TECHNICAL SUPPORT DOCUMENT TO THE DEVELOPMENT OF THE SOUTH AFRICAN SLUDGE GUIDELINES:

VOLUME 5: REQUIREMENTS FOR THERMAL SLUDGE MANAGEMENT PRACTICES AND FOR COMMERCIAL PRODUCTS CONTAINING SLUDGE

by

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EXECUTIVE SUMMARY

The new Sludge Guidelines have been developed with the sustainable, beneficial use/management of sludge in mind. The beneficial use options discussed in this document include thermal treatment of sludge and commercial products containing sludge.

Thermal treatment of sludge involves the total or partial conversion (combustion) of organic solids to oxidised end-products and oxidation and volatilisation of organic solids to end products with energy content. The advantages of thermal treatment are volume reduction, destruction of pathogens and toxic compounds as well as energy recovery. The end products of thermal treatment are fly and bottom ash which can either be used as raw products for commercial products disposed on landfill.

Commercial products containing sludge include fertilizer products (compost and pellets) as well as construction material (bricks, cement, aggregate). The quality of fertilizer products is very important since it is destined for use by the general public without any restrictions. Therefore only the best quality product will be permissible for alienation. Additional heat treatment forms part of the production process of construction material which destroys pathogens and organic pollutants present in the sludge, leaving the material stable. In most cases the metals are bound in an insoluble form in the final product, eliminating the environmental hazard.

Thermal treatment

Thermal treatment processes include total, sludge-only combustion in dedicated incinerators, co-combustion in industrial furnaces and cement kilns together with other wastes and non-combustion techniques (pyrolysis or starved-air combustion to produce end products with energy content).

The Guidelines is based on the following information:

- International research findings
- Local legislative and guiding documents
- International guidelines and legislative trends
- Practical considerations.

Thermal treatment of sludge can have negative effects on the environment, especially air quality, as well as human health. During thermal treatment pathogens and organic constituents in the sludge are destroyed but air quality should be managed to eliminate any negative effects that constituents present in the exit gas may have on the environment and public health. The final ash produced may contain metals should also be managed according to its potential hazard to the environment.

The Department of Environmental Affairs and Tourism (DEAT), Directorate: Air Pollution Control developed a set of guidelines for the 72 Scheduled Processes which are included in the Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965, Second Schedule). The APPA of 1965 has subsequently (11 September 2005) been replaced by National Environmental Management Air

Quality Act (NEM-AQA) (Act No. 39 of 2004), with the exclusion of certain. The excluded sections of NEM-AQA all deal with the licensing of listed activities. Therefore, at the time of writing the licensing of Scheduled Processes is still maintained under APPA and is being reviewed for completion by mid 2007. The aim of NEM-AQA is to reform the law regulating air quality in order to protect and enhance the quality of air in the Republic, taking into account the need for sustainable development, to provide for national norms and standards regulating air quality monitoring, management and control by all spheres of government; for specific air quality measures; and for matters incidental thereto. For existing thermal treatment plants the APPA Certificates will still apply, while new plants will receive new certificates under the NEMA-AQA.

The restrictions and requirements for thermal treatment include guidance on site design, management, air emissions and monitoring requirements. The different treatment processes have different air emission and monitoring guidelines. Sludge-only combustion is perceived as more “environment friendly” than co-incineration and therefore the applicable restrictions and requirements are more lenient.

Commercial products containing sludge/ash

The requirements for commercial products containing sludge are understandably much stricter than the controlled use of sludge products. Commercial products containing sludge can be divided into two classes, i.e. fertilizer products (compost and pellets) and construction materials (bricks, cement, etc.).

Fertilizer products intended for unrestricted use by the general public should be treated to produce a product of such a quality that it will not pose a risk to the user. Therefore only the best quality sludge, compost and fertilizer with Class A1a classification will be suitable for unrestricted use and distribution. Since composting of sludge is a cost effective treatment method, operational guidelines to attain Class A1a compost is provided in this document. Each batch of final fertilizer product leaving the plant for distribution has to be analysed and classified according to the sludge classification system.

The manufacturing processes of construction material usually include a heat treatment, leaving the material sterilized and stable. The metals are left in an insoluble form, eliminating environmental and human health risk.

Sludge can be used beneficially in the following ways:

- Thermal treatment to reduce volume, destroy pathogens and for energy recovery;
- Manufacturing of fertilizer products for unrestricted use by the general public. However, the final product must comply to Class A1a; and
- Manufacturing of construction material containing sludge and/or ash.

The risk the environment should be managed (thermal treatment) or eliminated (unrestricted use).

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1 INTRODUCTION

The new Sludge Guidelines have been developed with the sustainable, beneficial use/management of sludge in mind. Several beneficial use options for sludge have been identified. Use of sludge in agriculture at agronomic application rates not exceeding 10 t/ha/year is covered in Volume 2, while beneficial use at high application rates is discussed in Volume 4. Other beneficial use options include thermal treatment and commercial products containing sludge which is handled in separate Sections in Volume 5 (this volume).

Thermal treatment of sludge involves the total or partial conversion (combustion) of organic solids to oxidised end-products and oxidation and volatilisation of organic solids to end products with energy content (pyrolysis). The advantages of thermal treatment are volume reduction, destruction of pathogens and toxic compounds as well as energy recovery. The end products of thermal treatment are fly and bottom ash which can either be used as raw products for commercial products disposed on landfill. Thermal treatment mainly affects air quality due to potential pollutants in exit gas. Air emission limits and monitoring requirements for exit gas have been adopted to mitigate the negative effects to the environment and public health.

Commercial products containing sludge include fertilizer products (compost and pellets) as well as construction material (bricks, cement, aggregate). The quality of fertilizer products is very important since it is destined for use by the general public without any restrictions. Therefore only the best quality product will be permissible for alienation. Additional heat treatment forms part of the production process of construction material which destroys pathogens and organic pollutants present in the sludge, leaving the material stable. In most cases the metals are bound in an insoluble form in the final product, eliminating the environmental hazard.

1.1 Purpose of Volume 5

Volume 5 is divided in two parts. The first part addresses the use of thermal methods to manage sludge. The second part addresses the use of sludge to manufacture saleable products. These aspects were combined in one volume, as many of the saleable products include a thermal process in their manufacturing process. For example, the use of sludge in brick manufacturing could be seen as both a thermal process and producing a saleable product.

Volume 5 should be used for guidance on the:

- Use of thermal methods to manage sludge
    - Total combustion – This Volume addresses the requirements for the incineration of sludge with specific reference to the operational requirements and management of the air emissions and the ash residues.

  - Co-combustion – Sludge can also be co-incinerated in industrial processes such as industrial furnaces and cement kilns together with other wastes. This volume addresses the air emission and monitoring requirements for these practices.

  - Non-combustion – Partial oxidation and volatilisation of organic solids by pyrolysis or starved-air combustion to produce end products with energy content (e.g. methane, hydrogen, carbon monoxide)

- Use of sludge to produce saleable products

  The requirements for a saleable product are understandably much stricter than the controlled use of sludge products. Saleable products should be adequately disinfected.

  - Sludge composting – Composting is addressed in both Volumes 2 and 5. Some plants in South Africa generate compost that is not completely disinfected. For this type of compost, restrictions apply as addressed in Volume 2. For high quality compost destined for the general public, the process requirements and quality criteria are high, but few restrictions apply after the product leaves the manufacturing process. The same principles apply to manufacturing of other fertilizer products (pellets, etc.) from sludge.

  - Manufacturing bricks, cement, artificial rocks and other construction materials. Many innovative product applications have emerged internationally. Many of these applications are not financially viable in South Africa. However, this volume gives guidance on how to implement such a process in the South African legislative environment.

The purpose of this Volume is:

- To create an understanding of the operational and legal requirements for thermal treatment of sludge and saleable products containing sludge;

- To present guidelines for monitoring of incinerators used for sludge incineration as well as guidelines for ash handling;

- To present operational guidelines for composting of sludge and restrictions and requirements for other saleable products to be used as fertilizer; and

- To present restrictions and requirements applicable to the use of sludge for saleable products applied in construction (bricks, cement, etc.).

2 APPROACH AND METHODOLOGY

Part 1 gives the reader background on the reason and motivation for the development of Volume 5 as well as a short summary of the approach followed. The Guidelines is based on the following information:

- International research findings
- Local legislative and guiding documents
- International guidelines and legislative trends
- Practical considerations

Thermal treatment of sludge can have negative effects on the environment, especially air quality, as well as human health. Commercial products containing sludge may have negative impact on human health since the general public will be the end user of these products. The environmental and human health risk can be mitigated by either:

- Removing the constituents of concern from the sludge through a treatment process, or
- Placing a barrier between the receptor and the sludge.

During thermal treatment pathogens and organic constituents in the sludge are destroyed but air quality should be managed to eliminate any negative effects that constituents present in the exit gas may have on the environment and public health. The final ash produced may contain metals should also be managed according to its potential hazard to the environment.

Commercial products intended for unrestricted use by the general public should be treated to produce a product of such a quality that it will not pose a risk to the user. Therefore only the best quality sludge, compost and fertilizer with a Class A1a classification will be suitable for unrestricted use and distribution. The manufacturing processes of construction material leave the material sterilized and stable and the metals in an insoluble form, eliminating environmental and human health risk.

The thermal treatment of sludge and manufacturing of saleable products from it are discussed in separate sections in the guidelines since different restrictions and requirements apply to it.

3 THERMAL SLUDGE TREATMENT

Thermal treatment of sludge involves the following:

- Total or partial conversion of organic solids to oxidised end products (carbon dioxide and water) by incineration or wet-air oxidation

- Partial oxidation and volatilisation of organic solids by pylolysis or starved-air combustion to end products with energy content.

The major **advantages** of thermal reduction are:

- Maximum volume reduction
- Destruction of pathogens and toxic compounds
- Energy recovery potential

The major **disadvantages** include:

- High capital and operational costs
- Highly skilled operating and maintenance staff requirements
- Produced residuals (emissions and ash) may have adverse environmental effects
- Disposal of residuals may be uncertain and expensive (hazardous waste) (Metcalf & Eddy, 1991).

3.1 Incineration / Combustion

Sludge incineration is the firing of sludge at high temperatures in an enclosed device. The combustible fraction in sludge solids is characterised as volatile or char (fixed carbon). The amount of char produced depends on the sludge solid composition and volatile combustible burning characteristics. While efficient combustion at high temperatures with plenty of air minimises char production, poor combustion with smaller amounts of air yields higher amounts of fixed carbon. If the temperature of the hearth above the burning zone is too low for the destruction of the distilled organics, some or all of the volatilised organic matter may escape the combustion zone unburned. These organics usually are the cause for odour problems, especially with polymer conditioned sludge (Lue-Hing *et al*., 1992).

Utilizing sludge in cement kilns is basically a convoluted thermal disposal route involving drying the sludge, transporting it to the kiln and then burning it. The fossil fuel energy saved in the kiln by burning sludge must be balanced against that utilized in first drying and then transporting the sludge.

As a sludge disposal strategy, this is highly reliant on the willingness of the company operating the cement works to burn the sludge and therefore it is a relatively high-risk disposal strategy for water companies to undertake unless they have a suitable back-up plan should the cement company pull out of any contract or agreement to burn the sludge. If this were to happen, water companies would be left with a large amount of dried sludge, which is expensive to produce and is generally treated only to a conventional level.

If the thermal disposal route is to be taken, a dedicated thermal plant sited closer to existing waste water treatment works (and operated by the water companies themselves) may be a better option, potentially decreasing energy use in transport and providing a more secure disposal route (Lue-Hing *et al.,* 1992).

The thermal treatment of sludge include: *Drying* – the application of heat with the primary purpose of complete drying of the sludge only; and *Thermal Reduction* – the conversion of the organic complexion of raw sludge to more basic compounds such as carbon dioxide, oxides of nitrogen, water vapour, methane, hydrogen, etc. Table 3.a is a summary of the two broad categories of thermal processes.

Table 3.a: Thermal treatment processes for sludge (Metcalf and Eddy, 1991).

Process	Mechanical Process	Comments
Drying	Flash Dryers	Pulverising sludge in cage mil or by atomised suspension on presence of hot gases.
	Spray Dryers	High-speed centrifugal bowl into which sludge is fed or atomised sludge sprayed on top of drying chamber.
	Rotary Dryers	Direct heating – sludge in direct contact with hot gases Indirect heating – steam surrounds sludge
	Multiple-Hearth Dryers	Counter-current flow of heated air and finely pulverised sludge, which is raked continually to expose fresh surfaces.
	Multiple-Effect Evaporators	Proprietary processes such as Carver-Greenfield Process
Thermal Reduction	Complete Combustion	Rapid exothermic oxidation of combustible elements. Incineration is complete combustion.
	Pyrolysis	Destructive distillation, reduction or thermal cracking and condensation of organic matter under heat and/or pressure in the absence of oxygen.
	Partial Pyrolysis	Or "starved-air combustion" is incomplete combustion and occurs when insufficient oxygen is provided.
	Wet Oxidation	A form of incomplete combustion that occurs under high temperatures and pressures.

With sludge drying the water content is reduced by vaporisation of water into air, either by conventional sludge drying beds or by mechanical drying apparatuses. The purpose of heat drying is to remove the moisture from the wet sludge so that it can be incinerated efficiently or processed into fertiliser. Drying for the purposes of fertiliser manufacturing is done to reduce its weight and to prevent continued biological action. The moisture content of dried sludge is typically less than10%.

As shown in Table 3.a, thermal reduction processes include (a) the total or partial combustion of organic solids to oxidised end products (carbon dioxide and water); or (b) the partial oxidation and volatilisation of organic solids by pyrolysis or starved-air combustion to produce end products with energy content (e.g. methane, hydrogen, carbon monoxide). These processes have been considered as 'established' technologies, and include multiple-hearth furnaces, fluidised-bed furnaces, co-incineration and wet-air oxidation technologies. A number of additional thermal processes have also been developed. These 'other thermal processes' were classified by the US Water Environment Research Foundation (WERF 1998) as 'innovative' and 'embryonic' as summarised in Table 3.b. Finally, sludge can also be co-incinerated in industrial processes such as industrial furnaces and cement kilns.

Table 3.b: WERF classification of thermal technologies (Bridle 2001).

Established	Innovative	Embryonic
Multiple-hearth furnace	Deep shaft wet air oxidation	Catalytic extraction process
Fluidised bed furnace	Melting furnace	Co-gasification
Combustion with solid waste	Oxygen injection (incineration)	Electric-arc gasification
Wet air oxidation	RHOX process	Gasification of char from pyrolysis
	Sludge-to-oil conversion	Gasification
		Microwave incineration
		Molten salt incineration
		Supercritical water oxidation
		Total bio-combustion

Incineration and other forms of thermal treatment options have become an attractive alternative in recent years due to the resulting reduction of waste volume, the destruction of pathogens and toxic compounds, and the potential for recovering energy from the sludge. However, this form of treatment is high in capital and operational costs and it requires highly skilled operating and maintenance personnel. More so, the potential presence of metals and organic micro-pollutants such as poly-aromatic hydrocarbons (PAH), dioxins and furans in the air emissions and residual ashes has placed reservations on the application of this process due to the opposition from people living in the neighbourhood of the new plants. However, unlike other incineration operations (e.g. municipal solid waste, medical waste and hazardous chemicals), the presence of chlorine (which is responsible for dioxin and furan formation) in sewage sludge is low and therefore reducing the significance of such contaminants (Mininni 2001). This statement has further been supported by the conclusion reached in a study completed by the US Environmental Protection Agency (US EPA, 2001), which stated that "*…sewage sludge incineration would not appreciably increase dioxin concentrations in surrounding environmental media*". Additionally, it was found that the concentration of dioxins in sewage sludge fed into sewage sludge incinerators did not influence the amounts of dioxins being emitted from the incinerator. The key factors influencing the amount of dioxins being emitted are the combustion conditions in the incinerator, incinerator design, and the efficiency and operational conditions of any air pollution control devices used on the incinerator. The metals present in sewage sludge may be transferred to the gaseous phase depending on their volatility, and the presence of other species, with particular regard to chlorine, and conditions within the furnace (temperature, oxygen concentration, residence time) (Mininni 2001).

As shown in Table 3.a and Table 3.b, the most established forms of thermal treatment include incineration (complete combustion), pyrolysis, partial pyrolysis and wet oxidation. The most common types of incinerations include the multiple hearth furnace and fluidised bed furnace. The rotary kiln furnace, which is typically used for hazardous waste incineration, can also be suitable for sewage sludge due to its great adaptability.

3.1.1 Complete combustion

Sludge incineration is the firing of sludge at high temperatures in an enclosed device. The combustible fraction in sludge solids is characterised as volatile or char (fixed carbon). The amount of char produced depends on the sludge solid composition and volatile combustible burning characteristics. While efficient combustion at high temperatures with plenty of air minimises char production, poor combustion with smaller amounts of air yields higher amounts of fixed carbon. If the temperature of the hearth above the burning zone is too low for the destruction of the distilled organics, some or all of the volatilised organic matter may escape the combustion zone unburned. These organics usually are the cause for odour problems, especially with polymer conditioned sludge.

Multiple Hearth Furnace (HMF)

The design principle of a multiple hearth furnace is a vertical cylindrical reactor. The outer shell is constructed of steel, lined with refractory, and surrounds a series of horizontal refractory hearths. Burners, providing auxiliary heat, are located in the sidewalls of the hearths (EPA 1994). Rabble arms, supported by a single central shaft, rake the sludge radially across the hearths from the top to the bottom, in counter-current with air and hot gases. Three zones can be distinguished in the furnace: the drying zone in the upper part (with gas temperatures of 400^{o}C), the burning zone in the central-low part (gas and solid phases temperatures of 850-900^{o}C) and the ash cooling zone in the lowest part (temperatures of ashes and air generally <200^{o}C).

Scum may also be fed to one or more hearths of the incinerator. Scum is the material that floats on wastewater. It is generally composed of vegetable and mineral oils, grease, hair, waxes, fats, and other materials that will float.

Under normal operating condition, 50 to 100% excess air must be added to a MHF in order to ensure complete combustion of the sludge. Besides enhancing contact between fuel and oxygen in the furnace, these relatively high rates of excess air are necessary to compensate for normal variations in both the organic characteristics of the sludge feed and the rate at which it enters the incinerator. When an inadequate amount of excess air is available, only partial oxidation of the carbon will occur, with a resultant increase in emissions of carbon monoxide, soot, and hydrocarbons. Too much excess air, on the other hand, can cause increased entrainment of particulate and unnecessarily high auxiliary fuel consumption (EPA 1994). MHF may be operated with an afterburner.

Advantages include:

- Flexibility with respect to feed quantity and loading rates;
- Durability;
- Low fuel consumption due to effective eat recovery inside the equipment;
- Retention and residence time is higher for low volatility materials than in other types of incinerators; and
- The handling of high water content wastes and of a wide range of wastes with different chemical and physical properties.

Disadvantages include:

- Possible odour problems;
- Emissions of volatile substances due to the low temperature of exhaust gas;
- The need for excess air due to low turbulence;
- High maintenance costs due to many moving parts;
- Due to the longer residence times of the waste materials, temperature response throughout the incinerator when the burners are adjusted is usually very slow; and
- Variations in feed can alter the temperature profile and thus the positions of the zones, and thus difficulties in achieving complete oxidation of volatile organic materials placing an additional load on an afterburner can occur.

Fluidised Bed Furnace (FBF)

FBF consist of vertically oriented outer shell constructed of steel and lined with refractory. Air is filtered through nozzles (designed to deliver blasts of air) which are located at the base of the furnace within a refractory-lined grid. A bed of sand, approximately 0.75 metres thick, rests upon the grid.

FBFs fall into two categories: bubbling and circulating, the latter allowing a higher fluidisation velocity and an intensive mixing of air and fuel. Partially dewatered sludge is fed into the lower portion of the furnace. Air injected through the nozzles simultaneously fluidises the bed of hot sand and the incoming sludge. Temperatures of 750 to 925°C are maintained in the bed. As the sludge burns, fine ash particles are either returned to the FBF (circulating) or carried out the top of the furnace (bubbling). Two general configurations can be distinguished on the basis of how the fluidising air is injected into the furnace. In the “hot windbox” design the combustion air is first preheated by passing through a heat exchanger where heat is recovered from the hot flue gases. Alternatively, ambient air can be injected directly into the furnace from a cold windbox. A fluidised bed incinerator is a single stage process.

Advantages include:

- Adaptability to sludges at different moisture contents (disposal of solids, liquids, aqueous waste and gases);
- Simplicity of the furnace with no moving parts;
- Low excess air (due to high turbulence)
- Low production of oxides of nitrogen (NOx) due to effective control of combustion temperature (i.e. avoiding hot zones, which are conducive to increased NOx formation);
- Reliability (no moving parts);
- Flexibility for shock load;
- Heat storage capacity by sand bed; and

- Possible abatement of acidic compounds within the bed using additives such as limestone and dolomite.

Disadvantages include:

- The fact that bed diameters and height are limited by design technology;
- High levels of dust carryover in the flue gas; and
- Possible formation of a block of vitrified sand when salts with low melting points are present. This problem can be attenuated by the addition of chemicals to bind the alkaline salts.

Rotary Kiln Furnace (RKF)

Rotary kilns are generally used for small capacity applications. The RKF is a refractory-lined shell at which is inclined slightly (2-3%) from the horizontal plane with the upper end receiving both the sludge feed and the combustion air. A burner is located at the lower end of the kiln (EPA 1994). The kiln rotates at 0.25 to 1.50 rpm. Varying the rotational speed allows the solid residence time to be controlled and ensures adequate mixing. Excess air requirement ranges between 100-200%.

Advantages include:

- Possible melting of ash;
- No need for pre-treatments; and
- Can be adapted to many designs of feed mechanism.

3.1.2 Co-combustion

Virtually any material, that can be burned, can be combined with sludge in a co-incineration process. Common materials for co-combustion are coal, municipal solid waste (MSW), wood waste and agriculture waste. Thus, municipal or industrial waste can be disposed of while providing a self-sustaining sludge feed, thereby solving two disposal problems. There are two basic approaches to combusting sludge with MSW: use of MSW combustion technology by adding dewatered or dried sludge to the MSW combustion unit, and use of sludge combustion technology by adding processed MSW as a supplemental fuel to the sludge furnace (EPA 1994). The amount of sludge that can be incinerated depends on the speed of vaporisation of the large quantity of water contained in the sludge. This increases the volume of flue gas and contributes to the local cooling of the gas temperature.

Utilising sludge in cement kilns or power plants is basically a convoluted thermal disposal route involving drying the sludge, transporting it to the kiln or power plant and then burning it. The fossil fuel energy saved by burning sludge must be balanced against that utilised in first drying and then transporting the sludge.

As a sludge disposal strategy, this is highly reliant on the willingness of the company operating the power plant or cement works to burn the sludge and therefore it is a relatively high-risk disposal strategy for water companies to undertake unless they have a suitable back-up plan should the cement company pull out of any contract or agreement to burn the sludge. If this were to happen, water companies would be left with a large amount of dried sludge, which is expensive to produce and is generally treated only to a conventional level.

3.1.3 Other Combustion Techniques

Electric infrared incinerators consist of a horizontally oriented, insulated furnace. A woven wire belt conveyor extends the length of the furnace and infrared heating elements are located in the roof above the conveyor belt. Combustion air is preheated by the flue gases and is injected into the discharge end of the furnace. Electric infrared incinerators consist of a number of prefabricated modules, which can be linked together to provide the necessary furnace length (EPA 1994). The use of electric infrared furnaces is not so common (EPA 1995).

The cyclonic reactor is designed for small capacity applications. It is constructed of a vertical cylindrical chamber that is lined with refractory. Preheated combustion air is introduced into the chamber tangentially at high velocities. The sludge is sprayed radially towards the hot refractory walls (EPA 1994).

3.1.4 Non-combustion techniques

Conversion (Pyrolysis) Process

Because most organic substances are thermally unstable, they can be split through a combination of thermal cracking and condensation reactions into gas, liquid and solid phases upon heating in an oxygen free atmosphere. In contrast to incineration which is highly exothermic, the pyrolytic process is endothermic. The characteristics of the three major components of pyrolysis are:

- Gas stream containing hydrogen, methane, carbon monoxide, carbon dioxide and other gasses
- Fraction that consist of a tar and/or oil stream which is liquid at room temperature and contains acetic acid, acetone and methanol
- Char consisting of carbon plus any inert material that may have entered the process (Metcalf and Eddy, 1991).

Bridle (2001) analysed these thermal conversion processes (i.e. sludge-to-oil conversion) and identified that these fall within three principal variants, namely:

- Thermo-chemical conversion of dry sludges to oil;
- Thermo-chemical liquefaction of wet sludges to oil; and
- Conversion and combustion processes.

Thermo-chemical conversion of dry sludges, or low temperature conversion process, mimics nature in the way that liquid hydrocarbons are generated from organic substrates, with both thermal cracking and catalytic conversion playing major roles in the process. The alumino-silicates and heavy metals (particularly copper) in sewage sludge catalyse reactions to covert the lipids and proteins in the sludge to hydrocarbons. The conversion takes place between 400-500^{o}C in the absence of oxygen and at essentially atmospheric pressure. The oil produced by the process is similar in quality to a medium fuel oil and can be used for the generation of electricity. Thermo-chemical conversion processes offer the following environmental benefits:

- Complete destruction of all pathogens and viruses;
- Control of heavy metals, including mercury (recovered as processed sludge);
- Destruction of organo-chlorine compounds and
- Odour control

Consequently, gas cleaning is very simple and cheap. Emission standards are therefore easily attainable. The disadvantage of the technology is its capital-intensiveness and the relative complexity of the plants.

In the thermo-chemical liquefaction process, liquid sludge (20% total solids) is heated to about 300^{o}C and 10 MPa pressure for about 90 minutes to effect the liquefaction process. Heavy oil, char, gas and reaction water is generated. As for the processes of thermo-chemical conversion of dry sludges, all pathogens and viruses will be destroyed within the reactor.

With the conversion/combustion process, the gases produced at 450^{o}C are combusted rather than being condensed to produce a liquid fuel. Most of the work in Europe has been done on organic wastes, such as municipal solid waste (MSW), with or without small quantities of sewage sludge (Bridle 2001). An example of the process was the Siemens thermal waste recycling plant at Firth, Germany (constructed 1994 and recently decommissioned). The MSW is first shredded and then combined with dewatered sewage sludge before being converted at 450^{o}C, in the absence of oxygen, to produce a carbonised solid stream and a gas. The solids are separated to remove the glass, metals and ceramics from the carbonised material. The clean gas is then combusted at 1300^{o}C to produce steam and a granulated slag. Combustion off-gases are cleaned in a complex gas cleaning system incorporating wet scrubbers, electrostatic precipitators and fabric filters before venting to the atmosphere.

3.1.5 Other Thermal Processes

A number of other thermal technologies exist. Most of these are still in an early stage of development for commercial application and will not be discussed here. They include (Bridle, 2001):

- Melting furnace;
- Oxygen injection (incineration);

- RHOX process;
- Catalytic extraction process;
- Gasification;
- Co-gasification;
- Electric-arc gasification;
- Gasification of char from pyrolysis;
- Microwave incineration;
- Molten salt incineration;
- Supercritical water oxidation; and
- Total bio-combustion.

3.2 Air pollution Health Aspects

3.2.1 Carbon Monoxide

Carbon monoxide which is absorbed through the lungs reduces the blood's capacity to transport available oxygen to the tissues. Approximately 80-90% of the absorbed CO binds with haemoglobin to form carboxyhaemoglobin (COHb), which lowers the oxygen level in blood. Since more blood is needed to supply the same amount of oxygen, the heart needs to work harder. These are the main causes of tissue hypoxia produced by CO at low exposure levels. At higher concentrations, the rest of the absorbed CO binds with other heme proteins such as myoglobin and with cytochrome oxidase and cytochrome P-450.

CO uptake impairs perception and thinking, slows reflexes, and may cause drowsiness, angina, unconsciousness, or death. An exposure to concentrations of 45 mg/m^3 for more than two hours adversely affects a person's ability to make judgements. Two to four hours of exposure at 200 mg/m^3 raises the COHb level in the blood to 10-30% and increases the possibility of headaches. Exposure to 1 000 mg/m^3 raises the COHb level in the blood to 30% and causes a rapid increase in pulse rate leading to coma and convulsions. One to two hours of exposure at 1 830 mg/m^3 results in 40% COHb in blood, which may cause death (MARC 1991). Endogenous production of CO results in COHb levels of 0.4-0.7% in healthy subjects (WHO 2000). During pregnancy, elevated maternal COHb levels of 0.7-2.5% have been reported, mainly due to increased endogenous production. The COHb levels in non-smoking general populations are usually 0.5-1.5% due to endogenous production and environmental exposures. Non-smoking people in certain occupations (car drivers, policemen, traffic wardens, garage and tunnel workers, firemen, etc.) can have long-term COHb levels up to 5%, and heavy cigarette smokers have COHb levels up to 10%. Well-trained subjects engaging in heavy exercise in polluted indoor environments can increase their COHb levels quickly up to 10-20%. Epidemic CO poisonings in indoor ice arenas have been reported. To protect non-smoking, middleaged and elderly population groups with documented or latent coronary artery disease from acute ischemic heart attacks, and to protect fetuses of non-smoking pregnant mothers from untoward hypoxic effects, a COHb level of 2.5% should not be exceeded (WHO 2000).

The guideline values, and periods of time-weighted average exposures, have been determined in such a way that the COHb level of 2.5% is not exceeded, even when a normal subject engages in light or moderate exercise. The guideline values for CO are 100 mg/m^3 for 15 minutes, 60 mg/m^3 for 30 minutes, 30 mg/m^3 for 1 hour, and 10 mg/m^3 for 8 hours (WHO 2000).

3.2.2 Oxides of Nitrogen

NO_x, primarily in the form of NO, is one of the primary pollutants emitted during combustion. NO_2 is formed through oxidation of these oxides once released in the air. NO_2 is an irritating gas that is absorbed into the mucous membrane of the respiratory tract. The most adverse health effect occurs at the junction of the conducting airway and the gas exchange region of the lungs. The upper airways are less affected because NO_2 is not very soluble in aqueous surfaces. Exposure to NO_2 is linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics and decreased pulmonary function.

Available data from animal toxicology experiments indicate that acute exposure to NO_2 concentrations of less than 1 880 µg/m^3 (1 ppm) rarely produces observable effects (WHO 2000). Normal healthy humans, exposed at rest or with light exercise for less than two hours to concentrations above 4 700 µg/m^3 (2.5 ppm), experience pronounced decreases in pulmonary function; generally, normal subjects are not affected by concentrations less than 1 880 µg/m^3 (1.0 ppm). One study showed that the lung function of subjects with chronic obstructive pulmonary disease is slightly affected by a 3.75-hour exposure to 560 µg/m^3 (0.3 ppm) (WHO 2000).

Asthmatics are likely to be the most sensitive subjects, although uncertainties exist in the health database. The lowest concentration causing effects on pulmonary function was reported from two laboratories that exposed mild asthmatics for 30 to 110 minutes to 565 µg/m^3 (0.3 ppm) NO_2 during intermittent exercise. However, neither of these laboratories was able to replicate these responses with a larger group of asthmatic subjects. NO_2 increases bronchial reactivity, as measured by the response of normal and asthmatic subjects following exposure to pharmacological bronchoconstrictor agents, even at levels that do not affect pulmonary function directly in the absence of a bronchoconstrictor. Some, but not all, studies show increased responsiveness to bronchoconstrictors at NO_2 levels as low as 376-565 µg/m^3 (0.2 to 0.3 ppm); in other studies, higher levels had no such effect. Because the actual mechanisms of effect are not fully defined and NO_2 studies with allergen challenges showed no effects at the lowest concentration tested (188 µg/m^3; 0.1 ppm), full evaluation of the health consequences of the increased responsiveness to bronchoconstrictors is not yet possible.

Studies with animals have clearly shown that several weeks to months of exposure to NO_2 concentrations of less than 1 880 µg/ m^3 (1ppm) causes a range of effects, primarily in the lung, but also in other organs such as the spleen and liver, and in blood. Both reversible and irreversible lung effects have been observed. Structural changes range from a change in cell type in the tracheobronchial and pulmonary regions (at a lowest reported level of 640 µg/m^3), to emphysema-like effects. Biochemical changes often reflect cellular alterations, with the lowest effective NO_2 concentrations in several studies ranging from 380-750 µg/m^3. NO_2 levels of about 940 µg/m^3 (0.5ppm) also increase susceptibility to bacterial and viral infection of the lung. Children of between 5-12 years old are estimated to have a 20% increased risk for respiratory symptoms and disease for each increase of 28 µg/m^3 NO_2 (2-week average), where the weekly average concentrations are in the range of 15-128 µg/m^3 or possibly higher. However, the observed effects cannot clearly be attributed to either the repeated short-term high-level peak, or to long-term exposures in the range of the stated weekly averages (or possibly both). The results of outdoor studies consistently indicate that children with long-term ambient NO_2 exposures exhibit increased respiratory symptoms that are of longer duration, and show a decrease in lung function.

The World Health Organisation (WHO) published health guidelines for short-term (200 µg/m^3 for 1-hour exposure) and long-term (40 µg/m^3 for annual exposure).

3.2.3 Sulphur Dioxide

SO_2 is an irritating gas that is absorbed in the nose and aqueous surfaces of the upper respiratory tract, and is associated with reduced lung function and increased risk of mortality and morbidity. Adverse health effects of SO_2 include coughing, phlegm, chest discomfort and bronchitis.

Short-period exposures (less than 24 hours): Most information on the acute effects of SO_2 comes from controlled chamber experiments on volunteers exposed to SO_2 for periods ranging from a few minutes up to one hour (WHO 2000). Acute responses occur within the first few minutes after commencement of inhalation. Further exposure does not increase effects. Effects include reductions in the mean forced expiratory volume over one second (FEV_1), increases in specific airway resistance, and symptoms such as wheezing or shortness of breath. These effects are enhanced by exercise that increases the volume of air inspired, as it allows SO_2 to penetrate further into the respiratory tract. A wide range of sensitivity has been demonstrated, both among normal subjects and among those with asthma. People with asthma are the most sensitive group in the community. Continuous exposure-response relationships, without any clearly defined threshold, are evident.

Sub-chronic exposure over a 24-hour period: Information on the effects of exposure averaged over a 24-hour period is derived mainly from epidemiological studies in which the effects of SO_2, suspended particulate matter and other associated pollutants are considered. Exacerbation of symptoms among panels of selected sensitive patients seems to arise in a consistent manner when the concentration of SO_2 exceeds 250 µg/m^3 in the presence of suspended particulate matter. Several more recent studies in Europe have involved mixed industrial and vehicular emissions now common in ambient air. At low levels of exposure (mean annual levels below 50 µg/m^3; daily levels usually not exceeding 125 µg/m^3) effects on mortality (total, cardiovascular and respiratory) and on hospital emergency admissions for total respiratory causes and chronic obstructive pulmonary disease (COPD), have been consistently demonstrated. These results have been shown, in some instances, to persist when black smoke and suspended particulate matter levels were controlled for, while in others no attempts have been made to separate the pollutant effects. In these studies no obvious threshold levels for SO_2 has been identified.

Long-term exposure: Earlier assessments, using data from the coal-burning era in Europe judged the lowest-observed-adverse-effect level of SO_2 to be at an annual average of 100 µg/m^3, when present with suspended particulate matter. More recent studies related to industrial sources of SO_2, or to the changed urban mixture of air pollutants, have shown adverse effects below this level.

The World Health Organisation's air quality guidelines (AQGs) which were published in 2000 for sulphur dioxide have recently been revised (WHO, 2005). Although the 10-minute AQG of 500 µg/m³ has remained unchanged, the previously published daily guideline has been significantly reduced from 125 µg/m³ to 20 µg/m³. The previous daily guideline was based on epidemiological studies. WHO (2005) makes reference to more recent evidence which suggests the occurrence of health risks at lower concentrations. Although WHO (2005) acknowledges the considerable uncertainty as to whether sulphur dioxide is the pollutant responsible for the observed adverse effects (may be due to ultra-fine particles or other correlated substances), it took the decision to publish a stringent daily guideline in line with the precautionary principle. The WHO (2005) stipulates an annual guideline is not needed for the protection of human health, since compliance with the 24-hour level will assure sufficiently lower levels for the annual average. Given that the 24-hour WHO AQG of 20 µg/m³ is anticipated to be difficult for some countries to achieve in the short term, the WHO (2005) recommends a stepped approach using interim goals as shown in Table 3.c.

Table 3.c: WHO air quality guidelines and interim guidelines for sulphur dioxide

	24-hour Average Sulphur Dioxide (µg/m³)	**10-minute Average Sulphur Dioxide (µg/m³)**
WHO interim target-1 (IT-1) (2000 AQF level)	125	
WHO interim target-2 (IT-2)	50[(a)]	
WHO Air Quality Guideline (AQG)	20	500

(a) Intermediate goal based on controlling either (i) motor vehicle, (ii) industrial emissions and/or (iii) power production; this would be a reasonable and feasible goal to be achieved within a few years for some developing countries and lead to significant health improvements that would justify further improvements (such as aiming for the guideline).

3.2.4 Hydrogen Chloride

Hydrogen chloride is corrosive to the eyes, skin, and mucous membranes. Acute (short-term) inhalation exposure may cause coughing, hoarseness, inflammation and ulceration of the respiratory tract, chest pain, and pulmonary oedema in humans. Acute oral exposure may cause corrosion of the mucous membranes, oesophagus, and stomach, with nausea, vomiting, and diarrhoea reported. Dermal contact may produce severe burns, ulceration, and scarring. Chronic occupational exposure to hydrochloric acid has been reported to cause gastritis, chronic bronchitis, dermatitis, and photosensitization in workers. Prolonged exposure to low concentrations may also cause dental discolouration and erosion. No information is available on the reproductive or developmental effects of hydrochloric acid in humans. In rats exposed to hydrochloric acid by inhalation, severe dyspnoea, cyanosis, and altered oestrus cycles have been reported in dams, and increased foetal mortality and decreased foetal weight have been reported in the offspring. Similarly no information is available on the carcinogenic effects of hydrochloric acid in humans. In one study, no carcinogenic response was observed in rats exposed via inhalation. The US EPA has not classified hydrogen chloride with respect to potential carcinogenicity.

The Reference Concentration (RfC)[1] for hydrogen chloride is 20 μg/m^3 for chronic exposure. The U.S. Environmental Protection Agency (EPA) estimates that inhalation of this concentration or less over a lifetime would not likely result in the occurrence of chronic effects. The California Office of Environmental Health Hazard Assessment (OEHHA) provides a screening level of 2 100 μg/m^3 and 9 μg/m^3 for acute (1 hr) and chronic exposure respectively. WHO have recommended an odour threshold value of 100 μg/m^3

3.2.5 Particulate Matter

The impact of particles on human health is largely depended on (i) particle characteristics, particularly particle size and chemical composition, and (ii) the duration, frequency and magnitude of exposure. The potential of particles to be inhaled and deposited in the lung is a function of the aerodynamic characteristics of particles in flow streams. The aerodynamic properties of particles are related to their size, shape and density. The deposition of particles in different regions of the respiratory system depends on their size.

The nasal openings permit very large dust particles to enter the nasal region, along with much finer airborne particulates. Larger particles are deposited in the nasal region by impaction on the hairs of the nose or at the bends of the nasal passages. Smaller particles (PM10) pass through the nasal region and are deposited in the tracheobronchial and pulmonary regions. Particles are removed by impacting with the wall of the bronchi when they are unable to follow the gaseous streamline flow through subsequent bifurcations of the bronchial tree. As the airflow decreases near the terminal bronchi, the smallest particles are removed by Brownian motion, which pushes them to the alveolar membrane (CEPA/FPAC Working Group, 1998; Dockery and Pope, 1994).

Air quality guidelines for particulates are given for various particle size fractions, including total suspended particulates (TSP), inhalable particulates or PM10 (i.e. particulates with an aerodynamic diameter of less than 10 μm), and respirable particulates of PM2.5 (i.e. particulates with an aerodynamic diameter of less than 2.5 μm). Although TSP is defined as all particulates with an

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[1] The RfC is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily inhalation exposure of the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. Inhalation RfCs were derived according to the Interim Methods for Development of Inhalation Reference Doses (U.S. EPA, 1994). RfCs can also be derived for the non-carcinogenic health effects of substances that are carcinogens. The RfC is not a direct estimator of risk but rather a reference point to gauge the potential effects. Exceedance of the RfC does not imply that an adverse health effect would necessarily occur. As the amount and frequency of exposures exceeding the RfC increase, the probability of adverse health effects also increases.

aerodynamic diameter of less than 100 µm, and effective upper limit of 30 µm aerodynamic diameter is frequently assigned. PM10 and PM2.5 are of concern due to their health impact potentials. As indicated previously, such fine particles are able to be deposited in, and damaging to, the lower airways and gas-exchanging portions of the lung.

Table 3.d: WHO air quality guideline and interim targets for particulate matter (annual mean)

Annual Mean Level	PM10 (µg/m³)	PM2.5 (µg/m³)	Basis for the selected level
WHO interim target-1 (IT-1)	70	35	These levels were estimated to be associated with about 15% higher long-term mortality than at AQG
WHO interim target-2 (IT-2)	50	25	In addition to other health benefits, these levels lower risk of premature mortality by approximately 6% (2-11%) compared to WHO-IT1
WHO interim target-3 (IT-3)	30	15	In addition to other health benefits, these levels reduce mortality risks by another approximately 6% (2-11%) compared to WHO-IT2 levels.
WHO Air Quality Guideline (AQG)	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to PM2.5 in the American Cancer Society (ACS) study (Pope *et al.*, 2002 as cited in WHO 2005). The use of the PM2.5 guideline is preferred.

Table 3.e: WHO air quality guideline and interim targets for particulate matter (daily mean)

Daily Mean Level	PM10 (µg/m³)	PM2.5 (µg/m³)	Basis for the selected level
WHO interim target-1 (IT-1)	150	75	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short-term mortality over AQG)
WHO interim target-2 (IT-2)(a)	100	50	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short-term mortality over AQG)
WHO interim target-3 (IT-3)(b)	75	37.5	Based on published risk coefficients from multi-centre studies and meta-analyses (about 1.2% increase of short-term mortality over AQG)
WHO Air Quality Guideline (AQG)	50	25	Based on relation between 24-hour and annual levels

(a) 99th percentile (3 days/year)

(b) For management purposes, based on annual average guideline values; precise number to be determined on basis of local frequency distribution of daily means

During the 1990s the World Health Organisation stated that no safe thresholds could be determined for particulate exposures and responded by publishing linear dose-response relationships for PM10 and PM2.5 concentrations (WHO, 2005). This approach was not well accepted by air quality managers and policy makers. As a result the WHO Working Group of Air Quality Guidelines recommended that the updated WHO air quality guideline document contain guidelines that define concentrations which, if achieved, would be expected to result in significantly reduced rates of adverse health effects. These guidelines would provide air quality managers and policy makers with an explicit objective when they were tasked with setting national air quality standards. Given that air pollution levels in developing countries frequently far exceed the recommended WHO air quality guidelines (AQGs), the Working Group also proposed interim targets (IT) levels, in excess of the WHO AQGs themselves, to promote steady progress towards meeting the WHO AQGs (WHO, 2005). The air quality guidelines and interim targets issued by the WHO in 2005 for particulate matter are given in Table 3.d and Table 3.e.

3.2.6 Heavy Metals

Antimony

The concentration of antimony in air ranges from <1 nanogram per cubic meter of air (ng/m^3) to about 170 ng/m^3. Near companies where antimony ore is converted into metal or make antimony oxide, concentrations may be more than 1 000 ng/m^3. Exposure to 9 mg/m^3 of antimony for a long time can irritate eyes, skin, and lungs. Breathing 2 mg/m^3 of antimony for a long time can cause problems with the lungs (pneumoconiosis) heart problems (altered electrocardiograms), stomach pain, diarrhoea, vomiting and stomach ulcers.

It is not know if antimony can cause cancer or birth defects, or affect reproduction in humans. Antimony can have beneficial effects when used for medical reasons; it has been used as a medicine to treat people infected with parasites.

Arsenic

Arsenic occurs naturally in soil and minerals and therefore it may enter the air, water, and land from wind-blown dust and may get into water from runoff and leaching. Volcanic eruptions are another source of arsenic (ASTD, 2003). The major routes of arsenic absorption in the general population are ingestion and inhalation. Particulate arsenic compounds may be inhaled, deposited in the respiratory tract and absorbed into the blood. Inhalation of arsenic from ambient air is usually a minor exposure route for the general population. Tobacco smoke may contain arsenic, especially when the tobacco plants have been treated with lead arsenate insecticide. Although the use of arsenic pesticides is now prohibited in most countries, the natural content of arsenic in tobacco may still result in some exposure.

Occupational exposure to arsenic occurs primarily among workers in the copper smelting industry, at power plants burning arsenic-rich coal, and using or producing pesticides containing arsenic. Inhalation exposure to arsenic can also take place during production of gallium arsenide in the microelectronics industry, demolition of oil-fired boilers and metal ore mining (WHO 2000).

From both the biological and the toxicological points of view, arsenic compounds can be classified into three major groups: inorganic arsenic compounds; organic arsenic compounds; and arsine gas. The most common trivalent inorganic arsenic compounds are arsenic trioxide, sodium arsenite and arsenic trichloride. Pentavalent inorganic compounds include arsenic pentoxide, arsenic acid and arsenates, e.g. lead arsenate and calcium arsenate. Common organic arsenic compounds are arsanilic acid, methylarsonic acid, dimethylarsinic acid (cacodylic acid) and arsenobetaine (WHO, 2000).

Levels of arsenic in the air generally range from less than 1 to about 2,000 ng/m^3, depending on location, weather conditions, and the level of industrial activity in the area. However urban areas generally have mean arsenic levels in air ranging from 20 to 30 ng/m^3, most of which is attached to small particles (ASTD, 2003). Arsenic in air is present mainly in particulate forms as inorganic arsenic. It is assumed that methylated arsenic is a minor component in the air of suburban, urban and industrial areas and that the major inorganic portion is a variable mixture of the trivalent and pentavalent forms, the latter being predominant (WHO 2000).

Inhalation of high levels of inorganic arsenic is likely to result in a sore throat and irritated lungs. This may also result in the darkening of the skin and the appearance of small "corns" or "warts" on the palms, soles, and torso. A small number of the corns may ultimately develop into skin cancer. The exposure level that produces these effects is uncertain, but it is probably above 100 µg/m^3 for a brief exposure. Longer exposure at lower concentrations can lead to skin effects, and also to circulatory and peripheral nervous disorders. Some data suggest that inhalation of inorganic arsenic may also interfere with normal fetal development, although this is not certain. An important concern is the ability of inhaled inorganic arsenic to increase the risk of lung cancer (ASTD, 2003).

There is some information suggesting that children may be less efficient at converting inorganic arsenic to the less harmful organic forms. For this reason, children may be more susceptible to health effects from inorganic arsenic than adults (ASTD, 2003).

Beryllium

There is extensive evidence in humans that the respiratory tract is one of the primary targets of beryllium toxicity following inhalation exposure. In general, non-cancerous respiratory effects can be divided into two categories: acute beryllium disease and chronic beryllium disease also referred to as berylliosis or chronic berylliosis. Acute beryllium disease is a fulminating (sudden explosive) inflammatory reaction of the entire respiratory tract. The respiratory tract symptoms range from mild nasopharyngitis to a severe chemical pneumonitis, which may be fatal. Acute beryllium disease is usually associated with exposure to high concentrations of soluble beryllium compounds. Signs and symptoms observed in the affected workers included irritation of the nasal and pharyngeal mucous membranes, sore nose and throat, weight loss, laboured breathing, decreased vital capacity, anorexia, and increased fatigue.

Chronic beryllium disease (CBD) is an inflammatory lung disease characterized by the formation of granulomas with varying degrees of interstitial fibrosis. Chronic beryllium disease is a beryllium-specific immune response with primary manifestations in the lung. The symptoms associated with chronic beryllium disease include chest pain, cough, and/or dyspnea with relatively mild exertion.

A chronic inhalation reference concentration (RfC) of 0.02 µg/m^3 has been derived for beryllium (IRIS 2000). IARC (2001) has classified beryllium and beryllium compounds in Group 1, carcinogenic to humans. The EPA classifies inhaled beryllium in Group B1, a probable human carcinogen (IRIS

2002) and calculated an inhalation unit risk (the risk corresponding to lifetime exposure to 1 μg/m^3) of 2.4x10^{-3} per μg/m³ (IRIS 2003).

Cadmium

Inhalation exposure to cadmium in humans is derived from studies of workers exposed to cadmium fume or dusts in industries such as smelting, battery manufacturing, soldering, and pigment production. Food and cigarette smoke are the biggest sources of cadmium exposure for people in the general population. Air levels of cadmium in U.S. cities are low, ranging from less than I to 40 ng/m^3. Air levels greater than 40 ng/m^3 may occur in urban areas with high levels of air pollution from the burning of fossil fuels (ASTD, 2003).

Numerous studies have shown that acute inhalation exposure to cadmium can cause death in humans and animals. In humans, several fatal inhalation exposures have occurred in occupational accidents. During the acute exposure, the general symptoms are relatively mild but, within a few days following exposure, severe pulmonary oedema and chemical pneumonitis develop, leading to death due to respiratory failure (Beton *et al.*, 1966; Lucas *et al.*, 1980; Patwardhan and Finckh 1976; Seidal *et al.*, 1993).

Additional respiratory symptoms less frequently reported in workers occupationally exposed to cadmium are chronic rhinitis and impairment or loss of the sense of smell (Adams *et al.*, 1969; Bonnell 1955; Friberg 1950; Liu *et al.*, 1985; Rose *et al.*, 1992). The cause of these effects may be chronic irritation or necrosis of the nasal membranes, as they are generally found only in individuals with high-level exposure (ASTD, 2003).

Intermediate-duration exposure to cadmium results in similar respiratory effects as seen in the acute exposures. The level and duration of exposure determine the severity of the effects in a dose-response manner. Intermediate exposure levels in the 0.4-4 mg Cd/m^3 range generally result in serious lung damage (ASTD, 2003).

The relationship between occupational exposure to cadmium and increased risk of cancer (specifically lung and prostate cancer) has been explored in a number of epidemiologic studies. For inhalation exposures, the results of epidemiology studies that evaluated cadmium's effects on increased lung cancer are conflicting. Many of the studies had inadequate controls for confounding factors such as co-exposure with other metal carcinogens and smoking, and there is only a small number of lung cancer mortality cases in the only U.S. cohort studied. Overall, however, the results provide little evidence of an increased risk of lung cancer in humans following prolonged inhalation exposure to cadmium (ASTD, 2003).

The controversy about the adequacy of the human cancer data for cadmium is reflected in the cancer classifications from different agencies. The Environmental Protection Agency EPA has classified cadmium as a probable human carcinogen by inhalation (Group Bl), based on its assessment of limited evidence of an increase in lung cancer in humans (Thun *et al.*, 1985) and sufficient evidence of lung cancer in rats (IRIS 1996; Takenaka *et al*., 1983). EPA has calculated an inhalation unit risk of 1.8×10^{-3} per µg/m³ (IRIS 1996). The International Agency for Research on Cancer (IARC) has classified cadmium as carcinogenic to humans (Group 1) based on an assessment of sufficient evidence for carcinogenicity in both human and animal studies (IARC 1993).

A chronic inhalation reference concentration (RfC) of 0.9 µg/m³ has been derived by the US EPA.

Chromium

Trivalent chromium (III) is an essential nutrient for humans. On average, adults in the United States take in an estimated 60 µg of chromium daily from food. Exposure to chromium can also take place due to using consumer products such as household utensils, wood preservatives, cement, cleaning products, textiles, and tanned leather (ASTD, 2003).

The bronchial tree is the primary target organ for carcinogenic effects of hexavalent chromium (VI). The retention of chromium compounds from inhalation, based on a 24-hour respiratory volume of 20 m³ in urban areas with an average chromium concentration of 50 ng/m³, is about 3-400 ng. Individual uptake may vary depending on concomitant exposure to other relevant factors, e.g. tobacco smoking, and on the distribution of the particle sizes in the inhaled aerosol. Chromium has been determined as a component of cigarette tobacco produced in the United States, its concentration varying from 0.24 to 6.3 mg/kg, but no clear information is available on the fraction that appears in mainstream tobacco smoke (WHO, 2003).

In general, chromium (VI) is absorbed by the body more easily than chromium (III), but once inside the body, chromium (VI) is changed to chromium (III). When breathing air containing chromium, the chromium particles can be deposited in the lungs. Particles that are deposited in the upper part of the lungs are likely to be coughed up and swallowed. Particles deposited deep in the lungs are likely to remain long enough for some of the chromium to pass through the lining of the lungs and enter the bloodstream. Once in the bloodstream, chromium is distributed to all parts of the body. Chromium will then pass through the kidneys and be eliminated in the urine in a few days. Most individuals eat or drink a small amount of chromium daily. Most of the chromium that is swallowed never enters the blood and leaves the body within a few days through faeces. A small amount (about 0.4-2.1%) will pass through the lining of the intestines and enter the bloodstream. Chromium (III) present in food can attach to other compounds that make it easier for chromium to enter your bloodstream from your stomach and intestines. This form of chromium is used by the body to carry out essential body functions (ASTD, 2003). Without chromium (III) in the diet, the body loses its ability to use sugars, proteins, and fat properly, which may result in weight loss or decreased growth, improper function of the nervous system, and a diabetic-like condition.

The health effects resulting from exposure to chromium (III) and chromium (VI) are fairly well described in the literature. In general, chromium (VI) is more toxic than chromium (III). Breathing in high levels (greater than 2 µg/m³) chromium (VI), such as in a compound known as chromic acid or chromium (VI) trioxide, can cause irritation to the nose, such as runny nose, sneezing, itching, nosebleeds, ulcers, and holes in the nasal septum. These effects have primarily occurred in factory workers who make or use chromium (VI) for several months to many years (ASTD, 2003).

Long-term exposure to chromium has been associated with lung cancer in workers exposed to levels in air that were 100 to 1,000 times higher than those found in the natural environment. Lung cancer may occur long after exposure to chromium has ended. Breathing in small amounts of chromium (VI) for short or long periods does not cause a problem in most people. However, high levels of chromium in the workplace have caused asthma attacks in people who are allergic to chromium. Breathing in chromium (III) does not cause irritation to the nose or mouth in most people (ASTD, 2003).

The US EPA has calculated an inhalation unit risk of 1.2×10^{-2} per µg/m³ (IRIS 2003), whereas the WHO provided a range of 1.1×10^{-2} to 13×10^{-2} per µg/m³. A chronic inhalation reference concentration (RfC) of 0.1 µg/m³ has been derived by the US EPA.

Cobalt

Cobalt may enter air and water, and settle on land from wind-blown dust, seawater spray, volcanic eruptions and forest fires. Small amounts of cobalt may be released into the atmosphere from coal-fired power plants and incinerators, vehicular exhaust, industrial activities relating to the mining and processing of cobalt-containing ores, and the production and use of cobalt alloys and chemicals (ASTD, 2003).

Effects on the respiratory system following inhalation exposure to stable cobalt include irritation, fibrosis, asthma, pneumonia, and wheezing. Individuals can develop sensitivity to cobalt, and inhalation exposure to airborne cobalt can precipitate asthmatic attacks in sensitised individuals (ASTD, 2003).

Cobalt has not been shown to cause cancer in humans by the inhalation, oral, or dermal exposure routes. An occupational study reported an increased incidence of death from lung cancer in workers exposed to cobalt, but the difference was not statistically significant (ASTD, 2003).

Copper

Copper can enter the environment through releases from the mining of copper and other metals, and from factories that make or use copper metal or copper compounds. Copper can also enter the environment through domestic waste water, combustion of fossil fuels and wastes, wood production, phosphate fertilizer production, and natural sources (for example, windblown dust, from native soils, volcanoes, decaying vegetation, forest fires, and sea spray) (ASTD, 2003).

Copper is common in the environment. You may be exposed to copper by breathing air, drinking water, eating food, and by skin contact with soil, water, and other copper-containing substances. Most copper compounds found in air, water, sediment, soil, and rock are strongly attached to dust and dirt or imbedded in minerals (ASTD, 2003).

In the US concentrations of copper in air range from less than 1 ng/m^3 to about 200 ng/m^3. Near smelters, which process copper ore into metal, concentrations may reach 5 000 ng/m^3 (ASTD, 2003).

Long-term exposure to copper dust can irritate the nose, mouth, and eyes, and cause headaches, dizziness, nausea, and diarrhea. Intentionally high intakes of copper can cause liver and kidney damage and even death (ASTD, 2003).

The carcinogenicity of copper has not been adequately studied. An increase in cancer risk has been found among workers at copper smelters; however, the increased risk has been attributed to concomitant exposure to arsenic. Increased lung and stomach cancer risks have also been found in copper miners. However, a high occurrence of smoking and exposure to radioactivity, silica, iron, and arsenic preclude associating the risk with copper exposure. Animal studies have not found increased cancer risks in orally exposed rats or mice. IARC has classified copper 8-hydroxyquinoline in Group 3, unclassifiable as to carcinogenicity in humans and the EPA has classified copper in Group D, not classifiable as to human carcinogenicity (ASTD, 2003).

Lead

In Europe and the USA air concentrations of lead has decreased significantly over the past decade due to the phasing out of alkyl lead additives in petrol. The phasing out of alkyl lead additives in South African as been gradual: only in 2006 has lead been totally removed from regular petrol.

Lead is removed from the atmosphere by dry or wet deposition. The residence time of lead containing particles in the atmosphere varies according to a number of factors, such as particle size, wind currents, rainfall and height of emission. Fallout from the emissions of industrial sources, such as smelters, is limited mainly to the immediate vicinity. However, strong evidence indicates that a fraction of airborne lead is transported over long distances. As a result, a long-term global accumulation of lead has occurred in recent decades. This has been demonstrated convincingly by analyses of glacial ice and snow deposits in remote areas, such as the Greenland ice cap, until about 1960; however, subsequent measurements revealed a marked downward trend in the same glacial strata, corresponding to the global fall in the use of alkyl lead additives in petrol (WHO, 2000).

Shortly after lead gets into the body, it travels in the blood to the "soft tissues" (such as the liver, kidneys, lungs, brain, spleen, muscles, and heart). After several weeks, most of the lead moves into the bones and teeth. In adults, about 94% of the total amount of lead in the body is contained in the bones and teeth. About 73% of the lead in children’s bodies is stored in their bones. Some of the lead can stay in bones for decades; however, some lead can leave the bones and re-enter blood and organs under certain circumstances, for example, during pregnancy and periods of breast feeding, after a bone is broken, and during advancing age (ASTD, 2003).

The body does not change lead into any other form. Once it is taken in and distributed to the organs, the lead that is not stored in bones leaves the body in urine or faeces. About 99% of the amount of lead taken into the body of an adult will leave in the waste within a couple of weeks, but only about

32% of lead taken into the body of a child will leave in the waste. Under conditions of continued exposure, not all the lead that enters the body will be eliminated, and this may result in accumulation of lead in body tissues, notably bone (ASTD, 2003).

The effects of lead are the same whether it enters the body through breathing or swallowing. The main target for lead toxicity is the nervous system, both in adults and in children. Long-term exposure of adults to lead at work has resulted in decreased performance in some tests that measure functions of the nervous system. Lead exposure may also cause weakness in fingers, wrists, or ankles. Lead exposure may also cause anemia. At high levels of exposure, lead can severely damage the brain and kidneys in adults or children. In pregnant women, high levels of exposure to lead may cause miscarriage. High-level exposure in men can damage the organs responsible for sperm production (ASTD, 2003).

The WHO published a chronic exposure (annual) guideline of 0.5 µg/m^3.

Manganese

Manganese is an essential trace element and is necessary for good health. The human body typically contains small quantities of manganese, and under normal circumstances, the body controls these amounts so that neither too little nor too much is present (ASTD, 2003).

In urban and rural areas without significant manganese pollution, annual averages are mainly in the range of 0.01-0.07 µg/m^3; near foundries the level can rise to an annual average of 0.2-0.3 µg/m^3 and, where ferro- and silico-manganese industries are present, to more than 0.5 µg/m^3, with individual 24-hour concentrations sometimes exceeding 10 µg/m^3 (WHO, 2000).

When inhaled, manganese that enters the bloodstream passes first to the brain before being processed by the liver. Depending on its ability to cross the blood-brain barrier, this manganese may reach areas of the central nervous system and produce the characteristic neurotoxic effects of manganese. Although manganese is eliminated primarily by biliary excretion, it appears that inhaled manganese may not be as well regulated by this mechanism as is ingested manganese (WHO, 2000).

Neurobehavioural effects generally have reflected disturbances in the control of hand movements (e.g. tremor, reduced hand steadiness) and/or the speed of movement (e.g. longer reaction time, slower finger-tapping speed). Reproductive effects have included a smaller number of children born to manganese-exposed workers compared to matched controls, and various self-reported symptoms of sexual dysfunction. In recent studies at low to moderate occupational exposure levels, respiratory effects have been reflected primarily in self-reported symptoms of respiratory tract illnesses rather than in differences between objective spirometric measurements in manganese-exposed and control workers (WHO, 2000).

Most people who inhale manganese are involved in jobs where they are exposed to the metal. However, there is a possibility that people can be exposed to manganese in the air if they live near a plant that uses manganese, or if they live in a high traffic area and the automobiles burn manganese in the gasoline (e.g. MMT). A recent study showed that people who inhaled manganese from the air and who had high levels of manganese in their blood showed signs of neurological problems that were similar to those reported in occupationally-exposed persons. The neurological problems were most significant in the people aged 50 years and older. Breathing too much manganese dust can cause irritation of the lungs. Sometimes this makes breathing difficult, and it can also increase the chances of getting a lung infection, such as pneumonia. However, this can happen from breathing in many kinds of dust particles and not just those that contain manganese (ASTD, 2003).

The US EPA developed an RFC of 0.05 $\mu g/m^3$, whereas the WHO provides an annual average guideline of 0.15 $\mu g/m^3$.

Mercury

In humans, inhalation is a rapid route for mercury vapour intake. Mercury vapour is highly lipophilic and may readily cross the pulmonary air to blood barrier into the systemic circulation. The bioavailability factor for inhalation of mercury vapour ranges from 74 to 77 per cent (Hrudey *et al.*, 1996) and is generally assumed to be 80 per cent (WHO, 1987). The deposition and absorption of inhaled aerosols of inorganic mercury will depend on particle size and solubility (WHO, 1987). Quantitative data on absorption of inorganic and organic mercury aerosols in humans are limited or lacking. In small rodents, organic mercury compounds were readily and completely absorbed from the lung into the systemic circulation (Hrudey *et al.*, 1996 and WHO, 1987).

The body burden of mercury is distributed between three main compartments; namely, blood, brain and kidneys (Roach, 1992b), but mercury is distributed to all tissues of the body. The highest levels of mercury are eventually found in the kidney, but accumulation also occurs in the cells of the mucous membranes of the gastrointestinal tract. Mercury vapour can readily penetrate the placental and blood-brain barrier and will be retained in the brain for a long time. Inorganic mercury compounds cross these barriers only slightly, but organic mercury compounds readily cross these barriers and have a high affinity for the brain following ingestion exposure in humans (Hrudey *et al.*, 1996 and WHO, 1987).

Elimination from the body is generally slow and the average biological half time of inhaled mercury vapour in humans is more than a month (Roach, 1992b). The whole-body half time of inorganic mercury in adults is about 40 days (WHO, 1987) and that of methylmercury is usually between 70 and 80 days, but substantial individual differences occur (WHO, 1987). All forms of mercury are primarily excreted from the body via urine and faeces in humans. A small amount of mercury vapour from tissues can be exhaled from the lung (Lauwerys and Hoet, 1993 and Hrudey *et al.*, 1996). The biological half time in organs can also differ; in the kidney it is in the order of 2 months, but much longer in the central nervous system (Lauwerys and Hoet, 1993). It is estimated that the biological half time of elimination from the brain may exceed a year (Berlin, 1979).

Mercury vapour, inorganic mercury salts and organic (alkyl or phenyl) mercury compounds that are chronically inhaled affect the central and peripheral nervous systems. The earliest sign of mercurialism is a characteristic tremor. Other symptoms are irritability and, in severe cases, depression, insomnia, hallucinations, delusions and mania. Ingestion of mercuric compounds may lead to gastro-intestinal and kidney damage. Chronic exposure over long time periods may cause permanent damage to the brain, kidney and developing foetus (Hrudey al. 1996 and Roach, 1992a).

After exposure to mercury vapour the nervous system is the main target, but, depending on the dose, the oral mucosa and kidneys might also be affected. Short-term inhalation exposure to mercury vapour (in concentrations of 1.2 to 8.5 mg/m^3) may cause headaches, cough, chest pains, chest tightness and difficulty in breathing. It may also cause chemical pneumonitis, soreness of the mouth, loss of teeth, nausea and diarrhoea. Liquid mercury may irritate the skin (NIOSH, 1978). Long-term exposure to mercury concentrations in air at 100 μg/m^3 or higher may lead to mercurialism, characterised by symptoms such as gingivitis (sore and swollen gums), hypersalivation and metal taste in the mouth. Other associated oral effects are stomatitis (inflammation of the mouth) and loose teeth. Loss of appetite, weight loss and excessive fatigue are also common. Central nervous system effects manifest as tremor of the hands, eyelids, lips, tongue, or jaw; insomnia, personality change, irritability, indecision and intellectual deterioration and a cluster of psychological difficulties labelled erethism, which includes deficits in short-term memory and social withdrawal. The peripheral nervous system may also be affected, resulting in changes in nerve conduction velocity. Effects on the nervous system are usually reversible, as are renal effects in general (NIOSH, 1978; WHO, 1987 and Gerhardsson and Skerfving, 1996).

In the kidneys, mercury vapour can elicit the nephrotic syndrome, characterised by excessive loss of protein in the urine, as well as oedema (abnormal accumulation of fluid beneath the skin, or in one or more of the cavities of the body). Mercury air concentrations above 80 μg/m^3 increase the risk for neurological symptoms and adverse kidney effects. Low levels of exposure to 25 to 80 μg/m^3 are associated with mild proteinuria and enzymuria. Effects on pregnancy and birth in occupationally exposed women have been reported, but were insufficient to evaluate a dose-response relationship (WHO, 1987 and Gerhardsson and Skerfving, 1996).

Conflicting epidemiological studies were published regarding a correlation between mercury exposure and an increased incidence of lung cancer mortalities. All of the studies have limitations and increased cancer rates could be attributable to other concurrent exposures or lifestyle factors. Data concerning genotoxic effects are of an equally equivocal nature (IRIS, 2001). IARC (1993) has classified elemental mercury as "unclassifiable as to carcinogenicity to humans" (Group 3).

The approach of the WHO was to use the lowest-observed-effect-levels for the mildest adverse effect (proteinuria). The LOAEL was adjusted for continued exposure and a protection factor of 20 applied. Inorganic mercury compounds were estimated to be retained in the lungs about half as efficiently as inhaled mercury vapour, therefore the estimated guideline would be twice that of mercury vapour. The contribution of methylmercury to human intake by inhalation was considered negligible and guidelines were not given for this compound in ambient air (WHO, 1987). The annual ambient guideline for mercury vapour is 1 $\mu g/m^3$. The WHO originally arrived at a less stringent ambient guideline for inorganic mercury of 2 $\mu g/m^3$ (WHO, 1987), but was later adjusted to an annual average of 1 $\mu g/m^3$ based on a lowest-observed-adverse-effect-level of 0.020 mg/m^3 for renal tubular effects in humans (WHO, 2000). The inhalation Reference Concentration (RfC) developed by the US EPA is 0.3 $\mu g/m^3$ for chronic exposure (IRIS 2006).

Nickel

Numerous human and animal studies have identified the respiratory tract as the most sensitive target of inhaled nickel toxicity. Chronic bronchitis, emphysema, and impaired lung function have been observed in nickel welders and foundry workers. Co-exposure to other toxic metals such as uranium, iron, lead, and chromium confounds the interpretation of these studies. The predominant respiratory effect in animals exposed to nickel sulfate, nickel subsulfide, or nickel oxide is lung inflammation. Other lung effects include increased lung weight, alveolar macrophage hyperplasia, interstitial infiltrates, proteinosis, fibrosis, and impaired lung function (as evidenced by labored breathing). In addition to the pulmonary effects, nickel sulfate and nickel subsulfide exposure resulted in atrophy of the nasal olfactory epithelium (ASTD, 2003).

The carcinogenic effect of nickel has been well documented in occupationally-exposed individuals. Several cohorts of workers, particularly nickel refinery workers, found significant increases in the risk and incidence of lung and nasal cancers. For most of the studies, the exact nickel compound is not known, although it is believed that nickel sulfate and the combination of nickel sulfides and oxides are the causative agents.

Inhalation of all types of nickel compounds induces respiratory tract irritation, chemical pneumonia, emphysema and varying degrees of hyperplasia of pulmonary cells, and fibrosis (pneumoconiosis). Nickel may precipitate autoimmune phenomena and induce immuno-suppression *in vitro*; the clinical importance of such effects has not been reported (WHO, 2000).

Nickel can cross the placental barrier, thus being able to influence prenatal development by direct action on the embryo. Fetal death and malformations have been reported following injection of various species of nickel compounds in experimental animals (WHO, 2000).

The critical organ following inhalation exposure is the respiratory tract. After short-term high-dose inhalation exposure, lung irritation and pneumonia are critical effects. Increased mortality of nonmalignant respiratory disease has been reported in nickel refinery workers with more than 5 years of exposure, and pneumoconiosis has been reported following 12-20 years of exposure. No details on nickel compounds or exposure levels was given, but nickel oxide (Ni_2O_3) was found to be fibrogenic when instilled intratracheally. Tumour induction must, however, be regarded as the critical effect (WHO, 2000).

Severe lung damage has been recorded following acute inhalation exposure to nickel carbonyl. Reversible renal effects (in workers), allergic dermatitis (most prevalent in women), and mucosal irritation and asthma (in workers) have been reported following exposure to inorganic nickel compounds. Renal effects and dermatitis presumably relate both to nickel uptake by both inhalation and ingestion, in addition to cutaneous contact for dermatitis. Allergic asthma has been reported among workers in the plating industry following exposure to nickel sulfate. Cytogenic studies have been conducted in workers in the nickel-refining industry (crushing, roasting, smelting and electrolysis), in nickel carbonyl production, and in electroplating. Elevated levels of sister chromatid exchanges and chromosomal aberrations have been demonstrated in workers in nickel refining plants and in nickel platers; the main effect was chromosomal gaps. No effects were found in workers exposed to nickel carbonyl (WHO, 2000).

A common limitation of the occupational studies involves co-exposure to other metals, particularly arsenic and chromium, which are also carcinogenic. Increases in the incidence of lung tumors have also been observed in animals exposed to nickel subsulfide or nickel oxide, but not after nickel sulfate exposure. The Department of Health and Human Services in the US has determined that metallic nickel may reasonably be anticipated to be a human carcinogen and nickel compounds are known to be human carcinogens. Similarly, IARC classified metallic nickel in group 2B (possibly carcinogenic to humans) and nickel compounds in group 1 (carcinogenic to humans). EPA has classified nickel refinery dust and nickel subsulfide in Group A (human carcinogen). Other nickel compounds have not been classified by the EPA. Based on the occupational data, inhalation unit risk levels of 2.4×10^{-4} per $\mu g/m^3$ and 4.8×10^{-4} per $\mu g/m^3$ were derived by the EPA for nickel refinery dust and nickel subsulfide, respectively (ASTD, 2003). The WHO derived an inhalation unit risk factor of 3.8×10^{-4} per $\mu g/m^3$ (WHO).

Tin

Because inorganic tin compounds usually enter and leave your body rapidly after you breathe or eat them, they do not usually cause harmful effects. However, humans who swallowed large amounts of inorganic tin in a research study suffered stomach aches, anemia, and liver and kidney problems. Studies with inorganic tin in animals have shown similar effects to those observed in humans. There is no evidence that inorganic tin compounds affect reproductive functions, produce birth defects, or cause genetic changes. Inorganic tin compounds are not known to cause cancer. Inhalation, oral (eating or drinking), or dermal exposure to some organo-tin compounds has been shown to cause harmful effects in humans, but the main effect will depend on the particular organo-tin compound. There have been reports of skin and eye irritation, respiratory irritation, gastrointestinal effects, and neurological problems in humans exposed for a short period of time to high amounts of certain organo-tin compounds. There are no studies of cancer in humans exposed to organo-tin compounds. Studies of a few organo-tins in animals suggest that some organotin compounds can produce cancer. On the basis of no data in humans and questionable data from a study in rats, EPA has determined that one specific organo-tin, tributyltin oxide, is not classifiable as to human carcinogenicity; that is, it is not known whether or not it causes cancer in humans.

Vanadium

Several occupational studies indicate that absorption can occur in humans following inhalation exposure. An increase in urinary vanadium levels was found in workers exposed to less than 1 ppm of vanadium (Gylseth *et al*., 1979; Kiviluoto *et al*., 1981b; Lewis 1959; Orris *et al*., 1983). The vanadium concentration in serum was also reported to be higher than the non-occupationally exposed controls following exposure to vanadium pentoxide dust (Kiviluoto *et al*., 1981b). There is a possibility that oral exposure (mucociliary clearance) contributed to vanadium levels in the serum. The rate and extent of vanadium absorption in humans is not known (ATSDR, 2003).

The WHO proposed a 24-hour guideline of 1 µg/m³.

3.2.7 Health Thresholds for Carcinogenic Exposures

Unit risk factors are applied in the calculation of carcinogenic risks. These factors are defined as the estimated probability of a person (60-70 kg) contracting cancer as a result of constant exposure to an ambient concentration of 1 µg/m³ over a 70-year lifetime. In the generic health risk assessment undertaken as part of the current study, maximum possible exposures (24-hours a day over a 70-year lifetime) are assumed for all areas beyond the boundary of the proposed development site. Unit risk factors were obtained from the WHO (2000) and from the US-EPA IRIS database (accessed May 2005).

The definition of what is deemed to be an acceptable risk remains one of the most controversial aspects of risk characterisation studies. An important point to be borne in mind is the crucial distinction between voluntary and involuntary risks. The risk to which a member of the public is exposed from an industrial activity is an involuntary one. In general, people are prepared to tolerate higher levels of risk for hazards to which they exposure themselves voluntarily. There appears to be a measure of uncertainty as to what level of risk would be acceptable to the public. The US Food and Drug Administration (FDA) defined a carcinogenic risk of "one-in-a-million" (also expressed as 1:1 000 000 or $1x10^{-6}$) as "essentially zero" when applied to food additives, colour additives, and animal drugs. (A carcinogenic risk of 1×10^{-6} corresponds to a one-in-a-million chance of an individual developing cancer during their lifetime.). The US EPA has repeatedly rejected the opinion that it can establish a universal (i.e. "brightline") acceptable risk that should never be exceeded under any circumstances. In practical terms, however, the EPA almost never regulates at a theoretical risk below one-in-a-million (*de minimis*) and almost always regulates at a theoretical risk above one-in-ten-thousand or 1:10 000 (*de manifestis*) assuming the person to inhale the chemical for 70 years, 24-hours per day. The European Parliament and the European Council, when considering the proposal for a Directive on Drinking Water, agreed that an excess lifetime risk of one-in-a million should be taken as the starting point for developing limit values. Various authors (Kletz, 1976; Lees, 1980; Travis *et al*., 1987) similarly concluded that a *lethal* risk level of between 10^{-5} and 10^{-6} per year (i.e. 10^{-4} and 10^{-5} per lifetime) is generally regarded acceptable. Further work by Travis *et al*. (1987) indicated that for small populations, risks of less than 10^{-4} may also potentially be acceptable, whereas risks greater than 10^{-4} are likely to prompt action. Locally the Department of Environmental Affairs and Tourism

(DEAT) have only been noted to give an indication of cancer risk acceptability when they applied it to the development of dioxin and furan exposures from incinerators. According to the DEAT, emissions of dioxins and furans from a hazardous waste incinerator may not result in an excess cancer risk of greater than 1: 100 000 on the basis of annual average exposure (DEAT, 1994). A more recent reference can be made through the adoption of the South African National Standard for Benzene (SANS 1929:2004) of 5 μg/m³. This standard was based on the limit value developed by the European Community to be met by 2010. Depending on which unit risk factor is used, the equivalent incremental lifetime cancer risk for this standard varies from a minimum of 1.5:100 000 [California Air Resources Board] to 3.5:100 000 [WHO] and 3.9:100 000 [US EPA], respectively. These are all in the order of a few cases in a 100 000.

3.3 Potential environmental impact of incineration

Organic emissions from sludge incinerators include:

- Products of incomplete combustion.
- Compounds contained in sludge that are not completely burned during combustion.
- Products synthesised from products of incomplete combustion at low temperature zones.

In perfect combustion, carbon and hydrogen in organic material are oxidised to form carbon dioxide and water. However, when there is imperfect mixing of organic material with air or when there is not enough time to complete the oxidation reactions, when the flame temperature is not adequate perfect combustion cannot be achieved. If oxidation reactions are slowed down by the unavailability of oxygen or are prematurely terminated by flame quenching certain intermediate compounds become frozen during the process and appear in the final product. These products of incomplete combustion usually are paraffin, olefins, aromatics, and acetylenes. The reactions of these hydrocarbons with other species may produce compound like aldehydes, ketones, alcohols and acids. In the present of chlorides sulphur and nitrogen more complex compounds may be formed. Regardless of the type of material being incinerated, certain compounds are most frequently found as products of incomplete combustion in the gases. These compounds usually constitute about 10 to 15% of the total amount of organics emitted from all types of incinerators (Lue-Hing *et al.*, 1992).

Municipal sewage sludge can be incinerated in an environmentally acceptable manner. However, incineration does not result in the ultimate disposition of municipal sewage sludge since an ash residue will always remain. Generally, the mass of dry ash produced by municipal sewage sludge incineration ranges between 20 to 40% of the dry weigh of sludge solids fed to the incinerator. Incinerated sewage sludge has been described to be a good fertiliser because of it phosphorus and lime content. The enhancement of plant growth and plant uptake in soil amended with sewage sludge incinerator ash has not been studied extensively (Lue-Hing *et al.*, 1992).

The potential presence of metals and organic micro pollutants in the gaseous effluent and in residual ashes has restricted the application of this process due to opposition from people living in the neighbourhood of the new plants. The presence of chlorine, responsible for dioxins and furans formation, in sewage sludge is negligible and, therefore, the problem of the appearance of such contaminants is of minor importance with respect to the incineration of urban solid wastes. Metals can be present in sewage sludge at detectable concentrations and they may be transferred to the gaseous phase depending on their volatility, and the presence of other species, with particular regard to chlorine, and conditions inside the furnace (Spinosa & Vesilind, 2001).

3.4 Factors affecting incineration of sludge

The assessment of an incineration process, therefore, requires a preliminary chemical characterisation of sewage sludge to detect the presence of organic micro pollutants, heavy metals, chlorine, sulphur, phosphorus and nitrogen which could pose environmental problems due to the formation of toxic compounds or to their enrichment in the fly ashes. Calorific value is also an important parameter for the evaluation of auxiliary fuel requirement which could adversely affect the economics of the process (Spinosa & Vesilind, 2001).

The main **chemical characteristics** affecting sludge incineration are:

- Organic and inorganic chlorine
- Sulphur
- Phosphorus and nitrogen
- Other halogens
- Organic micro pollutants (chlorinated hydrocarbons, phenols and polyphenols, polychlorinated biphenils, pesticides and polynuclear aromatic hydrocarbons)
- Heavy metals.

The sulphur content of sewage sludge generally ranges between 0.5-2% dry weights. Because a fraction of the sulphur is present in the oxidised sulphate form, it is not all converted to sulphur dioxide during combustion. Sulphur dioxide in the emissions easily combines with moisture in the atmosphere to form sulphuric and sulphurous acids (Spinosa & Vesilind, 2001).

Phosphorus can be present in sewage sludge in concentrations ranging from 1-5% dry weight. During combustion phosphorus is mainly converted to calcium phosphate as P_2O_5, which can make up to 15% of furnace ash. Nitrogen is sewage sludge (2-12% dry weight) can be converted during combustion to molecular nitrogen (Spinosa & Vesilind, 2001).

Organic and inorganic chlorine play an important role in the tendency of chlorine radicals to bind to active radicals, such as O*, H* and OH*. This determines a decrease in the combustion rate with the possibility of toxic compounds formation. Chlorine is also responsible for the production of acidic compounds which are undesirable for corrosion problems, especially at high temperatures. The concentration of organic chlorine in sewage sludge is generally negligible (<50 mg/L dry weight) but inorganic chlorine can be more abundant depending on its presence in the sludge moisture and the use of ferric chloride as chemical conditioner (Spinosa & Vesilind, 2001).

Although the presence of organic micro pollutants in sewage sludge is detectable in some cases they generally do not pose problems in incineration. Previous characterisation of sewage sludge should include those compounds that are recognised to be unmanageable to thermal degradation, such as benzene, acetonitrile, toluene, chlorobenzene and all the polynuclear aromatic hydrocarbons (Spinosa & Vesilind, 2001).

Heavy metals are generally present in sewage sludge in highly variable concentrations depending on the presence of industrial contributions to the wastewater. Their presence has to be considered for the potential tendency to be transferred in the gaseous phase and to condense on to fine particles during gas cooling (Spinosa & Vesilind, 2001).

The main **physical-chemical characteristics** affecting incineration performance are:

- Dry matter and volatile solids – affecting both fuel requirement and exhaust gas production
- Calorific value – represents the amount of heat developed in combustion by the unit mass of material
- Thermal-analytical properties, as evaluated by thermal gravimetric analysis and differential scanning calorimetry – characterise the thermal behaviour of a substance during heating and cooling
- Presence of grease, scum and screenings – Grease, scum and screenings can be incinerated together with sludge, but they could pose some problems if the plant is not designed for this purpose. Screenings tend to clog feed mechanisms. Skimming generally contains more than 95% moisture and, therefore, such sludge should be thickened before incineration. The addition of scum and grease can result in operating and safety problems because their high energy content will involve an increased volume of exhaust gases that are suddenly produced in the heating space (Spinosa & Vesilind, 2001).

Solid residues of sludge incineration are generally classified as *bottom ashes* or *fly ashes*. The potential hazard generally increases as the gas temperature of the collecting device decreases. Landfilling is normally the cheapest method of ultimate disposal. Bottom ash can also be utilised for the manufacture of bricks and as filling material in civil/road construction and as a component in cement production. Ash mainly consists of insoluble silicates, phosphates, sulphates and refractory metal oxides, some of which may be soluble.

Metals likely condense on to fine particulate matter and therefore small, respirable-sized particles tend to have the highest metal concentrations. Toxicity may also depend on the actual form in which the metal is present and, consequently, on its availability. The ash metal concentration is generally different from that of feed sludge: there may be enrichment due to the reduction of mass on ignition, or a reduction due to enrichment in gaseous emissions. Zn and Pb display a marked enrichment in fly ashes, Cr appears basically inert to volatilisation and Cu tends to volatilise only in the presence of chlorine (Spinosa & Vesilind, 2001).

Public concern generally focuses on operational control and emission of pollutants such as heavy metals, acid gases and dioxins. Sources of potentially significant impact are:

- Poor working conditions and accidents
- Spills from sludge handling and storage
- Spills from sludge transport systems and ash removal equipment
- The handling and disposal of fly ash
- Dust explosion by dried sludge
- Start-up operations
- Disposal of exhaust gases via the emergency chimney
- Flue gas disposal exceeding pollutant limits.

The most significant **potential consequences** of incinerator activities are:

- Environmental effects from stack and fugitive emissions
- Soil and water pollution (particularly from sludge handling and storage areas, accidents, spills and pollutant fall-out)
- Public health effects
- Noise and vibration from plant operation and traffic
- Fire and emergencies
- Visual impact (stacks are often very high)
- Local undesirable land use.

Mitigation measures are likely to include:

- Careful and considered selection of site
- Control of emissions and noise
- Proper treatment and handling of solid and liquid residues
- Visual integration and screening.

The identification of potential pollutant hazards in stack emissions, with respect to toxicity, persistence in the environment and magnitude of release, is the first step in assessing the public health risks posed by an incinerator. Organic contaminants in stack emissions may be either uncombusted residues of chemicals present in the feed, or compounds generated during the combustion process.

Metals have traditionally been the focus of concerns regarding the potentially toxic nature of fly ashes. Organic compounds such as PAH, phthalates, chlorobenzenes, PCB, PCDD, and PCDF have also been detected. The mobility of chemicals in fly ash must be accurately evaluated to determine the hazard inherent in the incinerator residue.

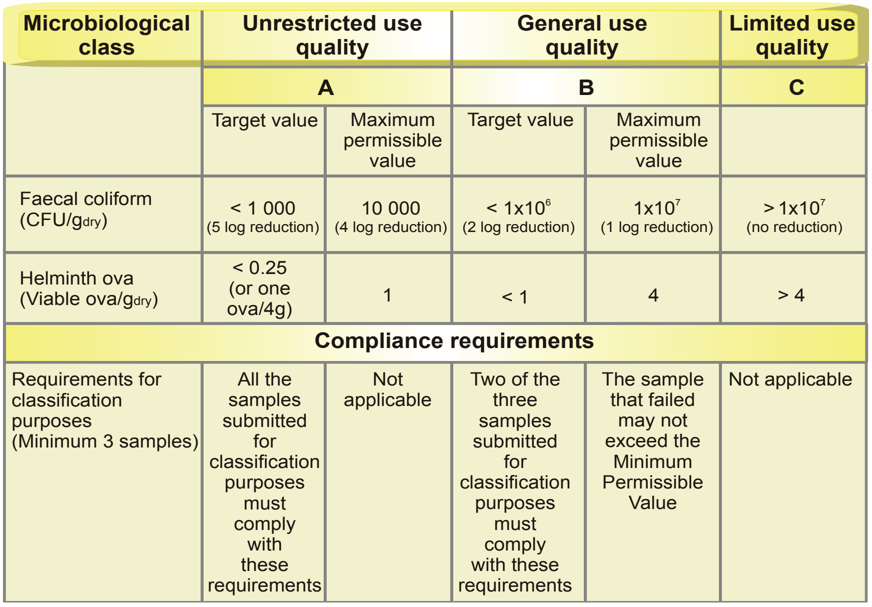
3.5 Sludge classification for thermal treatment

The sludge classification system remains the same as in the previous Volumes, consisting of a Microbiological class (A, B or C), Stability class (1, 2 or 3; based on the odour and vector attraction properties of the sludge) and a Pollutant class (a, b or c). Sludge classification is discussed in detail in Volume 1 of the Sludge Guidelines. It is not necessary to repeat the classification process, but the sludge producer/user should double-check that the sludge class is suitable for thermal treatment. Therefore, the classification system and parameters are repeated here for information purposes only.

3.5.1 Microbiological class

The Microbiological class classification system of Volumes 1 and 2 applies to thermal treatment as well (Table 3.f). Since thermal treatment will destroy the pathogens, all Microbiological classes will be allowed for thermal treatment and no monitoring if the sludge is necessary.

Table 3.f: Classification criteria for the Microbiological class

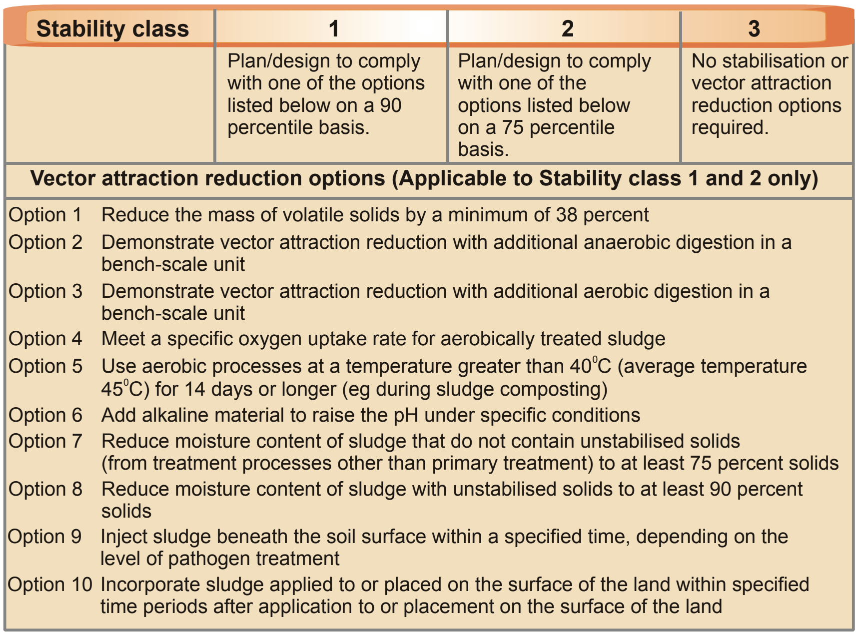


Microbiological class	**Unrestricted use quality**		**General use quality**		**Limited use quality**
	A		**B**		**C**
	Target value	Maximum permissible value	Target value	Maximum permissible value	
Faecal coliform (CFU/g$_{dry}$)	< 1 000 (5 log reduction)	10 000 (4 log reduction)	< 1x10^6 (2 log reduction)	1x10^7 (1 log reduction)	> 1x10^7 (no reduction)
Helminth ova (Viable ova/g$_{dry}$)	< 0.25 (or one ova/4g)	1	< 1	4	> 4
Compliance requirements					
Requirements for classification purposes (Minimum 3 samples)	All the samples submitted for classification purposes must comply with these requirements	Not applicable	Two of the three samples submitted for classification purposes must comply with these requirements	The sample that failed may not exceed the Minimum Permissible Value	Not applicable

3.5.2 Stability class

The same vector attraction reduction options apply as discussed in Volume 1 (Table 3.g). These vector attraction reduction criteria were adopted from the US EPA 503 Sludge rule (US EPA, 1993; US EPA 1994). These criteria (or very similar) have been adopted by many other countries including Australia. It should be noted that Options 9 and 10 are not applicable to thermal treatment.

Table 3.g: Determination of the Stability class



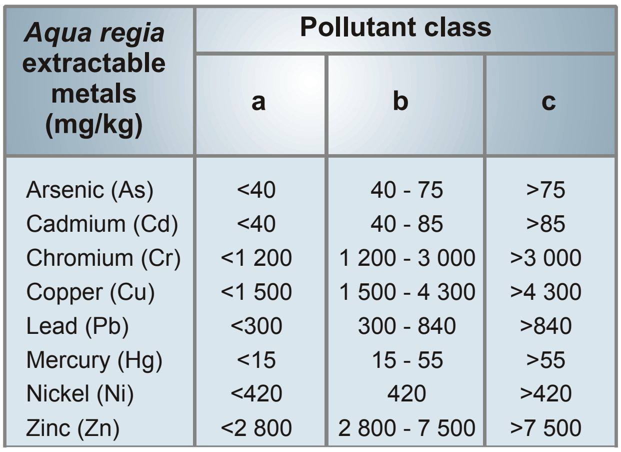
Stability class	**1**	**2**	**3**
	Plan/design to comply with one of the options listed below on a 90 percentile basis.	Plan/design to comply with one of the options listed below on a 75 percentile basis.	No stabilisation or vector attraction reduction options required.
Vector attraction reduction options (Applicable to Stability class 1 and 2 only)			
Option 1	Reduce the mass of volatile solids by a minimum of 38 percent		
Option 2	Demonstrate vector attraction reduction with additional anaerobic digestion in a bench-scale unit		
Option 3	Demonstrate vector attraction reduction with additional aerobic digestion in a bench-scale unit		
Option 4	Meet a specific oxygen uptake rate for aerobically treated sludge		
Option 5	Use aerobic processes at a temperature greater than 40^{o}C (average temperature 45^{o}C) for 14 days or longer (eg during sludge composting)		
Option 6	Add alkaline material to raise the pH under specific conditions		
Option 7	Reduce moisture content of sludge that do not contain unstabilised solids (from treatment processes other than primary treatment) to at least 75 percent solids		
Option 8	Reduce moisture content of sludge with unstabilised solids to at least 90 percent solids		
Option 9	Inject sludge beneath the soil surface within a specified time, depending on the level of pathogen treatment		
Option 10	Incorporate sludge applied to or placed on the surface of the land within specified time periods after application to or placement on the surface of the land		

Note: Options 9 and 10 do not apply for thermal treatment

3.5.3 Pollutant class

The Pollutant class determination of sludge in Volumes 1 and 2 was based on the total metal content (*aqua regia* digestion) of the sludge and apply to thermal treatment as well. Table 3.f indicate the recommended Pollutant class classification limits for sludge. Not all Pollutant classes may be suitable for thermal treatment due to the metals present in the exit gas during combustion.

Table 3.h: Pollutant class classification for sludge destined for thermal treatment



Aqua regia extractable metals (mg/kg)	Pollutant class		
	a	b	c
Arsenic (As)	<40	40 - 75	>75
Cadmium (Cd)	<40	40 - 85	>85
Chromium (Cr)	<1 200	1 200 - 3 000	>3 000
Copper (Cu)	<1 500	1 500 - 4 300	>4 300
Lead (Pb)	<300	300 - 840	>840
Mercury (Hg)	<15	15 - 55	>55
Nickel (Ni)	<420	420	>420
Zinc (Zn)	<2 800	2 800 - 7 500	>7 500

3.6 Legal requirements for thermal treatment

This section includes a summary of previous and more recent South African legislation. This is further complimented by a review of the US and European legislation. These legislative approaches are quite different. European Directives fix emission limits for various pollutants while the US Federal Register establishes requirements to protect public health and the environment when sewage sludge is fired in a dedicated incinerator, by imposing concentration limits with reference to sludge input and local input.

Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965)

The Department of Environmental Affairs and Tourism (DEAT), Directorate: Air Pollution Control developed a set of guidelines for the 72 Scheduled Processes which are included in the Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965, Second Schedule). In terms of this regulation, the Chief Air Pollution Officer (CAPCO) consulted these guidelines when issuing Air Pollution Certificates. The guidelines are not intended as statutory standards and served as a starting point for negotiations between CAPCO and the operator of a Scheduled Process. Incineration is governed by Process 39: Waste Incineration Processes (see Appendix A). Three classes of incineration were defined:

- Class 1 – Incinerators in which the waste serves as the fuel or supplementary fuel in an industrial process (e.g. the use of cement kilns or any other industrial boilers or furnaces for the disposal of noxious or hazardous materials)
- Class 2A – Incinerators for the disposal of waste that contains hazardous or potentially hazardous waste
- Class 2B-1 – Incinerators for the disposal of waste that contains medical waste at a rate above 10 kg/day

- Class 2B-2 – Incinerators for the disposal of waste that contains medical waste at a rate for less than 10 kg/day in rural areas only
- Class 3 – <100 kg/h Incinerators for the disposal of waste that contains "general waste", i.e. no toxic, hazardous, medical or organic halogen containing waste. These are suitable for incinerating waste from flats, offices and restaurants and which are designed to burn 100 kg/h or less.
- Class 3 – >100 kg/h Incinerators burning more than 100 kg/h "general waste" will be treated in accordance with the guidelines for Class 2 incinerators.

According to these definitions, sewage sludge incineration would be classified as a Class 2A incinerator, since the waste contains hazardous or potentially hazardous waste. The Scheduled Process guidelines (Appendix A) provide Basic design requirements, Operational requirements, Emission limits; and Monitoring requirements.

These items are summarised in Table 3.i.

Table 3.i: APPA Scheduled Process 39: Class 2A Incinerators.

DESIGN	OPERATION	MONITORING
Siting: • Should be sited in accordance with the relevant town planning scheme, the topography and be compatible with premises in the neighbourhood. • It should be housed in a suitably ventilated room.	Feeding: • Controlled hygienic, mechanical or automatic feeding methods have to be used which will not influence the air supply and temperature in the primary and secondary chambers of the incinerator negatively. • No waste is to be fed into the incinerator: ◘ at start up and until the minimum combustion temperatures have been reached. ◘ whenever the minimum combustion temperatures are not maintained. ◘ whenever the previous charge has not been completely combusted in the case of a batch loader. ◘ until such time as the addition of more waste will not cause the design parameters of the incinerator to be exceeded.	Air Pollution Emission Limits: • The total particulate emission should not exceed 180 mg/m³@ 11% O_2, 0% moisture and 101.3 kPa • Opacity of the smoke should not exceed 20%. • All the emissions to air other than steam or water vapour should be odourless and free from mist, fume and droplets. • The Chief Officer may require that the certificate holder have tests carried out by an accredited person or body to determine stack and/or ground level concentrations of the following substances: • Heavy metal composition of flue gas: ◘ Maximum of 0.05 mg/m³ for: – Cadmium and compounds as Cd – Mercury (Hg) – Thallium(Tl) ◘ Maximum of 0.5 mg/m³ for: – Chromium (Cr) – Beryllium (Be) – Arsenic (As) – Antimony (Sb) – Barium (Ba) – Lead (Pb) – Silver (Ag) – Cobalt (Co) – Copper (Cu) – Manganese (Mn) – Tin (Sn) – Vanadium (V) – Nickel (Ni) • Chloride as HCl < 30 mg/m³

		• Hydrofluoric acid as HF <30 mg/m^3 • Sulphur dioxide as SO_2 < 25 mg/m^3 • The average dioxin and furan concentration in the emissions should not exceed 80 ng/m^3 total dioxins and furans if measured for a period of 6 to 16 hours or 0.2 ng International Toxic Equivalent (I TEQ/m^3) or result in an excess cancer risk of 1:100 000 on the basis of annual average exposure. • Any substance that the Chief Officer may consider necessary, e.g. polycyclic hydrocarbons, benzene, etc.
<u>Combustion Chambers:</u> • The primary combustion chamber shall be accepted as the primary combustion zone and should be equipped with a burner/s burning gas or low sulphur liquid fuel. Other combustion methods will be judged on merits. Primary air supply is to be controlled efficiently. • The secondary combustion chamber shall be accepted as the secondary combustion zone and should be fitted with a secondary burner/s burning gas or low sulphur liquid fuel or any suitable fuel. Secondary air supply is to be controlled efficiently. Flame contact with all the gases should be achieved. • The residence time in the secondary chamber should be not less than2 seconds. • The gas temperature as measured against the inside wall in the secondary chamber, not in the flame zone, should be not less than 1100^{o}C. • The oxygen contents of the emitted gases should be not less than 11%. • Both the primary and the secondary temperatures should be maintained until all the waste has been completely combusted.	<u>Performance:</u> A 99.99% destruction and removal efficiency (DRE) for each principal organic hazardous constituent (POHC) in the waste feed where: $DRE = [(Win - Wout)/Win]*100$ where: *Win* = mass feed rate of the POHC in the waste stream fed to the incinerator, and *Wout* = mass emission rate of POHC in the stack prior to the release to the atmosphere.	<u>Temperature Monitoring:</u> • The temperature should be determined against the inside wall of both the primary and secondary combustion chambers. Care should be taken not to measure the burner flame temperature. • An audible and visible alarm should be installed to warn the operator when the secondary temperature drops to below the required temperature. • The temperature should be determined against the inside wall of both the primary and secondary combustion chambers. Care should be taken not to measure the burner flame temperature. • An audible and visible alarm should be installed to warn the operator when the secondary temperature drops to below the required temperature. • In addition to the above the following instruments may also be required: ◘ A carbon monoxide and/or oxygen meter/recorder ◘ A smoke density meter/recorder ◘ A gas flow meter/recorder ◘ A solid particulate meter/recorder • Any other instrument or measurement that the Chief Officer considers necessary

Stack: • The chimney should have a minimum height of 9 metres above ground level and clear the highest point of the building by not less than 6 metres for flat roofs or 3 metres for pitched roofs. The topography and height of adjacent buildings (i.e. closer than 5 times chimney height) should be taken into account. • If possible the chimney should be visible to the operator from the stoking floor. • The addition of dilution air after combustion in order to achieve the requirements of these guidelines is unacceptable. • The minimum exit velocity should be 10 m/s. • The stack shall be insulated to maintain the maximum outlet temperature. • Point for the measurement of emissions shall be provided.	Operation: • Materials destined for incineration should be of known origin and composition and may only be incinerated in a furnace that is registered for the incineration of that particular type of waste. • Record should be kept of the mass and/or volume, the type and origin of the waste to be incinerated. • The incinerator should be preheated to working temperature before charging any waste. • Overloading of the incinerator should be avoided at all times. • The incinerator should be kept in good working order at all times and should not be used if any component fails. Any malfunction should be recorded in a log book and reported to the relevant control authority. • It should be supplied complete with full operating instructions. The incinerator operator and all relevant staff should be trained to the satisfaction of the relevant control authority. • A list should be displayed at or near the control panel which identifies all trained operators. • The incinerator and its surrounds should be kept in a clean and neat condition at all times. • In cases where noxious or offensive gases are emitted that cannot be destroyed by secondary combustion, additional control equipment, e.g. scrubbers, bagfilters or electrostatic precipitators will be required.	

The South African National Environmental Management Air Quality Act No.39 of 2004.

The APPA of 1965 has subsequently (11 September 2005) been replaced by National Environmental Management Air Quality Act (NEM-AQA) (Act No. 39 of 2004), with the exclusion of sections 21, 22, 36 to 49, 51(1) (e), 51(1)(f), 60 and 61. The excluded sections of NEM-AQA, all deal with the licensing of listed activities. Therefore, at the time of writing the licensing of Scheduled Processes is still maintained under APPA and is being reviewed for completion by mid 2007.

The aim of NEM-AQA is to reform the law regulating air quality in order to protect and enhance the quality of air in the Republic, taking into account the need for sustainable development, to provide for national norms and standards regulating air quality monitoring, management and control by all spheres of government; for specific air quality measures; and for matters incidental thereto.

The approach of the NEM-AQA is to shift the focus to the receiving environment and to decentralise responsibilities to provincial and local government. This would require baseline air quality characterisation studies to be conducted for regions and provinces to identify areas and pollutants of concern. All sources within a region would have to be addressed and if identified as a main contributing source would be expected to develop and implement emission reduction strategies. Standardisation of various aspects of air quality management would be required including methodologies on monitoring, modelling, management and reporting. Public participation is a requirement of the impending act which would require industries to follow a transparent management approach. The NEM-AQA makes provision for the setting of ambient air quality standards and emission limits on National level, which provides the objective for air quality management. More stringent ambient standards may be implemented by provincial and metropolitan authorities.

The minister must, within two years of the date on which this section took effect, establish a national framework for achieving the object of this Act. This needs to include mechanisms, systems and procedures to attain compliance with ambient air quality standards, to give effect to the Republic’s responsibility to international agreements and to control emissions from point and non-point sources. In addition, national norms and standards needs to be set for air quality -monitoring; -management planning, – information management, and any other matter which the Minister considers necessary for achieving the object of this Act.

Chapter 2 states that substances and mixtures of substances that present a threat to health, well-being or the environment must be identified and national standards be established (including the permissible amount or concentration of each such substance or mixture of substances in ambient air). In addition, emission standards need to be established for each of these substances and mixtures of substances from point, non-point or mobile sources.

Chapter 4 of the impending Air Quality Act focus on Air Quality Management Measures. Section 21 of this chapter states that the Minister must, or MEC of a province may publish a list of activities which he/she thinks might have a negative effect on the environment (including health, social conditions, economic conditions, ecological conditions or cultural heritage) and this list can be amended from time to time by adding or removing activities. In addition, if an activity is listed, emission standards need to be set for pollutants emanating from such an activity.

Section 32 of Chapter 4 states that the Minister or MEC may prescribe measures for the control of dust in specified places or areas, steps that must be taken to prevent nuisance by dust; or other measures aimed at the control of dust.

In Section 33 reference is made to the ceasing of mining operations where a mine has to notify the Minister 5 years prior to closure, clearly stating plans for rehabilitation and prevention of pollution of the atmosphere by dust after those operations have stopped.

Section 60 of the Air Quality Act lists the ambient air quality standards which are discussed in the following subsections.

The Department of Environmental Affairs and Tourism (DEAT), Directorate: Air Pollution Control developed a set of guidelines for the 72 Scheduled Processes which are included in the Atmospheric Pollution Prevention Act (APPA) (Act No. 45 of 1965, Second Schedule). In terms of this regulation, sludge incineration is classified as Class 2A: Incinerators for the disposal of waste that contains hazardous or potentially hazardous waste. The APPA of 1965 has subsequently (11 September 2005) been replaced by National Environmental Management Air Quality Act (NEM-AQA) (Act No. 39 of 2004). The aim of NEM-AQA is to reform the law regulating air quality in order to protect and enhance the quality of air in SA, taking into account the need for sustainable development, to provide for national norms and standards regulating air quality monitoring, management and control by all spheres of government, for specific air quality measures and for matters incidental thereto.

3.6.1 Regulatory requirements

The regulatory requirements applicable to thermal treatment of sludge and ash handling is presented in Table 3.j.

Table 3.j: Regulatory requirements applicable to thermal treatment and ash handling

	Thermal treatment	**Sludge storage area**	**Ash handling**
APPLICABLE ACT GOVERNING PRACTICE	National Environmental Management Air Quality Act (NEM-AQA) (Act No. 39 of 2004)	Environment Conservation Act (Act No. 73 of 1989) National Environmental Management: Waste Management Act	
AUTHORISATION REQUIRED	Air Pollution Certificate	Disposal site Permit	Disposal site Permit
LEAD AUTHORITY	DEAT	DEAT	DEAT
REGULATORY INSTRUMENT	Air Pollution Certificate	Disposal site Permit	Disposal site Permit
REGULATORY GUIDELINES	Sludge Guidelines (Volume 5) and/or Ambient Air Quality Guidelines and/or Minimum Requirements (latest applicable versions)		

3.7 Restrictions and requirements for thermal treatment

Part A4 deals with the general restrictions and requirements for thermal treatment plants where sludge will be treated. It includes guidance on site design, management, air emissions and monitoring requirements.

3.7.1 Design requirements

Important design requirements for thermal treatment plants include site selection, the adherence to appropriate buffer zones and stack height of the incinerator.

Site selection

Selecting a site for the thermal treatment plant would have to take into account many factors, including optimum distance from the supplying wastewater treatment plants or processes, and environmental considerations. By careful layout within a site, and by locating the treatment plant as far as practicable from the nearest sensitive land use, the impact on neighbouring landholders can be reduced. Careful examination of the proposed site, activities, plant and installation, in conjunction with the relevant planning and environmental legislation (e.g. district or municipal Air Quality Management Plan), spatial development plan objectives and principles, and details of existing land uses in the vicinity, is necessary if the separation distance requirements of a proposal are to be addressed adequately.

Typical sensitive land uses include: community centres, offices, educational establishments, shopping centres, childcare centres, dwellings (multiple dwellings, detached dwellings, semi-detached dwellings, residential flat buildings), consulting rooms, hospitals, nursing homes, hotels, parklands, recreation areas or reserves, motels and caravan parks.

The compatibility of neighbouring industries themselves needs to also be considered, for example, food and beverage preparation premises would be incompatible. The reasons for incompatibility could often be highly individual, and need to be addressed on a case by case basis to ensure that sensible planning solutions are reached.

Allowance should be made for the possibility of future expansion on a site when setting up initial separation distances, otherwise the expansion could be prevented by the lack of available buffers.

The thermal treatment plant should be sited in accordance with the relevant town planning scheme, the topography of the area and have to be compatible with the land-use in the neighbourhood. It should also be an optimum distance from the supplying WWTP. The following aspects should be considered in conjunction with the relevant planning and environmental legislation (e.g. district or municipal Air Quality Management Plan) when a site is selected:

- Careful examination of the proposed site
- Envisaged activities

- Type of treatment plant and installation requirements
- Spatial development plan objectives and principles. Allowance should be made for the possibility of future expansion on a site when setting up initial separation distances, otherwise the expansion could be prevented by the lack of available buffers.
- Details of existing land uses in the vicinity. The compatibility of neighbouring industries themselves needs to also be considered, for example, food and beverage preparation premises would be incompatible. The reasons for incompatibility could often be highly individual, and need to be addressed on a case by case basis to ensure that sensible planning solutions are reached.

Buffer zones

The establishment of a separation distance between industrial activities and sensitive receptors should not be seen as an opportunity for additional air pollution, i.e. over legal limits. It should rather be viewed as a distance which would protect sensitive receptors from the impact of non-routine and upset emissions, or air emissions following accidental spills or fires. As implied by the NEM-AQA, routine air emissions must comply with regulatory and health risk guidelines anywhere beyond the plant boundary, including in this instance an established *buffer zone*.

The *buffer zone* is the area defined by the application of a *separation distance* to an *activity boundary*, where the activity plant boundary is considered to be the boundary drawn to enclose all activities, plant, buildings, other structures or other sources from which residual air emissions may arise. The activity boundary may not necessarily coincide with the property boundary, which would be the boundary for the purposes of applying the NEM-AQA. The *buffer boundary* is formed by a line drawn at the prescribed separation distance from the activity boundary.

The activity boundary includes all sources of potential air pollutant emissions, such as the sludge preparation area, storage facilities, drying processes, furnaces, boilers, ash handling and loading facilities. These must be identified and included within the activity boundary from which measurements are taken. The *measurement point* is the point on or adjacent to the nearest sensitive land use or zone at which a separation distance is assessed.

The recommended separation distance for sewage sludge thermal treatment installations (based on short-term ground-level impact predictions) is 350 m, as measured from the activity boundary to the measuring point. Where the distance between the measurement point and the activity boundary is less than the recommended separation distance, then the proponent should be requested to demonstrate why the lesser distance would be appropriate.

The recommended separation distance is based on the assumption that the emission limits (following section) can be met. In addition, it is assumed that the industry is complying with the requirements of all legislation (NEM-AQA). If site specific circumstances (e.g. local topography, state of the art technology, etc.) appear to indicate a reason for departing from the recommended distance, the advice of the relevant air pollution authority should be obtained in the first instance.

As a guide, the following criteria should be addressed when seeking a site-specific variation from the recommended separation distance:

- The scale of operation of the proposal is significantly smaller than 100 kg/h it will produce substantially lower emissions and will not be expanding;
- The standard of emission control technology to be used, e.g. the plant will have a standard of emission control technology significantly better than the good level of control normally applied to thermal treatment of sewage sludge;
- Evidence of the effectiveness of the proposed technology; and
- An environmental impact assessment of residual air emissions that illustrates the level of cumulative impact. This would take into account the existence of exceptional topographic, meteorological or other circumstances that will affect the emission or dispersion of residual emissions.

It is suggested that proponents seeking an amendment to the recommended separation distances will need to engage the services of experienced and appropriately qualified air pollution consultants.

The establishment of a separation distance between industrial activities and sensitive receptors should be viewed as a distance which would protect sensitive receptors from the impact of non-routine and upset emissions, or air emissions following accidental spills or fires.

The recommended buffer zone for sludge thermal treatment installations is 350 m, as measured from the site boundary to the nearest sensitive land use. **Note**: Where the buffer zone is less 350 m, the plant owner/operator should be able to demonstrate why the lesser distance would be appropriate.

The advice of the relevant air pollution authority should be obtained if site specific circumstances (e.g. local topography, state of the art technology, etc.) appear to indicate a reason for relaxation of the recommended buffer zone.

Combustion Chambers

- The primary combustion chamber shall be accepted as the primary combustion zone and should be equipped with a burner/s burning gas or low sulphur liquid fuel. Other combustion methods will be judged on merits. Primary air supply is to be controlled efficiently.
- The secondary combustion chamber shall be accepted as the secondary combustion zone and should be fitted with a secondary burner/s burning gas or low sulphur liquid fuel or any suitable fuel. Secondary air supply is to be controlled efficiently. Flame contact with all the gases should be achieved.
- The residence time in the secondary chamber should be > 2 seconds.
- The gas temperature as measured against the inside wall in the secondary chamber, not in the flame zone, should be > 1100^{o}C.

- The oxygen contents of the emitted gases should be > 11%.
- Both the primary and the secondary temperatures should be maintained until all the waste has been completely combusted.

Stack height

- The chimney should have a minimum height of 9 m above ground level and clear the highest point of the building by not less than 6 m for flat roofs or 3 m for pitched roofs. The topography and height of adjacent buildings (i.e. closer than 5 times chimney height) should be taken into account.
- The addition of dilution air after combustion in order to achieve the requirements of emission limits is unacceptable.
- The minimum exit velocity should be 10 m/s.
- The stack shall be insulated to maintain the maximum outlet temperature.
- Point for the measurement of emissions should be provided.

3.7.2 Management requirements

The management of sludge thermal treatment processes include:

- Monitoring instrument operation and maintenance;
- Temperature requirements;
- Efficient operation of air pollution control devices; and
- Prevent or limit negative effects on the environment and the risks to human health.

Feeding:

The following feeding requirements are applicable to thermal treatment:

- Controlled, hygienic mechanical or automatic feeding methods which will not negatively influence the air supply and temperature in the primary and secondary chambers of the incinerator, have to be used.
- No waste is to be fed into the incinerator under the following circumstances:
    - at start up and until the minimum combustion temperatures have been reached,
    - whenever the minimum combustion temperatures are not maintained,
    - whenever the previous charge has not been completely combusted in the case of a batch loader,
    - until such time as the addition of more waste will not cause the design parameters of the incinerator to be exceeded.

Minimum solids content

Sludge considered for thermal treatment should have a moisture content less than 20% (= 80% solids).

Performance:

A 99.99% destruction and removal efficiency (DRE) for each principal organic hazardous constituent (POHC) in the waste feed should be achieved. The DRE can be calculated as follows:

$$DRE = [(W_{in} - W_{out})/Win]*100$$

where:

W_{in} = mass feed rate of the POHC in the waste stream fed to the incinerator, and

W_{out} = mass emission rate of POHC in the stack prior to the release to the atmosphere

Operation:

- Sludge should be classified before treatment and may only be incinerated in a furnace that is registered for this purpose
- The incinerator should be preheated to working temperature before sludge is fed to the incinerator
- Overloading of the incinerator should be avoided at all times
- The incinerator should be kept in good working order at all times and should not be used if any component fails. Any malfunction should be recorded in a log book and reported to the relevant control authority
- The incinerator operator and all relevant staff should be trained to the satisfaction of the relevant control authority
- A list should be displayed at or near the control panel which identifies all trained operators
- The incinerator and its surrounds should be kept in a clean and neat condition at all times
- In cases where noxious or offensive gases are emitted that cannot be destroyed by secondary combustion, additional control equipment, e.g. scrubbers, bagfilters or electrostatic precipitators will be required.

Temperature Requirements

Combustion conditions must be maintained at the temperatures during which performance testing was conducted. Temperatures in excess of this may result in increased metal emissions from the stack. The sludge must be maintained at a temperature of 850°C for two (2) seconds (as measured near the inner wall or at another representative point of the combustion chamber).

Furthermore, each line of the incineration plant shall be equipped with at least one auxiliary burner. This burner must be switched on automatically when the temperature of the combustion gases after the last injection of combustion air falls below 850°C. It shall also be used during plant start-up and shut-down operations in order to ensure that the temperature is maintained at all times during these operations and as long as unburned sludge is in the combustion chamber.

3.8 Minimum solids content

Ideally sewage sludge considered for thermal treatment should have a low moisture content which would allow less energy input or recovery of energy in a form of steam (boilers) or electricity (generators). Only the organic component of sludge contains energy. This is typically 25 MJ/kg-dry solids (ds). When the inert, inorganic fraction is included, the available energy reduces to 16-20 MJ/kg-ds for raw sludge and 10-14 MJ/kg-ds for digested sludge. If the inorganic fraction could be separated before incineration, the energy content in this sludge would increase, the volume decrease and the ash production could be substantially reduced.

Sludge of up to 80% moisture can potentially be incinerated, but this would require the addition of energy. For example, the incinerating of raw sludge at 850°C would theoretically require about 8.9 MJ/kg-ds energy input, assuming 40% excess air (Lee and Tay, 2003). Similarly, for digested sludge the theoretically energy requirement would be about 14.9 MJ/kg-ds. The energy for other moisture values were calculated and summarised in Figure 3.a using the parameters given in Table 3.k. From the figure it can be seen that with digested sludge, the energy balance would be at about 38% moisture. For raw sludge, this point is at about 66% moisture.

Table 3.k: Thermal properties of sludge components (Lee and Tay 2003).

Component	Average Heat Capacity in 25 -850°C Temperature Range (kJ/kg-K)	Latent Heat at 850°C (kJ/kg)
Dry Solids	2.000	-
Water	2.182	2600
Air	1.320	-

The amount of excess air also has an influence on the energy demand. Decreasing the excess air to 30% would result in an energy balance at about 52% for digested sludge, and about 71% for raw sludge. Although incineration of sludge with 80% moisture is feasible, lower moisture content would reduce operating costs. Obviously, this cost saving needs to be compared against the cost of dewatering the cake from wastewater sludge.

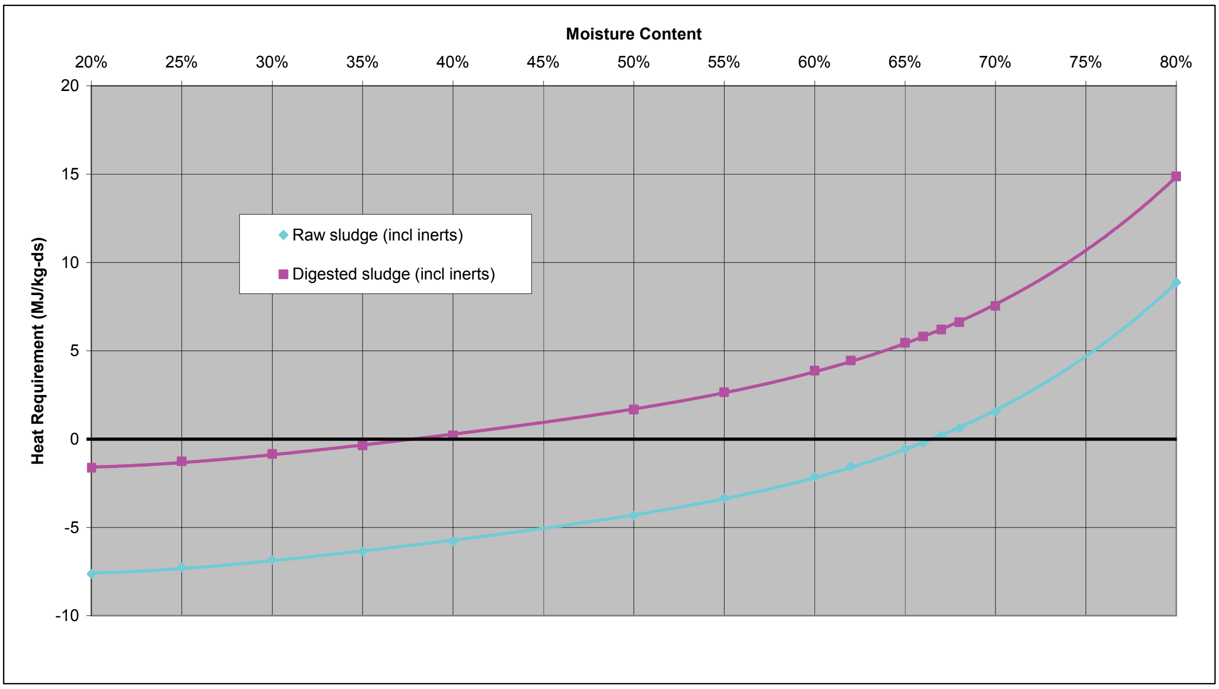


Figure 3.a: Calculated energy requirements for sludge incineration at 850°C with 40% excess air.

3.9 Air emissions

The emission of air pollutants during thermal treatment is inevitable. The extent of its impact (health and odour) can be minimised and controlled with a well-designed and properly operated process. Different air pollutants would be generated depending on the thermal treatment technology, i.e. whether the process is oxidising (e.g. combustion and wet air oxidation) or starved air (e.g. pyrolysis and partial pyrolysis). Although the gaseous products from pyrolysis differ from those produced in an incinerator, these gases are often also combusted in afterburners or boilers, and hence producing similar air pollutants. The pollutants generated can be grouped into:

- Inorganic gases – During the combustion process, oxygen reacts with carbon, hydrogen, sulphur, nitrogen and halides to form combustion products such as carbon dioxide (CO_2), water (H_2O), sulphur dioxide (SO_2), oxides of nitrogen (NO_x) and acid gases (e.g. HCl)
- Particulate matter – A fraction of the sludge ash and heavy metals present in the sludge feed will elutriate into the gas stream. An increase in furnace temperature will result in increasing releases of heavy metals. The heavy metals of greatest concern in the sludge incineration process are arsenic, cadmium, chromium, lead, mercury and nickel.
- Organic compounds – Volatile organic compounds (VOCs) are undesirable in furnace off-gas. These gases are visible, generate smoke, can be toxic and could result in the presence of odour.

3.9.1 Ambient Air Quality Criteria

Air quality limits and thresholds are fundamental to effective air quality management, providing the link between the potential source of atmospheric emissions and the user of that air at the downwind receptor site. Ambient air quality limits indicate generally safe exposure levels for the majority of the population, including the very young and the elderly, throughout an individual's lifetime.

The DEAT issued ambient air quality guidelines for several criteria pollutants, including particulates, sulphur dioxide, oxides of nitrogen, lead, ozone and carbon monoxide. The National Environmental: Air Quality Act, which commenced with on the 11th of September 2005, adopted these guidelines as national standards (given in Schedule 2 of NEM-AQA) These standards which largely reflect the national air quality guideline values established in the 1990s were considered to be dated and not in line with international best practice. In this light, the DEAT appointed SABS (South African Bureau of Standards) to assist in the facilitation of the development of ambient air quality standards.

A technical committee was established to oversee the development of standards. Three working groups were established by this committee for the drafting of ambient air quality standards for (i) sulphur dioxide, particulates, oxides of nitrogen and ozone, (ii) lead and (iii) volatile organic compounds, specifically benzene. Two documents were produced during the process, viz.:

- SANS 69 – South African National Standard – Framework for setting & implementing national ambient air quality standards
- SANS 1929 – South African National Standard – Ambient Air Quality – Limits for common pollutants

The latter document includes air quality limits for particulate matter less than 10 µm in aerodynamic diameter (PM10), dustfall, sulphur dioxide, nitrogen dioxide, ozone, carbon monoxide, lead and benzene. The South African National Standards (SANS) documents were approved by the technical committee for gazetting for public comment and were finalised and published in November 2004. The SANS limit values are now proposed to replace these standards as national ambient standards. This was published public comment in the Government Gazette of 9 June 2006. In the notice the minister indicates that margins of tolerance, compliance timeframes and permissible frequencies of exceedance will be included in the regulations or the national framework to be established in terms of Section 7 of the Act.

3.9.2 Suspended Particulate Matter

PM10 limits and standards issued nationally and abroad are documented in (Table 3.l) In addition to the PM10 standards published in schedule 2 of the Air Quality Act, the Act also includes standards for total suspended particulates (TSP), viz. a 24-hour average maximum concentration of 300 $\mu g/m^3$ not to be exceeded more than three times in one year and an annual average of 100 $\mu g/m^3$.

Table 3.l: Air quality standards for inhalable particulates (PM10).

Authority	Maximum 24-hour Concentration (µg/m³)	Annual Average Concentration (µg/m³)
SA standards (Air Quality Act)[2]	180(a)	60
RSA SANS limits (SANS:1929,2004)	75(b) 50(c)	40(d) 30(e)
Australian standards	50(f)	-
European Community (EC)	50(g)	30(h) 20(i)
World Bank	70(j)	50(j)
United Kingdom	50(k)	40(l)
United States EPA	150(m)	50(n)
World Health Organisation	(o)	(o)

Notes:

(a) Not to be exceeded more than three times in one year.

(b) Limit value. Permissible frequencies of exceedance, margin of tolerance and date by which limit value should be complied with not yet set.

(c) Target value. Permissible frequencies of exceedance and date by which limit value should be complied with not yet set.

(d) Limit value. Margin of tolerance and date by which limit value should be complied with not yet set.

(e) Target value. Date by which limit value should be complied with not yet set.

(f) Australian ambient air quality standards. (http://www.deh.gov.au/atmosphere/airquality/standards.html). Not to be exceeded more than 5 days per year. Compliance by 2008.

(g) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Compliance by 1 January 2005. Not to be exceeded more than 25 times per calendar year. (By 1 January 2010, no violations of more than 7 times per year will be permitted.)

(h) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Compliance by 1 January 2005

(i) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Compliance by 1 January 2010

(j) World Bank, 1998. Pollution Prevention and Abatement Handbook. (www.worldbank.org). Ambient air conditions at property boundary.

(k) UK Air Quality Objectives. www.airquality.co.uk/archive/standards/php. Not to be exceeded more than 35 times per year. Compliance by 31 December 2004

(l) UK Air Quality Objectives. www.airquality.co.uk/archive/standards/php. Compliance by 31 December 2004

(m) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html). Not to be exceeded more than once per year.

(n) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html). To attain this standard, the 3-year average of the weighted annual mean PM10 concentration at each monitor within an area must not exceed 50 µg/m³.

(o) WHO (2000) issued linear dose-response relationships for PM10 concentrations and various health endpoints with no specific guideline provided. WHO (2005) made available during early 2006 proposes several interim target levels (see Section 4.5).

3.9.3 Sulphur Dioxide

Ambient air quality guidelines and standards issued for various countries and organisations for sulphur dioxide are given in Table 3.m

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[2] On 9 June 2006 the Department of Environmental Affairs and Tourism gazetted new air quality standards for public comment (90 day comment period given). The proposed PM10 standards are given as 75 µg/m³ for highest daily (compared to the current standard of 180 µg/m³) and 40 µg/m³ for annual averages (compared to 60 µg/m³ at present) (Government Gazette No. 28899, 9 June 2006).

Table 3.m: Ambient air quality guidelines and standards for sulphur dioxide for various countries and organisations

Authority	Maximum 10-minute Average (µg/m^3)	Maximum 1-hourly Average (µg/m^3)	Maximum 24-hour Average (µg/m^3)	Annual Average Concentration (µg/m^3)
SA standards (Air Quality Act)	500(a)	-	125(a)	50
RSA SANS limits (SANS:1929,2004)	500(b)	-	125(b)	50
Australian standards	-	524(c)	209 (c)	52
European Community (EC)	-	350(d)	125(e)	20(f)
World Bank	-	-	125(g)	50(g)
United Kingdom	266(h)	350(i)	125(j)	20(k)
United States EPA	-	-	365(l)	80
World Health Organisation (2000)	500(m)		125(m)	50(m) 10-30(n)
World Health Organisation (2005)	500(o)		20(o)	(o)

Notes:

(a) No permissible frequencies of exceedance specified

(b) Limit value. Permissible frequencies of exceedance, margin of tolerance and date by which limit value should be complied with not yet set.

(c) Australian ambient air quality standards. (http://www.deh.gov.au/atmosphere/airquality/standards.html). Not to be exceeded more than 1 day per year. Compliance by 2008.

(d) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Limit to protect health, to be complied with by 1 January 2005 (not to be exceeded more than 24 times per calendar year).

(e) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Limit to protect health, to be complied with by 1 January 2005 (not to be exceeded more than 3 times per calendar year).

(f) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Limited value to protect ecosystems. Applicable two years from entry into force of the Air Quality Framework Directive 96/62/EC.

(g) World Bank, 1998. Pollution Prevention and Abatement Handbook. (www.worldbank.org). Ambient air conditions at property boundary.

(h) UK Air Quality Objective for 15-minute averaging period (www.airquality.co.uk/archive/standards/php). Not to be exceeded more than 35 times per year. Compliance by 31 December 2005.

(i) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Not to be exceeded more than 24 times per year. Compliance by 31 December 2004.

(j) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Not to be exceeded more than 3 times per year. Compliance by 31 December 2004.

(k) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Compliance by 31 December 2000.

(l) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html). Not to be exceeded more than once per year.

(m) WHO Guidelines for the protection of human health (WHO, 2000).

(n) Represents the critical level of ecotoxic effects (issued by WHO for Europe); a range is given to account for different sensitivities of vegetation types (WHO, 2000).

(o) WHO Air Quality Guidelines, Global Update, 2005 – Report on a Working Group Meeting, Bonn, Germany, 18-20 October 2005. Documents new WHO guidelines primarily for the protection of human health. The 10-minute guideline of 500 µg/m^3 published in 2000 remains unchanged but the daily guideline is significantly reduced from 125 µg/m^3 to 20 µg/m^3 (in line with the precautionary principle). An annual guideline is given at not being needed, since "compliance with the 24-hour level will assure lower levels for the annual average".

3.9.4 Oxides of Nitrogen

The standards and guidelines of most countries and organisations are given exclusively for NO_2 concentrations. South Africa's NO_2 standards are compared to various widely referenced foreign standards and guidelines in Table 3.n.

.

Table 3.n: Ambient air quality guidelines and standards for nitrogen dioxide for various countries and organisations

Authority	Instantaneous Peak (µg/m³)	Maximum 1-hourly Average (µg/m³)	Maximum 24-hour Average (µg/m³)	Maximum 1-month Average (µg/m³)	Annual Average Concentration (µg/m³)
SA standards (Air Quality Act)[3]	940(a)	376(a)	188(a)	150(a)	94
RSA SANS limits (SANS:1929,2004)	-	200(b)	-	-	40(b)
Australian standards		226(c)			56
European Community (EC)	-	200(d)	-	-	40(e)
World Bank	-	-	150 (as NO_x) (f)	-	-
United Kingdom	-	200(g)	-	-	40(h) 30(i)
United States EPA	-	-	-	-	100(j)
World Health Organisation (2000, 2005)	-	200(k)		-	40(k)

Notes:

(a) No permissible frequencies of exceedance specified
(b) Limit value. Permissible frequencies of exceedance, margin of tolerance and date by which limit value should be complied with not yet set.
(c) Australian ambient air quality standards. (http://www.deh.gov.au/atmosphere/airquality/standards.html). Not to be exceeded more than 1 day per year. Compliance by 2008.
(d) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Not to be exceeded more than 18 times per year. This limit is to be complied with by 1 January 2010.
(e) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Annual limit value for the protection of human health, to be complied with by 1 January 2010.
(f) World Bank, 1998. Pollution Prevention and Abatement Handbook. (www.worldbank.org). Ambient air conditions at property boundary.
(g) UK Air Quality Provisional Objective for NO_2 (www.airquality.co.uk/archive/standards/php). Not to be exceeded more than 18 times per year. Compliance by 31 December 2005.
(h) UK Air Quality Provisional Objective for NO_2 (www.airquality.co.uk/archive/standards/php). Compliance by 31 December 2005.
(i) UK Air Quality Objective for NOx for protection of vegetation (www.airquality.co.uk/archive/standards/php). Compliance by 31 December 2000.
(j) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html).
(k) WHO Guidelines for the protection of human health (WHO, 2000). AQGs remain unchanged according to WHO (2005).

3.9.5 Carbon Monoxide

The ambient air quality guidelines and other standards issued for various countries and organisations for carbon monoxide are given in Table 3.o.

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[3] On 9 June 2006 the Department of Environmental Affairs and Tourism gazetted new air quality standards for public comment (90 day comment period given). The proposed NO_2 standards are given as 200 µg/m³ for highest daily and 40 µg/m³ for annual averages (in line with the SANS limits) (Government Gazette No. 28899, 9 June 2006).

Table 3.o: Ambient air quality guidelines and standards for carbon monoxide for various countries and organisations

Authority	Maximum 1-hourly Average (µg/m³)	Maximum 8-hour Average (µg/m³)
SA Guideline(a)	40 000(a)	10 000(a)
SA SANS limits (SANS:1929,2004)	30 000(b)	10 000(b)
Australian standards	-	10 000 (c)
European Community (EC)	-	10 000(d)
World Bank	-	-
United Kingdom	-	10 000(e)
United States EPA	40 000(f)	10 000(f)
World Health Organisation	30 000(g)	10 000(g)

Notes:
(a) Issued in 1990s by CAPCO. No air quality standards for CO were included in the National Environmental Management: Air Quality Act.
(b) Limit value. Permissible frequencies of exceedance, margin of tolerance and date by which limit value should be complied with not yet set.
(c) Australian ambient air quality standards. (http://www.deh.gov.au/atmosphere/airquality/standards.html). Not to be exceeded more than 1 day per year. Compliance by 2008.
(d) EC Second Daughter Directive, 2000/69/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Annual limit value to be complied with by 1 January 2005.
(e) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Maximum daily running 8-hourly mean. Compliance by 31 December 2003.
(f) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html). Not to be exceeded more than one per year.
(g) WHO Guidelines for the protection of human health (WHO, 2000).

3.9.6 Lead

No air quality limits have been set for metals other than lead in South Africa. These are provided Table 3.p together with a number of other internationally adopted standards and guidelines.

Table 3.p: Ambient air quality guidelines and standards for lead.

Authority	Maximum 1-month/Quarterly Average (µg/m³)	Annual Average (µg/m³)
SA Standard (Air Quality Act)	2.5 (1-month)	
RSA SANS limits (SANS:1929,2004)	-	0.5(a) 0.25(b)
European Community (EC)	-	0.5(d)
World Bank	-	-
United Kingdom	-	0.5(e) 0.25(f)
United States EPA	1.5 (quarterly)(g)	-
World Health Organisation	-	0.5(h)

Notes:
(a) Limit value. Compliance date not yet set.
(b) Target value. Compliance date not yet set.
(d) EC First Daughter Directive, 1999/30/EC (http://europa.eu.int/comm/environment/air/ambient.htm). Annual limit value to be complied with by 1 January 2010.
(e) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Compliance by 31 December 2004.
(f) UK Air Quality Objective (www.airquality.co.uk/archive/standards/php). Compliance by 31 December 2008.
(g) US National Ambient Air Quality Standards (www.epa.gov/air/criteria.html).
(h) WHO Guidelines for the protection of human health (WHO, 2000).

3.10 Emission Limits

The NEM-AQA makes provision for the setting of emission limits on National level, which provides the objective for air quality management. More stringent limits may be implemented by provincial and metropolitan authorities. However, to date no emission limits have been published under NEM-AQA. These would most likely only be finalised by 2008/2009. Although not formally accepted as emission limits, the values provided in Table 3.i may still serve as guidance.

As indicated previously, the approach of the NEM-AQA is to shift the focus to the receiving environment. The setting of emission limits is therefore only one step in ensuring air concentration compliance. So, even if the emission proves to be within the limits, additional measures may still be required if the resulting ambient air concentration exceeds the air quality limit. This approach is aimed at addressing cumulative air pollution impacts resulting from all industries in a particular location.

Air pollution regulation in South Africa has recently being revised with the adoption of the NEM-AQA. The Act specifies that the minister must, within two years of the date on which this Act took effect (11 September 2005), establish a national framework for achieving the object of this Act. This needs to include mechanisms, systems and procedures to attain compliance with ambient air quality standards, to give effect to the Republic's responsibility to international agreements and to control emissions from point and non-point sources. In addition, national norms and standards needs to be set for air quality -monitoring; -management planning – information management, and any other matter which the Minister considers necessary for achieving the object of this Act. The NEM-AQA makes provision for the setting of ambient air quality standards and emission limits on National level, which provides the objective for air quality management. At the time of writing this guideline, emission limits have not been published. It should therefore be understood that the eventual limits set by NEM-AQA would supersede any guidelines included in this document.

The approach of the NEM-AQA is to shift the focus to the receiving environment, which makes provision for the setting of ambient air quality standards and emission limits. So, although the focus of the Act is on maintaining a measure of "healthy" ambient air, it still reserves the right to impose additional restrictions on air emissions. It is anticipated that these emission limits would be based on best available technologies and practices.

In effect, both the US ("risk-based") and European ("emission limit") methodologies comply to requirements of NEM-AQA, i.e. impact on the receiving environment and setting of emission limits, respectively. The former assumes an acceptable incremental health risk (in the form of a Risk Specific Concentration, or RSC for carcinogens, and 10% of the National Ambient Air Quality Standard for lead), which is used in the application of local meteorological conditions to determine the allowable sludge content of As, Cd, Cr, Ni and Pb. This is equivalent to establishing emission rates. Limits for Hg and Be are not based on the local dispersion potential. The different requirement for these two pollutants is due to the prior regulation, i.e. prior to the regulations developed for sewage sludge incineration.

The aim of the European Directive (also known as the *Waste Incineration Directive*, or WID) is to prevent or limit, as far as practicable, negative effects on the environment, in particular pollution by emissions into air, soil, surface and groundwater, and the resulting risks to human health. The Directive seeks to achieve this high level of environmental and human health protection by requiring the setting and maintaining of stringent operational conditions, technical requirements and emission limit values for plants incinerating and co-incinerating waste.

Guidelines for the negotiation of emission limit for incinerators were previously published under APPA, Schedule Process 39. These emission limits are compared with the WID in Table 3.q. Except for sulphur dioxide, the WID emission limits are all considerably more restrictive than the old APPA guidelines.

A similar comparison to the US legislation depends on the exit gas volume, and therefore on the particular thermal treatment device. Such a comparison is therefore not completed here. The US legislation could be regarded more lenient in the sense that it accommodates both local meteorological conditions and the added benefit of increased dilution through increasing the height of release (stack height) in the establishment of emissions. This difference could be significant when the facility is located in an area with a high ventilation potential.

Table 3.q: Daily average European emission limits for criteria pollutants

Pollutant	**Emission Limits (mg/m^3)**	
	EC WID Limit	**APPA Limit**
Total dust	10	180
Total organic carbon	10	99.99% DRE
HCl	10	30
HF	1	30
SO$_2$	50	25
NO and NO$_2$ expressed as NO$_2$ for existing incineration plants with a nominal capacity exceeding 6 t/h or new incineration plants	200 mg/m^3 (a)	(b)
NO and NO$_2$ expressed as NO$_2$ for existing incineration plants with a nominal capacity of 6 t/h or less	400 mg/m^3 (a)	
Cd	total 0.05 (c)	0.05
Tl		0.05
Hg	0.05 (c)	0.05
Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V	Total 0.5 (c)	0.5 Each
Be	-	0.5
Ba	-	0.5
Ag	-	0.5
Sn	-	0.5
Dioxins + Furans (expressed as International Toxic Equivalents)	0.1 ng/m^3 (d)	0.2 ng/m^3 (e)

(a) Until 1 January 2007 and without prejudice to relevant (Community) legislation the emission limit value for NO does not apply to plants only incinerating hazardous waste.
(b) The APPA do not regulate NOx emissions.
(c) Average for 30 min sample period.
(d) Average values measured over a sample period of a minimum of 6 hours and a maximum of 8 hours.
(e) Average values measured over a sample period of a minimum of 6 hours and a maximum of 16 hours.

Although the US regulation maybe a scientifically more sound approach, it does not cover all forms of thermal treatment technologies, such as pyrolysis, gasification or plasma processes. The mechanisms producing flue gases are quite different between primary combustion processes (e.g. incineration) compared with conversion processes followed by secondary combustion. The European Directive is in this instance a better approach since it provides the final emission limit, irrespective of the processes prior to atmospheric emission.

Guidance for sewage sludge thermal treatment could therefore be twofold, i.e.

- Limitations on heavy metal concentration in sewage sludge for combustion processes (including multiple-hearth, fluidised bed and electric furnaces) based on the US regulations; and
- Emission limits based on the European Directive for all other sewage sludge thermal treatment processes.

However, this may unfairly place certain newer and perhaps environmentally more improved technologies under stricter limitations. It is therefore recommended that the application of these guidelines follow a tiered approach (Figure 3.b).

The first tier is to determine whether the sludge thermal treatment technology is a combustion process or not. If the process is a combustion (not co-combustion) process, limitations on heavy metal composition in the sludge must be determined through a risk-based approach. Certain requirements are also placed on criteria pollutant and total hydrocarbon (or carbon monoxide) emissions. If the technology is different to combustion (e.g. pyrolysis), the focus shifts from a risk-based approach to a purely emission limitation with the adoption of the emission limits based on the WID. If the treatment is purely that of sewage sludge, only those pollutants normally associate with this waste requires monitoring. However, if co-combustion takes place, which may include solid waste incinerators, the full complement of the WID applies.

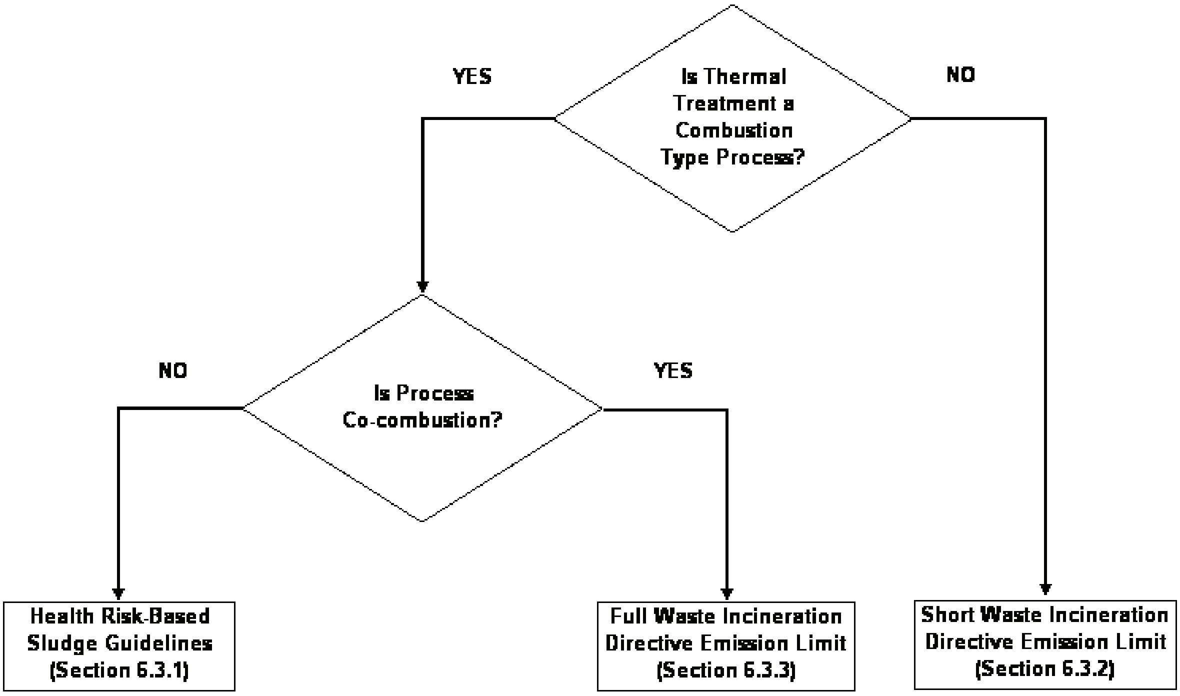

Figure 3.b: Decision tree to select emission guidelines for sewage sludge thermal treatment options.

3.10.1 Sludge quality limitations

A proposed risk-based methodology based on the regulations set forth in USA 40 CFR Part 503 (Standards for the Use or Disposal of Sewage Sludge). Sewage sludge is currently regulated in the USA by three EPA programmes under the Clean Air Act (CAA), the new source performance standards (NSPS) and the National Emissions Standards for Hazardous Air Pollutants (NESHAPs). The NSPS programme regulates emissions that threaten the National Ambient Air Quality Standards (NAAQS). The pollutants regulated under this programme are particulate matter and lead. Ambient lead concentrations are required to meet a quarterly standard of 1.5 $\mu g/m^3$. Sludge particulate emissions should never exceed 0.65 g-particulate/kg-dry sludge input, and should never discharge any gas that exhibits an opacity of 20% or more. The NESHAPs programme refers to emissions of mercury and beryllium. The total quantity of beryllium and mercury emitted from each incinerator must not exceed 10 g and 3 200 g, respectively, for any 24-hour period.

It is proposed to adopt the following general equation for determining the pollutant limits in sewage sludge:

$$C = CRSC \times \frac{86400}{DF \times (1 - CE) \times SF}$$

Where:

C = The pollutant limit (allowable daily concentration of arsenic, beryllium, cadmium, chromium, lead, mercury or nickel in sewage sludge, in milligrams per kilogram [mg/kg] of total solids, dry-weight basis)

CRSC = Chronic Risk Specific Concentration (the allowable increase in the annual average ground-level ambient air concentration for a pollutants at or beyond the property line of the site in micrograms per cubic metre ($\mu g/m^3$) (see table 3.r)

DF = Dispersion Factor (in micrograms per cubic meter per gram per second [$\mu g/m^3/g/s$], based on an annual average air dispersion model) (see Figure 3.c)

CE = Sewage sludge incinerator control efficiency for arsenic, beryllium, cadmium, chromium, lead, mercury or nickel (in hundredths, based on a performance test)

SF = Sewage sludge feed rate (in dry metric tons per day-dmt/day)

86 400 = Time conversion factor (number of seconds per day)

Table 3.r: Chronic risk specific concentrations for arsenic, beryllium, cadmium, chromium, lead, mercury and nickel.

Pollutant	Chronic Exposure Reference Concentration (µg/m³)	Chronic Concentration for 1:100 000 Lifetime Cancer Risk (µg/m³)	Fraction of Metal Emitted in Flue Gas Before Controls (%)	Chronic Risk Specific Concentrations (CRSC) (µg/m³)
Arsenic	0.03 (a)	0.0067(c)	95%	0.007
Beryllium	0.02 (b)	0.0042 (b)	10%	0.042
Cadmium	0.005 (c)	0.0056 (b)	98%	0.006
Chromium	0.1 (b)(e)	0.00021(c)(e)	10%	0.002/*R*
Lead	0.5 (c)(d)	-	42%	1.19
Mercury	1.0 (c)	-	100%	1.0
Nickel	0.05 (c)	0.026 (c)	10%	0.26

(a) California EPA.
(b) US EPA.
(c) World Health Organisation Guidelines for the protection of human health (WHO, 2000).
(d) RSA SANS limits (SANS:1929,2004).
(e) Hexavalent chromium.
(f) *R* = fraction of hexavalent chromium in total chromium emission.

Application of the equation requires the Chronic Risk Specific Concentration (Table 3.r), the dispersion factor (Figure 3.c) and a control efficiency (estimates from Table 3.t).

Table 3.s: APC control efficiencies (NPI 1999).

Pollutant	APC Type	Control Efficiency %
Chromium, Nickel, Beryllium, Copper, Lead	Fabric filter	95
	ESP	90
	Venturi quench/Venturi scrubber	90
Cadmium	Fabric filter	92
	ESP	88
	Venturi quench/Venturi scrubber	88
Arsenic, Mercury, Magnesium oxide	Fabric filter	30
	ESP	25
	Venturi quench/Venturi scrubber	50
Polychlorinated Dioxins & Furans	Fabric filter	50
	Venturi quench/Venturi scrubber	50

A slightly different approach was taken in the proposed methodology than the EPA methodology. Instead of basing the exposure on daily average dispersion and risk specific concentrations (RSCs), it was decided to base the equation on annual average dispersion factors and chronic exposures, i.e. chronic risk specific concentrations (CRSC). This was preferred since the health indicators for all the metals considered have been published as chronic exposures. It was therefore not necessary to convert to an equivalent daily exposure concentration. The metal split into top ash/flue gas and bottom ash was based on the work of Barton *et al.* (1991). The different approaches should result in similar answers – although the risk concentration is lower in the proposed method, the chronic (annual average) dispersion factor is also lower (by a factor of about 9-10).

Table 3.t:Risk specific concentrations for arsenic, cadmium and nickel.

Pollutant	(Daily) Risk Specific Concentrations (RSC) [Part 503 Rule] (µg/m³)	Chronic Risk Specific Concentrations (CRSC) (µg/m³)
Arsenic	0.023	0.007
Cadmium	0.057	0.006
Nickel	2.0	0.26
Chromium	0.0085/R	0.002/R

Example:

If the fenceline is 100 m from incinerator and stack is 10 m, then from (Figure 3.c), the DF = 9.7µg/m³/g/sec. Note the maximum DF is beyond 100 m and therefore this value needs to be used. If the maximum occurred before 100 m, then the value at 100 m could have been used.

For arsenic, i.e. CRSC = 0.007

The air pollution control is a fabric filter, CE = 0.95 (95%)

And the sewage sludge feed rate is 20 dmt/day

Then: $$C_{arsenic} = \frac{0.007 \mu g/m^3 \times 86400}{9.7(\mu g/m^3/g/s) \times (1-0.95) \times 20 dmt/day}$$

$$C_{arsenic} = 63 mg/kg$$

If the fenceline was at 350 m, the dispersion factor would be 4.6 µg/m³/g/s, and then the allowable concentration for arsenic would be 132 mg/kg.

The methodology for chromium is slightly different since it is necessary to determine the hexavalent fraction of the chromium emission. In the Part 503 Rule, estimated fractions for different incinerator types and pollution abatement technologies were given. These are summarised in Table 3.u. These fractions can be used in Table 3.r (i.e. substitute for *R*) when the chromium content in sewage sludge is calculated, as above.

Table 3.u: Hexavalent chromium fractions associated with incinerator emissions (Part 503 Rule).

Type of incinerator	Risk Specific Concentrations (RSC) (µg/m³)
Fluidized bed with wet scrubber	0.013
Fluidized bed with wet scrubber and wet electrostatic precipitator	0.037
Other types with wet scrubber	0.133
Other types with wet scrubber and wet electrostatic precipitator	0.531

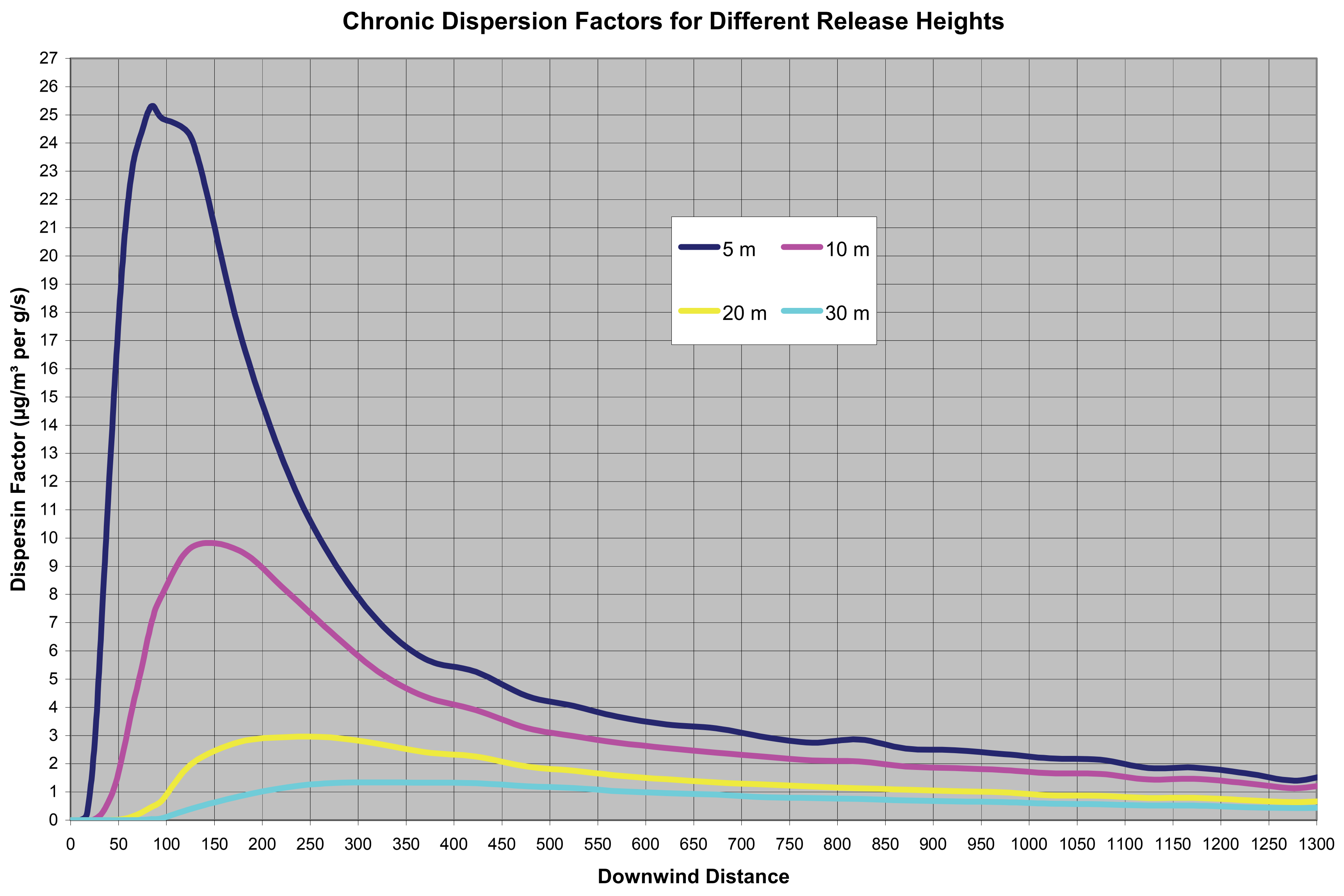

Figure 3.c: Annual average dispersion factors (DF) at various downwind distances and for different release heights.

Example 2:

Given: Without taking the fenceline into account, the maximum dispersion factor for a 10 m and 20 stack is 9.7 µg/m^3/g/sec and 3 µg/m^3/g/sec, respectively (Figure 3.c). For the chemical composition of sludge given in Table 3.v, the possible options for incineration were investigated. The sewage sludge feed rate is assumed to be100 dmt/day and no emission control is assumed.

Table 3.v: Chemical composition of case study sludge

Pollutant	**Chronic Risk Specific Concentrations (CRSC) (µg/m^3)**	**Sludge Composition (mg/kg)**	**Calculated Sludge Limit (mg/kg)**	
			Stack 10 m	**Stack 20 m**
Arsenic	0.007	1.43	*0.62*	*2.02*
Beryllium	0.042	0.01	3.74	12.10
Cadmium	0.006	0.18	0.53	1.73
Chromium(a)	0.04	0.733	3.56	11.52
Lead	1.19	34.95	106.00	342.72
Mercury	1.0	0.83	89.07	288.00
Nickel	0.26	9.5	23.16	74.88

(a) — Assumed R = 5%

From the results, only arsenic exceeds the limit for a 10 m stack. A release from 20 m results in better atmospheric dispersion and allows incineration of the given sludge. (Through iteration, it can be shown that a stack height of 17 m would be sufficient.). Alternatively, a fabric filter could be installed, with a control efficiency of 50% for arsenic, mercury and magnesium oxide. With this control in place, the sludge limit is calculated to be 1.25 mg/kg, and therefore still not acceptable. Increasing the stack height marginally to 11 m would be sufficient to allow the incineration of the sludge. The calculated limit is 1.62 mg/kg.

The Part 503 rule also require sludge furnaces to meet on an hourly average basis, over a month period, a total hydrocarbon emission level of 100 mg/L (measured as propane) corrected to 7% dry oxygen and 0% water. Continuous emission monitoring for THC is also required along with regular reporting to the regulatory authorities.

The total hydrocarbon (THC) emission level in stack gases are limited to 30 ppmv, as propane corrected to 7% oxygen, which is considered an indication for good combustion practice and surrogate for a health risk level on a reasonable worst case bases not to cause an incremental carcinogenic risk level higher than one in 100 000 for the most exposed individual. Part 503 rule allow continuous CO monitoring as a surrogate for THC monitoring if the concentration of CO does not exceed 100 ppm (volume basis) in the exhaust gas.

Facilities must demonstrate compliance with emission levels through testing. Moreover, sludge contaminated by PCB at levels >50 mg/L must be disposed of in a hazardous incinerator and accordingly regulated.

3.10.2 Emission guidelines for total sludge-only combustion

The emission guidelines depend on the type of thermal treatment technology (Figure 3.b). If the chosen thermal treatment technology involves combustion of sludge, producing combustion products like carbon dioxide, water, sulphur dioxide and oxides of nitrogen, the emission guidelines are risk-based. Emission guidelines for non-combustion thermal techniques and co-combustion of sludge with other waste are based on emission standards only.

Sewage sludge considered for thermal treatment should have a moisture content of less than 20%. If the chosen thermal treatment technology involves the combustion of sewage sludge to produce combustion products namely carbon dioxide, water, sulphur dioxide and oxides of nitrogen, the emission guidelines are based on health risk endpoints. The emission guidelines for all other thermal treatment technologies (including pyrolysis, wet air oxidation, co-combustion, etc.) are based on emission standards of the European Parliament and The Council of the European Union Directive 2000/76/EC (*Waste Incineration Directive* (WID)).

The US EPA identified arsenic, beryllium, cadmium, chromium, lead, mercury and nickel as the most significant heavy metals to monitor when considering sewage sludge incineration. It is therefore suggested that for all thermal treatment plants in which only sewage sludge is treated, only these heavy metals need regular monitoring, either of in the sludge content (using risk-based approach) or of the flue gas emission monitoring (using emission limits).

Furthermore, since the US EPA concluded (EPA 2001) that it was not necessary to set national standards for dioxin and dioxin-like compounds for sewage sludge incinerators, it is suggested that regular dioxin and furan measurements not be made a requirement, as stipulated in the WID.

3.10.3 Emission Limit Guidelines: Non-Combustion Techniques

In the determination of emission limit values (ELV's) for thermal treatment options other than sewage sludge combustion, e.g. pyrolysis, it is proposed that the WID emission limits for those pollutants specifically identified as potentially significant (Appendix C). Co-combustion processes are excluded from this. The WID emission limits were selected over the APPA Schedule Process 39 emission limits to be more in line with international norms. The only emission limit adopted outside the WID is that for beryllium. The emission limit from the APPA Schedule Process 39 is used for this purpose.

Since these processes may include conversion of gas at the temperature range where dioxins and furans could form, i.e. 250-400°C, it is required that the emission limit for dioxins and furans be complied with in addition to the limits set in Table 3.w. The emission limit is 0.1 ng/m^3 TEQ.

Table 3.w: Daily average emission limits for non-combustion sludge thermal treatment processes.

Pollutant	Emission Limits (mg/m³) Ave 30 min sample
Total dust	10
Total organic carbon	10
Cd	0.05
Hg	0.05
As	Total 0.5
Cr	
Pb	
Mn	
Ni	
Be	0.5

3.10.4 Emission Limit Guidelines: Co-Combustion Techniques

It is proposed that emission limits for thermal treatment options other than purely sewage sludge combustion, which includes co-combustion or conversion of combined wastes, be limited by the WID as it was published by the EC.

For the determination of air emission limit values for co-incinerators, Annex II of the WID (Appendix C) generally applies a mixing rule based on the principle that, in a mixed fuel/waste firing situation, the flue gases generated by the waste meet the emission limit values (ELVs) given in Annex V of the WID.

A few items need to be noted when applying the mixing rule:

- Where a total ELV (*C*) has been specified in Annex II it should be taken as an ELV under the WID.
- Annex II specifies limits for some heavy metals and dioxins which apply in full to the co-incineration plants without pro rata.
- If the resulting heat release from the incineration of hazardous waste amounts to less than 10% of the total heat released in the plant, V_{waste} must be calculated from a (notional) quantity of waste that, being incinerated, would equal 10% heat release, the total heat release being fixed.
- Where Annex II does not specify a total emission limit for a pollutant, it must be calculated by using the mixing rule. C_{proc} values specified in this annex must be used for pro rata calculations.
- Where Annex II does not specify a C_{proc} value, then limits in the permit are to be used in the mixing rule formula. In the absence of these, i.e. where the permit does not specify a limit for a pollutant, e.g. HCl for a combustion plant, actual measured values should be used.

Bearing in mind that the ELVs for waste and process fuels may be specified at different oxygen concentrations, the total emission limit calculated by the Annex II formula will require an equivalent oxygen concentration. This oxygen concentration is to be calculated by using the mixing rule and the partial volumes of the flue gases coming from waste and fuels.

The calculated oxygen levels, as discussed above, will vary with the proportion of waste being burnt. However, the regulators may require that actual emission monitoring data is supplied in a standard form, e.g. at 11% oxygen. This can be easily done by using the formula given in Annex VI of the WID as detailed below.

$$E_S = \frac{21 - O_S}{21 - O_M} \times E_M$$

where

E_S = calculated emission concentration at the standard percentage oxygen concentration

E_M = measured emission concentration

O_S = standard oxygen concentration

O_M = measured oxygen concentration

3.11 Monitoring requirements

It is required that the

- Operator/applicant shows that the proposed measurement techniques for emissions to air will comply with the requirements of internationally acceptable monitoring standards;
- Sampling and measurement procedures would satisfy the obligations imposed;
- Measurement equipment should be installed meaning thereby that temporary equipment is not acceptable (on long term basis);
- Location of the sampling or measurement points must be laid down by the regulator, and
- Calibration of continuous monitoring equipment and the periodic measurements of the emissions into the air must be carried out representatively and according to CEN standards. If CEN standards are not available, ISO standards, national/international standards which can provide data of equivalent scientific quality must be used.

Continuous monitoring and recording of the following must be done:

- THC (or CO) in the stack exit gas;
- Concentration of oxygen in the stack exit gas;
- Pressure
- Temperature near the inner wall or at another representative point of the combustion chamber as authorised by the regulator, and
- Water vapour content of the exhaust gas. (The continuous measurement of water vapour is not required if the sampled flue gas is dried before the emissions are analysed.)

Monitoring requirements are taken to include the substances to be measured, the frequency at which they should be measured and reported, the methods to be used, compliance criteria, calibration methods and the standards to be used.

3.11.1 Frequency of Monitoring

The minimum frequency of monitoring is given in Table 3.x. These were adopted from the Part 503 rule. Additional monitoring would be required for co-incineration and for non-combustion thermal treatment processes. These requirements are laid out in the WID.

Table 3.x: Monitoring frequency for sewage sludge incinerators.

Sludge monitoring (pollutant concentration)	**Amount of sewage sludge, fired (ton_{dry}/year)**		**Monitoring Frequency**
	Daily average	**Yearly average**	
As, Be, Cd, Cr, Pb, Hg and Ni concentrations	<5	<1 825	4 times per year
	5-45	1 826-16 500	6 times per year
	>45	>16 500	Monthly
Stack exit gas	**Monitoring Frequency**		
THC (or CO) concentration	Continuously, monthly averages reported, which is the arithmetic mean of hourly averages that include at least 2 readings per hour		
Oxygen concentration	Continuously		
Information needed to determine moisture content	Continuously		
Operational monitoring	Monitoring Frequency		
Combustion temperature in furnace	Continuously		
Air pollution control device conditions	As often as permitting authority requires		

3.12 Temperature Requirements

Combustion conditions must be maintained at the temperatures during which performance testing was conducted. Temperatures in excess of this may result in increased metal emissions from the stack. The incinerator may then be out of compliance until operated below the maximum allowed temperature or until shown to be in compliance with a new set of pollutant limits calculated using control efficiencies relevant to the new set of operating conditions.

The waste must be maintained at a temperature of 850°C for two seconds (as measured near the inner wall or at another representative point of the combustion chamber). If hazardous wastes with a content of more than 1% of halogenated organic substances, expressed as chlorine, are incinerated, the temperature has to be raised to 1 100°C for at least two seconds.

Furthermore, each line of the incineration plant shall be equipped with at least one auxiliary burner. This burner must be switched on automatically when the temperature of the combustion gases after the last injection of combustion air falls below 850°C or 1 100°C as the case may be. It shall also be used during plant start-up and shut-down operations in order to ensure that the temperature of 850°C or 1100°C as the case may be, is maintained at all times during these operations and as long as unburned waste is in the combustion chamber.

3.13 Record keeping requirements

The record keeping requirements for thermal sludge treatment is presented in Table 3.y.

Table 3.y: Record keeping requirements for Thermal treatment of sludge

Description of records to be kept by sludge user	
1	Copies of the applicable permits and/or licences
2	The original or certified copy of the contract between the sludge producer and the sludge user (if applicable)
3	Records related to Pollutant class (Concentrations of As, Cd, Cr, Pb and Ni)
4	Information showing that emission requirements for Be and Hg are being met, if applicable;
5	Sludge feed rate
6	Stack height
7	Dispersion factor
8	Control efficiency for As, Cd, Cr, Pb and Ni (for each incinerator)
9	Risk specific concentrations (RSC) for chromium, if applicable
10	Total hydrocarbon (THC) or carbon monoxide (CO) monthly average concentrations in the stack exit gas;
11	Oxygen concentration in the stack exit gas; and
12	Water vapour content of the exhaust gas
13	Combustion temperatures, including maximum daily combustion temperature, in the furnace;
14	Measurements for required air pollution control device operating conditions

4 COMMERCIAL PRODUCTS CONTAINING SLUDGE

This section of Volume 5 of the Guidelines was developed to promote the use of sludge in saleable products. It distinguishes between saleable products used as fertilizer (compost and pellets) and other saleable products primarily used in the construction business (cement, bricks, etc.).

The Guidelines for incorporating sludge in saleable products is based on the following information:

- International research findings
- Local legislative and guiding documents
- International guidelines and legislative trends
- Minimum risk to the user

Not much information is available on the manufacturing of commercial products from sludge and/or incinerator ash in South Africa, especially on products used in the construction industry. There is however guidelines on sludge composting and other fertilizer products containing sludge. The following constituents and properties of sludge have the potential to have negative effects on the use of sludge in saleable products:

- Pathogens – to protect the health of the general public, the final product should be Microbiological class A

- Odours – odours and vector attraction affect the public negatively (and could affect public health), therefore the stability of sludge is very important, especially when the final product is destined for use by the general public. The reduction of odours and vector attraction potential should be optimal.

- Metals – to protect the receiving environment, the final product should be Pollutant class a in the case of saleable products used as fertilizer.

The use of sludge or incinerator ash as raw material for manufacturing of saleable products other than fertilizer products will be less restrictive. Some form of thermal treatment form part of the production process, destroying the pathogens that may be present in the sludge and stabilises the final product. The metals in the final product will also be bound in an insoluble form, eliminating the potential for environmental pollution.

4.1 Sludge classification

The same classification system applies as described in Section of this document. This classification is especially important for sludge to be used to produce fertilizer products or compost. If a heat treatment is introduced in the manufacturing process to destroy pathogens and stabilize the product, the Microbiological class before treatment will not be applicable and the Stability class 1 requirements will be met. However, the Pollutant class classification before the manufacturing process will indicate whether the final product will meet the Class A1a requirements. High metal content sludge will not meet the criteria for compost since the process will not reduce the metal content.

The manufacturing process of construction materials usually include a heating process where pathogens are destroyed, leaving the product stable. The metals are also bound in an insoluble form, reducing the negative environmental and human health impact.

4.2 Operational guidelines for sludge composting

Composting is the process whereby prescribed organic material such as sewage sludge is decomposed and stabilised under aerobic conditions that promote the development of thermophilic temperatures through biological action to produce a final humus-like product that is stable, free of pathogens and plant seeds so that it can beneficially and safely be applied to land.

In order to achieve the correct conditions for successful composting to take place the following essential elements have to be observed:

- The sludge must be mixed with a "bulking agent" that provides structural support and created voids in the composting matrix to enable air to pass freely through the pile.
- The sludge/bulking agent mixture must have an optimal moisture content of between 50% and 60% by weight. If the mixture is too wet it fills the voids created by the bulking agent and prevents the flow of air. If the mixture is too dry the microbial kinetics is slowed and the biological composting activity will decline.
- Air must be introduced into the pile to promote the biological activity that stabilises the organic mass of the sludge and generates the heat required to pasteurise the sludge by killing off the pathogens present.
- Sufficient organic energy must be present in the feed sludge to enable the biological activity in the pile to generate the required pasteurising temperatures (65-70°C). Therefore sludges that have been well stabilised in anaerobic digesters or extended aeration activated sludge plants are not suitable for composting.

The nutrient mix of the sludge must be suitable to promote bacteriological growth. The optimal C:N ratio is approximately 20:1 and sewage sludges tend to contain sufficient nitrogen to meet this requirement. They also normally contain sufficient concentrations of other trace elements necessary for life and therefore this is not normally a problem.

The complexity of design and operation of a composting plant is directly affected by the standard of the final product required. If, as is the case here, an A1a product is required the composting plant will have to be designed and operated to very high standards. The major design and operational aspects of a composting plant to produce a Class A1a product are outlined below.

4.2.1 Different composting configurations

There are two basic types of composting systems, loosely referred to as "open" and "reactor" systems. The distinction between the two is made briefly below.

Open systems

These are batch composting systems that make us of piles of material laid out on concrete slabs. Two main configurations based on this principle are widely used and are described briefly below:

- Windrow Configuration

This system comprises of long piles, or "windrows" of sludge mixed with bulking agent. Oxygen is introduced into the piles primarily as a result of natural ventilation which is induced by the temperature gradients that develop within the pile. As the pile heats up due to biological action the air rises, drawing fresh air into the pile. In order to provide the porosity needed for effective natural ventilation a high proportion of bulking agent is required in the composting mixture. These piles are also agitated at regular intervals by breaking them up and reforming them using either front-end loaders or specialised equipment. This results in the redistribution of the material within the pile to ensure that all the material is subjected to the high temperature stabilisation and pasteurisation processes within the pile and also ensures that the pile remains porous to air movement.

Although this is a relatively simple and inexpensive composting system it is not considered reliable enough to produce a high quality compost product complying with the requirements of an A1a classification.

- Static Pile Configuration

In this configuration the compost is also laid out in long piles. However the piles are not broken up and reformed and the oxygen is supplied into the pile by means of forced aeration. The aeration system comprises of a blower connected to an air distribution system under the pile that introduces air into the pile, either by a blowing or sucking action. Because the pile is not broken up and reformed on a regular basis the material is not mixed and therefore much more care has to be exercised to ensure that the aeration is properly distributed throughout the pile so that it is all subjected to the necessary stabilising process and pasteurising temperatures.

The pile is formed as follows:

- The air distribution pipes which are connected to the blowers are covered in a layer of bulking agent approximately 300 mm to 400 mm high.
- The sludge cake/bulking agent mixture is formed into a pile above the bulking agent base. The pile is normally a maximum of 2.5 m high and the width is normally about 2.5 times the height.
- The pile is coved by a 200 mm to 300 mm thick insulating layer of cured final product to ensure that even the pile extremities attain the required pasteurising temperatures.

The static pile configuration is considered ideal for producing a class A1a compost under Southern African condition because it is relatively easy to control and monitor.

Reactor Configurations

Reactor configurations are those in which the sludge/bulking agent mix is placed in an enclosed reactor of some description where it is aerated and normally agitated in some way. Most of these are proprietary systems marketed by process contractors and tend to very capital intensive.

Several of these systems are described in some detail in "The Practical Handbook of Compost Engineering"[1] but due to their complex, high maintenance and capital intensive nature they are unlikely to be viable under Southern African conditions and are not addressed further in this text.

4.2.2 Design and operational considerations

In order to produce a Class A1a product the following aspects of a composting plant have to be considered and optimised:

- The sludge feedstock to be composted must contain sufficient organic energy to drive the biological process and generate the required pasteurising temperatures.
- An abundant supply of a suitable bulking agent has to be readily available at economically viable prices;
- Forced aeration will be required to ensure that the piles remain aerobic;
- Screening will be required to control the quality of the product and recover bulking agent for reuse;
- Properly designed maturation facilities will be required.
- Depending on the size of the plant bulk materials handling equipment will be required.
- Control of nuisance vectors such as odour and fly breeding will be required.

Each of the above-mention aspects is discussed in more detail below.

Nature of Sludge to be Composted

Firstly, for a composted sludge to be classified as A1a quality it must comply with the organic and inorganic pollutant limits laid out in section B3 of Volume 5 of these guidelines. The decomposed bulking agent adds relatively little to the mass of the compost and so the pollutant concentration of the final product remains essentially the same as that of the feedstock sludge. Therefore if the sludge to be composted does not comply with the limits it is unlikely that the final product will comply and it should be deduced that the sludge in question is not suitable for composting to A1a quality.

The biologically generated elevated temperature levels required in a composting pile are controlled by the following factors:

- The organic energy stored in the sludge;
- The amount of oxygen supplied;
- The amount of heat lost due to the evaporation of water contained in the sludge cake;
- The amount of heat lost in the exhaust gasses leaving the pile as a result of the aeration.

From the above it will be seen that the energy levels (or degree of stability) of the sludge is closely linked to the moisture content. The wetter the sludge cake the more energy is required in order to evaporate the excess water.

It therefore follows that stabilised sludges from anaerobic digesters and activated sludge plants will only contain sufficient energy to drive the composting process if they are dewatered to approximately 30-35%, whereas primary sludges only need to be dewatered to between 20-25%.

It is not recommended that waste activated sludge be used as compost feed stock on its own under any circumstances. It should be blended with primary sludge at no less than a 50:50 ratio by dry weight.

Every effort should be made to produce as dry a sludge cake as possible because this has a marked effect on the whole composting process, from bulk material handling to the energy requirements. Whereas it is possible to reduce the moisture content of the feed by recycling mature compost and mixing it with the sludge cake, this does not compensate for a lack of energy in the sludge feedstock because the recycle will be low in energy and its addition to the composting pile will add to the pile volume that the energy in the sludge has to heat.

Bulking Agent

Sludge cake is normally dewatered to solids contents of less than 20% solids by weight on sewage works in South Africa, but even a sludge dewatered to 25% will have very little structural strength to stand-up permanently in a pile and will have no pore spaces to allow air to pass through it. It therefore has to be mixed with a bulking agent comprising of large angular solid pieces which will form a three dimensional matrix. This will provide the sludge cake/bulking agent mixture with structural support and form voids large enough to be partially filled with wet substrate and to provide porosity to the pile for air flow through it. The void volume and slope of the pile is determined by the shape and size of the bulking agent particles.

The most widely used bulking agent is either wood chips or garden waste, although many other substances have been used such as straw, pelleted refuse, rice hulls and peanut shells. These are all biodegradable and over time are integrated into the final compost product and therefore have to be replaced on an on-going basis. They do, however have the advantages of being relatively soft and easy to handle.

On the other hand use has been made of largely inorganic substances such as shredded motor vehicle tyres and plastic pieces. These have the advantage of being virtually unbiodegradable and can therefore be readily removed from the compost and recycled and very little make-up is required. However they generally require a high initial capital outlay and they can result in the final product being contaminated with such items as stainless steel wire from the tyres. As a result they are not widely used.

Ideally bulking agent particles should be angularly shaped and be approximately 50 mm in size.

Depending on the size and nature of the bulking agent used and the solids concentration of the sludge cake, bulking agents are normally added to the sludge in proportion of between 1.5:1 to 3:1 by volume. For instance, ideally shaped wood chips would typically be mixed in a ratio as low as of 1.5:1, whereas garden waste would typically be mixed in a ratio of 3 : 1.

As stated above wood chips are the most commonly used bulking and they are available from the following sources

- Commercially from timber suppliers. This tends to be a very expensive source, but a steady supply of ideal bulking agent is assured;

- By providing free dumping of timber by tree felling companies. The composting company then has to chip the timber itself;
- Selective use of green yard waste which has to be collected, sorted to remove plastics, etc. and chipped.

Non-organic bulking agents such as shredded tyres are not widely used. For the reasons given above.

Forced Aeration

The aeration of the compost forms an integral and essential part of the composting process. Its major contribution to the process is three-fold namely

- It must satisfy the oxygen demand of the bacterial breakdown of organic waste within the sludge, which drives the stabilisation and pasteurisation function of the process.
- It contributes to the drying of the sludge. Moisture evaporates in the heated pile and the air flow carries away the vapour formed;
- The airflow can be used to control the temperature of the pile. If the aeration rate is too low the bacterial action will be retarded and the temperature will drop. If the rate is high enough to provide optimal bacterial action it may result in a build-up of the heat generated to a point that the pile becomes too hot for bacterial activity and in this event the airflow may have to be increased in order to carry away excessive heat generated.

Aeration is thus the key process control parameter for the process and its design and operation comprises of the following essential elements.

- The quantity of air required
- The air distribution system
- Whether the air should be blown into the pile or sucked into it
- The control of the process.

The quantity of oxygen, and hence air required for the system, is largely dependent on the organic and moisture content of the feed sludge and can be calculated using kinetic models[1]. However, generally speaking an average air flow of between 50 and 100 m^3/hr/ton (cubic metre of air per hour per ton of dry solids) treat is required. Allowance should however be made for peak flow rates of up to 400 m^3/hr/ton due to intermittent use of the blowers and the fact that the oxygen demand will be higher at the beginning of the composting cycle than at the end.

The air distribution system essentially comprises of perforated pipes laid at the base of the pile and connected to centrifugal blowers which either blow air into the pile or draw fresh air into it by sucking the exhaust gasses from the pile.

On small systems use is normally made of inexpensive, disposable, relatively small diameter, (150-200 mm) perforated plastic piping to form the air distribution network. The pipes are normally imbedded in a layer of bulking agent before the sludge cake/bulking agent pile is build above it. If care is exercised in removing the pile after treatment the pipes can be recovered and reused several times.

On larger, more sophisticated plants permanent distribution pipe systems are used, connected to permanently mounted centrifugal blowers. These can either comprise of pipe networks laid above ground or set in concrete slabs. The above ground networks are less expensive and easier to keep clean and unblock, but great care has to be exercised not to damage them when removing the treated compost with mechanical equipment.

Direction of Air Flow through the Pile – Air can be introduced into the pile in one or two ways

- Fresh, ambient air can be blown into the bottom of the pile using positive pressure from a blower or
- It can be drawn into the pile by the negative pressure created by the forced extraction of the hot process air from the bottom of the pile also using a blower.

Blowing air into the pile has the advantage of better flow distribution, better moisture removal, a lower bulking agent requirement, lower headlosses and the fact that consequently larger piles can be used. However it has the major disadvantage of creating potential odour problems and fly breeding. The exhaust gasses from the pile are discharged to the atmosphere in an uncontrolled, diffused manner and if they contain malodorous substances they can create a problem. Also the gaseous by-products of biothermal decomposition are forced to the outer layers of the pile where they condense and are very attractive to flies. This can result in major fly breeding problem developing.

Sucking out the exhaust gasses has the advantage that the discharge of the gasses occurs at a single point and can be controlled, and if necessary can be treated to remove malodorous substances. It also does not create an ideal fly breeding environment in the outer layers of the pile. However it does have the disadvantage of less efficient flow distribution and higher headlosses, etc. listed as advantages of the blowing option above.

Most blowers can operate under both positive and negative pressure and operators should experiment to establish which mode works best for their particular set of circumstances. Consideration can be given to operating in the suction mode for the first half of the composting cycle when malodours and fly breeding risks are at their greatest and in the blowing mode for the second half of the cycle when moisture removal is most important.

The **control of the aeration rate** can vary in sophistication from manual throttling of valves or on/off sequencing by timers to feedback control based on temperature or oxygen concentrations in the compost pile or exhaust gas stream. In the former, less sophisticated mode the operator would establish by experience what throttling valve setting or timing sequence would produce adequate temperatures in the pile and a stable, pasteurised product and would control the aeration accordingly.

In the latter mode either thermocouples or oxygen probes would be inserted into the pile or exhaust gas streams and used to modulate the air flow rate through a PLC to maintain a set point. This more sophisticated mode is recommended when operating a facility to produce a Class A1a product because it removes a large element of potential operator error. Temperature control is normally used for wetter substrates because the air flow requirement is dominated by the moisture removal function and the oxygen concentration is always high under these conditions. For drier substrates the air flow is dominated by the biological oxygen demand in the pile and so the oxygen concentration varies significantly in response to the air supply rate

Curing

After the initial high rate composting process using forced aeration has been active for the required 21 days, the compost has been pasteurised and stabilised to a large degree. However to achieve product quality commensurate with a clause A1a classification further stabilisation will be required in curing piles where the more slowly biodegradable products in the feed as well as the products of the biological degradation during the high rate composting phase are broken down. The normally accepted duration of the curing process is 30 days.

The product from the primary treatment stage can be screened and then placed in curing piles that are subjected to forced aeration. The advantage of this strategy is that the area required for the curing process is greatly reduced as well as the bulking agent inventory required on the site. The disadvantage is that aeration of the pile is necessary.

The alternative is to place the primary product in curing windrows before screening and to rely on natural ventilation through the bulking agent matrix caused by temperature gradients within the pile to provide the oxygen required. This will require more space, but will significantly reduce cost and operational complexity. A further advantage of this option is that the compost will be much drier after the curing process and hence the screening operation will be much more efficient.

Screening Out of Bulking Agents

In composting systems the provision of bulking agent constitutes a significant cost component of the system and so it has to be separated from the final product so that it can be reused as often as possible. Removing the bulking agent also ensures that the final product comprises of only fine, friable compost particles.

The effectiveness of the screening process is highly dependent on the moisture content of the product. At high moisture contents the wet sludge tends to adhere to the bulking agent and is screened out with it. Generally speaking it can be accepted that the screening efficiency will be only 30% if the moisture content is 60%. This improves to 70% if the moisture content is 50% and to 90% if the moisture content is 40%.

Depending on the size of the bulking agent and the moisture of the compost being screened, the screen opening size used is normally between 12 mm and 18 mm.

Recycling of Compost

As stated earlier the sludge cake produced on South African sewage treatment works tends to have relatively low solids content of below 20% by weight and this is generally too wet for effective composting. One way of overcoming this is to recycle treated compost that has normally been dried to approximate 60% solids during the composting process.

Two options are available for recycling the compact, namely

- The compost can be recycled prior to screening so that product and bulking agent are recycled together. This has the major advantage that the recycled product does not have to be screened which takes a significant load off the screening process.
- Only screened product is recycled which means that the recycled product has to pass through the screens, thereby greatly increasing the load on the screening equipment.

When it is considered that the bulking agent is recycled after screening anyway it makes sense that the recycle should occur ahead of screening. Recycling of compost also reduces the required mix ratio for bulking agent relative to feed cake from 2:1 to between 1.5:1 and 1:1 and therefore it is well worth considering.

Bulk Materials Handling Equipment

A major feature of operating a composting plant is the handling of the bulk materials. The following bulk handling functions are required:

- The dewatered sludge cake has to be transported from the dewatering facility to the composting facility and stockpiled;
- The bulking agent has to be transported to the composting facility and stockpiled;
- The sludge cake and bulking agent have to be transported to the mixing facility, where it has to be fed into the mixer;
- The sludge cake/bulking agent mixture has to be transported from the mixer to the composting area and formed into piles;
- The compost product has to be transported to the curing area and formed into piles;
- The recycled compost has to be transported to the mixing facility and mixed with the sludge cake/bulking agent stream;
- The final cured compost has to be transported to the screening facility and fed to the screens.
- The final screened compost product has to be transported from the screening facility to the final stockpile;
- The screened bulking agent has to be transported from the screening facility to the bulking agent stockpile.

The bulk material handling equipment requirements are discussed in more detail below.

Transport of Material

For very small plants treating up to 2 tons ds/d use can be made of a front-end loader to perform most of the transporting and stockpiling functions.

For larger plants (>2<10 tons ds/d) at least a tipper truck will be required for the transport and an additional front-end loader will probably be required.

For plants greater than 10 tons ds/d consideration will have to be given to the use of conveyor belts and mechanical stackers and reclaimers for formation and removal of the compost piles.

Mixing of the Sludge Cake and Bulking Agent

For small plants the mixing of the sludge cake and bulking agent can be undertaken on the composting slab using a front-end loader.

However for larger plants consideration will have to be given to using a pug mill. The mill will be fed from hoppers which in turn will be loaded using a front-end loader.

Formation of Piles

The formation of piles for small to medium sized plants is done using front-end loaders and, where necessary, tipper trucks.

For larger plants consideration n should be given to the use of stacker/reclaimers.

Screening

For small to medium sized plants use is normally made of rotating drum screens fed by conveyer belt or directly from a hopper.

For larger plants consideration should be given to vibrating or flexing screens that are designed for high solids loading rates.

Control of Odours

By its nature the composting process carries a high risk of odour nuisance from the production of such substances as volatile fatty acids, amines, aromatics, hydrogen sulphide, mercaptans and ammonia.

There are four main methods for removing these substances from the exhaust gasses from the composting process, namely absorption, adsorption, biological oxidation in activated sludge plants or biofiltration. Each option is described briefly below.

Absorption

This is the process where the odour creating substances are dissolved in a scrubbing liquid. These systems tend to be expensive and are complex to operate and have, to a large extent been replaced by adsorption and biological oxidation systems.

Adsorption

Adsorption is the process whereby specialised solid compounds such as activated carbon or specially treated alumina based media remove the malodorous compounds from the gas flows passed through them by adsorption onto their surface. These specialised media are packed into towers and the air to be treated is drawn through using blowers.

These systems are very effective in removing odours, but they suffer from the drawback that adsorption does not destroy the odour causing compound, but merely captures and stores it. They therefore have a finite capacity and have to be either regenerated or replaced once they have become saturated and odour break through starts to occur.

Oxidation in Activated Sludge Plants

Most malodorous compounds are broken down by biologically mitigated oxidation and therefore an activated sludge reactor is an ideal environment for this to occur.

On plants where use is made of fine bubble diffused air aeration systems the exhaust gas can be blended in with the aeration air ahead of the blowers. However consideration has to be given to possible corrosion potential created by the presents of sulphur products in the gas. Cognisance must also be given to the fact that the exhaust gases from the compost pile will be low in oxygen and will therefore reduce the efficiency of the aeration system. To overcome this use can be made of dedicated systems aimed at only disposing of the malodorous air, but this tends to be expensive as the air has to be compressed to at least 0.5 bar to overcome the hydrostatic water pressure in the tank.

Biofiltration

Biofiltration is a system used for scrubbing malodorous compounds from air using a biologically active, solid media bed. The compounds are absorbed/adsorbed from the aid stream and subsequently oxidised by the bacteria in the bed.

These systems are widely used on composting plants because the filter bed can be made up from the compost produced at the plant. The system requirements are described in more detail in the table below:

Recommended Design and Operating Parameters for Organic Media Biofilters [1]

Filter media	Biologically active, but reasonably stable Organic content >60% Porous and friable with 75-90% void volume

	Resistant to water logging and compaction Relatively low fines content to reduce gas headloss Relatively free of residual odour Specially designed mixtures of materials may be desirable to achieve the above characteristics
Moisture Content	50 to 70% by weight Provisions must be made to add water and remove bad drainage
Nutrient	Must be adequate to avoid rate limitations Usually not a problem with composting gases because of the high NH_3 content
pH	7 to 8.5
Temperature	Near ambient, 15-35 or 45°C
Gas pre-treatment	Humidification as necessary to achieve near 100% inlet gas humidity Dusts and aerosols should be removed to avoid media plugging
Gas loading rate	<100 m^3/h-m^2, unless pilot testing supports higher loadings
Gas residence time	30 to 60 sec, unless pilot testing supports a shorter residence time
Media depth	1 m
Elimination capacity	Depends on media and compound (about 2.2 mg H_2S/kg media VS per min for H_2S)
Gas distribution	The manifold must be properly designed to present a uniform gas flow to the filter media.

4.2.3 Considerations in monitoring the product quality

There are three main parameters that have to be monitored to ensure that the final compost product complies with the A1a classification, namely

- The microbiological standard
- The stability standard
- The pollutant standard.

Before any of these parameters can be tested for it must be assured that the sample being tested is statistically representative of the batch of compost it is taken from. The final product must comply with Class A1a.

4.3 Other commercial fertilizer products containing sludge

These fertilizer products can include:

- Pellets where sludge is dried and pelletized and used as fertilizer and soil conditioner (*i.e.* Swiss Combi heat drying process). The process provides an environmentally accepted method of converting sludge into dry, pathogen free granules which can be used as a fertilizer, for land reclamation or as a fuel.

  The minimum solids content of the feed sludge should be 15-40% solids. The dewatered sludge goes to a drying drum where the temperature is between 450°C at the inlet and 130°C at the outlet. Rotation of the drum provides uniform drying and also serves to transport the granular sludge, which then goes through a cyclone and then a screw conveyor for cooling. Finally a vibrating sieve separates the granules by size. Before the storage, the temperature of the granules is lowered to 35°C by means of a cooling screw. The metal content of the sludge may be a restriction.

- Active sludge pasteurisation (ASP) process – This proprietary process was developed in South Africa. It stabilizes and pasteurizes sludge while enriching it with the nutrients N and P. Dewatered sludge (stabilised or non-stabilised primary, secondary, tertiary sludge) of at least 15-20% dry solids is fed into the ASP process. The process consists primarily of an alkaline reactor, acid reactor and drier.

  Ammonia (NH_3) is added to the sludge, raising the temperature and pH of the sludge to about 60ºC and 12 respectively. This step provides pasteurisation of the sludge through high pH, high temperature and ammonia toxicity. In addition the NH_3 reacts with the organic matter in the sludge fixating part of the added NH_3.

  In the second stage of the process phosphoric acid (H_3PO_4) is added to neutralise the mixture to a pH of 7.0 while raising the temperature to about 70ºC. The non-chemically bound NH_3 is evaporated and reused. Dry warm air is blown over a thin layer of final product to evaporate the moisture and dry the sludge. The dried sludge is separated from the moist air in a cyclone separator to produce the final pelletised or granular product. It has a moisture content of about 15% (w/w) and is not unlike artificial fertiliser in size and appearance. It is registered as a quality grade agricultural fertiliser in South Africa.

To protect the receiving environment and the general public from any adverse effects of any constituents that may be present in the product, the quality of the product should be regulated. Therefore, the fertilizer product containing sludge will have to be sampled and analysed before distribution to the public. The final product has to comply with **Class A1a** in order to be distributed to the general public.

4.4 Construction materials containing sludge and/or incinerator ash

The majority of commercial products (other than fertilizer) produced with sludge and/or incinerator ash as raw material are used in the construction business. This includes, but is not limited to, bricks, cement, pumice and artificial aggregate. Most of the manufacturing processes include a heating process where potential hazardous microbiological constituents and organic material present in the sludge are destroyed, leaving the product harmless and stable. In most instances the inorganic pollutants (metals) are also converted to an insoluble form. However, some tests might be required to ensure that the environment and public health will be protected against potential negative effects.

4.4.1 Bricks

Incinerated sludge ash as well as dewatered sludge can be applied as raw material for brick manufacturing. The sludge brick was found to be superior to traditional bricks in compression strength, water absorption rate, abrasion strength and bending strength. Potential benefits are that the firing process locks away any toxic heavy metals in the sludge and also destroys any hazardous microbes and organic material. However, public acceptance may remain a problem and such bricks might need to meet additional standards to guarantee they don't pose health hazards.

The composition of the ash is a key factor in the quality of the brick. Some important factors are:

- The average particle size of the ash should be under 30 μm, otherwise the end product will be subject to hairline cracks. Thus, ash from a fluidized bed incinerator is better than ash from a multiple hearth incinerator because it yields finer ash.
- Organic substances and moisture present in the ash will cause cracking of the brick during firing. Therefore, the ignition loss of the ash and the moisture content of the ash should be below 1%.
- As the CaO content of the ash increases more hairline cracks will appear on the surface of the end product. Therefore, lime should not be used for conditioning of sludge during dewatering or thickening and the concentration of CaO in the ash should be less than 15%.
- Bricks manufactured from dewatered sludge
- The optimum conditions for manufacturing good quality bricks from sludge are:
- The raw material should include 10-20% sludge
- Moisture content of sludge should be 24%
- Firing temperature should be 880-1000^{o}C.

4.4.2 Cement

In principle, cement works can use suitable types of waste as an alternative fuel or raw material. However, this must not increase the emission of air pollutants from kilns or reduce the quality of the cement produced.

Portland cement manufacturers can use incinerated ash, dried sludge or dewatered sludge cake as a raw material for their product, depending on the manufacturers' operations. The major ingredients of Portland cement are CaO, SiO_2 and F_2O_3, traditionally supplied in the form of natural limestone and clay. However, sludge can substitute for a portion of these ingredients. This application for sludge holds significant potential for easing the final disposal of sludge and promoting environmental conservation. This is a cost effective practice since the cement manufacturer pays half of the energy costs to manufacture the thermal solids.

4.4.3 Pumice

Pumice is made using the same approach as bricks, with the addition of crushing and sieving processes. The kiln temperature can be changed to adjust the properties of the pumice to meet specific final use requirements. The final product can be used for the under layer of athletic fields because it rapidly drains excess water but holds sufficient moisture, thus maintaining the condition of the athletic field.

4.4.4 Artificial aggregates (slag)

Slag can be used as a substitute for natural coarse aggregate, including concrete aggregate and back-filling material, ready-mixed concrete aggregate, roadbed materials, permeable pavement, interlocking tiles and other secondary concrete products.

When dewatered sludge cake is heated and its moisture evaporates, the combustible organic matter is destroyed. The inorganic matter starts to melt into a molten slag. When it is cooled, a slag is formed. By using this melting process, the volume of the sludge is reduced, with increasing stability making it possible to use sludge as a recyclable resource. The metals present in the slag are immobile and the slag is safe to be used as aggregate material.

This process can begin with either dewatered sludge cake (cake slag) or incinerator ash (ash slag). Processing cake slag is fuel efficient, and the calorific value of the organic content of the sludge cake contributes to heat the furnace. In some cases, self-combustion is possible. However, the process requires an effective drying unit and skilful operation.

In the ash slag process fluctuations of the properties of the dewatered sludge cake are absorbed during incineration, thus simplifying the design and operation of the melting furnace. The incinerator and the melting furnace can be operated independently to maximise the performance of each.

Aggregate material can also be produced by blending incinerator ash with water (23%wt/wt) and a small amount of alcohol-distillation waste which acts as a binding agent. Pellets are formed from the mixture which is dried at 270^{o}C for 7-10 minutes. The pellets are then heated at 1050^{o}C on a fluidised bed kiln and air-cooled afterwards. Hard films are formed on the surfaces of the pellets but the inside stays porous. The final product is a spherical shaped pellet that could be used as fillers, planter soil, additives in flower vases, thermal insulator panels, rapid sand filters and water-infiltrating pavements.

4.4.5 Other potential saleable products

When slag is reheated at 1 623K for 30 minutes and then gradually air-cooled, it crystallizes. The end product then becomes a marble-like material with a semi-crystallised structure, like a manmade marble. The material is characterized by tough strength and high acid resistance and has been used for making jewellery and tombstones.

4.5 Monitoring requirements

Each batch of the final fertilizer compost product to be distributed to the public must comply with the A1a classification. It must be assured that the sample being tested is statistically representative of the batch of compost it is taken from.

No monitoring is required for construction materials?

4.6 Record keeping requirements

The following records should be kept by the sludge user manufacturing fertilizer from sludge:

- Copies of the applicable permits and/or licences
- The original or certified copy of the contract between the sludge producer and the sludge user (if applicable)
- Monitoring data of each batch of compost produced, pertaining to the:
  - Microbiological class
  - Stability class
  - Pollutant class

The following records should be kept by the sludge user manufacturing construction material from sludge and/or incinerator ash:

- Copies of the applicable permits and/or licences
- The original or certified copy of the contract between the sludge producer and the sludge user (if applicable)
- Monthly sludge/ash volumes processed

5 CONCLUSIONS

Volume 5 of the Sludge Guidelines informs the reader regarding thermal treatment of sludge as well as the production of commercial products containing sludge and/or incinerator ash. During thermal treatment of sludge the fossil fuel energy of the material is utilized but air quality might be compromised by the presence of organic pollutants, metals and other constituents in the exhaust gas. The incinerator ash may also contain elevated concentrations of metals and should be used/disposed appropriately. The legal requirements for sludge incineration and air emission limits for different types of thermal treatment processes are discussed. These air emissions should be monitored on a continuous basis to ensure compliance with the necessary permits.

Commercial products containing sludge and/or incinerator ash can be two-fold, i.e. fertilizer products and saleable products used mainly in the construction business. The fertilizer products are used by the general public without restrictions and, to protect the environment and public health, the quality of the final product should be restricted to Class A1a. Operational guidelines for sludge composting to achieve this quality product are also supplied.

Commercial products containing sludge used in the construction business use dewatered sludge and/or incinerator ash as raw materials. In most instances additional thermal treatment forms part of the production process, ensuring that all organic pollutants and pathogens are destroyed, that the final product are stable and that the metals are left in an insoluble form.

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Appendix 1: Recommended new procedure to determine Helminth ova in wastewater sludge

Method for analyses of wet sludge

Note: It is always preferable to work with small sub-samples as eggs may not be as easily released from a large sample to float out of the sludge when doing the $ZnSO_4$ Flotation Technique. Rather increase the number of sub-samples than try to overload each test-tube in order to keep the number of tubes down.

The number of sub-samples will also be dependent on the helminth ova load expected. This will require knowledge of the epidemiology of helminths in your particular area in South Africa. Consequently, more sub-samples must be done in an area of low endemicity and less in a highly endemic area.

1. Mix the sludge sample well by swirling and stirring with a plastic rod. From the total sample take 4 x 15 ml sub-samples and put them into 4 x 50 ml test tubes. (If the solid content is high this should be sufficient sample. If it is low you may need to take more 15 ml sub-samples).
2. Add either a few millilitres of 0,1% Tween80 **or** AmBic solution to the samples, vortex and add more wash solution. Repeat this procedure until the tubes are filled to about a centimetre from the top.
3. Place the 150 µm sieve in a funnel in a retort stand with a plastic beaker underneath to catch the filtrate. Filter the well-mixed tubes one at a time, rinsing out each tube and washing this water through the sieve as well.
4. Pour the filtrate into test tubes and centrifuge at 1389 g (±3000 rpm) for 3 min. Suction off the supernatant fluids and discard. Combine the deposits into a suitable number of tubes so that there is not more than 1 ml in a 15 ml tube or 5 ml in a 50 ml tube.
5. Re-suspend each of these deposits in a few millilitres of $ZnSO_4$ and vortex well to mix. Keep adding more $ZnSO_4$ and mixing until the tube is almost full.
6. Centrifuge the tubes at 617 g (±2000 rpm) for 3 min. Remove from the centrifuge and pour the supernatant fluids through the 20µm filter, washing well with water.
7. Collect the matter retained on the sieve and wash it into test tubes.
8. Centrifuge the tubes at 964 g (±2500 rpm) for 3 min; remove & discard the supernatant fluid. The deposits can then be combined into one test tube, using water to rinse out all the eggs and then centrifuge again at 964 g for 3 min. to get one deposit.
9. Once you have the final deposit, remove all of it using a plastic Pasteur pipette and place it onto one or more microscope slides. Place a coverslip over the deposit and examine microscopically using the 10x objective and the 40x objective to confirm any unsure diagnoses.
10. Each species of helminth ova is enumerated separately and reported as eggs per gram of sludge.

ERWAT Laboratory Services choose to examine the samples slightly differently from Step No. 7: The deposits are filtered through a 12 µm ISOPORE membrane, which is then rinsed with distilled water. The membrane is air-dried, cut in half and placed on a microscope slide. Immersion oil is used to clear the membrane before examining under the microscope.

Equipment required and related information

11. A centrifuge with a swing-out rotor and buckets that can take 15 ml and/or 50 ml plastic conical test tubes.
12. Vortex mixer.
13. Retort Stand with at least 2 clamps on it.
14. Large plastic funnels to support the filters (±220 mm diameter).
15. Filters / Sieves : 1x 150 µm; 1x 100 µm; 1x 20 µm.
16. Approx. 6 Plastic beakers (500 ml) & 3 Plastic wash bottles.
17. At least 4 glass "Schott" bottles (1 l, 2 l & 5 l sizes) for make-up and storage of the chemical solutions and de-ionized water.
18. Magnetic stirrer and stirring magnets.
19. 15 ml and 50 ml plastic conical test tubes.
20. 3 x Small glass beakers (100 ml).
21. Plastic Pasteur Pipettes & Plastic Stirring Rods.
22. Glass microscope slides (76 x 26 x 1,2 mm).
23. Square & Rectangular Cover-slips (22 x 22 mm & 22 x 40 mm).
24. A binocular compound microscope with 10x eyepieces, a 10x objective and a 40x objective.

Working out the g-force of your centrifuge

G-force (or g) = $(1{,}118 \times 10^{-5})\, r\, s^2 = 0{,}00001118 \times r \times s^2$

where : s = revolutions per minute (i.e. the speed you spin at)

r = the radius (the distance in centimetres from the centre of the rotor to the bottom of the bucket holding the tubes, when the bucket is in the swing-out position)

Reagents

Zinc Sulphate

$ZnSO_4$ (heptahydrate) is made up by dissolving 500 g of the chemical in 880 ml de-ionised or distilled water.

A hydrometer must be used to adjust the specific gravity (SG) to 1.3, using more chemical if the SG is too low or more water if it is >1,3.

This high specific gravity facilitates the floating of heavier ova such as *Taenia* sp. (SG = 1.27). It is not critical if the SG of the $ZnSO_4$ solution is just over 1.3 but it should **never** be below!

Ammonium Bicarbonate

The AMBIC solution is essentially a saturated ammonium bicarbonate solution. Ammonium bicarbonate can be obtained from Merck Chemicals and is made up by dissolving 119 g of the chemical in 1000 ml of de-ionised water.

0,1% Tween80

1 ml of Tween80 is measured out using a pipette and placed in 1000 ml of de-ionized or distilled water to give a 0,1% wash solution.

Note: Tween80 is extremely viscous and it is necessary to wash **all** of it out into the water in which it is made up, by alternately sucking up water and blowing it out using the same pipette.

Recommended new procedure to determine Helminth ova in composted sludge

1. Weigh out 2 or more 1g samples into 15 ml test tubes. You may use 50 ml test tubes if you have a centrifuge that can take these large tubes. If you do this, weigh out 3g maximum per tube.

2. Add a few millilitres of AMBIC **or** 0,1% Tween80 and vortex well. Add more solution to about 6 ml (in a 15 ml tube) / 20 ml (in a 50 ml tube) and vortex on and off, repeating the addition of solution and vortexing until the tubes are filled to 10 ml / 40 ml and have been vortexed over a period of about 30 min in total.

3. Centrifuge the tubes at 1389 g (±3000 rpm) for 3 min and discard the supernatant fluids. Re-suspend in de-ionized water and vortex to wash off the AMBIC or Tween80 and centrifuge again at 1389 g for 3 min. Discard the supernatant fluids.

4. Re-suspend each deposit in a few millilitres of $ZnSO_4$ and vortex well to mix. Keep adding more $ZnSO_4$ and mixing until the tube is almost full.

5. Centrifuge the tubes at 617 g (±2000 rpm) for 3 min. Carefully remove from the centrifuge and, using a plastic Pasteur pipette, transfer the supernatant to 3 or 4 test tubes. Fill these tubes with distilled water to **reduce** the SG of the $ZnSO_4$ so as not to damage the eggs and also to allow them to **deposit** upon centrifugation.

6. Centrifuge at 964 g (±2500 rpm) for 3 min; remove & discard the supernatant fluid. The deposits can then be combined into one test tube, using water to rinse out all the eggs and then centrifuge again at 964 g for 3 min. to get one deposit.

Note: At this point if the sample contains a lot of large particles of light debris that floated with the eggs egg. grass, you can filter the deposit through a 100 µm filter, collect the filtrate in test tubes and centrifuge again to get a deposit for microscopy.

7. Once you have the final deposit, remove all of it using a plastic Pasteur pipette and place it onto one or more microscope slides. Place a coverslip over the deposit and examine microscopically using the 10x objective and the 40x objective to confirm any unsure diagnoses.

8. Each species of helminth ova is enumerated separately and reported as eggs per gram of compost.