PUBLISHED DOCUMENT

PD CEN/TR 13767:2004

# Characterisation of sludges — Good practice for sludges incineration with and without grease and screenings

ICS 13.030.20

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British Standards

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# National foreword

This Published Document is the official English language version of CEN/TR 13767:2004. It supersedes the 2001 edition which is now withdrawn.

The UK participation in its preparation was entrusted to Technical Committee EH/5, Sludge characterisation, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this committee can be obtained on request to its secretary.

**Cross-references**

The British Standards which implement international or European publications referred to in this document may be found in the *BSI Catalogue* under the section entitled "International Standards Correspondence Index", or by using the "Search" facility of the *BSI Electronic Catalogue* or of British Standards Online.

**Summary of pages**

This document comprises a front cover, an inside front cover, the CEN/TR title page, pages 2 to 33 and a back cover.

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TECHNICAL REPORT

RAPPORT TECHNIQUE

TECHNISCHER BERICHT

# CEN/TR 13767

August 2004

ICS 13.030.20

Supersedes CR 13767:2001

English version

# Characterisation of sludges - Good practice for sludges incineration with and without grease and screenings

Caractérisation des boues - Bonne pratique d'incinération des boues avec ou sans graisse et refus de dégrillage

Charakterisierung von Schlämmen - Anleitung für die gute fachliche Praxis bei der Verbrennnung von Schlamm mit und ohne Fett und Rechengut

This Technical Report was approved by CEN on 26 February 2004. It has been drawn up by the Technical Committee CEN/TC 308.

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# Contents

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# Foreword

This document (CEN/TR 13767:2004) has been prepared by Technical Committee CEN/TC 308 “Characterization of sludges”, the secretariat of which is held by AFNOR.

This document supersedes CR 13767:2001.

Significant technical differences between this edition and CR 13767:2001 is taking account of the new Directive 2000/76/EC (incineration of waste).

The status of this document as CEN Technical Report has been chosen because the most of its content is not completely in line with practice and regulation in each member state. This document gives recommendations for a good practice but existing national regulations concerning the sludges incineration remain in force.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to announce this Technical Report: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

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## Introduction

The purpose of this document is to describe good practice of the sludge incineration in order to ensure a safe and economical operation. The main goals are to :

- describe the principal design parameters relevant to different process schemes ;
- assess the operating procedures able to perform optimal energy consumption, emissions control and equipment durability ;
- provide the responsible authorities with well established and easily applicable protocols for control purposes ;
- promote the diffusion of this practice and favouring the formation of a public opinion consensus ;

Potential advantages of high temperature processes include :

- reduction of volume and mass of sludge ;
- destruction of toxic organic compounds, if present ;
- energy recovery.

Anyway, priority should be given to reduction of pollutants at the origin and to recover if technically and economically feasible valuable substances (phosphorous and potassium) in sludge and derived products.

The following abbreviated terms necessary for the understanding of this document apply :

*COD* Chemical oxygen demand

*LOI* Loss On Ignition

*MHF* Multiple Hearth Furnace

*FBF* Fluidised Bed Furnace

*RKF* Rotary Kiln Furnace

*EF* Electric Furnace

*CF* Cyclone Furnace

*PCDF* Polychlorodibenzofurans

*PCDD* Polychlorodibenzodioxins

*PCB* Polychlorinated biphenyls

*PAH* Polycyclic aromatic hydrocarbons

*GCV* Greater Calorific Value

*LCV* Lower Calorific Value

*VOC* Volatile organic carbon

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## 1 Scope

This document describes good practice for the incineration of sludges with and without grease and screenings.

This document is applicable for sludges described in the scope of CEN/TC 308 specifically derived from :

- night soil ;
- urban wastewater collecting systems ;
- urban wastewater treatment plants ;
- treatment of industrial wastewater similar to urban wastewater (as defined in Directive 91/271/EC) ;

but excluding hazardous sludges from industry.

This document is not applicable to co-incineration of sludge and other wastes, (either urban or hazardous) (see CEN/TR 13768) and to the use of sludge in cement kilns.

Annex A gives tables of data for different typical parameters for sludge, furnace and ash.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 1085, *Wastewater treatment – Vocabulary*.

EN 12832, *Characterization of sludges – Utilisation and disposal of sludges – Vocabulary*.

EN 12255-8, *Wastewater treatments plants – Part 8 : Sludge treatment and storage.*

CEN/TR 13768, *Characterization of sludges – Good practice for combined incineration of sludge and household wastes.*

EN 13965-1, *Characterization of waste – Terminology – Part 1 : Material related terms and definitions*.

EN 13965-2, *Characterization of waste – Terminology – Part 2 : Management related terms and definitions.*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions which apply are those given in :

- Directive 91/271/EC (concerning urban waste water treatment) ;
- Directive 75/442/EEC (the Waste Framework Directive) as amended by EU Directive 91/156/EEC ;
- Directive 89/369/EEC (concerning prevention of atmospheric pollution derived from urban solid waste incineration plants) until 27/12/2005;
- Directive 2000/76/CE on Waste incineration
- EN 1085, EN 12832, and EN 13965-1 and -2.

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# 4 Sludge properties

Sludge characterisation for the assessment of combustion processes involves the evaluation of chemical and physical parameters and specific properties.

## 4.1 Chemical characteristics

The main chemical characteristics to be taken into account are :

— organic and inorganic chlorine ;

— sulfur ;

— phosphorus and nitrogen ;

— other halogens ;

— organic micropollutants with main regard to chlorinated hydrocarbons, phenols and polyphenols, polychlorinated biphenyls (PCB), pesticides and polycyclic aromatic hydrocarbons (PAH) ;

— elemental analysis of loss on ignition (LOI) ;

— trace elements.

The toxicity of emissions (gaseous, liquid, solid) from incineration generally depends on the presence of above chemicals at origin, when improper operating conditions occur.

*a) Sulfur*

The sulfur content of sewage sludge ranges generally from 0,5 % to 2 % by dry mass. Because a fraction of the sulfur is present in the oxidised sulfate form, not all of this sulfur is converted to sulfur dioxide during combustion. Sulfur dioxide then combines with moisture, either in the waste gas treatment system or in the atmosphere, to form sulfuric and sulfurous acids.

*b) Phosphorus and nitrogen*

Phosphorus can be present in sewage sludge in concentration ranging from 1 % to 5 % by dry mass. This concentration mainly depends on the phosphorus load in the wastewater system and on the level of phosphorus removal accomplished in the treatment plant. Nowadays in some countries the phosphorus concentration in urban wastewater is decreasing due to substitution of phosphorus in detergents with other products. During combustion phosphorus and phosphorus compounds are converted to calcium phosphate which can be present in the furnace ash up to 15 % mass fraction of $P_2O_5$. In certain conditions, leaching of phosphorus from ashes should be taken into account.

Nitrogen content of sewage sludge (2 % to 12 % dry mass) can be converted during combustion to molecular nitrogen or to $NO_x$, depending on the temperature and atmosphere inside the furnace. $NO_x$ formation from fuel bound nitrogen can be controlled by restricting the air flow to the minimum excess above the stoichiometric requirement and by staging the air flow to the furnace (see 8.1).

*c) Chlorine and other halogens* [1)]

Organic and inorganic chlorine compounds play an important role in the combustion processes for the tendency of the chlorine radicals to bind to active radicals, like O*, H* and OH*. This determines a decrease in the combustion rate with the possibility of toxic compounds formation. Chlorine and other halogens are also responsible for the presence in the exhaust gases of acidic compounds which are undesirable for corrosion problems involved, especially at high temperatures. The presence of organic chlorine in sewage sludge is generally negligible (less

1) Bromine can exert similar effects than chlorine but the organic compounds are easier formed and they can also be easier destroyed at high temperatures.

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than 50 mg/kg dry mass) but the concentration of inorganic chlorine can be some units per cent dry mass depending on chlorine presence in the sludge water fraction and on the use of inorganic conditioners. The industrial sludges similar to sewage sludge mentioned in Directive 91/271/EC, which derive from food and/or beverage transformation and production, do not contain organic chlorine. As for sewage sludge, inorganic chlorine can be present in such sludges if $FeCl_3$ is used as conditioner.

*d) Organic micropollutants*

Although the presence of organic micropollutants in sewage sludge can be in some cases noticeable, they generally do not pose problems in incineration. Chemical analysis can include, for particular cases of contaminated sludges, the compounds which are recognised to be recalcitrant to a thermal degradation.

*e) Elemental analysis*

Elemental analysis of loss on ignition (C, H, N, S, O) is important to predict flow rate and composition of flue gas and therefore to design the purification gas line. Typical elemental analysis of primary, secondary, mixed and digested sludge is given in Table A.1.

*f) Trace elements*

Trace element presence in sewage sludge has to be considered for their potential tendency to be transferred in the gaseous phase (especially for mercury). They (except mercury) can be concentrated in fly ashes collected in bag and electrofilters (arsenic, lead, cadmium and zinc). Mercury generally escapes with flue gases but can be filters condensed in scrubbers or captured by activated carbon filters.

Trace elements are generally present in sewage sludge in very variable concentrations depending on the presence of industrial effluents in the wastewater. Table A.2 gives an indication of the most common range of variation and the typical values of trace element concentrations, but it has to be pointed out that, currently, the trace element presence in sewage sludge is decreasing due to a more effective control of undesirable pollutants input to the sewerage system.

## 4.2 Physical-chemical characteristics

The main physical-chemical characteristics to be taken into account are :

— dry matter ;

— physical consistency ;

— loss on ignition (*LOI*) ;

— calorific value ;

— presence of grease, scum and screenings.

Rheological properties also play an important role, especially as far as the design of feeding system is concerned.

*a) Dry matter*

In incineration of sewage sludge dry matter is a variable affecting both fuel requirement and exhaust gas production. Generally any increase in dry matter is believed to be beneficial in the combustion for the reduction in fuel requirement. Until the condition for autogenous combustion is reached the increase in dry matter corresponds also to a decrease in combustion gases production. It should be pointed out that any further increase of dry matter beyond the limit of autogenous combustion could be not very convenient because this entails a more abundant gas production, especially if dilution air is used instead of water for the control of the combustion chamber temperature. The use of water, on the contrary, reduces the quantity of recoverable heat in the boiler.

Moreover, if after burning of combustion gases should be accomplished, the feeding of too dry a sludge to the furnace implies also very abundant fuel requirements in the after burning chamber due to high gas production.

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Therefore, thermal drying of sludge before incineration has to be properly designed and operated in order to attain an optimal drying level. Dried and dewatered sludges can be mixed, if necessary, to avoid too high not needed dry matter concentrations.

*b) Physical consistency*

Physical consistency of sludge should be adapted to furnace and its feeding system.

Depending on the dewatering device a crumbly product could be needed before feeding the incineration furnace.

*c) Loss on ignition and calorific value*

Calorific value of sludge is probably the most important parameter for the evaluation of combustion processes. It represents the heat quantity developed in the combustion by the unit mass of material in standard conditions.

As a first approximation the Greater Calorific Value (*GCV*) can be evaluated by the Du Long equation, if the elemental analysis of combustible material is known :

$$GCV = 32\,810\ C + 142\,246\ (H - O/8) + 9\,273\ S \qquad (1)$$

where

*GCV* is in kJ/kg LOI ; and

*C*, *H*, *O* and *S* are the mass fraction of the elements in the loss of ignition.

The above formula gives an overestimation of the heat value of sludges with high organic nitrogen content because : a) the nitrogen will be associated with the hydrogen as an amine, b) the production of nitrogen oxide in the amine combustion reduces the hydrogen heat release.

The following equation can be used to take into account the above effects :

$$GCV = 32\,810\ C + 142\,246\ (H - O/8) + 9\,273\ S - [2\,189\ N\ (1 - \mu) + 6\,489 N\ \mu] \qquad (2)$$

where

$\mu$ represents conversion (mass fraction) of nitrogen to nitrogen oxide, generally in the range 2 % to 7 %.

Lower calorific value (*LCV*) can be also evaluated (Nielsen & Simonsen, 1994) by measuring the chemical oxygen demand *COD* and the total Kjeldahl nitrogen (*TKN*) (ammoniacal + organic nitrogen) and using the formula :

$$LCV = 13\,700\ COD + 19\,000\ TKN \qquad (3)$$

where

*LCV* is in kJ/kg LOI ; and

*COD* and *TKN* are expressed in kg/kg LOI.

COD of sludge generally varies in the range of 1,5 kg to 1,8 kg $O_2$/kg LOI and *TKN* in the range 0,02 kg/kg LOI to 0,09 g/kg LOI.

Typical calorific values of municipal wastewater sludges range from 22 100 kJ/kg LOI to 24 400 kJ/kg LOI (anaerobically digested primary) to 23 300 to 27 900 (raw primary). Secondary sludges display values between 20 700 kJ/kg LOI and 24 400 kJ/kg LOI.

The variability of the calorific value mainly depends on the elemental analysis of sludges : when the hydrogen content is higher also the calorific value displays higher values as for primary sludge in comparison with secondary and with digested sludge.

*LCV* can be estimated considering the water present in the sludge (1 – *X*), being *X* the fraction of dry solids, and the combustion water (9 *H LOI*) :

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$$LCV \text{ (kJ/kg sludge)} = GCV\ X\ LOI - 2\,440\ (9\ H\ LOI + 1 - X) \quad (4)$$

where

*LOI* is the loss on ignition with respect to dry solids (kg/kg).

If the lower calorific value of loss on ignition is known ($LCV_{LOI}$) the lower calorific value of wet sludge can be easily evaluated by :

$$LCV = LCV_{LOI}\ X\ LOI - 2\,440\ (1 - X) \quad (5)$$

As a first approximation for $LCV_{LOi}$ a value of 23 000 kJ/kg LOI can be assumed.

d) *Presence of grease, scum and screenings*

Grease, scum and screenings can be incinerated together with sludges but generally they pose several problems.

Screenings clog feed mechanisms for certain types of furnace and therefore a grinding or shredding process is advisable before feeding.

Screenings also contain bulky and non-combustible materials, which create problems in the ash disposal system.

Skimming generally contains more than 95 % moisture and therefore they should be thickened to at least 25 % solids before incineration. Skimming is difficult to handle in the thickened state due to their viscosity and a heating process to 70 °C to 80 °C is generally requested to get skimming pumpable. This scum solids should be ground to a size not exceeding 6 mm. *GCV* of skimming and screenings are in the range 37 000 kJ/kg to 44 000 kJ/kg dry solids and 23 000 kJ/kg to 25 600 kJ/kg dry solids, respectively.

Quantities of screenings are strictly dependent on the screen opening : they can vary in the range of $3 \cdot 10^{-6}$ $m^3/m^3$ to $40 \cdot 10^{-6}$ $m^3/m^3$ of sewage for opening of 12 mm to 25 mm (the upper limits apply to the reduced openings). As dewatered sludge production can be approximately evaluated in 1 $l/m^3$ of sewage the screenings production can be accounted in approximately 0,2 % to 4 % in mass of sludge production, considering that the density of wet screenings is 640 $kg/m^3$ to 1 000 $kg/m^3$.

Quantities of scum are very much dependent on the quality of the sewage and on the collecting system in the wastewater treatment plant : the highest values can be as high as 17 g of dry solids/ $m^3$ of sewage which means up to 1,7 % of sludge production. At a concentration of 25 % this value increases to 6,8 %.

Addition of scum and grease can result in operating and safety problems : due to their high energy content an increased volume of exhaust gases are suddenly produced in the heating space. It could happen that suction blowers, responsible for vacuum production in the furnace are not able to draw off the developed explosive gas immediately, which, therefore, can escape in the ambient air.

An operator has to take measures against such a situation and has to control appropriately any addition of combustible material different from sewage sludge.

## 5 Combustion fundamentals

Combustion is an oxidation reaction carried out at high temperature: the union of oxygen with carbon, hydrogen and sulfur yields energy and products of combustion, namely, carbon dioxide ($CO_2$), water ($H_2O$) and sulfur dioxide ($SO_2$). Organic nitrogen is preferentially converted to nitrogen gas but a certain amount (2 % to 7 %) can also be further oxidised to nitrogen oxide (NO).

The nitrogen in the air is also candidate to be converted to oxides of nitrogen ($NO_x$). This phenomenon begins to be noticeable at temperatures higher than 1 100 °C and increases with any further increase of temperature.

The maximum temperature achieved by the combustion of a fuel will result from the balance between the energy produced and/or the energy input and that of combustion products. The heat released by the combustion of a substance is then used to increase the temperature of the combustion products to the equilibrium temperature. The

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amount of heat required to raise a unit weight of gas, liquid, or solid of one degree is the specific heat of the material. In Tables A.3 and A.4, the main properties of gaseous products of combustion are shown.

All oxidising combustion reactions require some excess air to ensure that the reaction proceeds rapidly to completion. The amount of excess air required is a function of time of stay, temperature and turbulence, commonly referred to as the "3Ts of combustion". Generally as turbulence is maximised, excess air can be decreased. Turbulence provides more opportunities of contact between fuel and oxygen and changes substantially for various types of combustion units. High efficiency burners may employ as low as 20 % to 30 % excess air while less efficient furnaces, like multiple hearth and rotary kiln furnaces, need 100 % to 125 % excess air at least. As excess air quenches the combustion temperature it is desirable to minimise the quantity to be employed especially when auxiliary fuel is needed to sustain combustion. This effect can be reduced by air pre-heating. If insufficient excess air is added to the furnace or if one or more of the "3Ts" concepts are lacking, the combustion operation will generate smoke and products of incomplete combustion), thus making incineration operation not acceptable.

# 6 Equipment characteristics

## 6.1 Incineration systems

Incineration plants, independently on the system and type of furnace used, is designed, equipped, built and operated to respect limits and prescriptions of the Directive 2000/76/EC.

Temperature and residence time is accordingly strictly observed. Each line of the incineration plant should be equipped with at least one auxiliary burner and with an automatic system preventing sludge feed when improper conditions occur. Exhaust gases should be discharged in a controlled fashion and in conformity with relevant European, national and regional air quality standards by means of a stack the height of which is calculated in such a way as to safeguard human health and the environment.

The type of incinerator most commonly in use for sludge incineration is the Fluidised Bed Furnace (FBF). Other types are : Multiple Hearth Furnace (MHF), Rotary Kiln Furnace (RKF), combination of MHF and FBF, Electric Furnace (EF) and Cyclone Furnace (CF).

They can be combined with a dryer.

*a) Fluidised Bed Furnace (FBF)*

It is a cylindrical refractory lined shell containing a sand bed fluidised during operation by air through a distributor plate below the bed. The temperature of the bed is controlled at about 750 °C. FBFs fall into two categories : bubbling and circulating. They are based on the same principle, but in the circulating bed unit a higher fluidisation velocity creates very intensive mixing of air and fuel. Particles are carried out of the vertical combustion chamber by the flue gas and are removed in a cyclone to be returned to the *FBF* through a loop seal. A cross section of a bubbling *FBF* is shown in Figure 2. Typical design parameters of a bubbling FBFs, which are much more common than circulating types, are reported in Table A.5.

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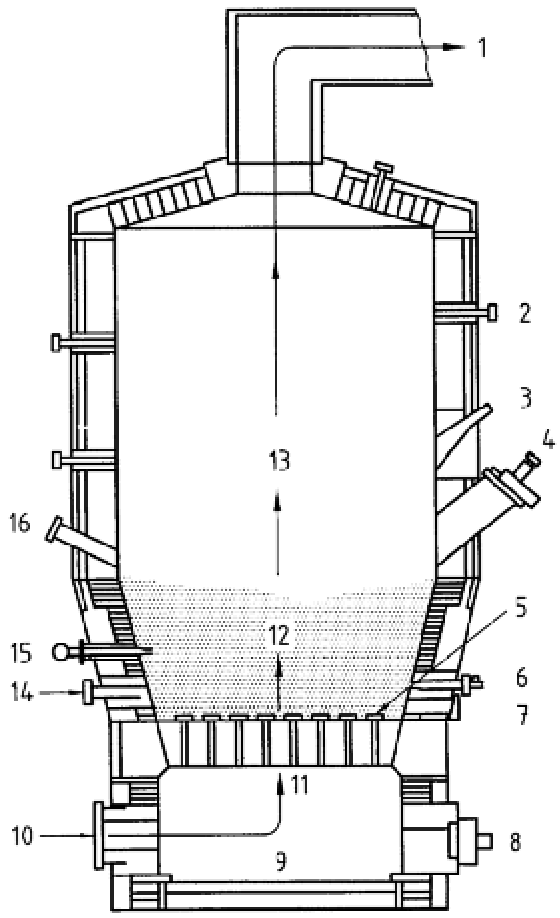


**Key**

1 Exhaust and ash
2 Pressure tap
3 Sight glass
4 Burner
5 Tuyeres
6 Fuel gun
7 Pressure tap
8 Start-up preheat burner for hot windbox
9 Windbox
10 Fluidizing air inlet
11 Refractory arch
12 Fluidised sand bed
13 Freeboard
14 Sludge inlet
15 Thermocouple
16 Sand inlet

**Figure 1 — Bubbling fluidised bed furnace (typical cross section)**

Advantages of FBFs are low excess air requirement, due to the high turbulence, low $NO_x$ production, due to effective control of combustion temperature, reliability (no moving parts), flexibility for shock load, adaptability to sludges at different moisture content (dewatered, partially dried, full dried), heat storage capacity by sand bed, and possible abatement of acidic compounds within the bed using additives, like limestone and dolomite.

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Disadvantages include ash and sand carry-over, and possible formation of a block of vitrified sand when salts with low melting points are present. This problem can be attenuated by an addition of chemicals to bind the alkaline salts.

*b) Multiple Hearth Furnace (MHF)*

It consists in a vertical cylindrical-refractory lined reactor containing a number of horizontal hearths. 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. A cross section of a multiple hearth furnace is shown in Figure 2. Three zones can be distinguished in the furnace: drying, with gas temperature up to 400 °C, burning (temperatures of gas and solid phases of 850 °C to 900 °C), ash cooling (temperatures of ashes and air generally lower than 200 °C).

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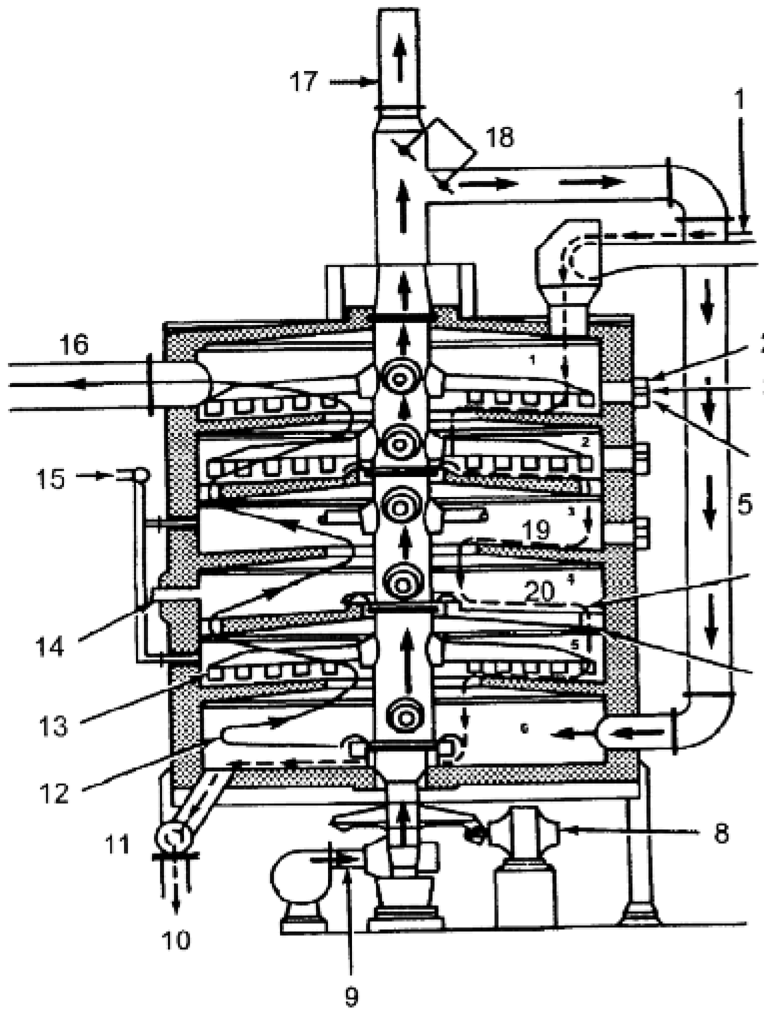


**Key**

1 Sludge cake, screenings and grit
2 Burners
3 Supplemental fuel
4 Combustion air
5 Shaft cooling air return
6 Solids flow
7 Drop holes
8 Rabble arm drive
9 Shaft cooling air
10 Ash discharge
11 Clinker breaker
12 Gas flow
13 Rabble arm (2 or 4 per hearth)
14 Auxiliary air ports
15 Scum
16 Exhaust gas
17 Cooling air discharge
18 Damper
19 In hearth
20 Out hearth

**Figure 2 — Multiple hearth furnace (typical cross section)**

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Typical design values of a MHF are : 2 m to 8 m (diameter), 4 to 14 (hearths, at least 8 desirable), 30 kg to 60 kg wet sludge/$m^2$·h (hearth loading rate), 100 % to 125 % (excess air).

Advantages are flexibility with respect to feed quality and loading rates, durability, low fuel consumption due to effective heat recovery inside the equipment.

Disadvantages are possible odour problems and emissions of volatile substances, due to the low temperature of exhaust gas, high need of excess air, due to the low turbulence and high maintenance costs, due to many moving parts. Moreover, high fuel consumption is needed, if afterburning of exhaust gases has to be accomplished, to take their temperature from 400 °C to 450 °C to at least 850 °C.

*c) Combination of multiple hearth furnace and fluidised bed furnace*

Essentially, it consists of a cylindrical brick-faced vertical combustion chamber, where in the lower part a sand bed is kept fluidised with the aid of combustion air. The fluidised bed is streamed with hot air from below via the windbox and the tuyeres.

The pre-drying layers with variable speed rotating hollow shaft and stirring arms are located in the upper part of the fluidised bed furnace. The lowest layer serves additionally as distributor level for the even feed of the pre-dried, crumbly sludge into the underlying fluidised bed. The flue gases, enriched with water vapour and odour laden components, are fed back into the baking zone of the fluidised bed for after burning in the fluidised bed.

The degree of drying of the MHF can be easily regulated, thus improving the overall performance of the process reducing the excess air amount.

As a result of the described process there is an extremely stable, self-sustaining incineration process characterised by low nitrogen oxide and carbon monoxide values in the flue gas. An advantage of this combination is also the possible reduction of the grate surface of the FBF, in comparison with a process where only a FBF is applied. The multi-layer fluidised bed furnace can be operated with an incineration air quantity which is dependent only on the CO and $NO_x$ content of the flue gas and is thus relatively small.

The above conditions can, however, be performed by pre-drying the sludge with different equipment.

*d) Rotary Kiln Furnace (RKF)*

It consists in a refractory-lined cylindrical shell mounted at a slight incline from the horizontal plane (2 % to 3 %) which slowly rotates (0,25 rpm to 1,50 rpm). Variation of rotational speed allows to control solids residence time and to ensure adequate mixing. Excess air requirement ranges 100 % to 200 %. A cross section of a rotating kiln furnace is shown in Figure 3.

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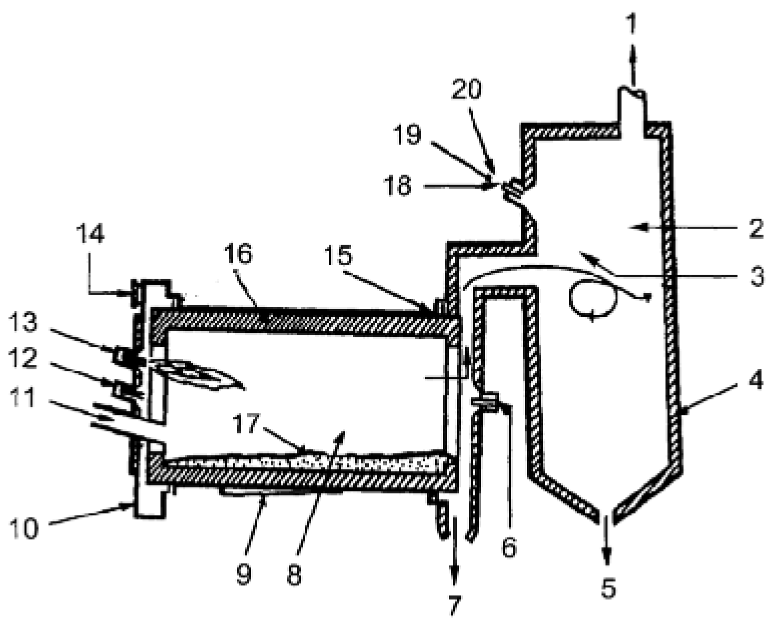


A) Rotary kiln B) Afterburner

**Key**

1 Discharge to quench or heat recovery
2 120 % to 200 % of excess air
3 1,3 s to 3,0 s means gas residence time
4 Refractory
5 Ash
6 Auxiliary fuel
7 Bottom ash
8 100 % to 200 % excess air
9 Incline
10 Kiln shroud
11 Sludges and other waste solids
12 Auxiliary fuel
13 Waste liquids
14 Combustion air
15 Rotary seals
16 Refractory
17 Sludge and other residues
18 Waste liquids
19 Auxiliary fuel
20 Air

**Figure 3 —Rotating kiln furnace (typical cross section)**

This technology is particularly suitable for incineration of hazardous wastes, due to its ability to treat a great variety of materials of different consistence and size.

Advantages consist in possible melting of ash (but blockage should be avoided), no need of pre-treatments, adaptation to many feed mechanisms designs.

Disadvantages are relatively low combustion efficiency, operating difficulties (sealing at both ends, refractory damages), high need of excess air, high fuel consumption.

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*e) Electric Furnace (EF)*

The Electric Furnace (EF) (or radiant heat, or infrared) is basically a conveyor belt system passing through a long rectangular refractory-lined chamber. EFs are available in sizes ranging from 1,2 m wide by 6,1 m long to 2,9 m by 29,3 m. Combustion air flows counter currently to the sludge. Excess air rates range 30 % to 70 %. No auxiliary fuel is required, because electricity is used to provide supplemental energy. This technology is particularly suitable for small plants and discontinuous operations.

*f) Cyclonic Furnace (CF)*

The Cyclonic Furnace (CF) is a single hearth unit where the hearth moves and the rabble teeth are stationary. CF introduces combustion air tangential into a cylindrical chamber, while the sludge is sprayed radially toward the heated walls of the chamber : combustion occurs rapidly enough that sludge does not adhere to the walls.

## 6.2 Support components

The performance of an incinerator is dependent upon the provision of proper support system equipment. This includes :

- receiving area ;
- pre-treatment ;
- storage and feeding system ;
- heat recovery ;
- flue gas cleaning ;
- ash handling ;
- wastewater disposal ;
- process monitoring.

*a) Receiving area*

It consists of loading/unloading equipment and storage vessels. The dry matter content and physical state (consistency) of the sludge will dictate selection and design, so the rheological characterisation appears useful in this designing step. Sludge should be generally stored in closed systems where air is extracted and treated for deodorization.

*b) Pre-treatment*

It is addressed to improve the burning quality or heat content of sludge. Thickening, conditioning and dewatering are the most common processes for reducing moisture. Both centrifugal and filter-type dewatering equipment can be used for removing water from sludge. It should be pointed out that concentrations of 30 % to 35 % (in some cases up to 40 %) can be achieved with filter-pressing using inorganic conditioners, which, on the other hand, determine a decrease in volatile content and an increase in dry solids quantity to be processed. Furthermore, slagging and clinkering can occur when metal salts are present. In addition, chlorides at elevated temperatures result in accelerated corrosion of metal parts and also in possible emissions. The use of polymers as dewatering aids resulted very effective, and their adoption instead of lime and ferric chloride has benefited furnace operation.

Further removal of water can be obtained by thermal drying. It can be thermodynamically advantageous provided that the moisture is removed with less energy than that required in the furnace. Indirect and direct contact dryers can be used.

When a thermal fluid is available (steam at medium pressure or diathermic oil at about 250 °C) indirect dryers are more effective as the production of exhaust incondensable gases is lower : it can be estimated in about 0,2 kg to 1,5 kg of gas/kg evaporated water.

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The advantages of thermal drying when coupled with incineration consist in the possibility to control the solids concentration to the right value, which allows an autogenous combustion with a minimum exhaust gas production to be performed. Sludge incineration line including a sludge dryer can be cost effective.

Addition of a supplemental combustible material at low cost, like appropriate biomass, is another option to reduce fossil fuel consumption.

Sludge dewatering and/or drying have also the important goal of producing a best adapted product for the proper feeding of the incineration furnace. It should be considered that during transportation/pumping the structure of the sludge can be altered with possible aggregation. To overcome this problem a dewatering system can be preferentially installed up or at least very close to the incineration furnace. When sludge produced in other plants is taken to a centralised incineration plant it is convenient to mechanically disrupt the sludge for size reduction before feeding the furnace.

*c) Storage and feeding system*

Adequate storage for dewatered sludge has to be included in a sludge incineration line to guarantee a steady and non-variable input to the furnace. During maintenance periods, approximately 2 weeks to 4 weeks per year, sludge should be disposed in an alternative way or it should be stored : in this latter case storage should be much more increased.

Conveyors, progressive cavity pumps, piston pumps, screw feeders and chain transporters can be used depending on sludge consistency.

*d) Heat recovery*

The systems for heat recovery include the boilers, with production of hot water or steam, and heat exchangers used for air pre-heating and/or flue gas after-heating.

The major concerns in applying a heat exchanger on dirty gas are fouling and plugging of the tubes due the solid accretion and abrasion of the tubes by the entrained solids. Due to the dirty nature of the gas, design of the tube heat exchangers has to be carried out with particular attention to the fouling problems. Attention should also be paid during operation in keeping the heat transfer surface clean. This can be done during normal operation of the unit by using soot blowers and/or mechanical cleaning.

The boiler [2)] generally consists in three different sections :

— a radiant section in which evaporation occurs at the design pressure in vertical tubes located on the refractory walls to form one or more rectangular channels ;

— a convective section in which superheating occurs in one or more banks of horizontal tubes ;

— an economiser in which the water is warmed from the temperature of the degasser to the boiling temperature (generally from 120 °C to 150 °C to 180 °C to 220 °C).

The exhaust gases enter the boiler at 850 °C to 950 °C in the radiant section, then pass through the convective section and leave the boiler from the economiser. Exit flue gas temperature from economiser depends on the design of the boiler : it can be as low as 250 °C when the electric energy recovery has to be accomplished, but it can be also as high as 500 °C when steam has to be produced to cover only the needs of dryer, air pre-heater and flue gas post heater.

This type of operation would allow to reduce considerably the problems of PCDD/PCDF formation in the boiler when gas temperature is in the range 250 °C to 400 °C. In a spray dryer, in fact, it is possible to reduce gas temperature from 500 °C to 200 °C - 250 °C very fast.

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[2)] The boiler should be provided with a dust hopper fitted with a screw conveyor for removing dust that settles out. Soot blowers are required for cleaning the tubes. Due to structure of the fire tube boilers, with many long tubes of relatively small diameter connected to a tube sheet, soot blowers might not be effective in eliminating deposits from the inside of the tubes. The use of high velocity could limit build-up of solids. However, in many cases, the result will be unsatisfactory due to the sticking nature of the particulate, which will cause plugged tubes, with consequent shutdown.

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Steam production in the boiler is highly dependent on the exhaust gas production and, therefore, on presence of a sludge dryer. Steam production from the boiler can be estimated in the range of 3 kg/kg to 8 kg/kg dry solids to be processed : the highest values are generally coupled with high auxiliary fuel consumption. Electric energy conversion can be estimated in the range 0,2 kWh/kg to 1,6 kWh/kg dry solids. The use of an induced draft fan after the scrubber is desirable with a waste heat boiler installation, in order to maintain a slight draft in the boiler and thereby prevent gas and dust leakage. If the steam demand is highly variable, the use of a hot gas by-pass duct to the scrubber inlet is advisable; otherwise, a condenser will be required during periods of low steam demand.

One of the major concerns in selecting a waste heat boiler is loss of steam as a consequence of incinerator troubles. In some cases, the boiler is equipped with burners for direct firing to allow continued steam production, but this increases considerably boiler cost and complexity [3].

The use of produced steam depends on local conditions and plant size.

Steam can be used for :

— electricity generation by conventional turbines, generally in large plants using high pressure (3 MPa to 10 MPa) and high temperature (350 °C to 500 °C) steam ;

— sewage sludge drying in indirect contact steam-sludge devices, like disk dryers, paddle dryers or thin film dryers. In this case steam is used at pressure of 0,6 MPa to 2 MPa and temperatures of 160 °C to 230 °C ;

— air preheating in finned exchangers ;

— exhaust gas post-heating to prevent the plume appearance and to ensure sufficient dispersion of the effluent gases ;

— district heating or industrial use, generally in smaller plants, but also in large plants. Steam can also be utilised to produce hot water for district heating.

Multiple utilisation is not uncommon especially in the large plants.

*e) Flue gas cleaning*

Air pollution control is required for the reduction of emissions which include particulate, volatile trace elements, organic pollutants (volatile and products of incomplete combustion), acidic compounds, nitrogen and sulfuric oxides. The main goal of any flue gas cleaning system is to cool down the exhaust gas thus condensing the most of the evaporated pollutants.

Equipment for gas purification can be classified in two main groups : the units, which are able to separate solid particles and those which reduce gaseous contaminants by absorption, adsorption and/or chemical reaction.

The equipment for solid particle entrapment includes impingement separators, cyclones, electrostatic precipitators and bag filters. They generally are able to remove particulate down to 5 mg/Nm$^3$, depending mainly on the particle size.

Impingement separators are essentially a series of baffles placed in the gas stream.

Cyclones are cylindrical or conical static chambers, where flue gases enter tangentially and solids particles are collected on the walls due to centrifugal force and then discharged from the bottom. The effectiveness of dry cyclonic separators on particles smaller than 15 µm is negligible, so they are often used coupled to other devices.

Electrostatic precipitators involve formation of gas ions, charging of particles, migration of charged particles toward a collecting electrode, neutralisation of charge and collection of separated particles. Between emitting and collecting electrodes a voltage of 20 kV to 100 kV is applied and this determines a strong electric field close to the emitting electrode (about 20 kV/cm) and a lower field in the vicinity of the collecting one (about 2 kV/cm). A strong

3) It could be preferable to firing the incinerator being the thermal efficiency nearly as high as direct-firing the boiler (65 % to 70 %).

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ionisation of dust particles is induced and they move towards the collecting conductive electrodes. System efficiency is strictly connected to the removal of particles from the collecting surface. The most common removal devices are rappers ; another method is to wet the collecting surfaces down. Electrostatic precipitators are effective for particulate removal including small size particles down to sub-micro metres range. Another key parameter is the particle resistivity : if it is high, particles are unable to get electrically charged.

Fabric filters or baghouses are a series of permeable bags which allow the passage of gas but not of particulate matter. Because of the pressure drop increase with filtering time due to dust accretion on the bag cloths, systems for surface cleaning are necessary : they include shaker mechanisms, compressed air, re-pressurisation and sonic apparatuses. Particles less than 1 µm can be caught by fabric filters or baghouses. A temperature control of the inlet gas stream is needed to avoid possible damage of the filtering cloth.

The systems used for gaseous contaminant abatement are generally subdivided in dry, semi-dry and wet systems.

In the dry systems, dry chemicals (generally lime or sodium bicarbonate) are introduced into a ductwork or a reaction tower or a re-circulating system. The gaseous pollutants are removed by adsorption and chemical reaction. Chemicals and reaction products are then removed by a system for particle separation. Lime requirement is generally up to 2 times to 2,5 times the stoichiometric value for $SO_x$.

In semi-dry system, slurry is introduced into the reactor. The sensible heat of the exhaust gases produce a complete evaporation of the liquid (water) in the slurry and therefore no liquid side-streams are generated. The mechanism of removal of contaminants is the same of that of the dry system. Both in dry and semi-dry systems careful control of material dispersion in the reaction zone and the recycling of the reaction products and of the excess reagent will minimise chemical consumption and prevent abundant production of fly ashes. In this case chemicals consumption can be lowered to 1,5 times to 2 times the stoichiometric need.

In wet devices, particles are firstly wetted by contact with liquid droplets and then impinged on a collecting surface. Acidic compounds in presence of water can result in significant acid formation with corrosion problems.

Wet cyclone collectors are basically dry cyclones provided with a water spray. Venturi scrubber is a throat where gases pass at high velocity in the range of 50 m/s to 180 m/s, through a contracted area which is followed by an expansion section for separation of particles ; water is injected at the throat or just upstream of the venturi section. The area ratio between the inlet and the throat typically is 4:1. The high velocity gas atomises the liquid into the gas stream. This type of device can be used both for gaseous contaminant and for particulate removal. The collection of the fine particles by the liquid droplets is accomplished by inertial impact during the time the droplets are being accelerated until their velocity approaches that of the gas. At this point the probability of inertial impaction (downstream from the throat) decreases rapidly [4)].

Tray and packed towers can be used for gaseous pollutant removal by liquid scrubbing which involves bringing the dirty effluent gas into contact with the scrubbing liquid. High interfacial surface area, turbulence and large mass diffusion coefficients accelerate absorption. Both in tray and packed towers gas enters the bottom and the clean gas exits at the top of the tower. Conversely, clean liquid enters the top and is withdrawn from the bottom. Tray scrubbers consist of a tower equipped with perforated plates and target baffles ; while packed towers are columns with one or more zones full of packing elements. The purpose for scrubbers are gas cooling, trace elements condensation, due to the low temperature of exit gases (60 °C to 70 °C), HCl, HF and $SO_2$ scrubbing, residual particulate removal, odour control and, to a lesser extent, VOC removal.

The chemicals consumption in wet device systems is only 10 % higher than the stoichiometric need.

Activated carbon adsorption can be used to remove organic micropollutants, with molar mass higher than 200, and mercury emissions. The adsorption process is discontinuous. The advantage of the physical adsorption is that the process is reversible. By lowering the pressure of the absorbate in the gas stream or by raising the temperature, the adsorbed contaminants can be desorbed without a change in chemical composition. Regeneration process is nowadays not carried out in the incineration plants because of economical aspects. The general requirements that should be met in the design or selection of suitable adsorption equipment include :

— provision for sufficient dwell time ;

4) The corrosive effect exerted by the gas/liquid mixture passing through the throat has to be considered. This problem can be controlled by a careful addition of water together with a proper design of the venturi throat (velocity, use of synthetic material).

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— adequate pre-treatment to remove high concentration of competing gases by other more effective and less expensive process ;

— good distribution of flow through the bed ;

— provision for renewing or regenerating the adsorbent bed after it has reached saturation.

In general gas velocities at the face of the bed are in the range 0,1 m/s to 0,5 m/s with dwell times within the bed in the range 0,6 s to 6 s.

Other processes were recently developed in which an addition of coke/activated carbon with lime is carried out together or separately in a spray dryer. This allows to reduce the problems of possible ignition of pure coke or activated carbon.

$NO_x$ emission control can be performed by catalytic processes (Selective catalytic reduction SCR) or by non-catalytic ones (Selective not catalytic reduction SNCR). Catalytic processes are conducted by impacting in the gas stream a mixture of air and ammonia in presence of a catalyst, which is generally palladium or vanadium oxide.

The process is performed at 300 °C to 350 °C and therefore the gas stream has to be warmed up to this temperature after the preliminary process (de-dusting, scrubbing). It should be considered that the catalyst has the tendency to become poisoned by the formation of ammonium sulfate that is formed on the catalyst in the presence of $SO_2$. A preliminary abatement of this contaminant is, therefore, very important. Non catalytic processes are based on the reaction of ammonia or urea with $NO_x$ with production of nitrogen gas at temperatures of 850 °C to 1 050 °C. The dilute solution is injected, atomised with pressurised air, in the hot gases. This produces radicals $NH_2$ which react with $NO_x$ bringing to formation of $N_2$, $H_2O$, $CO_2$ and minor quantities of $NH_3$. Efficiency of the process depends on the dosage of the reactive chemicals, on the injection point and on the mixing conditions between the reactive chemicals and the gas stream [5)].

Performance of SNCR process is considerably lower than that of SCR. $NO_x$ concentration in the treated stream can be hardly reduced down to 150 mg/Nm$^3$.

Flue gas recycle, or oxygen control, can help in reducing $NO_X$ production. Normally, more secondary air is required to provide turbulence than is needed for supplying oxygen. Flue gas re-circulation replaces 10 % to 20 % of secondary air, reducing oxygen and peak temperatures thereby reducing $NO_x$ formation.

The injection of ammonia can avoid the formation of dioxins in the cooler parts of the circuit. However, the production of $N_2O$ can increase.

*f) Bottom and fly ash handling*

The solid residues of sludge incineration are generally classified as bottom (if they are kept directly from the furnace) or fly ashes (if they are collected in the flue gas treatment devices). In sludge incineration by MHF or RKF bottom ashes are generally prevalent, while in FBF incineration fly ashes are much more abundant. In some FBF installations, however, discharging of heavy materials from the bed is also considered when the head losses in the bed reaches unsuitable values.

Bottom ash can be discharged from the incinerator by mechanical or pneumatic (dry methods) or hydraulic (wet method) systems.

If ash is handled dry, the method should ensure that dust does not become airborne. This can be accomplished either by proper containment or by dust suppression sprays.

These sprays should be limited to ensure they moisten and agglomerate the ash without leading to leachate problems. If handled wet, the ash should be drained before leaving the site.

Fly ash should be stored and transported in a manner that prevents fugitive dust releases. During silo and container filling, displaced air should be ducted to suitable dust arrestment equipment.

5) A capture system of $NH_3$ should be normally considered with respect to current and future limits at the emissions.

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It should be considered to keep fly ash and bottom ash separated also in the view of a possible future recovery of valuable elements (P, K and metals).

*g) Wastewater's disposal*

Waste water originated from the cleaning of exhaust gases can be discharged to the aquatic environment after separate treatment on condition that:

(i) the requirements of relevant European, national and local provisions are complied with in the form of emission limit values; and

(ii) the mass concentrations of the polluting substances do not exceed the emission limit values laid down.

Chemical-physical processes like neutralisation, trace elements precipitation, suspended solids removal are generally used.

Incineration plant sites, including associated storage areas for wastes, is designed in such a way to prevent the unauthorised and accidental release of any polluting substances into soil, surface water and groundwater. Moreover, storage capacity is provided for contaminated rainwater run-off from the incineration plant site or for contaminated water arising from spillage or fire-fighting operations.

The storage capacity should be adequate to ensure that such waters can be tested and treated before discharge where necessary.

*h) Process monitoring*

To maintain steady-state conditions and to guarantee high process efficiency, temperature, pressure and oxygen concentrations, in the furnace and in different sections of the incineration plant, should be properly controlled and continuously measured. In addition, the measurement of gas flow rate at the stack exit can indirectly give information on residence time and turbulence. Continuous monitoring of flue gas quality at the stack exit is needed to comply with regulatory constraints. Parameters to be continuously monitored at the stack exit generally include $NO_x$, provided that emission limit values are set, CO, total particulate, TOC, HCl, HF, $SO_2$, $O_2$, temperature, pressure and water vapour content. Periodical control of trace elements and some organic micropollutants should be also accomplished.

## 6.3 Design aspects

Important key parameters of incineration plant design deal with mechanical parts, refractory, and construction materials. Attention should also be paid to utilities, fuel availability, storage availability, housing requirements, noise levels, safety requirements, spare parts.

Refractory linings are employed to prevent damage to the structural steel shell and to reduce heat losses. Aluminosilicate refractory backed up by insulating brick is most commonly used ; properties of interest are resistance to chemical attack, hardness, heat conductivity, thermal expansion, bulk density, apparent porosity, mechanical strength, thermal shock resistance and chemical composition. Destructive conditions, which they are subjected to during operation, are abrasion, erosion, chemical attack, thermal cycles, mechanical load and high temperature. In particular, high $Al_2O_3$ content can show both glass formation and presence of expansive alkali-alumina-silica phases in presence of alkali. Chlorine reacts with alumina and silica oxides to form volatile chlorides, thus increasing porosity and reducing strength.

Refractory layers should be designed and installed to comply also with “gas tight” parameters which can be critical especially in FBF. The zone of FBF with sand bed has the highest pressure and non-gas-tight construction can result in gas leaks that subsequently form pockets behind the refractory. These pockets fill with combustible mixtures that can ignite and cause “hot spots” on the shell.

Construction materials, especially those used in heat recovery section, should be carefully chosen, considering maximum operating temperature and actions exerted on them by different chemical species that can be encountered in combustion gases.

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# 7 Operational procedures

## 7.1 General

The primary variables affecting incineration performance and costs are fuel and air requirement.

Fuel requirement strictly depends on dry matter and excess air needed to assure a complete combustion. Generally fuel requirement lower than or 70 $Nm^3$ of methane (or equivalent amount of other suitable fuels such as gas oil, town gas, etc.) for wet ton of sludge is considered suitable for an incineration process. When the calorific value of sludge and the heat content of combustion air, if it is preheated, balances the heat content of exhaust gases and the heat losses at the combustion temperature, an autogenous combustion is obtained. For FBF this can be accomplished with a dry matter of about 45 % (volatile concentration 70 % of dry solids) and about 25 % to 30 % for MHF without external air preheating. This concentration lowers to 38 % and 32 % for FBF with air preheating to 230 °C and 600 °C, respectively.

The stoichiometric quantity of air (in kg) is 4,31 times than that of oxygen. Depending on turbulence and therefore on incinerator system, 40 % to 200 % excess air is required to ensure effective operation.

Different procedures for start up and shut down should be adopted depending on furnace type. In any case, the refractory drying before the first start up is one of the most delicate and important operations to be carried out.

Temperature, pressure and oxygen concentrations are the main control parameters.

The temperature is controlled by acting on the fuel, if sludge is not auto-thermal, or by feeding surplus air or by injecting water in the opposite case. However, incineration by autogenous combustion can in some cases involve problems due to the instability of combustion, when amounts of combustibles vary in the feed.

Typical inconveniences of different incineration systems rely with explosions (non-proper start up operations), corrosion and slagging, blocking of feeding systems, emissions in the atmosphere not conforming to the limits.

In MHF incineration, moreover, attention to the presence of CO in the emissions and to the content of incomplete combustion products in the solids residues should be paid.

Maintenance operations have to be carried out with particular regard to the burners, the firebricks, the exhaust gas duct (especially the elbows), all the moving mechanical elements, and the exhaust gas cleaning system.

## 7.2 Specific

*1) Fluidised Bed Furnace*

FBF generally provides more flexibility in furnace operation than the MHF. The primary advantage of the FBF is the ability to operate less than 24 h for day. The FBF is also more responsive to variations in feed quality and rate than the MHF. However, the FBF is limited by fluidising air requirements, which means the unit should operate near design loading even for short periods.

If operated at higher rate than the nominal one, the up-flow velocity could be enough high that gas can carry over large particles with considerable amount of unburned organic. Moreover, gas residence time is reduced and non destroyed organic can also be present in the gaseous phase. On the contrary some reduction of sludge throughput is possible considering that fluidisation velocity is much higher than the minimum fluidisation rate of the bed and therefore a collapsing of the bed is quite unlikely.

With respect to MHF, FBF can better accommodate grease and scum which can be used as auxiliary fuel in sludge burning. These materials can burn in the well-mixed bed, which supplies good contact with combustion air.

The sludge is generally fed in the lower part of the furnace.

The air is fed in the wind box to ensure a proper air distribution below the orifice plate. Fluidising air is passed through this plate by tuyeres and fluidises the sand bed. The pressure drop ranges 250 mm to 600 mm $H_2O$ and strictly depends on the quantity and type of sand, which normally has a bulk density of 1 000 $kg/m^3$.

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The sand particle size ranges 0,1 mm to 2,0 mm depending on the fluidisation rate. The particle size in the bed determines the maximum span that will prevent transport of the bed out of the reactor. Since the freeboard height is 5 m to 6 m, residence time of combustion gases is generally of 5 s to 8 s that is much more than that usually considered in conventional afterburning chamber.

The depth of the static bed is usually 0,5 m to 2 m. During fluidisation this depth approximately doubles and therefore reaches 1 m to 4 m. The temperature of the bed is generally maintained at 750 °C to 820 °C by auxiliary burner(s) located below or just above the bed. The combustion gases, with the entrapped ashes, exit at the bed temperature. The sand bed acts as a heat reservoir thus reducing the temperature drop when the furnace is temporarily out of service.

Due to the high turbulence, the excess air can be as low as 40 %. Fuel consumption is generally higher than in a MHF, as a consequence of higher exhaust gases temperature, but the latter requires the afterburning chamber and therefore total fuel consumption (in the furnace and in the afterburning chamber) increases considerably in MHF-operation, thus making more convenient FBF. It should be pointed out that excess air in MHF is also higher than in FBF and therefore exhaust gas production is more abundant.

Efficient dewatering, pre-drying the sludge and/or pre-heating the air can reduce considerably fuel consumption.

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2) *Multiple Hearth Furnace*

Sludge feeding rate should be as much constant as possible to avoid flame extinction and migration of the combustion zone upward (in the case of a surplus heat in feeding sludge) or downward (increase of the moisture content).

Good operating mode implies that combustion zone should be kept in the lower part of the furnace, possibly on the 3rd and the 4th hearth from the bottom.

The multiple hearth furnaces should be inspected and cleaned on a regular basis to detect the presence of slagging and clinker deposits, preventing natural circulation of air, and of cracked refractory with possible loosing of material. The burner operation without impingement of any surface should be warranted.

Problems encountered with the internal parts of a multiple hearth furnace include failure of rabble arms and teethes, hearths and refractory. The frequency of corrective maintenance detected on several multiple hearth furnaces was approximately of 1 in 10 years for hearths, 1 in 4 years for refractory lining and 1 in 1,5 years for rabble arms and teeth. However, recent improvements in materials used to construct rabble arms and teeth have prolonged the life of the different components and especially their ability to withstand high temperatures. Most of the problems have generally been detected for the instruments and controllers due to instability, unreliability, high upkeep, presence of moisture in the instrument air and maintenance.

It is quite difficult after a variation to reach again stationary conditions because sludge requires more than one hour to reach the combustion zone. Therefore, the effects of control measures can be detected with delay.

Combustion can be controlled by several means, which eventually can be automated to held the desired set points within reasonable limits. The most used parameters include :

— hearth and outlet temperature ;

— oxygen content in the outlet gases and air flow rate ;

— centershaft rotational speed ;

a) hearth and outlet temperature

   — temperature on the different hearths is measured by thermocouples (in some critical point two at opposite sides of the hearth can be adopted) and values are recorded. The temperature of a hearth can be varied rapidly if a burner is present at that location or at the hearth below it. The firing rate has to be increased when the temperature shows a decline due to an increase in the moisture feed rate and/or to a decrease in the calorific value of sludge cake. A drier cake requires addition of supplemental dilution air to avoid a migration of the burning zone upward with a corresponding increase of the outlet temperature, while a less concentrated sludge implies consumption of auxiliary fuel in the burning zone ;

b) oxygen in outlet gases

   — oxygen content in the outlet gases is indicative of the excess air amount entering the furnace. For a non - autogenous sludge oxygen concentration in the outlet gases should be at least 6 % by volume which means operation at an excess air of about 60 % with respect to the stoichiometric value. Oxygen concentration shows a remarkable increase when dry matter overcomes the limit for autogenous combustion due to dilution air. The air flow rate is regulated by controlling the furnace draft which is generally maintained in the range 1 mm to 5 mm water column. A draft loss will force the furnace positive and the gas will not flow properly, creating a safety hazard and discharging hot gases from the furnace. Too much draft, on the contrary, will suck air through the sand seal at the top of the incinerator and will bring too much air into the system ;

   — combustion air is generally controlled considering an excess air with respect to the stoichiometric value of about 100 % and more. The cooling air of the shaft is partially used as combustion air at 180 °C to 230 °C ;

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c) centershaft rotational speed

— centershaft rotational speed can be manually controlled to move the burning zone downward (increase in rotational speed) or upward (decrease in rotational speed) and to control the sludge blanket on the hearths. Rotational speed has to be properly adjusted during start up operation and its variation generally has to be accomplished only following a changing in feed rate or in sludge water content.

*3) Rotary Kiln Furnace*

In RKF sludge occupies a volume generally lower than 10 % of that of the furnace. Residence time of the bottom ashes is of 1 h to 2 h and can be controlled by the rotating rate. The excess air can be as high as 200 %. Gas velocity is 2 m/s to 6 m/s and residence time 1 s to 3 s.

Capacity of RKF can be increased in the limits of the maximum throughput, by increasing the fuel and/or the drum-rotating rate, by decreasing the excess air or by preheating the air. In RKF operation care should be put to prevent possible local shocks to refractory, due to the presence within the sludge of other wastes having high calorific values.

RKF can operate co- or counter-current depending on calorific content of sludge to be incinerated. Counter-current mode could be preferable with wet sludge at solids concentration lower than 30 %, to guarantee a quite constant gas-solids temperature gap along the drum and a more efficient heat transfer and a better combustion of dried material. With *LCV* higher than 2 100 kJ/kg sludge co-current operation can be considered more appropriate as it allows reducing the fine particles entertainment in the exhaust gases.

An important aspect of the RKF operation regards the possible fusion of the ashes inside the drum in co-current operation and their subsequent solidification before they reach the discharge point. This inconvenience can cause a severe blocking of the solids flux and can be overcome by the installation of a second burner on the discharge site, to melt solidified material.

# 8 Management of residues

## 8.1 Flue gas

Pollutants in flue gas are particulate matters, carbon monoxide, sulfur oxides, hydrogen chloride, nitrogen oxides, toxic organic compounds and trace elements.

*a) Particulate matter*

Particulate production from sludge incinerators varies widely, depending on sludge nature and feed rate, incinerator type (highest for FBF, lowest for EF), operating temperature (following volatilisation), and turbulence. Additionally, if semi dry or dry systems are used, the separated particulate matter includes also the reaction products.

Either wet systems or dry ones can be used to remove particulate down to 5 mg/Nm$^3$ [6)].

Control of particulate matter emissions can be performed by different equipment (see 6.2).

*b) Sulfur oxides ($SO_2$) and hydrogen chloride (HCl)*

Wet scrubbing systems, like those used to capture particulate, and packed towers can be used to absorb acidic gases. Alkaline products are often added to water for enhancing removal efficiency of $SO_2$ ; the mechanism of removal is absorption with chemical reaction. Reductions in the effluent up to 15 mg/Nm$^3$ for $SO_2$ and 7,5 mg/Nm$^3$ for HCl are easily obtainable. In FBF operation a capture of $SO_2$ and in lesser extent of HCl can be performed directly in the furnace by an addition of lime and calcium carbonate to the bed.

6) The most suitable system is a venturi scrubber if problems could be created by the sticky nature of fly ash.

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c) *Nitrogen oxides ($NO_x$)*

Nitrogen oxide production in sludge combustion mainly depends on temperature, air distribution and nitrogen concentration in the solids and water matrix of feed sludge.

Nitrogen oxides ($NO_x$) in exhaust gases are mainly constituted by NO and in much minor quantity by $NO_2$, which, conversely, is much more toxic. The main mechanisms responsible of $NO_x$ production are :

— oxidation of nitrogen gas at high temperatures that becomes noticeable when temperature rises to 1 200 °C - 1 300 °C ;

— oxidation of organic nitrogen compounds present in sewage sludge.

d) *Organic compounds (included odours)*

They can be reduced through afterburning. Particularly recommended for MHF, possibly not necessary for FBF, if proper operating modalities are guaranteed.

Other option is the adsorption of organic substances on adsorptive media, such as activated carbon (the most widely used due to its low affinity for moisture), active coke, lime and their mixtures, silica gel, aluminium oxide and magnesium silicate.

This operation can be performed either in dedicated vessels (which allow also the regeneration of media) or by direct addition into the gas stream before the particulate removal devices.

e) *Trace elements*

Heavy metals are generally associated to particulate matter, and emission depends on the their volatility, the combustion temperature, and the presence of other chemical species, like chlorine, which are able to form volatile compounds.

Metal volatility, typically decreases according to the sequence Hg, As, Cd, Zn, Pb and Cu. Boiling temperatures of some metals and nutrients, and their compounds are reported in Table A.6. Metal and compound volatilisation is likely to occur when boiling temperatures do not exceed operating combustion temperature by more than 90 °C. Beyond temperature, other factors have influence on metal volatilisation with particular regard to the presence of chlorine, which can increase volatilisation of Cd, Zn, Pb and Cu, and to the presence of pyrolysis pockets in the combustion chamber, which could be a critical factor for Zn.

Mercury is the most volatile metal and can pose severe problems if present in sewage sludge at concentration higher than 3 mg/kg to 4 mg/kg dry solids and if no special removal system is considered at the installation.

Co, Cr, Cu, Fe, Mn and Ni can be considered non volatile metals and their appearance in the emissions, that can be accounted for 2 % to 11 % of the feed metal, is linked to the particulate presence. Their concentrations in the bottom and fly ashes of the incineration furnace do not depend on its operating mode.

Concentration limits of pollutants at the stack exit have to meet the European, national and regional regulations.

## 8.2 Ashes

Metals likely condense onto fine particulate matter and therefore small, respirable-sized particles tend to have the highest metal concentrations. Moreover, toxicity might also depend on the actual form in which the metal is present (see different carcinogen potential of chromium VI and III) and, consequently, on its availability. Ashes mainly consist of insoluble silicates, phosphates, sulfates and refractory metal oxides, some of which can be soluble. Typical composition of a bottom ash from a MHF is shown in Table A.7 [7)].

7) Attention to the quality of the bottom ash from a *MHF* should also be paid as far as TOC content is concerned.

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The metal concentration of ashes is generally different from that of feed sludge: there may be an enrichment, due to the reduction of loss of ignition, and in same cases a reduction, due to the loss in the emissions in gaseous form or in particulate.

Generally speaking, leachate from sludge ashes represents a small potential source of pollution in a global context.

The dry ash handling systems are suitable when the ultimate disposal site is far from the plant and a long storage time before disposing of will occur.

Wet handling systems can create several problems, such as wear of pumping and piping equipment, plug-ups at bends or restrictions and corrosion above slurry vessels. Control of trace elements concentration in the wastewater to be disposed off is very important to respect standard limits.

Frequent analysis of ash is needed to confirm effective burnout (TOC is less than 3 % or loss on ignition less than 5 %).

According to the types of furnace, to the regulation and to ash quality, ash can be either landfilled or valorised as construction material, filling product and additive in cement production. All these routes affect sludge incineration cost.

Prior to determining the routes for the disposal or recycling of the residues from incineration, appropriate tests should be carried out to establish the physical and chemical characteristics and the polluting potential of the different incineration residues. The analysis concerns the total soluble fraction (including nitrogen, phosphorus and potassium) and heavy metals soluble fraction.

Considering that certain types of ash can contains a rather large amount of phosphorous and other valuable nutrients and micro-nutrients, it can be useful to keep them separated from other waste, in view of recovery.

### 8.3 Wastewater

Wastewater derived from cleaning of exhaust gases and any polluted water exceeding acceptance limits for their discharge into the aquatic environment should be treated in a wastewater treatment plant to respect European, national and local standards. Wastewater can contain chlorides, sulfites, sulfates, phosphates, particulate matter and trace elements.

As the stream does not generally contain biologically degradable organic substances, successful treatment should involve physical-chemical processes.

## 9 Environmental impact assessment

In the most of the Member States general rules and recommendations regarding environmental impact assessment and security measures for different plants are already in force. Whenever appropriate such rules have to be respected also for incineration plants.

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# Annex A

**Table A.1 — Typical analysis of loss on ignition (*LOI*) of sewage sludge**

| Elemental analysis of *LOI* | Primary | Secondary | Mixed | Digested |
|---|---|---|---|---|
| C % | 60,0 | 53,0 | 57,0 | 67,0 |
| H % | 7,5 | 7,0 | 7,0 | 5,0 |
| O % | 28,0 | 30,5 | 30,0 | 25,0 |
| N % | 3,0 | 9,0 | 5,0 | 2,2 |
| S % | 1,5 | 0,5 | 1,0 | 0,8 |
| Total | 100 | 100 | 100 | 100 |

**Table A.2 — Concentrations of metals in sewage sludge**

| Metal | Concentration range (mg/kg dry solids) | Typical concentration (mg/kg dry solids) |
|---|---|---|
| Arsenic | 0,3 to 20 | 2 |
| Cadmium | 1 to 50 | 5 |
| Cobalt | 5 to 30 | 12 |
| Chromium | 40 to 1 500 | 70 |
| Copper | 160 to 1 600 | 260 |
| Lead | 80 to 850 | 100 |
| Mercury | 1 to 12 | 2 |
| Manganese | 100 to 600 | 150 |
| Molybdenum | 4 to 35 | 10 |
| Nickel | 20 to 240 | 30 |
| Vanadium | - | 30 |
| Zinc | 900 to 4 200 | 1 100 |

**Table A.3 — Properties of gaseous products of combustion**

| Compound | Density at 0 °C and 101 kPa ($kg/m^3$) | Specific volume at 0 °C and 101 kPa (L/mole) | Gas constant R (kPa·L/°K·mole) |
|---|---|---|---|
| $CO_2$ | 1,955 | 22,5 | 8,3224 |
| $O_2$ | 1,413 | 22,35 | 8,2719 |
| $N_2$ | 1,250 | 22,39 | 8,282 |
| $SO_x$ | 2,797 | 22,88 | 8,4638 |
| $H_2O$ | 0,803 | 22,43 | 8,2921 |
| Air | 1,297 | 22,36 | 8,2719 |

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**Table A.4 — Specific heats of different compounds (kJ/kg·°C) and relevant enthalpies vs. Temperatures (kJ/kg)**

| Compound | Specific heat (kJ/kg °C) | a | b | c | d | Specific enthalpy Reference gas state 0 °C, liquid state for water 0 °C (kJ/kg) |
|---|---|---|---|---|---|---|
| $CO_2$ | $Cp = a + bT + d/(T + 273,1)^2$ | 1,0546 | $2,61x10^{-4}$ | - | $-1,8595x10^4$ | $aT + bT^2/2 – d/(T + 273,1) + d/273,1$ |
| $O_2$ | $Cp = a + bT + d/(T + 273,1)^2$ | 1,0908 | $3,3741x10^{-5}$ | - | $-2,4548x10^4$ | $aT + bT^2/2 - d/(T + 273,1) +d/273,1$ |
| $N_2$ | $Cp = a + bT$ | 1,0123 | $1,4946x10^{-4}$ | - | - | $aT + bT^2/2$ |
| $SO_2$ | $Cp = a + bT + cT^2$ | 0,5941 | $3,169x10^{-4}$ | $-5,427x10^{-8}$ | - | $aT + bT^2/2 + cT^3/3$ |
| $H_2O$ (steam) | $Cp = a + bT + cT^2$ | 1,9439 | $2,0504x10^{-4}$ | $3,1155x10^{-7}$ | - | $aT + bT^2/2 + cT^3/3 + 2\ 504,5$ |
| NO | $Cp = a + bT + d/(T + 273,1)^2$ | 1,1318 | $3,2503x10^{-5}$ | - | $-2,1804x10^4$ | $aT + bT^2/2 - d/(T + 273,1) +d/ 273,1$ |
| HCl | $Cp = a + bT$ | 0,7955 | $9,6436x10^{-5}$ | - | - | $aT + bT^2/2$ |

**Table A.5 — Typical design parameters for fluidised bed furnace**

| Parameter | Value |
|---|---|
| Bed diameter | 1,5 m to 8 m |
| Freeboard diameter | 1,5 m to 10 m |
| Height | 6 m to 10 m |
| Solid loading rate | 120 kg/m$^2$ h to 300 kg/m$^2$ h |
| Excess air | 40 % to 100 % with respect to the stoichiometric need |
| Radiation loss | 2 % to 4 % of the developed heat |
| Bed expansion | 1,5 to 3 times of the height of the fixed bed |
| Sand losses | 0,05 g/Nm$^3$ to 0,5 g/Nm$^3$ of exhaust gas |
| Velocity at the bottom | 1 m/s to 1,4 m/s |
| Velocity in the freeboard | 0,7 m/s to 1,1 m/s |
| Height of the freeboard | 5 m |
| Thermal loading | 500 kW/m$^2$ to 900 kW/m$^2$ |
| Bed temperature | 750 °C |
| Freeboard temperature | 850 °C |
| Internal pressure | -0,2 kPa to 0 kPa |
| Head losses in the bed | 1,5 kPa to 3 kPa |

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**Table A.6 — Boiling temperature of metals and compounds**

| Compound | Boiling temperature (°C) |
|---|---|
| $As_2O_3$ | 193 |
| $As_4$ | 615 (sublimes) |
| BaO | 2 000 |
| $BeCl_2$ | 520 |
| BeO | 3 900 |
| Br | 59 |
| $CaBr_2$ | 810 |
| Cd | 767 |
| $Cd(NO_3).24H_2O$ | 132 |
| $CdCl_2$ | 960 |
| CdO | 900 to 1 000 |
| Co | 2 900 |
| $CoCl_2$ | 1 049 |
| Cr | 2 200 |
| $CrO_2Cl_2$ | 117 (sublimes) |
| Cu | 2 300 |
| $Cu_2Cl_2$ | 1 366 |
| CuCl | 1 366 |
| $CuCl_2$ | 993 |
| Fe | 3 000 |
| $FeCl_2$ | 670 |
| $FeCl_3$ | 315 |
| $FeCl.36H_2O$ | 280 |
| Hg | 357 |
| $HgBr_2$ | 322 |
| HgCl | 383,7 |
| $HgCl_2$ | 304 |
| K | 720 |
| $KO_2$ | decomposed |
| $K_2O$ | decomposed |
| $K_2O_2$ | decomposed |
| Mg | 1 110 |
| $MgCl_2$ | 1 412 |
| MgO | 3 600 |
| Mn | 1 900 |
| $Mn(NO_3).26H_2O$ | 129,5 |
| $MnCl_2$ | 1 190 |
| Mo | 3 700 |
| $MoCl_5$ | 268 |
| Ni | 2 900 |
| $NiCl_2$ | 973 |
| $P_2O_5$ | 300 (sublimes) |
| Pb | 1 620 |
| $PbBr_2$ | 918 |
| $PbCl_2$ | 954 |
| PbO | 1 535 |
| $SeO_2$ | 317 |
| $SnCl_2$ | 623 |
| V | 3 000 |
| $VCl_4$ | 148,5 |
| Zn | 907 |
| $Zn_3P_2$ | 1 100 |
| $ZnBr_2$ | 650 |
| $ZnCl_2$ | 732 |
| $ZnI_2$ | 624 |
| $ZnO_2$ | 1 800 |

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**Table A.7 — Typical composition of ashes from FBF and MHF**

| Compound | Average concentration for FBF ash (%) | Concentration range for MHF bottom ash (%) |
|---|---|---|
| $Al_2O_3$ | 14,9 | 5 to 20 |
| CaO | 15,2 | 10 to 30 |
| Iron oxides | 10,3 | 2 to 25 |
| $K_2O$ | 1,4 | 0,1 to 1,0 |
| MgO | 2,1 | 1 to 3 |
| $Na_2O$ | 0,8 | 0,1 to 1,0 |
| $P_2O_3$ | 14,2 | 3 to 15 ($P_2O_5$) |
| $SiO_2$ | 34,5 | 20 to 60 |
| $TiO_2$ | 0,7 | 1 to 3 |
| MnO | 0,1 | - |
| ZnO | - | 0,1 to 0,5 |

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