%
Mercury	4.50E-04	0.2%	8.80E-02	43.9%	4.08E-03	2.0%	1.08E-01	53.9%	2.01E-01	1.88E-01	93.871%
Silver	3.18E-03	4.1%	6.10E-02	78.4%	1.36E-02	17.5%	0.00E+00	0.0%	7.78E-02	1.68E-03	2.160%
Thallium	3.13E-02	4.7%	6.13E-01	92.2%	2.09E-02	3.1%	0.00E+00	0.0%	6.65E-01	2.10E-04	0.032%
Chlorine	1.06E+01	7.3%	3.31E+00	2.3%	9.51E+01	64.9%	3.74E+01	25.5%	1.47E+02	9.07E-02	0.062%

TABLE B23 METAL MATERIAL BALANCE FOR TEST H1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	9.10E-04	0.0%	3.33E+00	11.2%	1.41E-02	0.0%	2.63E+01	88.7%	2.96E+01	8.80E-04	0.003%
Beryllium	1.81E-03	0.5%	3.08E-02	8.0%	2.27E-03	0.6%	3.49E-01	90.9%	3.84E-01	3.00E-05	0.008%
Cadmium	1.81E-03	0.3%	3.08E-02	5.4%	4.94E-02	8.7%	4.85E-01	85.5%	5.67E-01	5.90E-04	0.104%
Chromium	2.45E-02	0.4%	1.05E+00	15.4%	3.42E-01	5.0%	5.39E+00	79.2%	6.81E+00	8.10E-04	0.012%
Lead	8.16E-03	0.0%	2.47E+00	14.4%	6.59E-01	3.9%	1.40E+01	81.7%	1.71E+01	3.73E-03	0.022%
Antimony	3.22E-02	1.7%	6.17E-01	32.5%	4.13E-02	2.2%	1.21E+00	63.6%	1.90E+00	9.60E-04	0.051%
Barium	5.81E-02	0.2%	2.84E+00	8.7%	1.28E+00	3.9%	2.85E+01	87.2%	3.27E+01	5.62E-03	0.017%
Mercury	4.50E-04	0.0%	9.48E-02	8.0%	3.63E-03	0.3%	1.08E+00	91.6%	1.18E+00	6.53E-01	55.219%
Silver	3.18E-03	4.0%	6.17E-02	77.7%	1.45E-02	18.3%	0.00E+00	0.0%	7.94E-02	1.55E-03	1.952%
Thallium	3.22E-02	4.8%	6.17E-01	92.1%	2.04E-02	3.0%	0.00E+00	0.0%	6.70E-01	2.12E-03	0.317%
Chlorine	9.66E+00	6.1%	1.97E+00	1.2%	9.07E+01	56.9%	5.71E+01	35.8%	1.59E+02	9.07E-02	0.057%

TABLE B24 METAL MATERIAL BALANCE FOR TEST H2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	1.36E-03	0.0%	4.35E+00	21.7%	1.13E-02	0.1%	1.57E+01	78.3%	2.01E+01	7.50E-04	0.004%
Beryllium	1.81E-03	0.5%	3.04E-02	8.9%	1.81E-03	0.5%	3.08E-01	90.1%	3.42E-01	3.00E-05	0.009%
Cadmium	1.81E-03	0.2%	3.04E-02	3.9%	6.30E-02	8.2%	6.76E-01	87.6%	7.71E-01	5.40E-04	0.070%
Chromium	2.99E-02	0.4%	1.19E+00	16.5%	4.28E-01	5.9%	5.56E+00	77.1%	7.21E+00	6.40E-04	0.009%
Lead	8.16E-03	0.1%	2.42E+00	25.3%	7.75E-01	8.1%	6.33E+00	66.4%	9.53E+00	2.45E-03	0.026%
Antimony	3.27E-02	1.6%	6.04E-01	28.8%	4.08E-02	1.9%	1.42E+00	67.7%	2.10E+00	9.20E-04	0.044%
Barium	5.63E-02	0.2%	2.84E+00	10.0%	1.92E+00	6.8%	2.35E+01	83.0%	2.83E+01	4.03E-03	0.014%
Mercury	4.50E-04	0.1%	8.98E-02	10.9%	3.18E-03	0.4%	7.30E-01	88.7%	8.23E-01	8.12E-01	98.611%
Silver	3.18E-03	4.0%	6.03E-02	76.0%	1.59E-02	20.0%	0.00E+00	0.0%	7.94E-02	4.30E-04	0.542%
Thallium	3.27E-02	5.0%	6.04E-01	91.9%	2.04E-02	3.1%	0.00E+00	0.0%	6.57E-01	5.10E-04	0.078%
Chlorine	9.47E+00	6.2%	1.33E+00	0.9%	8.60E+01	55.9%	5.71E+01	37.1%	1.54E+02	9.07E-02	0.059%

TABLE B25 METAL MATERIAL BALANCE FOR TEST H3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	4.42E-05	1.1%	2.20E-03	57.1%	7.58E-06	0.2%	1.60E-03	41.5%	3.85E-03	4.56E-07	0.012%
Beryllium	1.56E-05	11.6%	4.92E-05	36.6%	7.10E-06	5.3%	6.25E-05	46.5%	1.34E-04	4.19E-08	0.031%
Cadmium	1.37E-06	0.1%	1.47E-04	7.0%	7.10E-06	0.3%	1.95E-03	92.6%	2.11E-03	4.20E-06	0.199%
Chromium	3.31E-04	1.1%	1.49E-02	47.8%	2.26E-05	0.1%	1.59E-02	51.0%	3.12E-02	8.39E-06	0.027%
Lead	1.39E-04	0.7%	2.32E-03	11.8%	2.23E-05	0.1%	1.72E-02	87.4%	1.97E-02	8.39E-06	0.043%
Chlorine	1.68E-02	13.0%	5.78E-02	44.7%	6.57E-03	5.1%	4.83E-02	37.3%	1.29E-01	1.22E-04	0.094%

TABLE B26 METAL MATERIAL BALANCE FOR TEST 11

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	2.94E-05	1.0%	2.20E-03	76.0%	9.82E-06	0.3%	6.55E-04	22.6%	2.89E-03	4.17E-07	0.014%
Beryllium	1.73E-05	13.8%	4.36E-05	34.8%	7.11E-06	5.7%	5.74E-05	45.8%	1.25E-04	4.17E-07	0.333%
Cadmium	1.29E-06	0.1%	1.51E-04	9.7%	7.11E-06	0.5%	1.39E-03	89.7%	1.55E-03	4.17E-07	0.027%
Chromium	2.61E-04	0.8%	1.73E-02	53.6%	8.75E-05	0.3%	1.46E-02	45.3%	3.22E-02	8.08E-06	0.025%
Lead	1.00E-04	0.5%	3.02E-03	15.0%	3.92E-04	1.9%	1.66E-02	82.5%	2.01E-02	8.08E-06	0.040%
Chlorine	2.01E-02	11.0%	5.23E-02	28.5%	6.15E-03	3.4%	1.05E-01	57.2%	1.84E-01	6.11E-05	0.033%

TABLE B27 METAL MATERIAL BALANCE FOR TEST 12

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	5.18E-05	2.3%	2.19E-03	97.7%	0.00E+00	0.0%	0.00E+00	0.0%	2.24E-03	4.10E-07	0.018%
Beryllium	2.73E-05	29.5%	6.52E-05	70.5%	0.00E+00	0.0%	0.00E+00	0.0%	9.25E-05	4.10E-07	0.443%
Cadmium	2.29E-05	18.5%	1.01E-04	81.5%	0.00E+00	0.0%	0.00E+00	0.0%	1.24E-04	4.10E-06	3.309%
Chromium	4.82E-04	3.2%	1.45E-02	96.8%	0.00E+00	0.0%	0.00E+00	0.0%	1.50E-02	8.19E-06	0.055%
Lead	1.71E-04	7.4%	2.15E-03	92.6%	0.00E+00	0.0%	0.00E+00	0.0%	2.32E-03	8.19E-06	0.353%
Chlorine	1.76E-02	21.1%	6.59E-02	78.9%	0.00E+00	0.0%	0.00E+00	0.0%	8.35E-02	6.16E-05	0.074%

TABLE B28 METAL MATERIAL BALANCE FOR TEST 13

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	3.12E-01	8.7%	3.82E-01	10.6%	2.90E+00	80.7%	3.59E+00	2.00E-04	0.006%
Beryllium	0.00E+00	0.0%	2.70E-02	11.0%	2.50E-03	1.0%	2.17E-01	88.0%	2.46E-01	3.00E-05	0.012%
Cadmium	0.00E+00	0.0%	7.00E-02	3.4%	5.27E-01	25.9%	1.44E+00	70.7%	2.04E+00	4.70E-03	0.231%
Chromium	0.00E+00	0.0%	3.62E+00	29.6%	9.89E-01	8.1%	7.64E+00	62.4%	1.22E+01	9.00E-04	0.007%
Lead	0.00E+00	0.0%	7.70E-02	0.3%	3.16E+00	12.1%	2.29E+01	87.6%	2.61E+01	5.20E-02	0.199%
Chlorine	0.00E+00	0.0%	2.84E+01	13.3%	1.85E+02	86.7%	0.00E+00	0.0%	2.13E+02	0.00E+00	0.000%

TABLE B29 METAL MATERIAL BALANCE FOR TEST J1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	2.81E-01	8.8%	1.50E-02	0.5%	2.88E+00	90.7%	3.18E+00	5.00E-04	0.016%
Beryllium	0.00E+00	0.0%	2.10E-02	8.8%	2.70E-03	1.1%	2.16E-01	90.1%	2.40E-01	5.00E-05	0.021%
Cadmium	0.00E+00	0.0%	6.10E-02	3.0%	6.25E-01	30.3%	1.38E+00	66.8%	2.07E+00	1.20E-02	0.581%
Chromium	0.00E+00	0.0%	2.15E+00	19.4%	1.10E+00	9.9%	7.86E+00	70.7%	1.11E+01	2.00E-03	0.018%
Lead	0.00E+00	0.0%	7.80E-02	0.3%	3.64E+00	11.7%	2.74E+01	88.1%	3.11E+01	2.48E-01	0.797%
Chlorine	0.00E+00	0.0%	1.48E+01	7.3%	1.88E+02	92.7%	0.00E+00	0.0%	2.03E+02	0.00E+00	0.000%

TABLE B30 METAL MATERIAL BALANCE FOR TEST J2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	3.40E-01	9.2%	2.13E-01	5.8%	3.15E+00	85.1%	3.70E+00	2.00E-04	0.005%
Beryllium	0.00E+00	0.0%	2.30E-02	8.8%	2.70E-03	1.0%	2.36E-01	90.2%	2.62E-01	3.00E-05	0.011%
Cadmium	0.00E+00	0.0%	6.50E-02	2.8%	6.19E-01	26.4%	1.66E+00	70.8%	2.34E+00	8.40E-03	0.358%
Chromium	0.00E+00	0.0%	2.34E+00	20.7%	1.16E+00	10.3%	7.79E+00	69.0%	1.13E+01	1.00E-03	0.009%
Lead	0.00E+00	0.0%	3.80E-02	0.1%	3.66E+00	12.6%	2.54E+01	87.3%	2.91E+01	6.40E-02	0.220%
Chlorine	0.00E+00	0.0%	7.31E+00	3.7%	1.92E+02	96.3%	0.00E+00	0.0%	1.99E+02	0.00E+00	0.000%

TABLE B31 METAL MATERIAL BALANCE FOR TEST J3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	1.70E+00	39.5%	2.60E+00	60.5%	0.00E+00	60.5%	4.30E+00	1.00E-04	0.002%
Beryllium	1.00E-02	1.4%	1.00E-01	14.1%	6.00E-01	84.5%	0.00E+00	84.5%	7.10E-01	3.00E-05	0.004%
Cadmium	1.00E-02	0.9%	3.00E-01	27.0%	8.00E-01	72.1%	0.00E+00	72.1%	1.11E+00	2.00E-04	0.018%
Chromium	2.00E-01	1.0%	1.27E+01	66.1%	6.30E+00	32.8%	0.00E+00	32.8%	1.92E+01	4.00E-04	0.002%
Lead	6.00E-02	0.2%	1.80E+00	7.0%	2.39E+01	92.8%	0.00E+00	92.8%	2.58E+01	5.60E-03	0.022%
Chlorine	7.00E-01	0.3%	6.95E+01	33.1%	1.40E+02	66.6%	0.00E+00	66.6%	2.10E+02	0.00E+00	0.000%

TABLE B32 METAL MATERIAL BALANCE FOR TEST K1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	3.00E-01	5.6%	2.40E+00	44.4%	2.70E+00	50.0%	0.00E+00	50.0%	5.40E+00	3.00E-04	0.006%
Beryllium	1.00E-02	1.6%	3.00E-02	4.7%	6.00E-01	93.8%	0.00E+00	93.8%	6.40E-01	3.00E-05	0.005%
Cadmium	3.00E-03	0.2%	5.00E-01	41.6%	7.00E-01	58.2%	0.00E+00	58.2%	1.20E+00	4.00E-04	0.033%
Chromium	2.00E-01	1.1%	1.21E+01	65.8%	6.10E+00	33.2%	0.00E+00	33.2%	1.84E+01	1.90E-03	0.010%
Lead	2.00E-02	0.1%	2.00E+00	8.0%	2.30E+01	91.9%	0.00E+00	91.9%	2.50E+01	1.02E-02	0.041%
Chlorine	1.40E+00	0.7%	6.90E+01	32.3%	1.44E+02	67.1%	0.00E+00	67.1%	2.14E+02	0.00E+00	0.000%

TABLE B33 METAL MATERIAL BALANCE FOR TEST K2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	2.00E-01	3.9%	2.10E+00	41.2%	2.80E+00	54.9%	0.00E+00	54.9%	5.10E+00	1.00E-04	0.002%
Beryllium	1.00E-02	1.2%	1.00E-01	12.3%	7.00E-01	86.4%	0.00E+00	86.4%	8.10E-01	3.00E-05	0.004%
Cadmium	1.00E-02	1.0%	3.00E-01	29.7%	7.00E-01	69.3%	0.00E+00	69.3%	1.01E+00	1.00E-04	0.010%
Chromium	1.00E-01	0.5%	1.23E+01	66.1%	6.20E+00	33.3%	0.00E+00	33.3%	1.86E+01	3.00E-04	0.002%
Lead	1.00E-02	0.0%	2.10E+00	8.1%	2.37E+01	91.8%	0.00E+00	91.8%	2.58E+01	1.40E-03	0.005%
Chlorine	7.00E-01	0.3%	6.62E+01	32.0%	1.40E+02	67.6%	0.00E+00	67.6%	2.07E+02	0.00E+00	0.000%

TABLE B34 METAL MATERIAL BALANCE FOR TEST K3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	3.60E-02	0.5%	8.62E-01	11.6%	0.00E+00	0.0%	6.54E+00	87.9%	7.44E+00	3.50E-04	0.005%
Beryllium	8.00E-03	0.7%	1.48E-01	12.6%	0.00E+00	0.0%	1.01E+00	86.7%	1.17E+00	1.20E-04	0.010%
Cadmium	0.00E+00	0.0%	1.30E-02	0.9%	3.80E-02	2.7%	1.34E+00	96.3%	1.39E+00	9.40E-04	0.067%
Chromium	1.96E-01	4.3%	2.61E+00	57.9%	7.99E-01	17.7%	9.03E-01	20.0%	4.51E+00	6.30E-04	0.014%
Lead	4.10E-02	0.4%	8.10E-01	7.3%	2.82E+00	25.3%	7.49E+00	67.1%	1.12E+01	1.39E-03	0.012%
Chlorine	2.91E+00	1.6%	3.92E+01	22.0%	1.36E+02	76.4%	0.00E+00	0.0%	1.78E+02	0.00E+00	0.000%

TABLE B35 METAL MATERIAL BALANCE FOR TEST L1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	3.10E-02	0.4%	8.45E-01	11.4%	1.00E-03	0.0%	6.54E+00	88.2%	7.42E+00	1.30E-04	0.002%
Beryllium	7.00E-03	0.6%	8.10E-02	7.4%	0.00E+00	0.0%	1.01E+00	92.0%	1.10E+00	9.00E-05	0.008%
Cadmium	0.00E+00	0.0%	1.00E-02	0.7%	3.70E-02	2.7%	1.34E+00	96.6%	1.39E+00	8.00E-05	0.006%
Chromium	1.51E-01	4.1%	1.86E+00	50.9%	7.37E-01	20.2%	9.03E-01	24.7%	3.65E+00	7.90E-04	0.022%
Lead	6.20E-02	0.6%	7.62E-01	6.9%	2.76E+00	24.9%	7.49E+00	67.6%	1.11E+01	7.50E-04	0.007%
Chlorine	3.31E+00	2.1%	2.56E+01	16.4%	1.27E+02	81.5%	0.00E+00	0.0%	1.56E+02	0.00E+00	0.000%

TABLE B36 METAL MATERIAL BALANCE FOR TEST L2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	3.30E-02	0.4%	8.47E-01	10.0%	0.00E+00	0.0%	7.58E+00	89.6%	8.46E+00	3.30E-04	0.004%
Beryllium	8.00E-03	0.6%	1.04E-01	8.1%	0.00E+00	0.0%	1.18E+00	91.3%	1.29E+00	1.20E-04	0.009%
Cadmium	0.00E+00	0.0%	0.00E+00	0.0%	3.60E-02	0.8%	4.75E+00	99.2%	4.79E+00	8.00E-05	0.002%
Chromium	1.52E-01	4.1%	1.90E+00	51.2%	7.91E-01	21.3%	8.71E-01	23.5%	3.71E+00	7.10E-04	0.019%
Lead	3.80E-02	0.3%	6.57E-01	5.8%	2.80E+00	24.5%	7.92E+00	69.4%	1.14E+01	8.40E-04	0.007%
Chlorine	3.63E+00	2.3%	2.53E+01	15.7%	1.32E+02	82.0%	0.00E+00	0.0%	1.61E+02	0.00E+00	0.000%

TABLE B37 METAL MATERIAL BALANCE FOR TEST L3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	0.00E+00	0.0%	2.23E-02	0.4%	5.96E+00	99.6%	5.98E+00	3.00E-04	0.005%
Beryllium	0.00E+00	0.0%	3.00E-03	1.1%	4.00E-04	0.1%	2.68E-01	98.7%	2.71E-01	2.00E-05	0.007%
Cadmium	0.00E+00	0.0%	1.60E-02	2.3%	1.03E-01	15.2%	5.63E-01	82.5%	6.82E-01	7.00E-04	0.103%
Chromium	0.00E+00	0.0%	7.22E-01	9.6%	1.41E+00	18.6%	5.43E+00	71.9%	7.56E+00	6.00E-04	0.008%
Lead	0.00E+00	0.0%	2.26E-01	1.9%	3.63E+00	30.3%	8.14E+00	67.8%	1.20E+01	1.02E-02	0.085%
Chlorine	0.00E+00	0.0%	4.70E+00	1.9%	2.41E+02	98.1%	0.00E+00	0.0%	2.46E+02	0.00E+00	0.000%

TABLE B38 METAL MATERIAL BALANCE FOR TEST M1

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	5.60E-02	1.0%	1.55E-02	0.3%	5.55E+00	98.7%	5.62E+00	7.00E-04	0.012%
Beryllium	0.00E+00	0.0%	0.00E+00	0.0%	5.10E-04	0.2%	3.00E-01	99.8%	3.01E-01	2.00E-05	0.007%
Cadmium	0.00E+00	0.0%	9.00E-03	1.0%	9.77E-02	10.9%	7.89E-01	88.1%	8.96E-01	9.00E-04	0.100%
Chromium	0.00E+00	0.0%	6.05E-01	7.7%	1.25E+00	15.8%	6.05E+00	76.5%	7.90E+00	9.00E-04	0.011%
Lead	0.00E+00	0.0%	1.68E-01	1.6%	3.10E+00	30.0%	7.06E+00	68.3%	1.03E+01	1.12E-02	0.108%
Chlorine	0.00E+00	0.0%	4.70E+00	1.9%	2.37E+02	98.1%	0.00E+00	0.0%	2.42E+02	0.00E+00	0.000%

TABLE B39 METAL MATERIAL BALANCE FOR TEST M2

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	0.00E+00	0.0%	3.74E-02	0.5%	6.91E+00	99.5%	6.95E+00	7.00E-04	0.010%
Beryllium	0.00E+00	0.0%	7.00E-03	2.1%	4.10E-04	0.1%	3.21E-01	97.7%	3.28E-01	2.00E-05	0.006%
Cadmium	0.00E+00	0.0%	1.80E-02	2.1%	1.02E-01	12.2%	7.19E-01	85.7%	8.39E-01	1.30E-03	0.155%
Chromium	0.00E+00	0.0%	6.98E-01	7.7%	1.34E+00	14.8%	7.02E+00	77.5%	9.05E+00	1.10E-03	0.012%
Lead	0.00E+00	0.0%	2.75E-01	3.0%	3.22E+00	34.8%	5.75E+00	62.2%	9.25E+00	1.24E-02	0.134%
Chlorine	0.00E+00	0.0%	4.70E+00	2.1%	2.24E+02	97.9%	0.00E+00	0.0%	2.28E+02	0.00E+00	0.000%

TABLE B40 METAL MATERIAL BALANCE FOR TEST M3

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	0.00E+00	0.0%	2.40E-02	0.4%	6.40E+00	99.6%	6.42E+00	1.10E-03	0.017%
Beryllium	0.00E+00	0.0%	1.40E-02	2.4%	8.00E-04	0.1%	5.71E-01	97.5%	5.86E-01	1.00E-04	0.017%
Cadmium	0.00E+00	0.0%	1.40E-02	1.2%	8.15E-02	7.0%	1.07E+00	91.8%	1.17E+00	2.30E-03	0.197%
Chromium	0.00E+00	0.0%	9.56E-01	7.0%	2.11E+00	15.5%	1.06E+01	77.5%	1.37E+01	2.30E-03	0.017%
Lead	0.00E+00	0.0%	5.07E-01	2.7%	6.50E+00	35.0%	1.16E+01	62.3%	1.86E+01	8.30E-02	0.447%
Chlorine	0.00E+00	0.0%	0.00E+00	0.0%	3.55E+02	100.0%	0.00E+00	0.0%	3.55E+02	0.00E+00	0.000%

TABLE B41 METAL MATERIAL BALANCE FOR TEST M4

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	0.00E+00	0.0%	2.72E-02	0.8%	3.35E+00	99.2%	3.38E+00	1.20E-03	0.036%
Beryllium	0.00E+00	0.0%	0.00E+00	0.0%	5.00E-04	0.1%	4.88E-01	99.9%	4.88E-01	1.00E-04	0.020%
Cadmium	0.00E+00	0.0%	2.10E-02	1.8%	9.63E-02	8.1%	1.07E+00	90.1%	1.19E+00	4.40E-03	0.371%
Chromium	0.00E+00	0.0%	8.82E-01	8.3%	2.07E+00	19.4%	7.71E+00	72.3%	1.07E+01	3.00E-03	0.028%
Lead	0.00E+00	0.0%	5.44E-01	3.5%	6.26E+00	40.1%	8.82E+00	56.5%	1.56E+01	6.60E-02	0.422%
Chlorine	0.00E+00	0.0%	0.00E+00	0.0%	3.16E+03	100.0%	0.00E+00	0.0%	3.16E+03	0.00E+00	0.000%

TABLE B42 METAL MATERIAL BALANCE FOR TEST M5

Metal	Coal	Percent	Feed	Percent	WDF	Percent	Spike	Percent	Total In	Stack	Stack/In
Arsenic	0.00E+00	0.0%	6.50E-02	0.8%	1.86E-02	0.2%	8.53E+00	99.0%	8.61E+00	4.10E-03	0.048%
Beryllium	0.00E+00	0.0%	0.00E+00	0.0%	1.60E-03	0.4%	4.45E-01	99.6%	4.47E-01	1.00E-04	0.022%
Cadmium	0.00E+00	0.0%	3.20E-02	3.1%	7.19E-02	6.9%	9.40E-01	90.0%	1.04E+00	9.80E-03	0.939%
Chromium	0.00E+00	0.0%	1.03E+00	6.5%	2.17E+00	13.7%	1.26E+01	79.8%	1.58E+01	5.40E-03	0.034%
Lead	0.00E+00	0.0%	3.82E-01	2.4%	5.36E+00	34.1%	9.99E+00	63.5%	1.57E+01	1.22E-01	0.775%
Chlorine	0.00E+00	0.0%	0.00E+00	0.0%	3.34E+02	100.0%	0.00E+00	0.0%	3.34E+02	0.00E+00	0.000%

TABLE B43 METAL MATERIAL BALANCE FOR TEST M6

Metal	Total In	Stack	Stack/In
Arsenic	3.22E-01	1.29E-03	0.401%
Beryllium	1.36E-02	4.54E-04	3.333%
Cadmium	3.72E-01	2.09E-03	0.561%
Chromium	3.92E+00	3.65E-03	0.093%
Lead	7.83E+00	3.51E-02	0.448%
Antimony	2.54E-01	1.46E-02	5.732%
Barium	1.09E+01	1.37E-02	0.126%
Mercury	5.44E-02	1.44E-02	26.500%
Silver	4.99E-02	4.11E-04	0.825%
Thallium	3.22E-01	1.30E-03	0.404%
Chlorine	4.26E+02	4.49E-01	0.105%

TABLE B44 METAL MATERIAL BALANCE FOR TEST N1

Metal	Total In	Stack	Stack/In
Arsenic	6.26E+00	4.94E-03	0.079%
Beryllium	5.03E-01	1.74E-04	0.035%
Cadmium	1.13E+00	4.81E-03	0.424%
Chromium	1.67E+01	9.66E-04	0.006%
Lead	1.96E+01	6.99E-02	0.356%
Antimony	3.30E+00	1.45E-02	0.438%
Barium	1.52E+01	1.16E-01	0.761%
Mercury	9.07E-03	8.66E-04	9.550%
Silver	7.08E-01	1.22E-03	0.172%
Thallium	4.27E+00	9.25E-04	0.022%
Chlorine	1.94E+02	7.17E-02	0.037%

TABLE B46 METAL MATERIAL BALANCE FOR TEST P1

Metal	Total In	Stack	Stack/In
Arsenic	8.77E+00	1.23E-03	0.014%
Beryllium	1.36E-02	4.72E-04	3.467%
Cadmium	7.76E-01	3.41E-03	0.440%
Chromium	1.43E+01	1.36E-03	0.009%
Lead	2.29E+01	8.80E-02	0.384%
Antimony	2.51E+00	1.50E-02	0.599%
Barium	1.35E+01	1.58E-02	0.117%
Mercury	1.36E+00	2.28E-03	0.167%
Silver	6.35E-02	3.52E-04	0.554%
Thallium	4.40E-01	1.35E-03	0.307%
Chlorine	3.79E+02	9.53E-02	0.025%

TABLE B45 METAL MATERIAL BALANCE FOR TEST N2

Metal	Total In	Stack	Stack/In
Arsenic	2.81E+00	1.42E-03	0.050%
Beryllium	5.90E-02	4.54E-05	0.077%
Cadmium	2.90E-01	3.56E-03	1.225%
Chromium	1.37E+01	3.65E-03	0.027%
Lead	7.02E+00	9.62E-02	1.370%
Antimony	5.17E-01	2.10E-02	4.053%
Barium	6.51E+00	4.11E-02	0.631%
Mercury	1.36E-02	1.81E-03	13.267%
Silver	2.61E+00	4.13E-03	0.158%
Thallium	5.90E-01	1.37E-02	2.331%
Chlorine	2.12E+02	9.80E-02	0.046%

TABLE B47 METAL MATERIAL BALANCE FOR TEST P2

Metal	Total In	Stack	Stack/In
Arsenic	6.29E+00	2.63E-03	0.042%
Beryllium	6.35E-02	2.08E-04	0.328%
Cadmium	3.36E-01	2.62E-03	0.780%
Chromium	1.41E+01	8.21E-04	0.006%
Lead	1.58E+01	1.26E-01	0.795%
Antimony	3.45E+00	1.59E-02	0.461%
Barium	8.82E+00	2.74E-02	0.311%
Mercury	9.07E-03	1.09E-03	12.000%
Silver	4.08E-02	5.26E-04	1.289%
Thallium	3.22E-01	3.25E-03	1.008%
Chlorine	2.56E+02	7.44E-04	0.000%

TABLE B48 METAL MATERIAL BALANCE FOR TEST Q1

Metal	Total In	Stack	Stack/In
Arsenic	7.33E+00	2.24E-03	0.031%
Beryllium	9.53E-02	1.22E-04	0.128%
Cadmium	1.19E+00	6.21E-04	0.052%
Chromium	2.63E+01	6.71E-04	0.003%
Lead	1.46E+01	9.34E-03	0.064%
Antimony	4.63E-01	1.95E-02	4.206%
Barium	1.42E+01	1.62E-02	0.114%
Mercury	9.07E-03	7.62E-04	8.400%
Silver	8.16E-02	5.62E-04	0.689%
Thallium	5.13E-01	2.78E-03	0.542%
Chlorine	3.67E+02	4.58E-01	0.125%

TABLE B49 METAL MATERIAL BALANCE FOR TEST Q2

Figure B1 Total metal input during waste fuel test F6

Figure B2 Distribution of metal input during test F6

Figure B3 Factor of increase in metal input during test F6

Figure B4 Total metal input during test F7

Figure B5 Distribution of metal input during test F7

Figure B6 Factor of increase in metal input during test F7

Figure B7 Total metal input during test F8

Figure B8 Distribution of metal input during test F8

Figure B9 Factor of increase in metal input during test F8

Figure B10 Total metal input during test F9

Figure B11 Distribution of metal input during test F9

Figure B12 Factor of increase in metal input during test F9

Figure B13 Total metal input during test G4

Figure B14 Distribution of metal input during test G4

Figure B15 Factor of increase in metal input during test G4

Figure B16 Total metal input during test G5

Figure B17 Distribution of metal input during test G5

Figure B18 Factor of increase in metal input during test G5

Figure B19 Factor of increase in metal emissions during test F6

Figure B20 Factor of increase in metal emissions during test F6

Figure B21 Factor of increase in metal emissions during test F8

Figure B22 Factor of increase in metal emissions during test F9

Figure B23 Percentage of input Silver emitted

Figure B24 Percentage of input Arsenic emitted

Figure B25 Percentage of input Barium emitted

Figure B26 Percentage of input Beryllium emitted

Figure B29 Percentage of input Mercury emitted

Figure B30 Percentage of input Nickel emitted

Figure B31 Percentage of input Lead emitted

Figure B32 Percentage of input Antimony emitted

Figure B33 Percentage of input Selenium emitted

Figure B34 Percentage of input Thallium emitted

Figure B35 Percentage of input Vanadium emitted

Figure B36 Percentage of input Zinc emitted

Figure B37 CKD/Clinker ratio for Silver

Figure B38 CKD/Clinker ratio for Arsenic

Figure B39 CKD/Clinker ratio for Barium

Figure B40 CKD/Clinker ratio for Beryllium

Figure B41 CKD/Clinker ratio for Cadmium

Figure B42 CKD/Clinker ratio for Chromium

Figure B43 CKD/Clinker ratio for Mercury

Figure B44 CKD/Clinker ratio for Nickel

Figure B45 CKD/Clinker ratio for Lead

Figure B46 CKD/Clinker ratio for Antimony

Figure B47 CKD/Clinker ratio for Selenium

Figure B48 CKD/Clinker ratio for Thallium

Figure B49 CKD/Clinker ratio for Vanadium

Figure B50 CKD/Clinker ratio for Zinc