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Characterization of sludges — Guideline of good practice for thermal processes

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National foreword

This Published Document is the UK implementation of CEN/TR 16788:2014. It supersedes PD CEN/TR 13767:2004 and PD CEN/TR 13768:2004 which are withdrawn.

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Charakterisierung von Schlämmen - Anleitung für die gute fachliche Praxis thermischer Prozesse

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Foreword

This document (CEN/TR 16788:2014) has been prepared by Technical Committee CEN/TC 308 “Characterization of sludge”, the secretariat of which is held by AFNOR.

This document supersedes CEN/TR 13767:2004 and CEN/TR 13768:2004.

Introduction

It is recognized that wastewater sludge is a potential source of valuable resources. Material recycling is higher in the waste hierarchy (ref. 2008/98/EC Directive) than recovery (energy and material). Sludge incineration and other organic matter treatments by thermal processes (gasification, pyrolysis and wet oxidation) should deal with materials which do not meet beneficial use requirements. They represent a consistent year round solution. To decide which type of solution is appropriate for a particular sludge, Figure 1 should be consulted.

Thermal processes involve, among others, reduction of volume and weight, highest destruction of toxic organic compounds, possible recovery of phosphorus and other useful materials. Drawbacks include high costs and complexity of plant operation.

In all cases, the energy balance (including energy for removing water etc.) and carbon footprint of the processes should be calculated to verify the environmental benefit of the process.

A good performance of a thermal processing plant also depends upon the provision of proper auxiliary equipment and devices, which include receiving and storage systems, pre-treatments equipment, feeding system, flue gas cleaning, heat recovery, ash handling, wastewater disposal and process monitoring.

The purpose of this Technical Report is to describe good practice for sludge incineration and other organic matter treatments by thermal processes 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 balance, emissions control and equipment durability;

— provide the responsible authorities with well-established and easily applicable protocols for control purposes;

— promote the diffusion of good practice;

— contribute to taking appropriate decisions.

Priority should be given to reduction of pollutants at the origin and to recover, if technically and economically feasible, valuable substances (e.g. phosphorus) from sludge and derived products.

As part of a process and company quality approach, the relevant issues are therefore:

— exploiting the operating data and the statutory inspections carried out;

— rendering the process reliable, optimizing and of perpetuating it, as well as guaranteeing a permanent development;

— maintaining a climate of confidence between the authorities, the sludge producers, the transporters, the incineration plant and waste disposal site operators and allowing the services to be provided on a contractual basis.

The local considerations to be taken into account are:

— the adoption of a more convenient solution with respect to other options;

— the geographical context, the client population and therefore the potential input material as well as the expected developments;

- the proximity of the sewage treatment plant and the local transportation network;
- the capacity of treatment plants.

All of the recommendations of this document constitute a framework within which the thermal processes can be proposed in addition to and/or as a substitution for land utilization, landfilling when allowed, or any other process when relevant situations occur and appropriate conditions are met.

The management of sludges both upstream and downstream of the treatment process to ensure that it is suitable for the outlets available is outlined in CEN/TS 13714:2013.

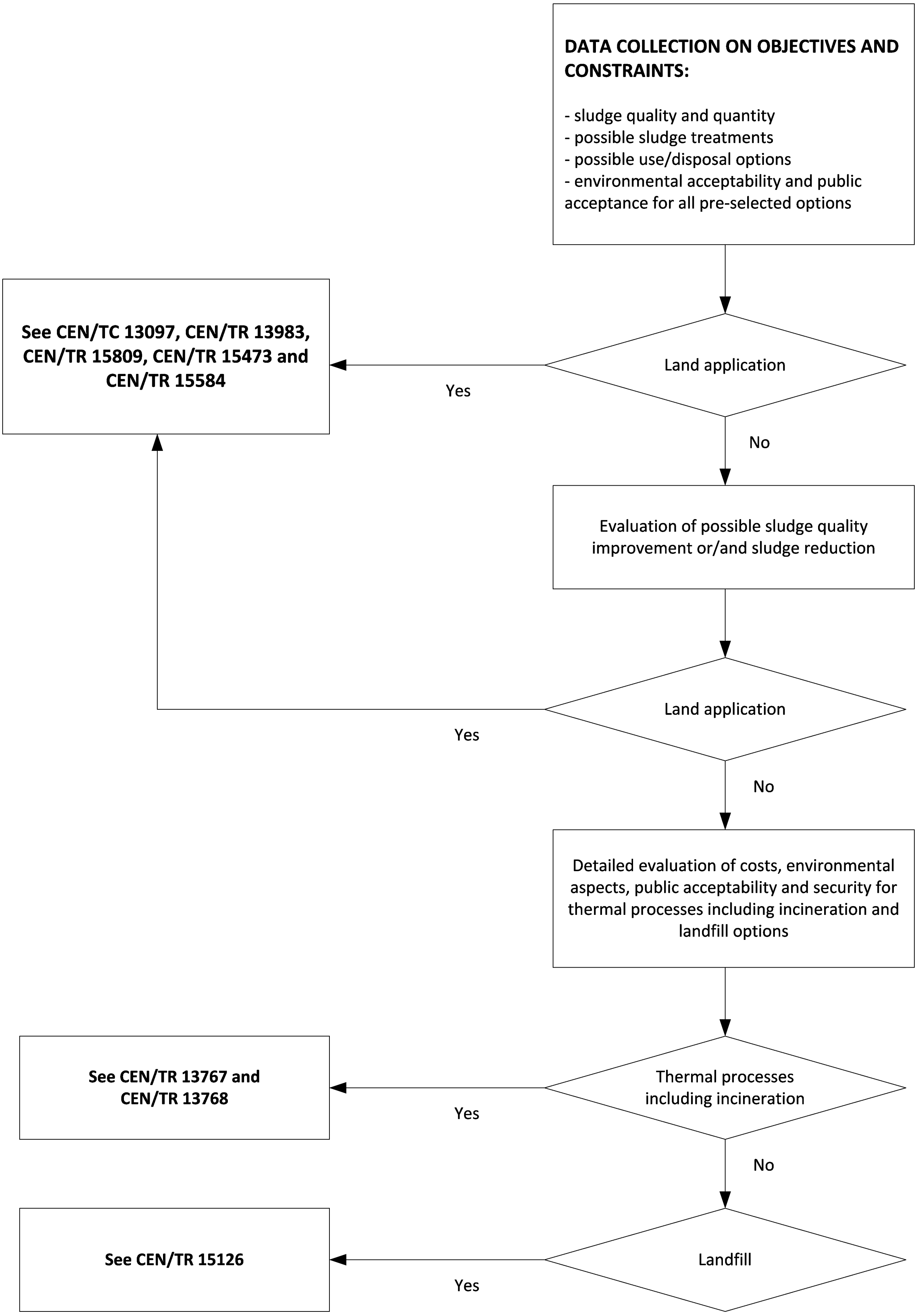


Figure 1 — A basic scheme for deciding on sewage sludge use/disposal options and the relevant CEN/TC 308 guidance documents

1 Scope

This Technical Report describes good practice for the incineration and other organic matter treatment by thermal processes of sludges.

Thermal drying, thermal conditioning and thermal hydrolysis are excluded.

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

- storm water handling;
- night soil;
- urban wastewater collecting systems;
- urban wastewater treatment plants;
- treating industrial wastewater similar to urban wastewater (as defined in Directive 91/271/EEC);

but excluding hazardous sludges from industry.

2 Normative references

Not applicable.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
thermal treatment
reduction of organic matter by incineration, gasification, pyrolysis and wet air oxidation

3.2
thermal process
technique for the application of thermal treatment

3.3
combined thermal treatment
thermal treatment of sludge and other waste in the same device

3.4
pyrolysis
thermal treatment without supply of oxygen

3.5
gasification
thermal treatment with less than the stoichiometric supply of oxygen or air (partial combustion)

3.6
furnace
enclosed chamber where combustion of organic matter takes place

3.7
boiler
specific part of the thermal treatment plant where heat exchange takes place in view of recovering heat and energy

3.8
flue gas treatment
any physical or chemical process aimed at cleaning the gas emission resulting from the thermal treatment with the regard to their discharge into the atmosphere

3.9
bottom ash
combustion residue collected at the bottom of combustion furnaces

3.10
fly ash
solid material that is entrained in a flue gas stream

3.11
energy recovery
activity to use combustible waste as a means to generate energy through thermal treatment with recovery of heat

3.12
recycling
activity in a production process to process waste materials for the original purpose or for other purposes, excluding energy recovery

3.13
slag
partially glassy by-product obtained by cooling a mineral liquid phase

3.14
energy efficiency
amount of energy and/or heat recovery in relation to the energy content of input material

3.15
wet air oxidation
aqueous-phase oxidation of organics under pressure, using either air or oxygen as the oxidant

3.16
syngas
mixture of gases (including carbon monoxide, hydrogen, methane, etc.) produced from gasification or pyrolysis process

3.17
char
combination of non-combustible materials and carbon produced from devolatization, gasification or pyrolysis process

3.18
combustion
chemical and exothermical reaction with full oxidation of combustible materials

4 Abbreviations

For the purposes of this document, the following abbreviations apply.

BAT	Best Available Techniques
COD	Chemical oxygen demand
DM	Dry Matter
ELV	Emission Limit Values
GCV	Greater (or gross) Calorific Value
HTFB	High Temperature Fluidized Bed
LCV	Lower (or net) Calorific Value
LOI	Loss On Ignition
LPO	Low pressure oxidation
MHF	Multiple Hearth Furnace
MHV	Medium heating value
MSW	Municipal solid waste
NO_x	Nitrogen oxides
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PCDD	Polychlorodibenzodioxins
PCDF	Polychlorodibenzofurans
RKF	Rotary Kiln Furnace
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
TOC	Total organic carbon
UDG	Up-draught or Counter-current gasifier
WWTP	Wastewater treatment plant

5 Regulatory aspects

European regulations on thermal treatment of waste have been merged in Directive 2010/75/EU on industrial emissions. This text merges seven previous European directives concerning the main industrial sectors and especially the directives on the incineration of wastes (Directive 2000/76/CE) and on integrated pollution prevention and control (Directive 2008/1/CE).

For the European regulation, an incineration plant is dedicated to the thermal treatment of wastes with or without recovery of the combustion heat generated. This includes the incineration by oxidation of waste as well as other thermal treatment processes such as pyrolysis, gasification or plasma processes in so far as the substances resulting from the treatment are subsequently incinerated (this is not applicable if the gases resulting from the thermal treatment of waste (pyrolysis or gasification) are purified to such extent that they are no longer a waste and they cause emission no higher than those resulting from the burning of natural gas).

Incineration plant shall operate with a permit including provisions related to operating condition and emission limit values. Best Available Techniques shall be considered for all stages of the life cycle of the thermal treatment plant: conception, operation and closure.

Some of the operating conditions are, among others the following:

— a level of incineration, such that the slag and bottom ashes TOC content, shall be less than 3 % or their loss on ignition less than 5 % of the dry weight of the material shall be achieved;

- the gas resulting from the process shall reach, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavourable conditions, the temperature of 850 °C. If hazardous waste with a content of more than 1 % of halogenated organic substances is incinerated the temperature shall be at least 1 100 °C. These temperatures shall be measured near the inner wall or at another representative point of the combustion chamber as authorized by the competent authority and kept for 2 s;
- an automatic system to prevent waste feed shall be operated when temperatures are below prescribed values;
- any heat generated by the incineration process shall be recovered as far as practicable.

Limits are also given for (i) water discharges from the cleaning of exhaust gases, (ii) flue gas emission and (iii) residues which shall be recycled, where appropriate, directly in the plant or outside in accordance with relevant legislation.

The Emission Limit Values (ELV) are fixed in accordance with the emission values which are reachable with the implementation of the Best Available Techniques (BAT). With the revision of the integrated pollution prevention and control directive (2008/1/EC) and the publication of the Industrial Emission Directive (2010/75/EU), the ELV cannot exceed the Best Available Technique associated emission level.

The emission limit values are reported in Annex A. It can be seen that the main difference from the previous directives is the half-hourly average emission limit values.

6 Sludge properties

6.1 General

Sludge characterization for the assessment of thermochemical processes involves the evaluation of both technical and economic parameters. The main technical characteristics to evaluate the suitability of thermochemical processing are dry matter or moisture content, calorific value, ash content. The main economic parameters are cost of processing, collection and transport, and the characteristics of the recovered materials and by-products.

6.2 Physico-chemical characteristics

6.2.1 General

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

- dry matter (or moisture content);
- loss on ignition;
- calorific value;
- amount of grease, scum and screenings.

Physical consistency, together with rheological properties, also play an important role, especially as far as the design of feeding system is concerned.

6.2.2 Dry matter

The dry matter (DM), or moisture content, is of primary importance for thermal processes because it strongly affects the Lower Calorific Value (LCV) of organic material which decreases when the moisture content increases.

In thermal processing of sewage sludge dry matter is a parameter affecting both fuel requirement and exhaust gas production. Generally speaking, any increase in dry matter is believed to be beneficial in the combustion for the reduction in fuel requirement. When the condition for autogenous combustion, at a given temperature, 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 involves a more abundant gas production, due to dilution air or water needed for the control of the combustion chamber temperature depending on design of incineration plant. However, the use of water, 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.

6.2.3 Loss on ignition

The loss on ignition represents the portion mass escaping as gas as a result of the ignition of the dry mass of sludge.

The loss of ignition is generally used as a measure of the volatile matter content but it should be noted that inorganic substances or decomposition products (e.g. H_2O, CO_2, SO_2, O_2) are released or absorbed and some inorganic substances are volatile under the reaction conditions.

It is measured by heating sludge in a furnace at (550 ± 25) °C and expressed as percent of the dry mass. The loss on ignition can be used as an assessment of the organic part of the sludge, and is therefore related to its heat value.

The presence in the sludge of iron with oxidation during ignition from iron (II) to iron (III), and of calcium hydroxide or calcium oxide, when sludge is conditioned with lime, can involve decreasing of the loss on ignition value (EN 12879).

6.2.4 Calorific value

Calorific value of sludge is a very important parameter for the evaluation of thermal processes, as it represents the heat quantity developed in the combustion process by the unit mass of material in standard conditions.

The Calorific Value can be expressed as (see EN 15170):

- Greater (or Gross) calorific value (GCV) at constant volume with both the water of the combustion products and the moisture of the sludge as liquid water;
- Lower (or Net) calorific value (LCV) obtained by calculation from the Gross calorific value provided that either the hydrogen content of the sludge or the amount of water found in the combustion test has to be determined.

Sludge usually contains much water, combustible and incombustible solids. Therefore their calorific value, especially on the “as received” basis – is quite low.

The calculation of calorific value of sludge is based on LOI (loss on ignition or organic matter content).

Typical calorific values of municipal wastewater sludge 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 sludge display values between 20 700 kJ/kg *LOI* and 24 400 kJ/kg *LOI*.

GCV and LCV values can be calculated according to the standard method EN 15170, while the procedures for the theoretical calculation of GCV and LCV are reported in Annex B.

6.2.5 Grease, scum and screening

Grease, scum and screenings can be thermally treated together with sludge but generally they pose several problems.

Screenings clog feed mechanisms for certain types of furnace and therefore grinding or shredding is advisable before feeding. Screenings also contain bulky and incombustible materials, which create problems in the ash disposal system.

Skimmed material generally contains more than 95 % moisture and therefore it should be dewatered to at least 25 % solids before treatment. Skimming is difficult to handle in the dewatered state due to its viscosity and a heating process to 70 °C - 80 °C is generally requested to get skimming pumpable. After dewatering, scum solids should be ground to a size not exceeding 6 mm. *GCV* of skimming and screenings are in the range 37 000 to 44 000 kJ/kg DM and 23 000 to 25 600 kJ/kg DM, respectively.

Quantities of screenings are strictly dependent on the screen openings: they can vary in the range of $3x10^{-6}$ m^3/m^3 to $40x10^{-6}$ $m^3/m^3$of sewage for openings 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 DM/m^3 of sewage which means up to 1,7 % of sludge production. At a concentration of 25 % this value increases to 6,8 %.

The quantity of any added material, especially grease, scum and screening, is limited by the capacity and the efficiency of the gas treatment.

6.2.6 Physical consistency and others

The physical consistency of the sludge will influence the selection and design of thermal processes.

Therefore, the evaluation of specific parameters giving information on this aspect (e.g. flowability, solidity, piling behaviour) appears useful in this designing step.

Other characteristics influencing thermal processes are particle size, bulk density and morphology.

6.3 Chemical characteristics

6.3.1 General

The main chemical characteristics to be taken into account are:

- sulphur;
- phosphorus;
- nitrogen;
- chlorine and other halogens;
- organic micro pollutants;
- trace elements (especially mercury).

The presence of the above mentioned chemicals has to be known in order to prevent or minimize toxic emissions (gaseous, liquid, solid) from thermal processes.

Typical elemental composition of primary, secondary, mixed and digested sludge is given in Table C.1.

6.3.2 Sulphur

The sulphur content of sewage sludge ranges generally from 0,5 % to 2 % of dry matter.

In anaerobic digestion, sulphate is converted to sulphide by sulphate reducing bacteria. Some of it precipitates with iron and other metals as insoluble sulphides, while some other is stripped as hydrogen sulphide and is transferred to the biogas stream from which it can be removed by scrubbers. The amount of residual sulphides in anaerobically digested sludge is proportional to the metal content in the raw sludge. If sludge is not treated anaerobically, most of the sulphate remains in solution as such. If poly ferrous sulphate and ferric chloride are used as inorganic conditioners in thickening and dewatering, sulphur content increases. Sometimes, this can affect the cost of acid gas removal (e.g. in flue gas desulfurization, FGD). Because a fraction of the sulphur is present in the oxidized sulphate form, not all of this sulphur is converted to sulphur dioxide during combustion. Sulphur dioxide then combines with moisture, either in the waste gas treatment system or in the atmosphere, to form sulphuric and sulphurous acids.

6.3.3 Phosphorus

Phosphorus may be present in sewage sludge in concentration ranging from 1 % to 5 % dry matter. This concentration mainly depends on the phosphorus load in the wastewater system and on the level of phosphorus removal accomplished in the treatment plant.

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; therefore, recovery of phosphorus from ashes should be considered.

6.3.4 Nitrogen

Nitrogen content of sewage sludge ranges from 2 % to 12 % of dry matter; typical values are around 5 % to 7 % of volatile solids in a mixed primary and secondary sludge. Organic nitrogen 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).

6.3.5 Chlorine and other halogen

Organic and inorganic chlorine compounds play an important role in the combustion processes after tendency of the chlorine radicals to bind active radicals, like O*, H*, OH*, RO*, thus determining a decrease in the combustion rate with potential formation of toxic compounds. Chlorine and other halogens are also responsible for the presence in the exhaust gases of undesirable acidic compounds inducing corrosion problems especially at high temperatures. The presence of organic chlorine in sewage sludge is generally negligible (less than 50 mg/kg DM) but the concentration of inorganic chlorine may exceed some units per cent dry mass depending on the chlorine content in the sludge water and on the use of inorganic conditioners. The agroindustry sludge, similar to sewage sludge mentioned in Directive 91/271/EC, from food and/or beverage transformation and production, do not contain organic chlorine. As for sewage sludge, inorganic chlorine can be present in such sludge after the use of $FeCl_3$ as conditioning agent.

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

6.3.6 Organic micro pollutants

Although the presence of biopersistent organic micro pollutants (such as chlorinated hydrocarbons, phenols and polyphenols, polychlorinated biphenyls (PCB), pesticides and polycyclic aromatic hydrocarbons (PAH) and pharmaceuticals) in sewage sludge may be in some cases noticeable, they generally do not pose relevant problems in thermal processing.

Formation of dioxins can be a serious problem depending on the gas treatment and the temperature of the incineration. Dioxins can be formed again (*de novo* synthesis) during the gas treatment, especially in the range of temperature 200 °C to 600 °C, for sludge with a high content in organochlorine compounds, this can be avoid by a rapid quench of the exhaust gas. Significant formation of particularly stable compounds has been evidenced in oxygen-deficient environments.

6.3.7 Trace elements

The presence of trace element, such as mercury, arsenic, lead, cadmium and zinc, in sewage sludge shall be considered for their tendency to be transferred in the gaseous phase. Except for mercury, they may be concentrated in fly ashes collected in bag and electrofilters. Mercury generally escapes with flue gases but can be condensed in scrubbers or captured by activated carbon filters.

Trace elements are generally present in sewage sludge at variable concentrations depending on the proportion of industrial effluents in the wastewater. Table C.2 shows the typical concentration range of trace elements.

7 Thermal processes fundamentals

7.1 Incineration

Incineration (or combustion) is an oxidation reaction carried out at high temperature which makes it possible to reduce both the mass and volume of the materials being treated by reducing them to ash, while taking advantage of their inherent energy potential. The contained water, converted into vapour, and the organic matter converted into combustion gases are discharged into the atmosphere after treatment.

The reaction of oxygen with carbon, hydrogen and sulphur yields energy and products of combustion, namely, carbon dioxide (CO_2), water (H_2O) and sulphur dioxide (SO_2). Organic nitrogen is preferentially converted to nitrogen gas but a certain amount (2 % to 7 %) can also be further oxidized 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 reactions taking place are:

$$C + O_2 \rightarrow CO_2 + 393.77J$$

$$C_xH_y + (x + y/4)\ O_2 \rightarrow xCO_2 + y/2\ H_2O$$

Incineration produces a waste gas composed primarily of carbon dioxide (CO_2) and water (H_2O). Other air emissions include nitrogen oxides, sulphur oxides, etc. The inorganic content of the waste is converted to ash.

In the case of lack of oxygen (generally referred as starved-air combustion) the reactions are characterized as incomplete combustion ones, where the produced CO_2 reacts with C that has not been consumed yet and is converted to carbon monoxide (CO) at higher temperatures:

$$C + CO_2 + 172.58J \rightarrow 2CO$$

The temperature achieved in the combustion process will depend on the balance between the energy inputs and the energy outputs. Nevertheless, concerning European legislation it shall be ensured that the temperature is higher than 850 °C during a 2 s time period.

All oxidizing combustion reactions require some excess air to ensure that the reaction proceeds rapidly to completion. Air required for combustion is mainly a function of time of stay, temperature and turbulence, commonly referred to as the “3Ts of combustion”. Generally as turbulence is maximized, 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 % (1,2 to 1,3 times the stoichiometric amount of air) excess air while less efficient furnaces, like multiple hearth and rotary kiln furnaces, need 100 % to 125 % (2,00 to 2,25 times the stoichiometric amount of air) excess air at least. As excess air quenches the combustion temperature it is desirable to minimize 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.

The influence of cake concentration on fuel consumption, air requirements and flue gas production in incineration of sewage sludge is known. It has been shown that fuel consumption, air and flue gas production may be expressed as a linear function of cake concentration, with line slopes changing at the two points identified by the operating modes of (i) minimum concentration for autogenous combustion in the furnace, and (ii) minimum concentration for no air requirements in the afterburning chamber.

The ash consisting of inorganic material and incombustible organic substances, has to be managed for recovery or disposal according to national regulations.

Incineration comprises three principal phases corresponding to three conversion zones:

- the first step of combustion is the drying of the waste through contact with hot gases and decomposition into volatile materials which rapidly reach their ignition temperature;
- continuation of combustion as the waste moves or is moved through the furnace;
- gradual conversion into bottom ash which is then extracted and cooled down.

To avoid consuming make-up energy from fossil sources, it is desirable to achieve a thermal balance, i.e. so that the heat supplied by the combustion of the organic matter is sufficient to evaporate the water, to heat the combustion air and to raise all the combustion gases to a particular temperature (laid down by national regulations). Combustion in the system is then said to be self-sustaining. In order to achieve self-sustaining conditions, sludge have to be sufficiently dewatered or dried.

7.2 Gasification

Gasification is the process of conversion by reactions with gasifying agents of a solid biomass feed material to a combustible gas (syngas). Gasification starts by providing external heat and a less than stoichiometric supply of oxygen or air to allow some combustion of the carbon to CO_2, which then reacts with solid carbon, to produce CO.

Temperatures in a gasifier range from 500 °C to 1 700 °C depending on the process. This process works better if the sludge can be previously dried with a minimum DM content of 70 % this needs a high effective pre drying stage which could increases expenses.

The main reactions taking place during gasification are:

$$C + O_2 \rightarrow CO_2 \text{ (oxidation, exothermic)}$$

$$C + H_2O \rightarrow CO + H_2 \text{ (water evaporation/ gas reaction, endothermic)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (exothermic)}$$

$$C + CO_2 \rightarrow 2CO \text{ (Boudouard reaction, endothermic)}$$

$$C + 2H_2 \rightarrow CH_4 \text{ (} CH_4 \text{ formation, exothermic)}$$

Main factors affecting the process are final temperature, residence time, rate of heating, gas atmosphere and pressure.

In principle, gasification offers some advantages over combustion; a gas has better burning properties in relation to a solid; the burning process is easier to control, needs less air excess, allows for simpler burner construction, causes no particle emissions, less air pollution and less fouling of the heat exchange equipment. Further, gases can be burned in internal combustion engines and can be easily applied in combined cycles.

Conventional gasification of sewage sludge also generates a solid residue (char) that still contains some volatile material and inorganic pollutants depending of the quality of the input material and process. The disadvantages with respect to incineration include relatively complex system, and variable costs; There is no clear evidence about the fate of heavy metals in conventional gasification systems.

In addition, for sludge there is no industrial application.

7.3 Pyrolysis

Pyrolysis (also referred as Carbonization) is thermal degradation in the absence of an oxidizing agent at temperatures of 400 °C - 800 °C.

The products from pyrolysis are a solid residue (mainly char) and a synthetic gas (syngas), while some of the volatile components form tars and oils that can be removed and reused. Char is a combination of non-combustible materials and carbon. The syngas is a mixture of gases (including carbon monoxide, hydrogen, methane, etc.).

The low temperature of operation eliminates the formation of SO_2 and NO_x and the gas and solid fractions produced can be used as a fuel.

The initial reaction is decomposition where organic components of low volatility are converted into other more volatile ones:

$$C_xH_y \rightarrow C_cH_d + C_mH_n$$

Reactions occurring during the early stages include condensation, hydrogen removal and formation of ring compounds that lead to solid residues from organic substances of low volatility:

$$C_xH_y \rightarrow C_pH_q + H_2 + \text{coke}$$

CO and CO_2 will be produced and the interaction with water is possible if oxygen is available to the process.

The relative proportions of the three products, i.e. gas, liquid and char, depend very much on the pyrolysis method and reaction parameters. Basically there are four types of pyrolytic reactions, i.e. conventional or Slow Pyrolysis, Flash Pyrolysis, Fast Pyrolysis, Catalytic Pyrolysis.

Pyrolysis is not effective in either destroying or physically separating inorganics. Byproducts containing heavy metals may require stabilization before final disposal. Volatile metals may be removed as a result of the higher temperatures associated with the process, but they are not destroyed.

7.4 Wet (air) oxidation

The wet oxidation, also called Wet Air Oxidation (WAO) is based on aqueous-phase oxidation of the organics in sewage sludge, using either air or oxygen as the oxidant.

The oxidation reactions occur at a temperature above the boiling point of water (100 °C), but below the critical point (374 °C) above which this is the domain of Supercritical Wet Oxidation (SCWO). The oxidation reactions occur at temperatures of 150 °C to 320 °C and at pressures from 10 to 220 $x10^2$ kPa. Higher temperatures require higher pressure to maintain a liquid phase in the system.

For sludge, the oxidation takes place at 250 °C - 300 °C and 50 to 100 $x10^2$ kPa.

The process can involve any or all of the following reactions:

$$\text{Organics} + O_2 \rightarrow CO_2 + H_2O + RCOOH \text{ (short chain organic acids)}$$

$$\text{Sulphur species} + O_2 \rightarrow SO_4^{-2}$$

$$\text{Organic Cl} + O_2 \rightarrow Cl^{-1} + CO_2 + RCOOH$$

$$\text{Organic N} + O_2 \rightarrow NH_3 + CO_2 + RCOOH$$

$$\text{Phosphorus} + O_2 \rightarrow PO_4^{-3}$$

The majority of commercial wet oxidation systems are used to treat industrial wastewater.

7.5 Others

Plasma technology is established for waste. It is just being tested for sludge.

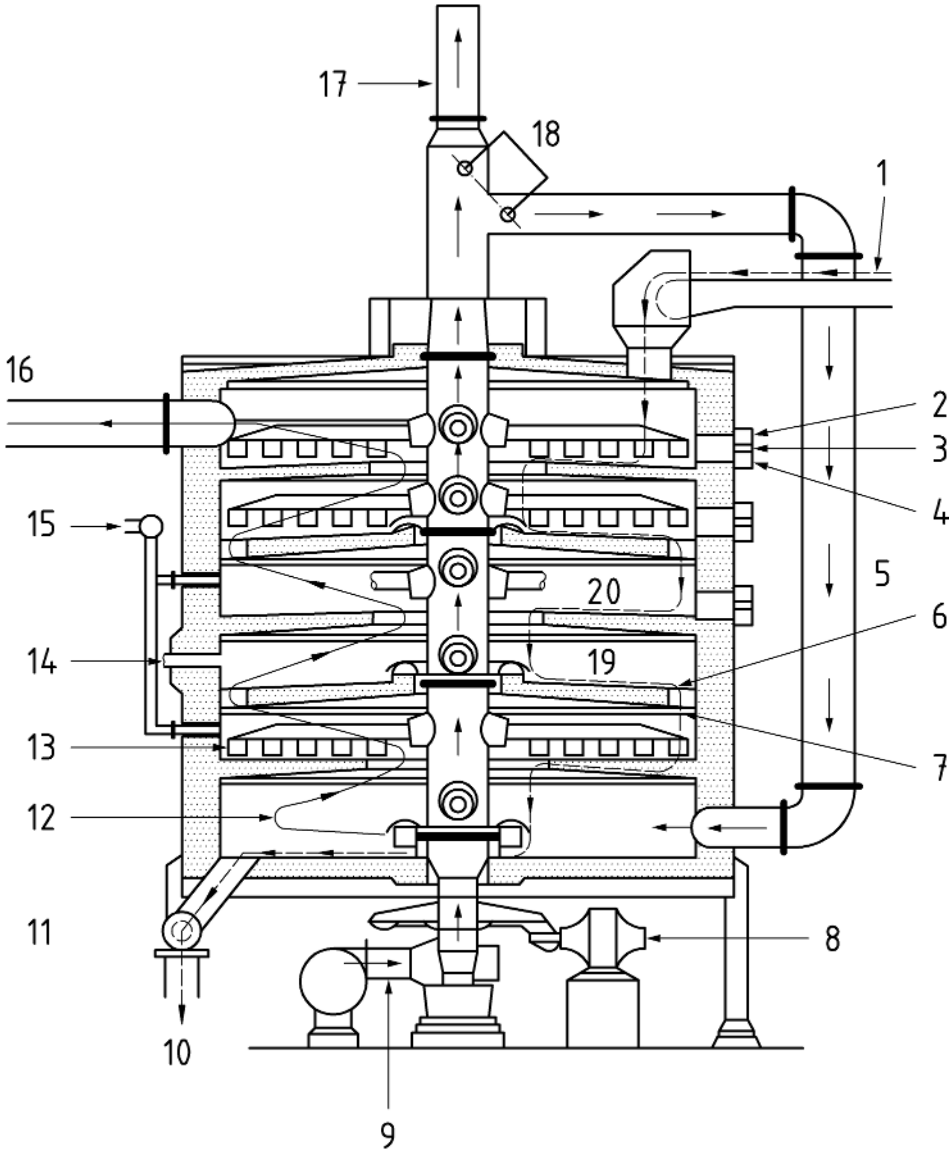
8 Equipment

8.1 Incineration devices

8.1.1 General

The types of device most commonly used for sludge mono-incineration are the Fluidized Bed Furnace (FBF), the Multiple Hearth Furnace (MHF), including combination of MHF and FBF.

Other types are the Rotary Kiln Furnace (RKF), the Electric Furnace (EF) and Cyclone Furnace (CF).



Key

1	sludge cake screenings and grit	11	clinker breaker
2	burners	12	gas flow
3	supplemental fuel	13	rabble arm (2 or 4 per hearth)
4	combustion air	14	auxiliary air ports
5	shaft cooling air return	15	scum
6	solids flow	16	exhaust gas
7	drop holes	17	cooling air discharge
8	rabble arm drive	18	damper
9	shaft cooling air	19	in hearth
10	ash discharge	20	out hearth

Figure 2 — Multiple hearth furnace (typical cross section)

For sludge co-incineration, Stocker type incinerators and power stations are commonly used.

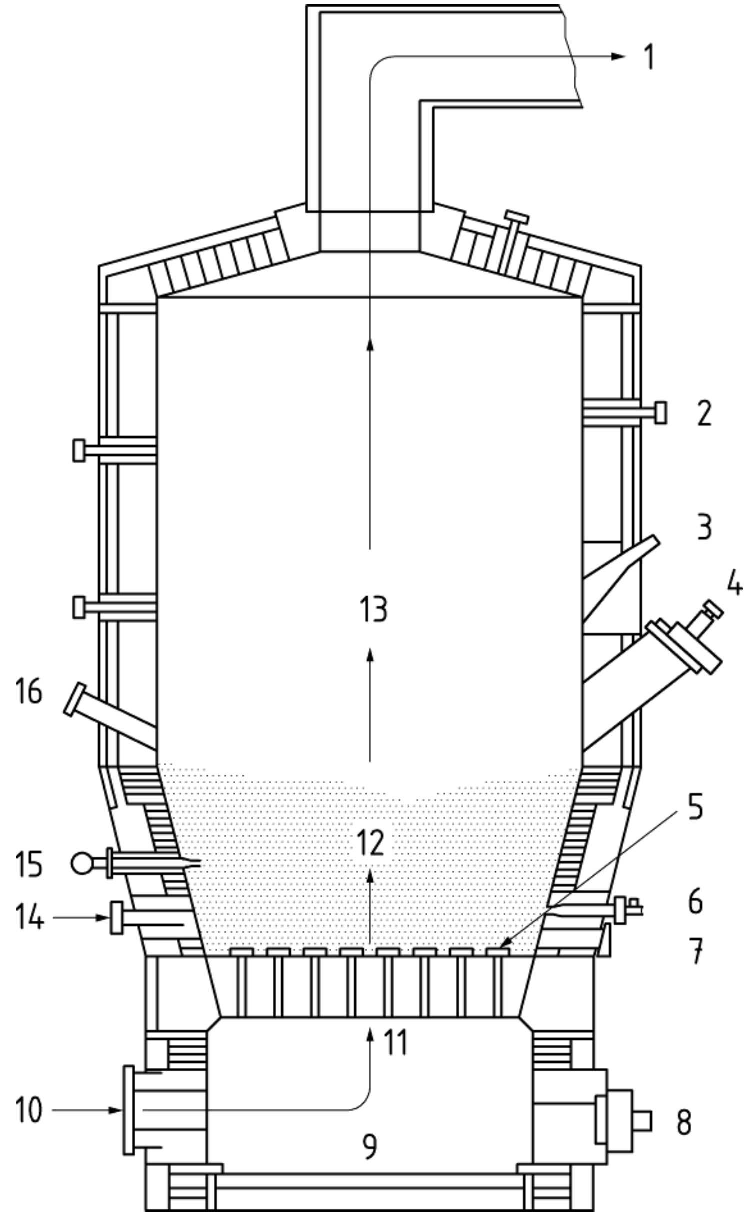
8.1.2 Fluidized Bed Furnace (FBF)

It consists of a cylindrical refractory lined shell containing a sand bed fluidized during operation by air through a distributor plate below the bed. The temperature of the bed is controlled above 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.

Circulating fluidized bed furnaces are common for firing coal or other high-calorific fuels in power stations therefore they are not used for sludge incineration.

A cross section of a bubbling FBF is shown in Figure 3.



Key

1	exhaust and ash	9	windbox
2	pressure tap	10	fluidizing air inlet
3	sight glass	11	refractory arch
4	burner	12	fluidized sand bed
5	tuyeres	13	freeboard
6	fuel (and water) injection lances	14	sludge inlet
7	pressure tap	15	thermocouple
8	start-up preheat burner for hot windbox	16	sand inlet

Figure 3 — Bubbling fluidized 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.

The FBF can be designed with a hot wind box (400 °C to 700 °C) that reduces the auxiliary fuel consumption in case of wet sludge feeding. Hot wind box means, that the incineration air will be warmed up by means of a flue gas pre-heater. Disadvantages include sand carry-over with the ash, and possible formation of a block of vitrified sand when salts with low melting points are present. This problem can be solved by an addition of chemicals to bind the alkaline salts or by filling in fresh sand at a proper time. In the urban sludge treatment the risk of vitrified block sand is very low.

FBF are usually designed to operate in authermal conditions (neither use of oil nor natural gas). Therefore a pre-drying is normally needed.

FBF is the BAT for sludge incineration.

8.1.3 Multiple Hearth Furnace (MHF)

It consists of 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.

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.

8.1.4 Combination of FBF and MHF

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

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 characterized 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 fluidized 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.

8.1.5 Others

Rotary Kiln Furnace consists of 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 %.

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.

Operation involves low combustion efficiency, high need of excess air and high fuel consumption.

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.

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.

8.2 Gasification devices

Commercially available furnaces include Fixed bed reactors, Entrained bed, Fluidized bed, Multiple hearth (see Figure 2), Rotary kiln, and some other patented processes.

Looking to the applications, a further distinction can be made between power gasifiers and heat gasifiers. Power gasifiers require a more or less tar- and dust-free gas, while heat gasifiers are not very sensitive to these types of impurities.

- Fixed bed gasifiers: have a stationary reaction zone typically supported by a grate and operate at low temperatures (400 °C - 650 °C) for the outlet gas and have high thermal efficiency. Small-scale gasifiers are generally of this type. Up-draught, or Counter current gasifier (UDG) (see Figure 4), is the oldest and simplest type of gasifier. The air intake is at the bottom and the gas leaves at the top. The tars and volatiles produced during this process will be carried in the gas stream. Ashes are removed from the bottom of the gasifier. In the down-draught gasifiers (DDG) primary gasification air is introduced at or above the oxidation zone in the gasifier. The producer gas is removed at the bottom of the device, so that fuel and gas move in the same direction, as shown in Figure 5. Downdraught gasifiers have the potential of producing a tar-free gas suitable for engine applications.

- In the entrained flow gasifiers the feedstock (fuel) is suspended by the movement of gas to move it through the gasifier. Finely pulverized fuel (100 µm - 600 µm) is gasified within seconds at high temperatures (1 500 °C - 1 900 °C). The feed is entrained with oxygen and steam in a co-current flow, which requires an air separation unit which increases costs and energy use. The gasification process quick reaction time allows for a very high throughput, less problem with caking fuels, and highly efficient carbon conversion. Due to the high temperature of the outlet gas (1 250 °C – 1 600 °C), the product gas contains no tar or methane, but requires a large effort in gas cooling.

In Fluidized-bed gasifiers the turbulent mixing results in uniformity of the product gas and gives a maximum heat and mass transfer between the gases and solids. It also results in a high throughput, although not quite the level of entrained flow gasifiers. Operating temperatures are around 600 °C - 1 000 °C depending on heating methods, indirect heating being the lower. Depending on design, biomass can be fed into the top, bottom, or middle of the moving bed. Heat to drive the gasification reaction can be provided in a variety of ways in fluidized bed gasifiers.

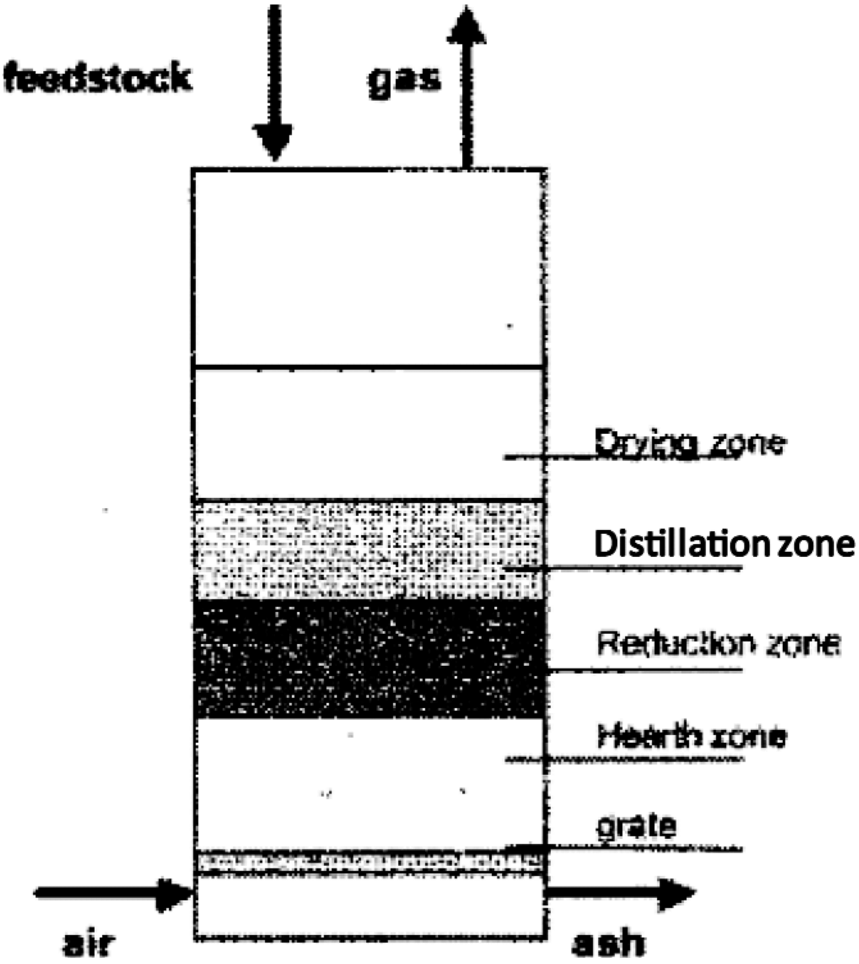


Figure 4 — Up-draught or counter-current gasifier (UDG) (typical cross section)

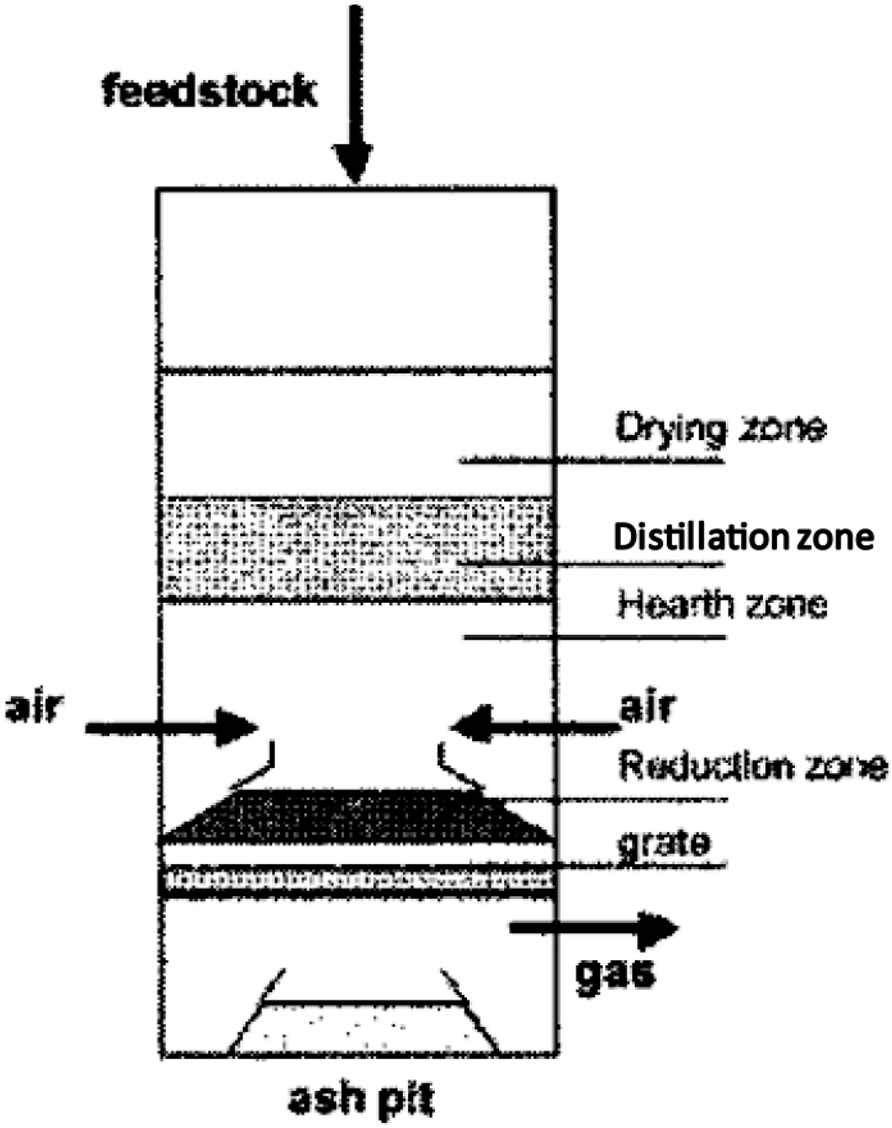


Figure 5 — Down-draught or co-current gasifier (DDG)

8.3 Pyrolysis Devices

Several types of pyrolysis units are available, including the fluidized bed furnace, the multiple hearth furnace (see Figure 2), and the rotary kiln. These units are similar to incinerators except that they operate at lower temperatures and with less air supply.

Other processes/devices are the Ablative process pyrolyser, the Rotating cone reactors, and the Molten-salt oxidation.

In the Ablative processes the biomass particles are moved at high speed against a hot metal surface. The process is dependent on surface area and the use of mechanical drivers, making it more complex and more expensive to scale up to larger facilities.

In Rotating cone reactors, pre-heated hot sand and biomass particles are introduced into a rotating cone. Like other shallow transported-bed reactors relatively fine particles are required to obtain a good liquid yield.

In Molten-salt oxidation, combustible waste is oxidized at 500 °C – 950 °C in a bath of molten salts. There is no direct flame, and this prevents many of the problems associated with incineration.

8.4 Wet air oxidation devices

Commercial systems typically use a bubble column reactor, where air or pure oxygen is bubbled through a vertical column that is full of the hot and pressurized fluid to be treated. Fresh fluid (wastewater or sludge) enters the bottom of the column and oxidized fluid wastewater exits the top. The heat released during the oxidation is used to maintain the operating temperature, together with the use of heat exchangers. Other systems use fully/perfectly mixed reactor.

8.5 Design aspects

General indications on design aspects of different thermal treatment devices are difficult to be given because a lot of different systems are available on the market, each generally covered by patents or specific trademarks.

Main factors to be taken into consideration in sizing a thermal treatment device include:

- the amount of sludge;
- the specific amount of water to be evaporated (in relation to dry matter content);
- the calorific value.

In the case of combustion, above three parameters allow the determination of a nominal operating point expressed as the thermal capacity of the furnace and with respect to which various operating zones are determined. These different zones are represented in an operating diagram called a combustion chart.

It is recommended that this type of chart is used prior to carrying out any sludge/waste combined incineration, irrespective of the envisaged furnace type, the composition of the sludge and waste to be supplied.

Concerning the combustion air, the stoichiometric amount is that which should be injected into the furnace in order to provide the amount of oxygen essential for achieving the combustion reactions.

The different zones for introduction and distribution of the combustion air are particularly important.

Common technical data of FBFs are bed diameter (1,5 m to 8 m), height (6 m to 12 m), excess air (40 % to 100 %), bed expansion (1,5 to 3 times of the fixed bed).

Common technical data of a MHF are diameter (2 m to 8 m), number of hearths (4 to 14), hearth loading rate (30 kg to 60 kg wet sludge/m^2/h), excess air (100 % to 125 %).

Refractory linings are very important because they are employed to prevent damage to the structural steel shell and to reduce heat losses. They should be designed and installed to comply also with “gas tight” parameters which can be critical especially in FBF. Alumino-silicate refractory backed up by insulating brick is most commonly used. Properties of interest are for example resistance to chemical attack, hardness, heat conductivity, thermal expansion, bulk density, apparent porosity, mechanical strength, thermal shock resistance, chemical composition.

Construction materials used in the 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.

Process air distribution by nozzles is another key point in FBFs.

Sludge feeding for incineration can be achieved by:

- distributing onto a fluidized bed by a bulk fuel spreader,

- feeding to the fluidized bed through openings in the furnace top cover or
- injecting into the furnace using screw pumps and injection lances at the fluidized bed level.

It is also to be considered that anaerobic digestion reduces organic content of sludge, and therefore its calorific value, but also produces biogas which can be a source of energy for the thermal treatment process. Further organic compounds containing organic sulphur are degraded by anaerobic digestion and together with organic compounds are reduced to ammonia nitrogen and sulphide sulphur. Such forms of N and S are easily released from sludge into sludge liquor (N) and into biogas (S) thus reducing the amount of such compounds in the flue gas.

8.6 Auxiliary equipment

8.6.1 General

The performance of incineration, gasification and pyrolysis processes is dependent upon the provision of proper support system equipment which mainly includes:

- transport, receiving area, storage and feeding systems;
- heat recovery;
- flue gas cleaning;
- ash and other residue handling;
- wastewater (coming from gas cleaning) treatment;
- process monitoring.

8.6.2 Transport, receiving area, storage and feeding systems

Sludge can be transported by barge, rail truck or pipeline. The most suitable method depends on whether the sludge is in the liquid or dewatered condition and transport duration. Transport by trucks is the most widespread method due to its relatively low investment costs and the high degree of flexibility. Rerouting and alteration of collection points is simplified.

The receiving area includes unloading equipment and storage vessels. Dry matter content and physical consistency of the sludge will influence their selection and design.

To avoid emission of malodours, sludge should be stored in closed systems from which air is extracted and treated. Attention should be paid to the explosive and fire risks related to handling sludge and carbonized materials. It should be advantageous to store sludge on the thermal treatment plant site, because this provides a buffer between the sludge production and its treatment.

Particular attention should be paid to appropriate planning of maintenance operations.

8.6.3 Heat recovery

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

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.

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 economizer. Exit flue gas temperature from economizer can be as low as 250 °C when electrical energy is recovered. It can be also as high as 500 °C when steam is produced.

Steam production from the boiler can be estimated in the range of 3 kg/kg to 8 kg/kg dry solids to be processed. 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 to 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.

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

Steam can be used for electricity generation by conventional turbines, sludge drying in indirect contact steam-sludge devices, air preheating in finned exchangers, exhaust gas post-heating to prevent the plume appearance and to ensure sufficient dispersion of the effluent gases, and district heating or industrial use.

8.6.4 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 sulphuric 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.

More details of equipment for gaseous emissions cleaning are reported in Clause 11, Management of residues.

8.6.5 Ash and other residue handling

The solid residues of sludge combustion are generally classified as bottom (if they are taken directly from the furnace) or fly ashes (if they are collected in the flue gas treatment devices). In sludge treatment by MHF bottom ashes are generally prevalent, while in FBF incineration fly ashes are much more abundant. Larger particles such as sand can be evacuated directly from the sand bed using an evacuation valve placed at the base of the sand bed.

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 does requiring the replacement of sand.

More details of equipment for solid residues treatment are reported in Clause 11, Management of residues.

8.6.6 Wastewater treatment

Wastewater is originated from wet scrubbers. It can contain pollutants, like trace elements, acidic compounds and solids at levels that require treatment to meet effluent standards. Chemical-physical processes like neutralization, trace elements precipitation, suspended solids removal are generally used.

More details on wastewater treatment are reported in Clause 11, Management of residues.

8.6.7 Process monitoring

To maintain steady-state conditions and to guarantee high process efficiency, at least temperature, pressure and oxygen concentrations, in the furnace and in different sections of the treatment 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 locally applicable.

A periodic monitoring of toxic metals of sludge should be carried out to ascertain the standard limits are respected. Control of trace elements and some organic micropollutants should be also accomplished.

In all cases, it will be particularly important to determine the ranges within which change is acceptable and/or unacceptable for parameters of interest. Among all of these parameters, a selection of those, which should be regularly monitored and/or inspected, should be proposed.

9 Operational aspects

9.1 General

Thermal treatment processes should be operated continuously as this leads to a minimum of energy consumption and wear costs. It is to be considered that there are considerable uncertainties about the technologies rather than incineration because much of the data on the performance, the emissions, the residues and financial performance of these plants comes from the individual companies, and are often contradictory.

Thermal processes generally require appropriate preliminary treatments to improve the burning quality or heat content of sludge. Thickening, conditioning and dewatering (see Guide 11) and drying (see Guide 9) are the most common processes for reducing moisture. Also anaerobic digestion plays an important role. Raw and digested sludge can still emit CH4 and CO_2. Therefore it is important to develop special activities in order to avoid dangerous situations.

Inorganic conditioners determine a decrease in volatile content (reduction in sludge heat content) and an increase in dry solids quantity (increase of ash amount) to be processed. Further, slagging and clinkering can occur when metal salts are present, while chlorine and other halogens are responsible for the presence in the exhaust gases of acidic compounds which are undesirable for corrosion problems involved, especially at high temperatures. The use of polymers as dewatering aids is very effective, and their adoption instead of lime and ferric chloride when the sludge is to be incinerated.

Addition of lime to slow down sludge fermentation may have a positive impact on transport and storage, but the life cycle of the refractories can be reduced due to alkaline degradation at these temperature levels, and additional clogging occur in the furnace's boiler unit.

The advantages of thermal drying when coupled with incineration consist of the possibility to control the solids concentration to the right value, which allows an autogenous combustion with a minimum exhaust gas production to be obtained.

Dried and dewatered sludges can be mixed, if necessary, to avoid dry matter concentrations higher than needed.

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

Operating and safety problems can arise from addition of scum and grease because, due to their high energy content, an increased volume of exhaust gases is suddenly produced in the heating space.

Suction blowers shall be able to draw off the developed explosive gas immediately to prevent any escape in the ambient air.

Thermal processing plants 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.

Anaerobic digestion reduces organic content of sludge, and therefore its calorific value, but also produces biogas which can be a source of energy for the thermal treatment process. Further organic compounds containing organic sulphur are degraded by anaerobic digestion and together with organic compounds are reduced to ammonia nitrogen and sulphide sulphur. Such forms of N and S are easily released from sludge into sludge liquor (N) and into biogas (S) thus reducing the amount of such compounds in the flue gas.

The dewatered cake can still emit CH_4 and CO_2 gas actively, therefore if the cake is stored in closed space for a long time before feeding the furnace, cracks in the feeding tank could occur.

In the following sections, specific aspects of incineration, gasification and pyrolysis are discussed.

9.2 Incineration

9.2.1 General

Generally speaking, the primary variables affecting incineration performance and costs are the waste calorific value, the fuel consumption and in some cases the air requirement.

An autogenous combustion is obtained when the calorific value of sludge and the heat content of combustion air, if preheated, balances the heat content of exhaust gases and the heat losses at the combustion temperature.

Fuel requirement strictly depends on dry matter and excess air needed to ensure a complete combustion. Generally, fuel requirement lower than 70 m^3 of methane (measured under normal conditions of temperature and pressure) per wet ton of sludge is considered suitable for an incineration process.

The stoichiometric quantity of air (in kilogram) is 4,31 times than that of oxygen. Depending on incinerator type, 3 % to 6 % O_2 residue in the excess air is generally required to ensure effective operation.

The temperature is controlled by acting on the fuel, if sludge is not autothermal, or by feeding surplus air or by injecting water in the opposite case.

Typical inconveniences of incineration systems depends on corrosion, slagging and blocking of feeding systems.

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.

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.

Specific operational aspects for the most used furnace types are discussed in the following sections.

9.2.2 Fluidized Bed Furnace (FBF)

Stationary fluidized bed incineration plants make up about 90 % of the capacity of municipal mono-incineration plants. For about 30 years, stationary fluidized bed furnaces as well as multiple hearth furnaces have proven to be very well suited for incinerating sewage sludge, a fuel with very specific characteristics.

One of the advantages of the FBF is the ability to operate with a higher flexibility than other systems. It is very responsive to variations in feed quality and rate. The sand bed acts as a heat reservoir thus reducing the temperature drop when the furnace is temporarily out of service.

However, the FBF is limited by fluidizing air requirements, which means the unit should operate near design loading even for short periods.

Mechanically dewatered sludge can only be incinerated in fluidized bed furnaces after preliminary partial drying or in combination with pre-heating of combustion air to > 500 °C. The most common combination for sludge incineration is a stationary fluidized bed furnace with disk dryers or thin film dryers as a pre-treatment step. Preliminary drying is not necessary, if the heating value of the sludge is increased to 4,000 kJ/kg - 4,500 kJ/kg by adding coal or other high-calorific substances.

Sludge which is to be incinerated

- can be distributed onto the fluidized bed by a bulk fuel spreader,
- can be fed to the fluidized bed by using openings in the furnace top cover or,
- can be injected into the furnace using thick matter pumps and injection lances at the fluidized bed level.

A very even distribution of the sludge over the entire furnace cross section is achieved by using bulk fuel spreaders. When expanded, the hot fluidized bed offers ideal conditions for mass and heat transfer.

If, in addition to sludge, also screenings are to be incinerated, these shall be comminuted and bulk materials shall be removed beforehand.

The air is fed in the wind-box to ensure a proper air distribution below the orifice plate. Fluidizing air is passed through this plate by nozzles and fluidizes the sand bed. The depth of the static bed is usually 0,5 m to 1 m. During fluidization this depth approximately doubles and therefore reaches 1 m to 2 m.

The pressure drop of the bed ranges from 750 mm to 1 500 mm H_2O. The total pressure drop and strictly depends on nozzle design and the quantity and bulk density of sand. Quartz sand has a bulk density of 1 500 kg/m^3. The sand particle size ranges 0,5 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.

The fluidized bed sand is subject to abrasion, which means that very fine dust-like sand particles will be discharged with the ash in the flue gas. Normally, the removed amount of sand is replaced by the sand contained in the incinerated sludge. If the sludge does not supply sufficient sand quantities, then extra sand has to be added. If the amount of sand in the fluidized bed increases above a certain permitted level, it needs to be reduced to the permitted amount using a special fluid bed ash discharge system. This process is controlled by measuring pressure drop in the fluidized bed.

Fluidized bed furnaces are equipped with injection lances, which can be used to add auxiliary fuels such as oil or gas directly to the fluidized bed, in order to raise combustion temperature. These lances can also be used to inject water, if temperatures are too high and the fluidized bed needs to be cooled. Next to a preheat burner for start-up, fluidized bed furnaces are normally also equipped with a freeboard burner. During the start-up phase, the freeboard burner is used to ensure that combustion temperatures are raised above 850 °C as required by emission rules.

The temperature of the bed is generally maintained at 750 °C to 820 °C. For controlling the combustion temperature without auxiliary fuels, either steam or flue gas pre-heaters are used. Above the fluidized bed incineration of CO and combustible dust takes place. So the temperature increases to 850 °C - 950 °C in the freeboard. The combustion gases, with the entrapped ashes, exit with freeboard temperature. The combustion zone above the fluidized bed has to be large enough to allow the complete burnout of all combustible material. According to emission rules a minimum gas residence time of 2 s > 850 °C is required. Remaining fly ash is discharged from the furnace with the flue gas. Flue gases are then passed to the heat recovery system, the dust separation step and further flue gas purification processes.

In order to keep carbon monoxide and nitrogen monoxide formation as low as possible, fluidized bed furnaces are equipped with a staged air supply system. Therefore the fluidized bed furnace is operated at sub-stoichiometric combustion, which produces a minimal NOX-fraction and an increased carbon monoxide fraction. The carbon monoxide is then incinerated in the afterburner chamber by adding secondary air. This type of staged combustion enables to keep the limit values for NOX and CO stated in emission rules without requiring additional NOX removal measures.

Fluidized bed furnaces for sludge incineration have been designed for combustion capacities up to 12,000 kg/h DM and 40 MW thermal.

Circulating fluidized bed furnaces (with external gas cyclones) have so far not been used for incineration of municipal sewage sludge. Their advantages only become apparent for larger combustion heat capacities above 50 MW and for fuels with higher heating values.

9.2.3 Multiple Hearth Furnace (MHF)

Autogenous combustion can be accomplished with dry matter of about 25 % to 30 %, because in this system a drying process is integrated.

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.

Problems encountered with the internal parts of MHF include failure of rabble arms and teeth, hearths and refractories.

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. The most used parameters include hearth and outlet temperature, oxygen content in the outlet gases and air flow rate, centershaft rotational speed.

Temperature on the different hearths is measured by thermocouples. It can be varied rapidly if a burner is present at that location or at the hearth below it.

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.

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 higher than 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.

Combustion air is generally controlled considering an excess air with respect to the stoichiometric value of about 100 % and more. It follows that exhaust gas production in MHF is more abundant than in FBF.

The cooling air of the shaft is partially used as combustion air at 180 °C to 230 °C. 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.

9.3 Technologies without operational background in sewage sludge: Gasification/ Pyrolysis

9.3.1 General

The number of plants with gasification and pyrolysis process is too low to permit relevant information about the operational activities. Non-combustion systems may give rise to the following types of hazards.

9.3.2 Hazards

With the short experiences, we have some hazards have to be considered as:

- Hazardous gaseous emissions: *an important constituent of produced gas is carbon monoxide (CO) which is extremely toxic and dangerous. However, for gasification/pyrolysis systems generally working under suction, in case of gas leak no dangerous gas will escape from the device during operation. If CO emission should unlikely occur, problems could arise only in the immediate vicinity of the plant because CO quickly reacts with atmosphere* O_2 *to form* CO_2*. This aspect is of particular concern during start-up and shut-down periods, thus suggesting installation of venting systems or a chimney or in well ventilated buildings.*

- Fire and explosion hazards: *fire hazards may result from high surface temperature of equipment, risks of spark during refuelling, and flames emerging from air inlets. However, relatively simple safety measures are able to eliminate above risks. Gas explosions may also occur if hot gases are mixed with sufficient air amount to cause spontaneous combustion.*

- Hazardous liquid effluent: *this includes production of ashes, which can be disposed of in the normal way, and tar/phenol containing condensates, whose amount is depending on equipment type. Amounts from down-draft gasifiers are generally small, so tar/phenol contamination is relatively minor, while large quantities derive from up-draft and open-core systems, thus requiring introduction of appropriate disposal systems.*

10 Management of energy and material products

10.1 General

In addition to energy and heat, a large number of products can be recovered, depending on the process, from sludges, including phosphorus, oils, liquid and solid residues, gases, building materials, coagulants, etc.

10.2 Incineration

The combustion of organic matter is an exothermic process, i.e. heat is generated and is transferred to the flue gases which can allow heat to be potentially recovered before being discharged into atmosphere.

The recovered energy can be used for several applications:

- pre-treatment of sludge;
- heating;
- steam production;
- electric energy production;
- etc.

A very important aspect connected to the sludge thermal processes, incineration in particular, is the possible recovery of phosphorus.

Phosphorus has to be regarded as the most valuable product in the sludge as it is a finite resource. However, recovered phosphorus should be cleaned or separated in a non-polluted fraction from the sludge, suitable as a concentrated P resource to replace traditional P-based mineral fertilizers.

The use of biomass ashes showed to be a promising method to recover P with no differences in the ecotoxicity levels of treated wastewaters and supernatants; however, recovery technologies need harmful substances, in particular heavy metals, to be selectively separated from valuable P, and quality standards to be met by ash.

Different P-recycling options are considered to be potentially available in future. For example:

- direct application of sewage sludge ash as a slow-release, calcium-rich, fertilizer due to ash alkalinity and low P solubility;
- use of ash as a substitute for P-rock by the fertilizer industry or P–producing industry;
- other P-recovery technologies.

It is relevant to store ash from incineration plants to have it ready for use when technical and economical options are available.

In the wet-chemical processes, an acidic or alkaline digestion of ash is followed by a separation of P from dissolved heavy metals, considered that organics contaminants and pathogens are destroyed during combustion at appropriate temperature. However, these procedures appear to be still too energy and/or chemical consuming.

Emerging technologies for P recovery from sludge ash include BioCon (recovery of P as phosphoric acid), SEPHOS (two-stage process producing aluminium phosphate and calcium phosphate), SUSAN (thermo-chemical process for separation of P and heavy metals). The Mephrec process (metallurgic P recycling) allows P and energy to be simultaneously recovered by a smelting-gasification technology.

Ash can be also valorised as construction material, filling product and additive in cement production.

In particular, bricks produced from incinerated sludge ash do not show heavy metals leach from the finished bricks, even in adverse environments with pH levels as low as 3. The moulding process is the key to success in making the brick from 100 % ash without any additives, therefore it shall be carefully carried out. Also temperature should be carefully controlled to prevent “black core”, the phenomenon that occurs when organic substances are poorly oxidized. A slow cooling cycle is then necessary to avoid breaking from thermal strain. The properties of the sewage sludge brick are superior to those of traditional bricks in all respects, including compression strength, water absorption rate, abrasion strength, and bending strength; however, problems of moss growth, ice, and whitening appeared.

Pumice is manufactured using the same approach as sewage bricks, with the addition of crushing and sieving processes. Pumice is a possible substitute of volcanic gravel used for the underlayer of athletic fields.

When volume reduction and the immobilization of heavy metals are the primary aims, slag is a possible solution because the volume can be reduced to only 4 % of the original one. Operational data showed that 80 % of the metal elements included in the sludge cake remain in the ash, provided that an appropriate temperature of the incinerator is maintained. Two different kinds of slag can be manufactured: water-cooled slag and air-cooled slag. Both varieties are vitreous, and meet the standards of the crushed gravel used for concrete, but their compression strength is not comparable to that of natural gravel. Air-cooled slag is 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.

Other obtainable product is an artificial lightweight aggregate (ALWA). Compared with commercially lightweight aggregates, this ALWA has greater sphericity, lower specific gravity, and less compressive strength. Major reuses include fillers for clearance between kerosene storage tanks and room walls, planter soils, flower vase additive, thermal insulator panel, substitution of anthracite media of rapid sand filters, water-infiltrating pavement. Because of its elasticity, attractive appearance and avoidance of rainwater pooling, this material can be used for walkways pavement.

A further potential use for the sludge is as a substitute raw material for Portland cement in replacement of portion of major ingredients, such as CaO, SiO_2, and F_2O_3, traditionally supplied in the form of natural limestone and clay. Manufacturers accept incinerated ash, dried sludge, or dewatered sludge cake, depending on the operation type; the concentration of P_2O_5 is the most important factor to be considered for this application.

In all cases, the environmental and economic aspects in the specific situation shall be carefully evaluated.

10.3 Gasification / Pyrolysis

The gasification process uses heat, pressure and steam to convert solids into a syngas which is a mixture of CO, H_2 and other gases, and other by-products like char or slag, oils, and reaction water.

Syngas, whose heating value from sewage sludge is around 4 MJ/m^3, can be used to produce electric power, valuable products such as chemicals, fertilizers, substitute natural gas, hydrogen, steam and transportation fuels.

The direct use of the gas in a furnace is the simplest application as it generally requires little or no gas treatment, except for dust removal. For efficiency reasons, a close coupling of the gasifier to the furnace is required.

Combustion in a gas turbine is potentially very attractive due to the favourable properties of gas turbines themselves, such as low cost of maintenance, potential high inlet temperatures favouring high thermodynamic efficiencies and the possibility of using the exhaust gas in a steam generation cycle (combined cycle). For an optimal integrated cycle the gasifier has to be pressurized (10 bar to 30 bar), thus involving increases in the complexity of installation.

Using of gas in internal combustion engines is possibly the most attractive way of generating shaft power or electricity from biomass, unless minimum gas quality requirements are got, with special reference to dust and tar.

The produced solid residue has high adsorption ability.

The gas product can be used as fuel in oil combustion engines.

Most gasifiers also produce a glass like by-product, called slag. With gasification, sulphur is removed as elemental sulphur or sulphuric acid. Other secondary products from gasification include methanol, fuel alcohol, and ammonia.

In a purified state, the hydrogen component of syngas might be used to directly power hydrogen fuel cells for electricity generation and fuel cell electric vehicles propulsion, though deep research is still needed.

End products of pyrolysis include oils/liquids, solid residues, and gases, such as hydrogen, methane and carbon monoxide whose relative proportions depend on the operational conditions of the process.

Pyrolysis could be attractive because solid or semi-solid biomasses can be converted to liquid products with consequent advantages in transport, storage, combustion and flexibility in production and marketing. In transport the bulk and energy densities of the material are important, so oil and slurry mixtures have a clear advantage. Storage and handling are also important because of seasonal variations in production and demand.

The liquid product is a dark brown oil composed of highly oxygenated hydrocarbons with an appreciable proportion of water. Solid char may also be present. These properties can make it relatively unstable in both chemical and physical terms and could cause some problems in utilization and upgrading. Characteristics which affect its utilization are water content, particulate level, oxygen content, pH polymerization at temperatures above 100 °C, compatibility with conventional fuels.

The easiest way to utilize the fuel is to use it in combustion process. Alternatively, the oil can be upgraded to either a special engine fuel or converted into a syngas through a gasification process and, thereafter, to biofuel.

The devolatization of biomass during pyrolysis reactions yields a solid residue, known as char. An outlet for the char might be slurrying it with the oil, or with water, or both.

The produced gas may be used to drive the pyrolysis process if an indirectly heated process is used, or it can be employed to dry the feed, or generate power. It is usually used for drying or heating the biomass/sludge.

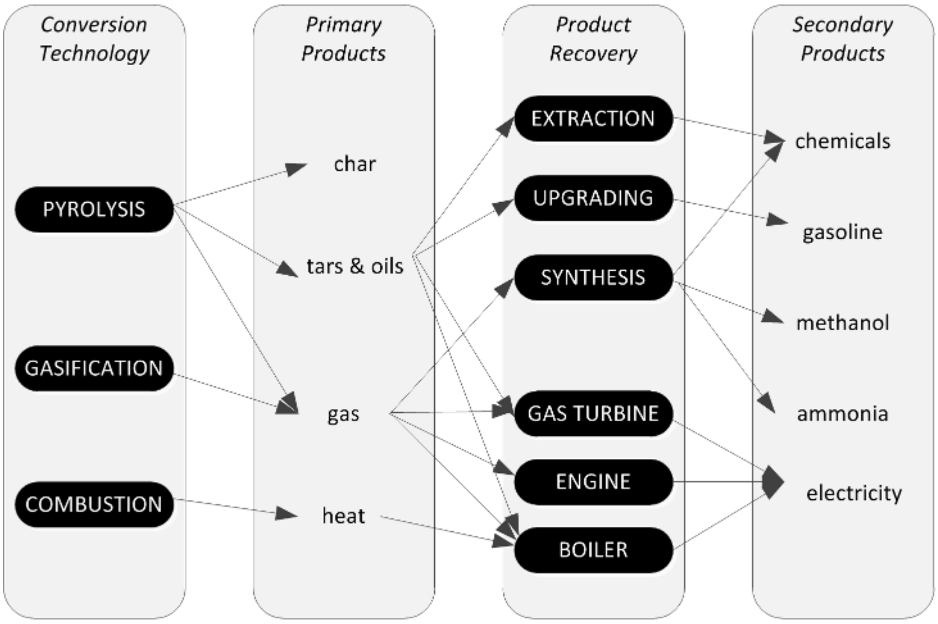
In addition, to syngas use for directly manufacturing products, each individual component of syngas might be isolated and purified for other purposes, such as:

- hydrogen: electricity generation, transportation fuels;
- nitrogen: fertilizers, pressurizing agents;
- carbon monoxide: chemical industry feedstock, fuels;
- carbon dioxide: injection into sequestration wells;
- minerals and solids: slag for road beds;
- sulphur: chemical industry.

Liquid or gaseous products are easier to handle in the combustion process and this is particularly important in retrofitting existing equipment without major reconstruction of the units, while bio-oils, char-oil slurries and char-water slurries are likely to require only relatively minor modifications of the equipment or even non in some cases. Also gas turbines can be readily fired with bio-oil and slurry fuels although care is needed with the alkali ash residue in the char content of the slurry.

10.4 Resume 10.1 through 10.3

The management of final product are summarized as follows in the table:



10.5 Wet Oxidation

Being an autothermal process, the process does not require, except during start-up, any external heat to keep the system at required temperature. This is achieved first by using heat exchangers to recover heat in mineralized sludge and secondly by the heat released by exothermic oxidation reactions.

Heat can be recovered directly by heat exchange in the reactor, or from the effluent leaving the reactor, while inorganic components, like phosphates and/or coagulants, can be recovered from the process effluent which consists of a slurry of inorganic ash in a water phase.

The aqueous stream contains about 20 % of the original organics in the sludge and significant quantities of nitrogen, so it is either returned to the head of the wastewater treatment plant or treated separately and discharged. The residual solids, mainly consisting of carbonates, silicates, phosphates and non-leachable heavy metals, complies with the criteria of landfilling for inert waste or non-dangerous waste. Energy can be recovered from the system, as hot water.

11 Management of residues

11.1 General

Residues include flue gas, ash, and wastewaters. They are discussed in the following together with equipment for their treatment which are all relevant to incineration, gasification and pyrolysis processes, unless differently stated.

11.2 Flue Gas

11.2.1 Composition/parameters

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

Particulate matter

Particulate production from sludge thermal processing varies widely, depending on sludge nature and feed rate, device type (highest for FBF), 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/m^{3}1) measured under normal conditions of temperature and pressure.

Sulphur 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/m^3 measured under normal conditions of temperature and pressure for SO_2 and 7,5 mg/m^3 measured under normal conditions of temperature and pressure 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.

Alternatively, the abatement of sulphur derivatives may be based on catalytic processes thus chemically reducing the pollutants to the elemental state.

Nitrogen oxides (NO_x)

Nitrogen oxide production in sludge combustion depends mainly 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 temperature that becomes noticeable when temperature rises to 1 200 °C – 1 300 °C;
- oxidation of organic nitrogen compounds present in sewage sludge.

As the release of NO_2 during sludge incineration could significantly contribute to the problem of GreenHouse Gases emissions, countermeasures such as raising temperatures in the secondary chamber (free board temperature in FBF) and multi-air blowing in FBF are adopted.

Organic compounds (including odours)

They can be reduced through afterburning which is 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.

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

Trace elements

Heavy metals are generally associated to particulate matter, and emission depends on their volatility, combustion temperature, and 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 C.3. 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.

11.2.2 Equipment

Equipment for flue gas purification can be classified in two main groups:

- units which are able to separate solid particles;
- units which reduce gaseous contaminants by absorption, adsorption and/or chemical reaction.

The equipment for solid particle entrapment includes:

- impingement separators,
- cyclones,
- electrostatic precipitators,
- bag filters.

Above equipment are generally able to remove particulate down to 5 mg/m^3 measured under normal conditions of temperature and pressure, depending mainly on the particle size.

Impingement separators are essentially a series of baffles placed in the gas stream which allow particulate to be deposited on.

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 µ 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, neutralization 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 ionization 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; for this application the Polytetrafluoroethylene (PTFE) is the material preferable to make the 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-pressurization and sonic apparatuses. Particles less than 1 µ 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 and activated carbon) are introduced into a ductwork or a reaction tower or a recirculating system to have minimum two second of reaction time. The gaseous pollutants are removed by adsorption and chemical reaction. Chemicals and reaction products are then removed by a system for particle separation.

In semi-dry system, slurry is introduced into the reactor. The significant 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 minimize chemical consumption and prevent abundant production of fly ashes. In this case chemicals consumption can be lowered to 1,5 / 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 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 atomizes 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 rapidly2).

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, Volatile organic carbon (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

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2) 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).

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 economic aspects.

The general requirements that should be met in the design or selection of suitable adsorption equipment include:

— provision for sufficient dwell time;

— 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 other processes 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).

SCR is conducted by impacting in the gas stream a reducing agent, generally ammonia or urea, in presence of a catalyst, which is generally based on the use of metals such as nickel, platinum, palladium, vanadium, with formation of H_2O and N_2.

Chemical reactions occurring in the process are the same of the SNCR one, but at a lower temperature (ranging about 300 °C - 400 °C) and with higher performances (about 80 %). Denox systems which can operate at lower temperature (around 170 °C - 180 °C) are available on the market.

It should be considered that the catalyst has the tendency to become poisoned by the formation of ammonium sulphate that is formed on the catalyst in the presence of SO_2. A preliminary abatement of this contaminant is, therefore, very important.

SNCR is based on the reaction of ammonia or urea with NO_x with production of nitrogen gas at temperatures of 800 °C to 1 100 °C. The dilute solution is injected, atomized with pressurized 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 stream3).

Performance of SNCR is considerably lower than that of SCR. NO_x concentration in the treated stream can be hardly reduced down to 150 mg/m^3 measured under normal conditions of temperature and pressure.

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.

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

11.3 Ashes

11.3.1 Composition/Parameters

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, sulphates and refractory metal oxides, some of which can be soluble. Typical composition of ash is shown in Table C.3[4].

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 some cases a reduction, due to the loss in the emissions in gaseous form or in particulate.

Frequent analysis of ash is needed to confirm effective burnout (3 % residual carbon or 5 % of loss of ignition is common in incineration processes, but 0,1 % could be achieved).

In some incinerator the flue gas treatment is a 2 steps process:

- Ashes separation (e.g. cyclone or ESP);
- Acidic gas neutralization and capitation of reaction products (e.g. baghouse filter).

11.3.2 Equipment

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

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

Dry systems should ensure that dust does not become airborne. This can be accomplished either by proper containment or by dust suppression sprays. Spraying 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.

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 of is very important to respect standard limits.

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.

In generally and especially for P recovery in view of a recovery of valuable elements (P, K and metals) from sludges, it is appropriate to keep fly ash and bottom ash separated.

11.4 Wastewater

Wastewater is mainly originated from bottom ash quenching and wet gas treatment (e.g. by scrubbers).

Wastewater may also derive from several other points, such as the fly ash handling system, various sluice-ways and fly ash conveying.

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

Depending on the liquids used and the gaseous contaminants removed, wastewater can contain chlorides, sulphites, sulphates, phosphates, particulate matter, heavy metals and trace elements, at levels that require treatment to comply with standards for discharge into sewer systems or receiving water bodies.

If the stream contains little biologically degradable organic substances, physical-chemical processes are usually enough to achieve the required quality standards for the effluent. The usual treatment sequence is coagulation, flocculation and settling. In the case of higher amounts of biologically degradable organic substances, a specific treatment should be applied.

In case trace organics are present (such as dioxins, furans, polychlorinated hydrocarbons, phenols, etc.) appropriate treatments, e.g. filtration and subsequent activated carbon adsorption units, are required.

Recirculation which is not a dilution process can be adopted to minimize the amount of water to be discharged. Wastewater from bottom-ash quenching is recycled after chemical-physical treatment and the make-up water is in the order of 10 %–20 % of the total water. The higher the saline content, the higher the make-up water, in order to allow discharge not exceeding the quality standards for slats, namely chlorides.

12 Economic aspects

Thermal processes are not used in situations of competition with others solutions for sludge management. Comparison of the costs of the options of, in theory, possible solutions for sludge on a site is not always helpful.

It is, also, to be considered that there are uncertainties about the relevant parameters to compare these technologies because the data of the performance of the studied thermal process are not easy to have in a predetermined frame easy to verify.

The sludge itself is not comparable from one plant to another because:

- the wastewater network is different,
- the wastewater treatment is not the source of a common sludge,
- the necessary pretreatments for the sludge before entering the thermal process are not the same.

Moreover, the amount of sludge of different plants varies in a wide range; therefore specific solutions are necessary.

As a matter of fact, in 2013 there is an insufficient number of plants with similar thermal processes to obtain a sufficient amount of data to access a relevant economic synthesis for this document.

13 Co-management with other organic wastes

13.1 General

From a general point of view, wastewater sludge generally has a high water content, and in some cases high levels of inert materials, so its calorific value is often low. By combining sludge with other combustible materials in a co-management scheme a feed having both a low water content and a heat value high enough to sustain combustion with little or no supplemental fuel could be created.

Common materials for co-management schemes are municipal solid waste (MSW), agriculture wastes, coal and wood. However, each case is differing from others as a consequence of different qualitative and quantitative characteristics of wastes involved; it is, therefore, impossible to make considerations applicable to all possible situations, so in the following the co-management of sludge with MSW will be more extensively discussed.

Further, co-incineration of sewage sludge with MSW or coal may have cost advantage over mono-incineration, depending on supply and transport factors.

In addition to above general considerations, reasons which lead the decision-makers to choose combined treatment of sludge and other organic waste derive from several considerations including:

- the impossibility to apply any other process or the availability of alternative already existing solutions, throughout whole or part of the year, in particular in the case of technical shutdown;
- the geographical, economic and social contexts, as well as the expected developments;
- the proximity of the sewage treatment plant to the thermal treatment plant and the local road network;
- the extent to which the thermal treatment plants are used (capacity of devices, charge levels, etc.);
- the variations due to seasonal activities and production peaks both in sludge and other organic waste.

Considering combined treatment as one of the options for sludge management, two approaches are possible:

- the treatment site accepts over the course of time materials of different origin, type, and quantity, and should be readily adaptable to guarantee in any case optimum performance;
- the treatment site does not offer any flexibility, so a quantitative or qualitative limitation will be demanded on the site, and a reflection, taking into account the technical and economic constraints, should be conducted in order to examine the influence of any modification in sludge production to achieve a perfect material/process match.

Finally, it is worthwhile specifying that thermal plants are installations which, for technical and maintenance reasons, operate between 7 000 h/y and 8 000 h/y, so it will be advisable to provide for a selective and appropriate organization with the water treatment site administrator during the plant shutdown periods, particularly in the case of a plant equipped with one treatment line only.

Under these conditions, it is then a question of knowing the sludge parameters and characteristics which can influence the combined treatment process with a view to making provision for the necessary installations, the behaviour and flexibility of the equipment to be implemented, as well as the possible additional maintenance and wear.

The operational departments of the treatment plants has to reserve the right to refuse a sludge, which can present one or more abnormal parameters, e.g. a particularly high content of one or more trace elements and for which the unit's equipment:

- will not allow to guarantee safe operations and compliance with current emission limits;
- will generate residues whose quality will no longer allow a disposal in conformity to the provisions in force (regulation and/or current technical-economic conditions).

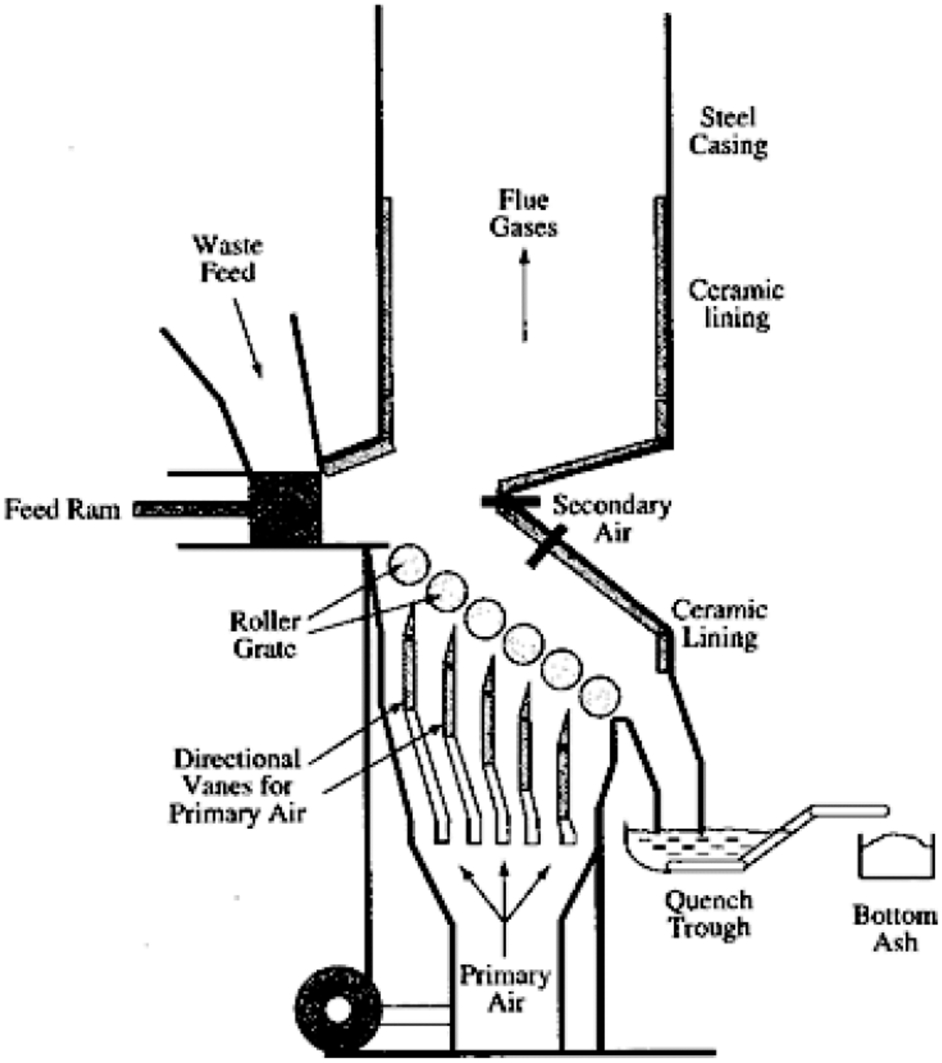
With specific reference to their dryness, sludge types that can be envisaged for combined management include mechanically dewatered sludge, and partially or totally heat-dried sludge using thermal dryers.

13.2 Specific considerations

According to EU Directives, co-incineration plant: is defined as any stationary or mobile plant whose main purpose is the generation of energy or production of material products and which uses wastes as a regular or additional fuel or in which waste is thermally treated for the purpose of disposal.

Four furnace types can be mainly used for sludge/MSW combined incineration. These are:

- stoker type furnaces containing mechanical components (bars or grates) driven by a translational motion (linear movement). The grate is either inclined or horizontal (see Figure 6);
- roller furnaces comprising stepwise arranged rotating cylinders (circular movement);
- reciprocating or rotary kilns. The axis is slightly inclined to the horizontal;
- fluidized bed furnaces, which can comprise two types: bubbling fluidized beds (see Figure 3).and circulation fluidized bed.


Steel Casing
Flue Gases
Waste Feed
Ceramic lining
Feed Ram
Secondary Air
Roller Grate
Ceramic Lining
Directional Vanes for Primary Air
Quench Trough
Bottom Ash
Primary Air

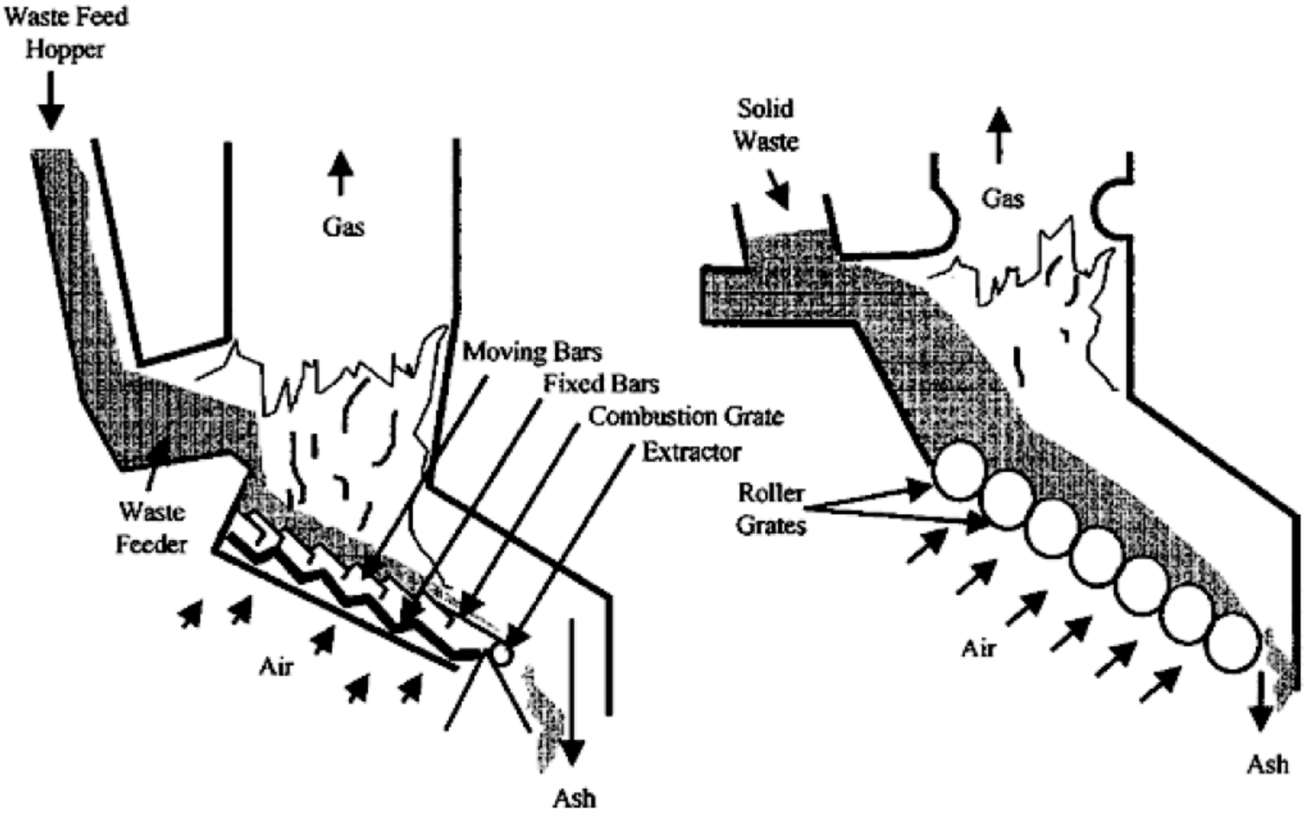


Figure 6 — Grate furnace

Whatever the furnace type involved, two essential functions should be combined:

— treatment of waste either alone or in mixed form, in order to convert it into ash with the lowest possible percentage of Total Organic Carbon, while avoiding the formation of more or less melted blocks of bottom ash (caking);

— distribution of the air used for combustion and cooling down of the mechanical components or of the sole plate according to two types of air versus current or combined air-current designs.

In the case of co-combustion, main advantage is that the excess heat from MSW can be recovered for sludge drying, thus allowing the need of auxiliary fuel to be reduced or avoided. Generally, a heat balance is reached when the per-capita quantities of MSW and sludge at 25 %–30 % solids are combined. Unlikely, particulate emissions are higher, although their abatement is not a problem with modern technologies.

Any case, considered that the calorific value of MSW is usually situated between 7 000 kJ/kg and 11 000 kJ/kg, a lower calorific value (LCV) caused by the sludge/household waste mixture less than 7 000 kJ/kg should be avoided, because of the subsequent problem of complex mixing of the two wastes.

The introduction of sludge into a household waste furnace results mainly in an increase in the volume of the combustion gases, in their humidity and in their SO_2 content.

Besides the sludge characteristics, the possible different waste-sludge combined treatment depend on the constraints resulting from the complete treatment line, taking into account the design and flexibility of the furnace-boiler-waste gas treatment facility.

The technical means for introduction wastes into the furnace will be designed so as to mix in the most appropriate manner possible the sludge with the household waste and to avoid all concentration points and all risks of clogging on the refractoried surfaces of the furnace.

Annex D gives information on various systems to input sludge into a household waste incineration plant.

In all cases, the introduction of an additional waste material into the thermal treatment system should not interfere in any significant manner with the initial performance of the system.

In order to maintain satisfactory conditions and to avoid any adverse effects on the resistance of the refractory materials, it is desirable not to exceed a thermal overload and therefore an increase in waste gas enthalpy in the region of 5 %, this figure being dependent on the lower calorific value (LCV) of the sludge.

A distinction will also be made between the introduction of a sludge in a paste-like physical state in a solid one (see CEN/TR 15463).

In the case of a paste-like sludge the amount of sludge which can be incinerated depends mainly on the quantity of excess air available if it is wished to maintain the furnace's thermal capacity. The quite rapid vaporization of the large quantity of water contained in the sludge will increase the volume of the gas in the furnace and thus contribute to “locally cooling down” the temperature of the gases. Taking these elements into account, it appears wise to limit the raw sludge household waste weight ratio between 10 % and 20 % for grate, roller or reciprocating type furnaces and around 30 % of fluidized bed type furnaces.

In the case of a pre-dried sludge (around 60 % for example, an interesting case for which the calorific value of the sludge is close to that of household waste), the quantity of sludge which can be incinerated depends on the available thermal capacity, the furnace type and its mechanical functioning. At nominal operation, all additions of sludge will be made to the detriment of the household waste.

In the case of sludge dried to about 90 %, the calorific value of the resultant mixture will be considerably increased and only the combustion chart will allow a reasonable ratio to be defined. This type of combined incineration will only be used insofar as the quantity of household waste treated is less than the furnace's nominal capacity.

Particularly for this latter case, the distribution of the sludge over the bed of household waste should be well carried out in order to avoid the emergence of oxygen starved zones which can give rise to an increase in the quantity of unburned residues in the bottom ash and in the CO content in the combustion gases and a possible not homogeneous temperature in the furnace. This remark is not valid in the case of fluidized beds.

New installations will be, therefore, dimensioned so as to take into account a total volume of waste gas greater than the volume given off by the combustion of household waste alone.

Concerning all the pollutants to be treated, each installation has its own limitation thresholds (or maximum pollutant load values at the entry of the purification system). It will be advisable to verify the compatibility of the treatment process with the addition of sludge. Likewise, if the combined incineration is not continuous (e.g. only operates on one or two units, namely 8 h to 16 h a day) particular attention should be paid to the relevant local regulations in force for pollutant emissions - continuous, average rate per hour per day, etc.

In this latter case, care will be taken to see that the furnace's regulation system manages these periods, with our without sludge, so as not to disrupt combustion and the resulting elements (gaseous, liquid and solid effluent).

Finally, in sludge co-incineration in MSW incinerators and power plants, P recovery might not be feasible, due to the dilution of the P-containing sludge ash with ash from the co-fuel and to the presence of other pollutants t in MSW.

Summarizing, each case is in fact a specific case, whether it is a question of existing or new installations, defined by:

— the combustion chart;

— the furnace type;

- the possible location of the introduction system (s);
- the compliance with the “3T rule”;
- the combustion gas treatment capacity;
- the dividing up of the sludge mineral ashes into bottom ash and fly ash;
- observance of the regulations.

Additional specific considerations on co-gasification and co-pyrolysis are at the moment not available due to scarcity of experiences and lack of documented data.

13.3 Additional storage and transports aspects

13.3.1 General

In addition to storage and transport aspects already described, the following apply in the case of co-management of sludge and other organic waste, especially MSW.

13.3.2 Storage

Sludge can be stored with MSW either directly by tipping into the pit, or by using spray, or any other method in order to spread it right through the pit. Any choice depends on local situation.

Two elements are essential in the quality of the sludge to be tipped: dryness and consistency. In the case of liquid or semi-paste-like sludge, there is a risk of MSW becoming wet and water accumulating by gravity at the bottom of the pit. An identical gravity phenomenon can occur with solid sludge of low particle size, difficult to remove with a grapple.

In all cases, tipping sludge into a pit creates an additional work for the crane operator so that the mixture will be as homogeneous as possible. This work should be carried out in parallel with the management of MSW in pits and therefore requires a dual function for the crane driver.

In fact, this is a possible solution where sludge quantity is low compared to the MSW and/or on a selective basis. According to how dry the sludge can be and the proportions anticipated, a study should be envisaged, even prior characterization tests.

Attention should also be paid to the explosive and burning risks related to dried sludge, as well as to the odour problems, which are directly linked to the quality of the sludge (e.g. raw sludge) which will lead to the calculations of the unloading hall system being revised: additional deodorization can prove necessary.

It is advantageous to store sludge on the thermal treatment plant site, because it provides a buffer between the sludge production and its treatment, which can sometimes be discontinuous. If the storage facility area is close to the treatment plant, the sludge can possibly be stored directly in this area and to feed the treatment plant by pipeline.

The storage facility area will regroup sludge of different origins, irrespective of its condition. It can therefore take the form of a pit, a tank or silo. It is located within the treatment plant site perimeter in a separate properly identified area, different from the storage area where other wastes treated on the site are stored. Input to the storage facility should be either by pipeline (for liquid or paste-like sludge) or by skips (for paste-like or solid sludge).

Mention should be made of the particular case of solid sludge arriving at the site for treatment, for which a possibility of direct tipping into the waste pit can be examined.

The sludge container should be equipped with a level measurement system or (except when it is merely a pit for which a simple visual inspection by the operators should prove sufficient) a filling system and a draining-off connection device.

Provision should be made for sludge recovery from the bottom of pits, tanks or silos. Likewise, consideration should be given to recovering water used for cleaning working areas and the containers themselves.

The storage containers should be adequately dimensioned. It is wise to have at least one storage volume equivalent to the quantities of sludge, which will be treated by combined treatment over a 72 h period. This volume should be calculated on the basis of treatment device furnace operation at the constructor's rated capacity and confirmed by the operator, taking into account a nature of waste which is always highly variable and on the basis of a ratio of treated sludge to domestic refuse which is dependent on the size of the furnaces and on the principle adopted for combined treatment. The hazards relating to the supply of sludge will also be taken into consideration.

Sludge mixing can also be taken into consideration, as the combined treatment plant should be capable of treating all the sludge brought to the site, i.e. from different origins and sewage plants.

The constituent materials of the equipment should be insensitive to the products being stocked in order to avoid any premature ageing.

Prior to installation, particular attention should be paid to the maintenance of the equipment.

The relevant national and/or local regulations in force should be observed.

13.3.3 Transport

Transport consists of conveying the sludge from the sewage treatment plant to the co-treatment plant, if possible in a single stage. It includes the sludge loading and unloading operations.

The transport system should be designed so as to guarantee maximum containment and limited nuisance due to smells. Transport should not give rise to any accidental spillage of sludge onto the roadways and the various manoeuvring areas. In the event of the travelling distances being long, modification of the sludge should be taken into consideration.

Vehicles used should be suited to the different categories of roads.

It is not to be forgotten that transport can be carried out via pipeline where the plant and treatment plants are close enough to one another for this to be technically and economically feasible. The pumping conditions and the outputs to be applied will then be particularly examined.

Transport by barge or railways should also be considered depending on specific local situations.

14 Assessment of impacts

14.1 General

Similarly to economic aspects, information available on such kind of assessment for thermal processing of sludges is quite limited, especially for less conventional technologies, to allow general and reliable conclusions to be drawn.

Generally speaking, in the course of the operation of incineration installations, emissions and consumptions arise, whose existence or magnitude is influenced by the installation design and operation.

The potential impacts of thermal treatment installations involve environmental, economic, and social aspects.

14.2 Environmental aspects

They include:

- the evaluation of the overall process emissions to soil, water and air (including odor and other fugitive emissions mainly from storage);
- the consumption and nature of raw materials and resources used in the process and their energy efficiency;
- the amount and quality of end products, process residues and/or secondary resources;
- the process noise and vibration;
- the reduction of the storage, handling and processing risks of hazardous wastes;
- the need to prevent accidents and to minimize the consequences for the environment.

14.3 Economic aspects

They include:

- the overall energy balance (consumption and production) of the system considering availability and cost of energy;
- the raw material (reagent) consumption;
- the cost effectiveness;
- the reliability of the technology;
- the recovery and recycling of substances generated and used in the process;
- the marketability of end products;
- the transport of incoming sludge and outgoing residues;
- the requirements for extensive sludge pretreatment.

14.4 Social aspects

They include:

- the formation of a public consensus on the facilities installation;
- the evaluation of the level of applicability of existing regulations, rules and recommendations in the specific geographical and social contexts;
- the acceptance by local population.

Within this framework, appropriate decisions should be based on the Best Available Techniques (BAT) concept taking into consideration the technical characteristics of the installation concerned, its geographical location and local environmental conditions to ensure a high level of protection for the environment as a whole.

The life-cycle assessment (LCA) technique can help avoiding a narrow outlook on environmental concerns. It allows the impacts associated with all the stages of a product life from raw material extraction thru materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling to be assessed by:

- compiling an inventory of relevant energy and material inputs and environmental releases;
- evaluating the potential impacts associated with identified inputs and releases;
- interpreting the results to help you make a more informed decision.

The main aspects to be considered in a life-cycle assessment are energy consumption and related cost and migration and transformation of pollutants both in the thermal process itself and in application or use of by-products. Furthermore, assessment of direct emissions of CO_2, CH_4, NO_x and indirect emissions derived from energy consumption, chemical agents, etc. from original sludge to application of product is also important.

Annex A
(informative)

Emission limit values

(Directive 2010/75/EU)

Table A.1 — Emission limit values for discharges of waste water from the cleaning of waste gases

Polluting substances	Emission limit values for unfiltered samples (mg/l except for dioxins and furans)	
Total suspended solids as defined in Annex I of Directive 91/271/EEC	(95 %) 30	(100 %) 45
Mercury and its compounds, expressed as mercury (Hg)	0,03	
Cadmium and its compounds, expressed as cadmium (Cd)	0,05	
Thallium and its compounds, expressed as thallium (Tl)	0,05	
Arsenic and its compounds, expressed as arsenic (As)	0,15	
Lead and its compounds, expressed as lead (Pb)	0,2	
Chromium and its compounds, expressed as chromium (Cr)	0,5	
Copper and its compounds, expressed as copper (Cu)	0,5	
Nickel and its compounds, expressed as nickel (Ni)	0,5	
Zinc and its compounds, expressed as zinc (Zn)	1,5	
Dioxins and furans	0,3 ng/l	

Table A.2 — Air emission limit values for waste incineration plants

Polluting substances	Daily average emission limit values (mg/Nm^3)	Half-hourly average emission limit values (mg/Nm^3)	
		100 %	97 %
Total dust	10	30	10
Gaseous and vaporous organic substances, expressed as total organic carbon (TOC)	10	20	10
Hydrogen chloride (HCl)	10	60	10
Hydrogen fluoride (HF)	1	4	2
Sulphur dioxide (SO_2)	50	200	50
Nitrogen monoxide (NO) and nitrogen dioxide (NO2), expressed as NO_2 for:			
- existing waste incineration plants with a nominal capacity exceeding 6 tonnes per hour or new waste incineration plants	200	400	200
- existing waste incineration plants with a nominal capacity of 6 tonnes per hour or less	400	-	-
Carbon monoxide	50	100	

Polluting substances	Average emission limit values
Cadmium and its compounds, expressed as cadmium (Cd)	Total: 0,05 mg/Nm^3
Thallium and its compounds, expressed as thallium (Tl)	
Mercury and its compounds, expressed as mercury (Hg)	0,05 mg/Nm^3
Antimony and its compounds, expressed as nickel (Sb)	Total: 0,5 mg/Nm^3
Arsenic and its compounds, expressed as arsenic (As)	
Lead and its compounds, expressed as lead (Pb)	
Chromium and its compounds, expressed as chromium (Cr)	
Cobalt and its compounds, expressed as chromium (Co)	
Copper and its compounds, expressed as copper (Cu)	
Manganese and its compounds, expressed as chromium (Mn)	
Nickel and its compounds, expressed as nickel (Ni)	
Vanadium and its compounds, expressed as chromium (V)	
Dioxins and furans	0,1 ng TEQ/Nm^3

Annex B
(normative)

Calorific Value calculations

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:

$$\mathrm{GCV} = 32\,810\ \mathrm{C} + 142\,246\ (\mathrm{H} - \mathrm{O}/8) + 9\,273\ \mathrm{S} \qquad \text{(B.1)}$$

Where

GCV is in kJ/kg LOI (organic matter), 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, and 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:

$$\mathrm{GCV} = 32\,810\ \mathrm{C} + 142\,246\ (\mathrm{H} - \mathrm{O}/8) + 9\,273\ \mathrm{S} - [2\,189\ \mathrm{N}\ (1 - \mu) + 6\ 4894\mathrm{N}\ \mu] \qquad \text{(B.2)}$$

Where

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

The Lower calorific value can be evaluated by measuring the chemical oxygen demand *COD* and the total Kjeldahl nitrogen (*TKN*) (ammoniacal + organic nitrogen). and using the formula:

$$\mathrm{LCV} = 13\,700\ \mathrm{COD} + 19\,000\ \mathrm{TKN} \qquad \text{(B.3)}$$

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*):

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

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:

$$\mathrm{lCv} = \mathrm{lCvLOI} \; \mathrm{X} \; \mathrm{LOI} - 2\,440\,(1 - \mathrm{X}) \qquad \text{(B.5)}$$

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

Annex C
(informative)

Tables

Table C.1 —Typical elemental composition of organic matter (*LOI*) of sewage sludge

Elemental composition 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 C.2 — Trace elements in sewage sludge ashes (DM) [mg/kg] (source XXX)

	Min	Max	Ø	Median
As	4,2	124,0	17,5	13,6
Cd	< 0,1	80,3	3,3	2,7
Co	7,3	83,5	28,1	20,7
Cr	58	1502	267	159,7
Cu	162	3467	916	785
Hg	0,1	3,6	0,8	0,5
Mn	334	6488	1914	1307
Mo	7,5	112	25,3	20,0
Ni	8,2	501	106	74,8
Pb	< 3,5	1112	151	117
Zn	552	5515	2535	2534

Table C.3 — Matrix elements in sewage sludge ashes (DM) [%]

	Min	Max	∅	Median
Al_2O_3	1,3	38,1	9,7	9,1
CaO	8,5	52,9	19,3	14,7
Fe_2O_3	2,6	29,0	14,1	13,6
K_2O	< 0,008	2,0	1,0	1,1
MgO	0,5	6,5	2,3	2,2
Na_2O	0,2	3,6	1,0	0,8
P_2O_5	3,4	30,0	16,8	18,1
SO_3	0,8	17,1	3,6	2,4
SiO_2	5,2	51,8	26,4	26,3
TiO_2	0,1	2,5	0,6	0,6
ZnO	0,1	0,7	0,3	0,3

Annex D
(normative)

Various systems to input sludge into a household waste incineration plant

D.1 General

In order to complement this practical document, it is worthwhile pointing out some input systems. The list is not exhaustive and can be complemented at any time.

It can be divided into two major parts:

- the input of sludge whose dry matter content < 35 %;
- the input of sludge whose dry matter content > 65 %.

D.2 Sludge whose dry matter content < 35 %

There is a lot of feeding systems:

- through a crane (mixed waste);
- through a hopper;
- into the furnace, at various points;
- pipe;
- side wall or ceiling;
- output of post combustion;
- post combustion.

According to the systems, the sludge will be:

- injected in form of “cakes”;
- pulverised in form of drops;
- cut into slices.

D.3 Sludge whose dryness is > 65 %

There are several methods to input sludge into a furnace:

- sludge can be directly discharged from the pit into the drop chute through an air conveyor, a screw or bucket conveyor. The hopper will be fed as regularly as possible in order to mix small quantities of household waste with sludge;
- sludge can be directly discharged into the furnace;

- sludge can be directly dumped into the household waste pit.

D.4 Sludge whose dry matter content between 35 % to 65 %

No recommendation can be made in this document since storage and transfer technologies are not yet mastered for this kind of sludge.

D.5 Drying the sludge in the household waste incineration plant

Drying the sludge in the plant changes the sludge whose dryness is about 20 % into sludge of 60 % to 90 % dryness by using the energy recovered from household wastes. In this way, solid and incinerated sludge generate power.

Depending on the drying method, the sludge drying can generate a polluted liquid effluent that has been treated. Some problems can occur if drying is carried out an incineration plant limited in its liquid discharges.

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