



BSI Standards Publication

Sludge recovery, recycling, treatment and disposal — Guidance on thermal treatment of sludge

National foreword

This Published Document is the UK implementation of CEN ISO/TR 20736:2023. It is identical to ISO/TR 20736:2021. It supersedes [PD ISO/TR 20736:2021](#), which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee EH/5, Sludge characterization.

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

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2023
Published by BSI Standards Limited 2023

ISBN 978 0 539 26121 9

ICS 13.030.20

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 August 2021.

Amendments/corrigenda issued since publication

Date	Text affected
31 July 2023	This corrigendum renumbers PD ISO/TR 20736:2021 as PD CEN ISO/TR 20736:2023

English Version

Sludge recovery, recycling, treatment and disposal -
Guidance on thermal treatment of sludge (ISO/TR
20736:2021)

Valorisation, recyclage, traitement et élimination des
boues - Lignes directrices pour le traitement
thermique des boues (ISO/TR 20736:2021)

Schlammgewinnung, -verwertung, -behandlung und -
beseitigung - Leitfaden für die thermische Behandlung
von Schlamm (ISO/TR 20736:2021)

This Technical Report was approved by CEN on 26 June 2023. It has been drawn up by the Technical Committee CEN/TC 308.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.



EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

European foreword

The text of ISO/TR 20736:2021 has been prepared by Technical Committee ISO/TC 275 "Sludge recovery, recycling, treatment and disposal" of the International Organization for Standardization (ISO) and has been taken over as CEN ISO/TR 20736:2023 by Technical Committee CEN/TC 308 "Characterization and management of sludge" the secretariat of which is held by AFNOR.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN shall not be held responsible for identifying any or all such patent rights.

Any feedback and questions on this document should be directed to the users' national standards body. A complete listing of these bodies can be found on the CEN website.

Endorsement notice

The text of ISO/TR 20736:2021 has been approved by CEN as CEN ISO/TR 20736:2023 without any modification.

Sludge recovery, recycling, treatment and disposal — Guidance on thermal treatment of sludge

*Valorisation, recyclage, traitement et élimination des boues — Lignes
directrices pour le traitement thermique des boues*



Reference number
ISO/TR 20736:2021(E)

AVA Documents
Document Sharing Hub
© ISO 2021



COPYRIGHT PROTECTED DOCUMENT

© ISO 2021

All rights reserved. Unless otherwise specified, or required in the context of its implementation, no part of this publication may be reproduced or utilized otherwise in any form or by any means, electronic or mechanical, including photocopying, or posting on the internet or an intranet, without prior written permission. Permission can be requested from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

Contents

Page

Foreword	vi
Introduction	vii
1 Scope	1
2 Normative references	1
3 Terms and definitions	1
4 Abbreviated terms	3
5 Sludge properties	4
5.1 General	4
5.2 Physico-chemical characteristics	4
5.2.1 General	4
5.2.2 Dry matter	4
5.2.3 Loss on ignition	4
5.2.4 Calorific value	5
5.2.5 Grease, scum and screening	5
5.2.6 Physical consistency and others	6
5.3 Chemical and microbiological characteristics	6
5.3.1 General	6
5.3.2 Sulfur	6
5.3.3 Phosphorus	7
5.3.4 Nitrogen	7
5.3.5 Chlorine and other halogens	7
5.3.6 Organic micro pollutants	7
5.3.7 Trace elements	8
5.3.8 Pathogens	8
6 Thermal processes fundamentals	8
6.1 General	8
6.2 Drying	9
6.3 Hydrolysis	10
6.4 Incineration	11
6.5 Pyrolysis	12
6.6 Gasification	13
6.7 Thermolysis	14
6.8 Carbonization	14
6.9 Wet oxidation	14
6.10 Melting	15
6.11 Pasteurization	15
7 Technologies	16
7.1 General	16
7.2 Drying	16
7.2.1 Direct dryers	16
7.2.2 Indirect dryers	20
7.2.3 Solar dryers	22
7.3 Hydrolysis	23
7.4 Incineration	24
7.4.1 Fluidized bed furnace	24
7.4.2 Multiple hearth furnace (MHF)	28
7.4.3 Hybrid furnace	31
7.4.4 Others	32
7.5 Pyrolysis	33
7.6 Gasification	33
7.7 Thermolysis	35
7.8 Carbonization	35

7.9	Wet oxidation	36
7.10	Melting	37
7.11	Pasteurization	39
7.12	Emerging technologies	40
7.12.1	General	40
7.12.2	Oxidation technologies	40
7.12.3	Enzymatic sludge hydrolysis	41
7.12.4	Plasma gasification	41
7.12.5	Ultrasound pretreatment	41
7.12.6	Microwave irradiation	41
7.12.7	Infrared radiation	42
7.13	Design aspects	42
7.14	Auxiliary equipment	42
7.14.1	General	42
7.14.2	Transport, receiving area, storage and feeding systems	43
7.14.3	Heat supply and recovery	43
7.14.4	Gas cleaning	44
7.14.5	Ash and other residues handling	44
7.14.6	Wastewater treatment	44
7.14.7	Process monitoring	44
7.14.8	Safety systems	45
8	Operational aspects	45
8.1	General	45
8.2	Drying	46
8.3	Hydrolysis	46
8.4	Incineration	46
8.4.1	General	46
8.4.2	Fluidized bed furnace	47
8.4.3	Multiple hearth furnace	48
8.5	Pyrolysis	49
8.6	Gasification	49
8.7	Thermolysis	49
8.8	Carbonization	49
8.9	Wet oxidation	49
8.10	Melting	50
8.11	Pasteurization	50
8.12	Hazards	50
9	Management of energy and secondary resources	50
9.1	General	50
9.2	Drying	51
9.3	Hydrolysis	51
9.4	Incineration	51
9.5	Pyrolysis	52
9.6	Gasification	53
9.7	Thermolysis	54
9.8	Carbonization	54
9.9	Wet oxidation	54
9.10	Melting	54
9.11	Pasteurization	54
9.12	Thermal treatments and circular economy	55
10	Management of residues	55
10.1	General	55
10.2	Flue gas	55
10.2.1	Characteristics and parameters	55
10.2.2	Equipment	57
10.3	Ashes	59
10.3.1	Composition/parameters	59

10.3.2	Processes and equipment	60
10.4	Wastewater	61
11	Decommissioning of installations	61
11.1	General	61
11.2	Specific considerations	61
12	Co-management with other organic wastes	62
12.1	General	62
12.2	Specific considerations	63
12.3	Additional storage and transport aspects	65
12.3.1	General	65
12.3.2	Storage	65
12.3.3	Transport	66
13	Assessment of sustainability	66
13.1	General	66
13.2	Environmental aspects	67
13.3	Economical aspects	67
13.4	Social aspects	67
Annex A	(informative) Calorific values calculations	69
Annex B	(informative) Various systems to input sludge into a household waste incineration plant	70
Annex C	(informative) Case studies	72
Annex D	(informative) Regulatory aspects	86
Bibliography		89

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 275, *Sludge recovery, recycling, treatment and disposal*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

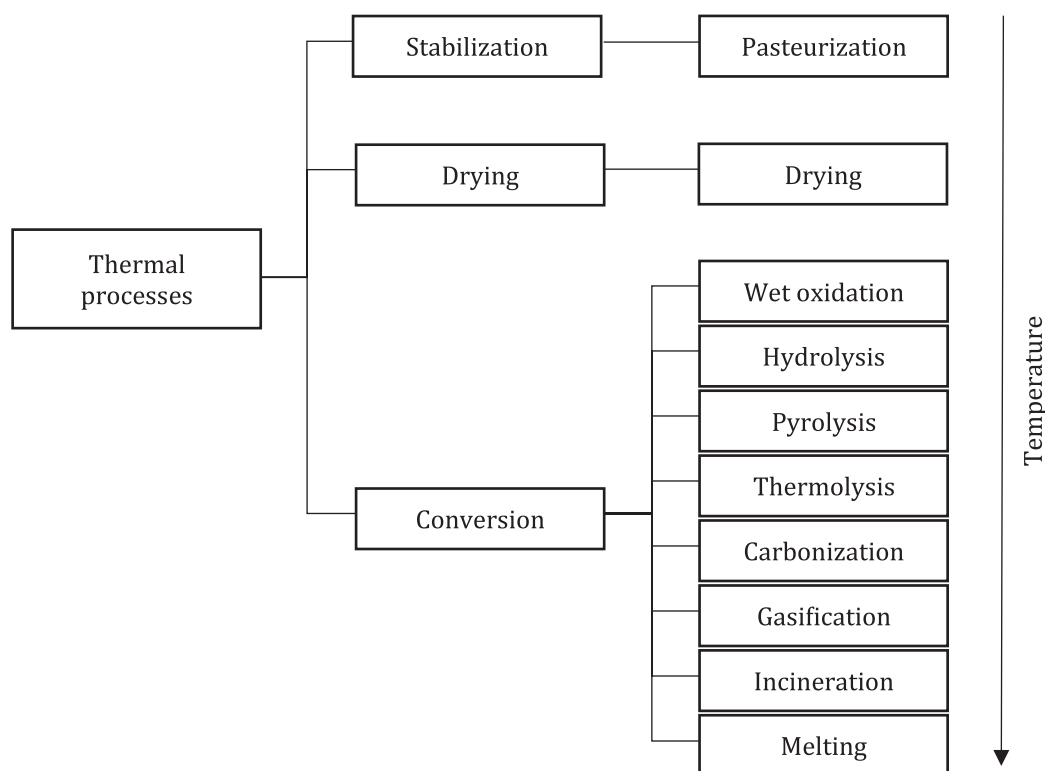
Sludge treatment and management is globally a growing challenge for most countries:

- sludge is a by-product of water treatment process produced in large quantities as new wastewater treatment facilities are built and the existing ones are upgraded to keep up with the population growth;
- sludge treatment and disposal constitutes one of the most significant costs associated with water and wastewater treatment;
- stricter regulations on conventional outlets such as beneficial agricultural land, composting, landfilling require more treatment due to concerns about the long-term impacts on public health and environment;
- sludge is now being considered as a source of renewable energy, and also a source of valuable components such as carbon and nutrients.

The growing trend to recover energy and resources from waste sludge and stricter regulations on outlets have created interest in a number of thermal treatments and may meet, under certain conditions, the circular economy principles.

The objective of this document is to pragmatically present the methods for thermal treatment of sludge by covering the different process fundamentals, the associated technologies and operational aspects, the management of energy, valuables and residues, the aspects related to impacts and integration of installations referring to them.

[Figure 1](#) highlights the thermal processes covered according to their main function and operating temperature.



NOTE The processes listed in the right column and connected to conversion and drying as main functions also achieve the sludge stabilization.

Figure 1 — Thermal processes covered by this document

Sludge recovery, recycling, treatment and disposal — Guidance on thermal treatment of sludge

1 Scope

This document describes good practices for the incineration and other organic matter treatment by thermal processes of sludges.

Thermal conditioning is excluded.

This document applies to sludges specifically derived from:

- storm water handling;
- night soil;
- urban wastewater collecting systems;
- urban wastewater treatment plants;
- treating industrial wastewater similar to urban wastewater.

It includes all sludge that may have similar environmental and/or health impacts but excludes hazardous sludge from industry and dredged sludge.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1

melting

thermal treatment which makes sludge or ash temperature raising over melting point of sludge inorganic substances

3.2

drying

thermal treatment for evaporating water from dewatered sludge to control water content by heating

3.3

carbonization

part of *pyrolysis* (3.4), focusing on production of a solid secondary resource so-called bio-charcoal

3.4

pyrolysis

thermal treatment without supply of oxygen

[SOURCE: CEN/TR 16788, 3.4]

3.5

gasification

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

3.6

char

combination of non-combustible materials and carbon produced from devolatilization, *gasification* ([3.5](#)), *pyrolysis* ([3.4](#)) or *carbonization* ([3.3](#)) process

3.7

bio-charcoal

biochar

solid secondary resource, generated from carbonization (or pyrolysis) process

3.8

thermal treatment

treatment in which heat is applied to remove moisture, microbial content and organic compounds

3.9

thermal process

technique for the application of *thermal treatment* ([3.8](#))

3.10

combined treatment

treatment of sludge and other waste in the same device

3.11

furnace

enclosed chamber where combustion of organic matter takes place

3.12

boiler

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

3.13

flue gas treatment

any physical or chemical process aimed at cleaning the gas emission resulting from the *thermal treatment* ([3.8](#)) with regard to their discharge into the atmosphere

3.14

bottom ash

combustion residue collected at the bottom of a combustion furnace

3.15

fly ash

solid material that is entrained in a flue gas stream

3.16

energy recovery

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

3.17**recycling**

activity in a production process to process waste materials for the original purpose or for other purposes, excluding *energy recovery* (3.16)

3.18**slag**

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

3.19**energy efficiency**

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

3.20**wet oxidation****wet air oxidation**

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

3.21**syngas**

mixture of gases (including carbon monoxide, hydrogen, methane, etc.) produced from *gasification* (3.5) or *pyrolysis* (3.4) process

3.22**combustion**

chemical and exothermic reaction with full oxidation of combustible materials

3.23**autothermal conditions**

conditions that keep combustion without auxiliary fuel and/or other external energy

3.24**paste-like sludge**

sludge capable of continuous flow under the effect of pressure above a certain threshold and having a shear resistance below a certain threshold

[SOURCE: CEN/TR 15463, 1.2.b]

3.25**solid sludge**

sludge having a shear resistance above a certain threshold

[SOURCE: CEN/TR 15463, 1.2.c]

4 Abbreviated terms

BAT	Best available technology
CFBF	Circulating fluidized bed furnace
DM	Dry matter
FBF	Fluidized bed furnace
GCV	Greater (or gross) calorific value
LCV	Lower (or net) calorific value
LOI	Loss on ignition

MHF	Multiple hearth furnace
MSW	Municipal solid waste
PFBF	Pressurized fluidized-bed furnace
SCR	Selective catalytic reduction
SNCR	Selective not catalytic reduction
3T	Temperature, turbulence and (residence) time

5 Sludge properties

5.1 General

Sludge characterization for the assessment of thermal processes involves the evaluation of both technical and economic parameters. The main technical characteristics to evaluate the suitability of thermal process are DM 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.

5.2 Physico-chemical characteristics

5.2.1 General

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

- DM (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.

5.2.2 Dry matter

The DM, or moisture content, is of primary importance for thermal processes because it strongly affects the LCV of organic material which decreases when the moisture content increases.

In thermal processing of sewage sludge DM is a parameter affecting both fuel requirement and exhaust gas production. Generally, any increase in DM is believed to be beneficial in the combustion for the reduction in fuel requirement. When the condition for autothermal combustion, at a given temperature, is reached the increase in DM corresponds also to a decrease in combustion gases production. Any further increase of DM beyond the limit of autothermal 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.

5.2.3 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 $550\text{ }^\circ\text{C} \pm 25\text{ }^\circ\text{C}$ (see Reference [4]) or $600\text{ }^\circ\text{C} \pm 25\text{ }^\circ\text{C}$ (see Reference [18]) 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 (see EN 15935).

5.2.4 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):

- GCV at constant volume which is absolute value of the specific energy of combustion, in Joules, for unit mass of a solid sludge burned in oxygen in a calorimetric bomb under the conditions specified. The products of combustion are assumed to consist of gaseous oxygen, nitrogen, carbon dioxide and sulfur dioxide, of liquid water (in equilibrium with its vapour) saturated with carbon dioxide under the conditions of the bomb reaction, and of solid ash, all at the reference temperature;
- 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 can 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 can be expressed per LOI (loss on ignition) or DM.

Typical calorific values of municipal wastewater sludge range from 22,1 MJ/kg LOI to 24,4 MJ/kg LOI (anaerobically digested primary) to 23,3 MJ/kg LOI to 27,9 MJ/kg LOI (raw primary). Secondary sludge displays values between 20,7 MJ/kg LOI and 24,4 MJ/kg LOI.

Given typical values of organic matter content (LOI), the calorific value of sludge would generally be in the range of 12 MJ/kg to 17 MJ/kg DM for non-digested sludge, 10 MJ/kg to 12 MJ/kg DM for digested sludge.

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 A](#).

5.2.5 Grease, scum and screenings

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 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 $70\text{ }^\circ\text{C}$ to $80\text{ }^\circ\text{C}$ 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 $3 \times 10^{-6} \text{ m}^3/\text{m}^3$ to $40 \times 10^{-6} \text{ m}^3/\text{m}^3$ 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 $1 \text{ l}/\text{m}^3$ 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 $640 \text{ kg}/\text{m}^3$ to $1\,000 \text{ kg}/\text{m}^3$.

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.

5.2.6 Physical consistency and others

The physical consistency of the sludge influences 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 (see Reference [2]).

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

5.3 Chemical and microbiological characteristics

5.3.1 General

The main characteristics to be taken into account are:

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

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

Typical elemental composition depends also on the type of sludge, primary, activated or digested primary sludge (see Reference [13] for more details).

5.3.2 Sulfur

The sulfur content of sewage sludge ranges generally from 0,5 % to 2,1 % of DM.

In anaerobic digestion, sulfate is converted to sulphide by sulfate 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 sulfate remains in solution as such. If sulfate containing compounds are used as inorganic conditioners in thickening and dewatering, sulfur content increases. Sometimes, this can affect the cost of acid gas removal (e.g. in flue gas desulfurization). Because a fraction of the sulfur is present in the oxidized sulfate form, not all of this sulfur is converted

to sulfur dioxide during combustion. Sulfur dioxide then combines with moisture, either in the waste gas treatment system or in the atmosphere, to form sulphuric and sulphurous acids.

5.3.3 Phosphorus

Phosphorus may be present in sewage sludge in concentration ranging from 1 % to 16 % DM.

However, phosphorus concentration in dry sludge can be widely changed, depending on wastewater treatment system prior to sludge treatment. 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, combustion ashes represent a useful source of phosphorus and its recovery should be considered.

5.3.4 Nitrogen

Nitrogen content of sewage sludge ranges from 2 % to 12 % of DM; 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 [8.4](#)). Nitrous oxide, N_2O , is generated as a result of reaction in thermal oxidation processes, which has approximately 300 times as high as CO_2 in terms of greenhouse gas effect.

5.3.5 Chlorine and other halogens

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 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 as chlorine but the organic compounds are more easily formed and they can also be more easily destroyed at high temperatures.

5.3.6 Organic micro pollutants

Although the presence of biopersistent organic micro pollutants (such as chlorinated hydrocarbons, phenols and polyphenols, polychlorinated biphenyls, pesticides and polycyclic aromatic hydrocarbons 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 incineration. Dioxins are rarely formed in sewage sludge mono-incineration process as the concentrations of dioxin precursor and unburned carbon are very low. 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 avoided by a rapid quench of the exhaust gas. Significant formation of particularly stable compounds has been evidenced in oxygen-deficient environments. However, rapid quenching is not necessary when the concentration of chlorine is low. Different reviews on quality of sewage sludge are available (see Reference [\[19\]](#)).

5.3.7 Trace elements

The presence of trace element, such as mercury, arsenic, lead, cadmium and zinc, in sewage sludge should be considered for their tendency to be transferred in the gaseous phase. Except for mercury, they may be concentrated in fly ashes collected by commonly used particulate control devices like impingement separators, cyclones, bag filters, ceramic filters 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 1](#) shows the typical concentration range of trace elements.

Table 1 — Trace elements in sewage sludge ashes (DM)

Values in mg/kg

	Min.	Max.	Mean	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	6 488	1 914	1 307
Mo	7,5	112	25,3	20,0
Ni	8,2	501	106	74,8
Pb	< 3,5	1 112	151	117
Zn	552	5 515	2 535	2 534

5.3.8 Pathogens

Sewage sludge contains a mixture of different organisms, both saprophytes and pathogens. Most of microorganisms originate from human faeces. Main pathogenic organisms found in sewage sludge belong to the groups of enteric bacteria, parasites, viruses and fungi. Their concentrations depend on the wastewater treatment method and the physico-chemical processes the sludge went through. Their concentrations depend on the wastewater treatment method and the physico-chemical processes the sludge went through^[11].

Sludge reintroduction in natural systems (land application) involves the adoption of precautionary quality criteria especially on the limit values for pathogens to prevent harmful effects on environment and human health.

6 Thermal processes fundamentals

6.1 General

This clause summarizes fundamentals related to each technology by covering:

- the phenomena involved: reactions, reactants, products;
- the requirements and optimal conditions for application;
- the expected quality on sludge/products quality;
- the possible positioning in the sludge treatment line.

6.2 Drying

Thermal drying is a process in which thermal energy is delivered to the sludge in order to evaporate water. Sludge drying process reduces the mass and the volume of the product, making its storage, transport, packaging and retail easier and also enables further energy-efficient thermal treatment.

Water present in sludge may be of the following types.

— Free water

Free water includes two subcategories. On the one hand supernatant water which is removable by natural gravity and thickening devices, and on the other hand bulk water which is trapped in flocs removable by dewatering devices.

— Bound water

Bound water is only removable by thermal processes and could be divided in three subcategories: internal or capillary water, surface water and chemically bound water.

Through the process, the sludge passes by several phases (see [Figure 2](#)). The number of these phases' changes according to the sludge quality and depends on the implemented drying method and the operating conditions. The different phases relate to decreasing evaporation rate when moisture content falls.

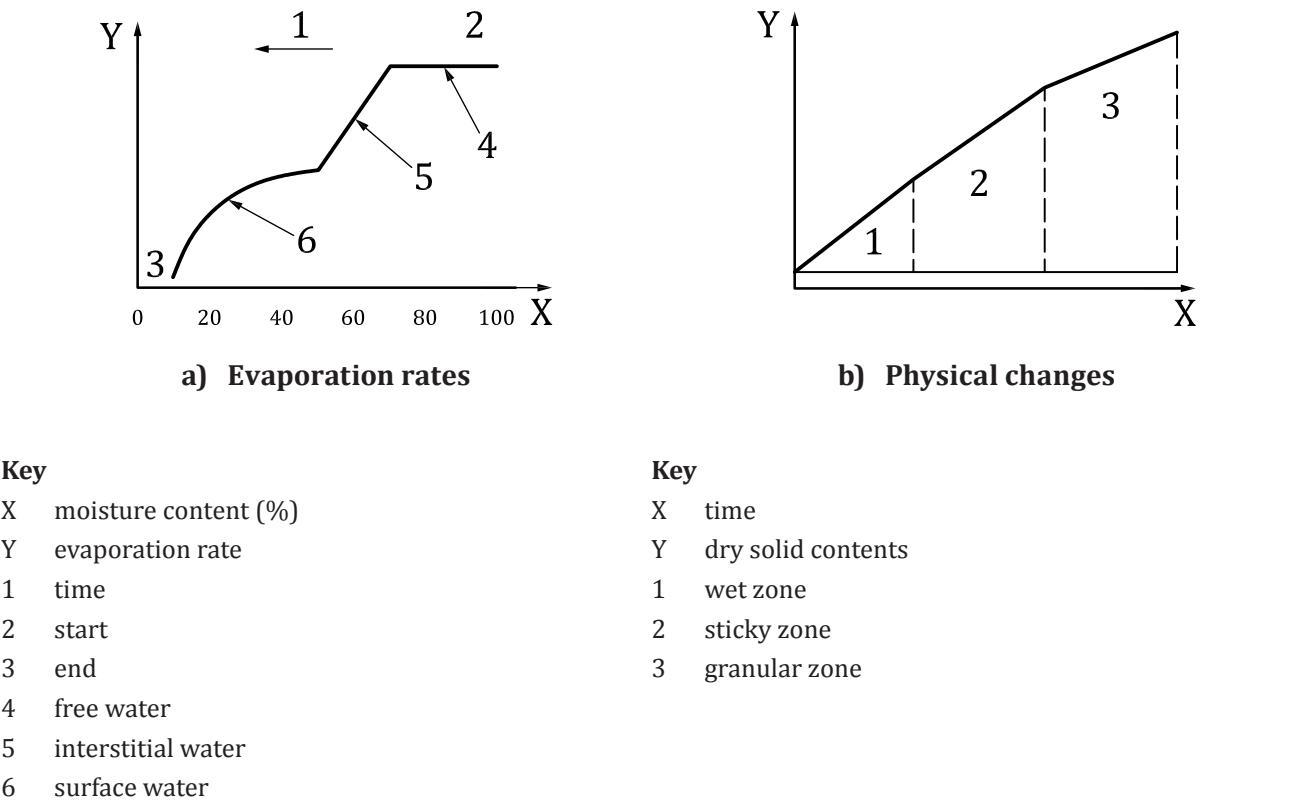


Figure 2 — Status changes during sludge drying time

Dried sludge has solid content usually greater than 90 % when drying is applied as final treatment. When sludge drying is applied prior to incineration, the solid content of dried sludge is generally 60 % to 70 %. Drying achieves sludge hygienization.

Under atmospheric pressure, water evaporation starts at 100 °C. Evaporation of 1 kg of water at 100 °C requires 2 257 kJ (0,63 kWh). Energy requirements in addition include the energy needed to increase

the sludge temperature to slightly above 100 °C, plus energy losses in the drying system. Consequently, energy demands for all dryers range from 0,7 kWh/kg to 1,4 kWh/kg evaporated water.

The exchanges of mass and heat between sludge and air are essential for the drying process. The heat exchange is achieved through radiation, convection, conduction and mixture thereof.

Drying constitutes an important stage among the sludge management options.

- It reduces the volume of sludge and consequently decreases the cost of handling, transport and storage of the final product which is in addition sanitized.
- It increases the calorific value of the sludge which permits to use it, as a fuel or a co-fuel in cement kilns, in coal-fired power plants, municipal waste incinerators and sludge incinerators or other thermal treatments.

The waste to energy approach is currently a growing solution for sludge management.

6.3 Hydrolysis

Thermal hydrolysis disintegrates the cell structure of bacteria into an easily digestible and dewaterable product by applying temperature.

It involves the application of heat above high temperature for a defined time period. One can distinguish thermal hydrolysis and thermal pressure-mediated hydrolysis. The pressure greatly favours the release of both carbohydrates and proteins.

The optimal temperature is approximately 170 °C for a time period of 20 min to 40 min and a pressure in the range 600 kPa to 1 500 kPa.

The reactions result in two sets of impacts depending on the temperature applied. Details are provided in [Table 2](#).

Table 2 — Impacts of temperature application on sludge quality

For temperature up to optimum temperature range	For temperature beyond optimal temperature to sub-critical water range
— Improves downstream sludge anaerobic digestibility, thus biogas production and higher digester loading rates — Improves dewaterability — Decreases apparent viscosity — Decrease pathogenic content — Increases solubility of carbohydrates — Increases solubility of proteins, thus ammonia and alkalinity — Has negligible influence of solubility of lipids — Reduces average particle size	— Decreases downstream sludge anaerobic digestibility — Significantly increases production of refractory material and colour — Further reduces apparent viscosity — Further improves dewaterability

The temperature increase is achieved using steam. The steam demand is determined by the energy required to heat up the sludge from the inlet temperature to the outlet conditions and by the need to make up any system losses. The thermal energy required is approximately 0,3 MWh/TDS under optimal conditions. It varies according to influent sludge temperature, temperature difference, sludge physical properties.

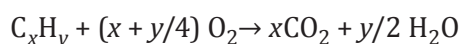
6.4 Incineration

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 sulfur yields energy and products of combustion, namely, carbon dioxide (CO₂), water (H₂O) and sulfur dioxide (SO₂). Organic nitrogen is preferentially converted to nitrogen gas but a certain amount (2 % to 7 %) can also be further oxidized to nitrogen oxide (NO) and to nitrous oxide (N₂O).

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:



Incineration produces a waste gas composed primarily of carbon dioxide (CO₂) and water (H₂O). Other air emissions include nitrogen oxides, sulfur 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 CO₂ reacts with C that has not been consumed yet and is converted to carbon monoxide (CO) at higher temperatures:



The temperature achieved in the combustion process depends on the balance between the energy inputs and the energy outputs. The temperature should be 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 15 % to 30 % (1,15 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 generates 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 autothermal 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, should be properly managed for recovery or disposal.

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 in autothermal condition. In order to achieve autothermal conditions, sludge should be sufficiently dewatered or dried.

6.5 Pyrolysis

Pyrolysis is an endothermic thermochemical process where the organic matter in sludge is broken down in an environment lacking in oxygen compared to the stoichiometry required for the thermal oxidation of organic matter. It occurs in the absence of oxygen or in the presence of oxygen to such a small extent that pyrolysis reactions significantly prevail over gasification reactions. While pyrolysis reactions occur in gasification and combustion processes as precursor reactions, pyrolysis can also be operated as a separate process. It operates at temperatures of 400 °C to 800 °C. Pyrolysis treatment can be applied for a countermeasure for Hexavalent chromium (Cr⁶⁺) emission control.

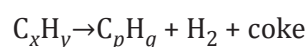
Pyrolysis essentially devolatilizes the fuel. The products from pyrolysis are a solid residue (mainly char) and a synthetic gas (syngas), while some of the volatile components form tars and oils that can be removed and reused. Char is a combination of non-combustible materials and carbon. The syngas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

The low temperature of operation eliminates the formation of SO₂ 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:



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:



CO and CO₂ are 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 reactor type and operating conditions. Basically, there are three types of pyrolytic reactions, i.e. conventional or Slow Pyrolysis, Flash or Fast Pyrolysis and Catalytic Pyrolysis.

In general pyrolysis processes are operated at temperature ranges of 400-700°C, lower than gasification or incineration processes (typically > 850 °C). Two general strategies can be distinguished, slow pyrolysis and fast pyrolysis.

Slow pyrolysis utilizes low temperatures around 400 °C over a long period of time to maximize char formation.

Flash/fast pyrolysis involves high heating rates (500 °C/s to 1 000 °C/s), moderate temperatures (450 °C to 500 °C), short gas residence times (<2 s), and rapid quenching of the vapours. It favours reduction of the solid waste volume and liquid yield depending on the temperature. The vapours are intensively condensed yielding a so-called bio-oil.

The addition of catalysts to the pyrolysis system (catalytic pyrolysis) further increases gas yield.

The main parameters affecting the product distribution and energy content of pyrolytic products include temperature, heating rate, and residence time in the reaction zone. Most pyrolysis processes operate at atmospheric pressure. Vacuum pyrolysis can shorten the residence time of volatile products in the high-temperature zone, reducing the secondary decomposition and increasing the heat value of the gas products. Its implementation is however difficult in practice.

Pyrolysis is not effective in either destroying or physically separating inorganics. By-products 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.

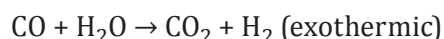
6.6 Gasification

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.

In contrast to combustion, for gasification addition of oxygen is at least limited (autothermal gasification) or completely absent (allothermal gasification, not to be confused with pyrolysis). With the first type, a portion of the gasifier feedstock is partially combusted in the reactor to sustain the process. With the latter type, an external energy source sustains the process.

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 increase both capital and operational expenses. From an energetic perspective, it is sensible to use the heat generated through combustion of product gas in a combustion chamber to offset the heat demand of the dryer. Depending on the dried solids content of the sludge after mechanical dewatering and the heating value of the sludge, the heat demand can in many cases be completely satisfied.

The main reactions taking place during gasification are:



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

Operation of the gasifier at slight overpressure (maximum 50 kPa) is adequate for heat and power applications. For autothermal gasification, a gasifying medium containing oxygen is supplied in a controlled manner so that sub-stoichiometric conditions prevail in the reactor. Gasification reactions liberate CO, H_2 , CO_2 , H_2O and CH_4 . When air is used as a gasifying medium the resulting gas contains a significant portion of inert nitrogen and is thus classified as a LHV (low heating value) product gas. Typical heating values for a product gas generated from dried sewage sludge range from 3 MJ/m³ to 5 MJ/m³.

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. Commercial plants are available, see [Annex C](#).

Sludges are generally pre-treated before gasification. For most pyrolysis applications, drying and size-reduction are required in the pre-processing steps. This may also include blending. The moisture content is a key parameter. Gasification runs best at moisture contents between 5 % and 10 % of water content. Thus, the thermal drying process represents a significant heat consumer in the thermal sludge treatment process. From an energetic perspective, it is sensible to use the heat generated through combustion of product gas in a combustion chamber to offset the heat demand of the dryer. Depending on the dried solids content of the sludge after mechanical dewatering and the heating value of the sludge, the heat demand can in many cases be completely satisfied.

Combustion and gasification processes may employ a pyrolysis process upstream of the main reactor as part of a staged thermal treatment process. The main advantage of a staged-combustion process is the generation of a homogenous gaseous fuel allowing for a more controlled combustion. Staged gasification processes for combined heat and power applications may use a pyrolysis reactor upstream of the gasifier in order to minimize the tar content of the product gas before combustion in a combined heat and power motor, thus increasing the overall energy conversion in the motor. The main difference between a separate pyrolysis process and staged-combustion or staged-gasification processes is that a char product is generated with the former, while the char is typically valorised in the latter applications, discharging an ash by-product.

6.7 Thermolysis

Thermolysis constitutes an extreme pyrolysis process as it takes place in the absence of any exogenous oxygen.

6.8 Carbonization

Carbonization is a general name of process that is focusing on production of a solid secondary resource so-called bio-charcoal and it has been used for production of wooden charcoal since long ago. When sewage sludge is heated under low or no oxygen supply, pyrolysis reaction is started by evaporating moisture content and releasing adsorbed gases and bio-charcoal that mainly consists of carbon is generated after completion of releasing synthetic gas (syngas or pyrolysis gas). The operation temperature is between 250 °C and 800 °C, depending on a type of reactor and a targeted calorific value of bio-charcoal. Products of carbonization process are bio-charcoal and syngas. For other characteristics, refer to [6.5](#).

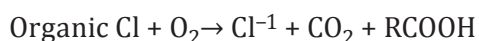
6.9 Wet oxidation

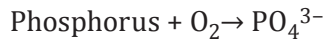
Wet oxidation, also called wet air oxidation (WAO) is based on aqueous-phase oxidation of the organics in sewage sludge, using oxygen from either air or oxygen gas as oxidant

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

For sludge, the oxidation takes place at 250 °C to 300 °C and 50×10^2 kPa to 100×10^2 kPa.

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





6.10 Melting

Sludge melting also called “sludge vitrification” is the technology which melts inorganic matters (mainly its silica compound) in the sludge raising its temperature over melting point, typically found in the range 1 100 °C to 1 250 °C. Consequently, melting is performed in furnaces generally operated under 1 200 °C to 1 350 °C and up to 1 500 °C.

There are two application points of melting, which are: dewatered sludge after drying and ash from sewage sludge incineration.

Upon heating, moisture and organic matter in the sludge are evaporated and combusted like under incineration, furthermore low boiling point metals such as cadmium are also evaporated. From ash, low boiling point substances are evaporated and transferred to the flue gas. The evaporated substances are solidified again during cooling of the flue gas for heat recovery and detoxication.

Melting sewage sludge produces melt-solidified slag. Depending on the cooling method, slag is classified as granulated slag, air-cooled slag and crystallized slag. There are roughly two methods of cooling melted slag which are rapid cooling and gradual cooling. In case of rapid cooling, slag forms brittle granular and in case of gradual cooling, slag forms crush stone-like shape with a stronger hardness than rapid cooling. Both types of slag can be used for construction material such as road material and resource as concrete secondary product (see JIS A5031:2006) and fertilizer.

The melting process is more effective than the conventional incineration process for reducing the volume of sludge. The bulk density of slag is two and the half times that of the fly ash. Low boiling point substances are evaporated under such high temperature and induced from melting furnace as a part of flue gas. The evaporated substances are solidified again by cooling during flue gas heat recovery and flue gas treatment. Though the bulk density of incinerated ash might be around 600 kg/m³ (as dry ash), that of the melting slag might be around 1 500 kg/m³. In case of treating heavy metals contaminated sludge by chromium for example, melting technology can be applied for the purpose of stabilization that confined heavy metals into the slag. It is easier to treat the slag than the fly ash from incineration, and the hazardous substances are better fixed in the slag without leach.

6.11 Pasteurization

This process really achieves sludge disinfection by destruction or inactivation of pathogenic organisms contained in the sludge. Destruction is defined as the physical disintegration of the organism, while inactivation is defined as the cancellation of its ability to infect.

The survival of microorganisms is a function of a number of factors including the characteristics of their species, local temperature and antagonistic conditions. For a population of specific microorganisms, the lethal effect is gradual and the kinetics generally follow the exponential Chick's law of disinfection where the surviving fraction (X_t) is dependent on the starting population number (X_0) the treatment time interval ($t - t_0$) and the specific decay rate, k dependent on temperature:

$$X_t/X_0 = e^{-k(t - t_0)}$$

Consequently, the requirement for pasteurization is that all sludge be held above a predetermined temperature for a minimum time period^[12].

The process of pasteurization involves the heating of sludge to a relatively high temperature but below water boiling point and often below the point of protein denaturation. Pasteurization at 70 °C for at least 1 h is an effective approach to eliminate most pathogens under detection limits but the method fails to eliminate bacterial endospores using standard pasteurization procedures. For example, Salmonella is killed within 30 min in sludge heated up to 70 °C. Typically, conditions range from four hour-treatment at 55 °C to 30 min or longer at 70 °C for using the treated sludge on agricultural land to prevent any health or environmental risks from residual pathogens according to national requirements^{[15],[16]}. Pasteurization differs from sterilization that uses much higher temperatures, usually at or above the

boiling point of water. Ideally, pasteurization should be included either before or after the regular stabilization processes (digestion, composting, or liming) which are also able to lower to a certain extent the pathogenic microbial content and alter the sewage sludge so that it becomes a less effective medium for microbial (re)growth or recontamination and thus a product suitable for use as a crop fertilizer. Pasteurization is typically combined with subsequent anaerobic digestion which may be at mesophilic temperatures, which would result in the generation of energy rich biogas in the same facility to cover the energy requirements of the pasteurization stage.

Pasteurization is employed extensively in Western Europe.

7 Technologies

7.1 General

An overview of each device based on each fundamental technology listed in [Clause 6](#) is described in this clause, including general design aspects and auxiliary equipment.

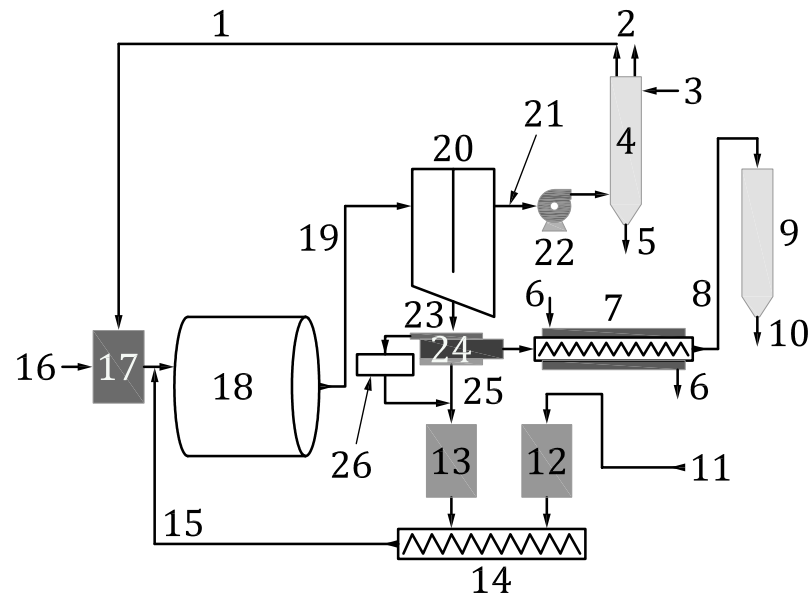
7.2 Drying

In general, the dryers used are based on those found in chemical and agro-processing industries. Thermal drying typically needs to be preceded by, or done in conjunction with a dewatering process. A typical drying system includes the dryer itself, materials handling devices and storage equipment, heat generation and transfer equipment, air movement and distribution equipment, emissions control equipment, and ancillary systems. Drying systems are characterized according to different methods for heat transfer to sludge which are convection, conduction, radiation heating. Multiple methods can be involved of heat transfer in hybrid systems which are generally categorized by their primary method of heat transfer. Depending upon the drying technology used, dried sludge is obtained in various forms (granules, pellets, fines) and densities.

7.2.1 Direct dryers

Dryers that use convection for heat transfer are also referred to as “direct” dryers in which the moisture from the sludge is removed by the carrier gas. In such systems, the heat transfer occurs thanks to the direct contact of hot air/mixture of air and exhaust gas with wet sludge. The hot air/gas is most often produced by a gas or oil-fired furnace at high temperature. The drying process produces vapour that is a mixture of steam, air, and released gases from the sludge. The vapour and gas mixture needs to be cleaned. The treatment of the condensate may be complicated due to the presence of ammonium hydroxide (NH_4OH) or volatile organic carbon (VOC). The dried sludge is separated from the hot exhaust gas, screened and processed for partial recycling back in some technologies to the dryer and routing to storage vessels. Intensive sludge recirculation implemented in some dryers enables to overcome difficulties due to the plastic phase occurrence but the uniformity of the mix and flow are difficult to control in connection with the sticky behaviour of the sludge. After cooling for condensation, the exhaust air/gas is partly (70 % to 90 %) recycled back to the dryer. The rest of the air/gas is treated in air pollution control equipment (filter or cyclone for dust removal, biofilter and thermal oxidation for odours and other undesired components) and then vented. The main direct drying units are rotary drum dryers, belt dryers and fluidized-bed dryers. The specific energy consumption ranges from 700 kWh to 1 400 kWh per ton of evaporated water. The working capacity usually ranges from 5 000 kg/h to 15 000 kg/h of evaporated water.

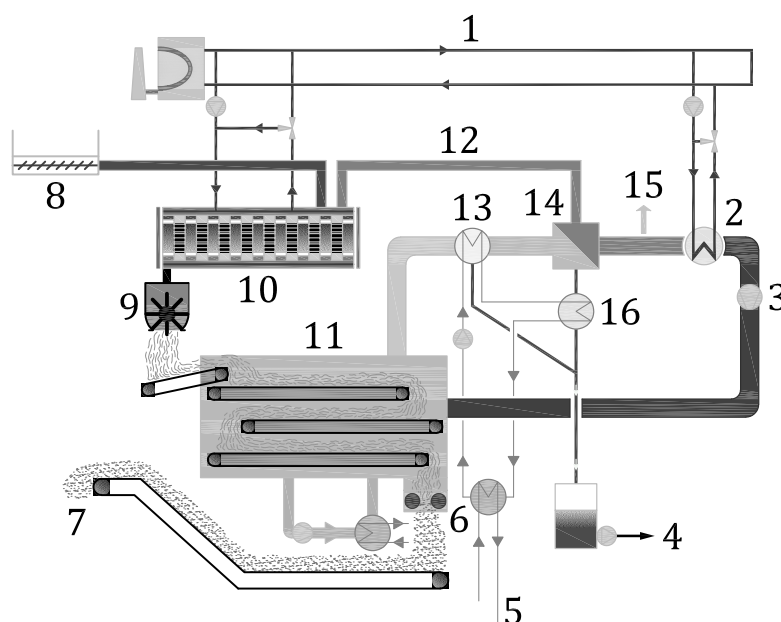
Representative schematic diagrams are shown in [Figure 3](#) and [Figure 4](#).



Key

1	recycle air	14	mixer
2	air exhaust to air pollution control	15	feed
3	cooling water	16	fresh air and fuel
4	condenser	17	furnace
5	condensate	18	drum dryer
6	water	19	dry solids and recycle air
7	product cooler	20	air/solids separator
8	cooled pellets	21	air
9	storage silo	22	fan
10	dried biosolids	23	dry solids
11	wet cake from dewatering system	24	screen
12	wet cake bin	25	recycled dry solids
13	recycle bin	26	crusher

Figure 3 — Rotary drum dryer system



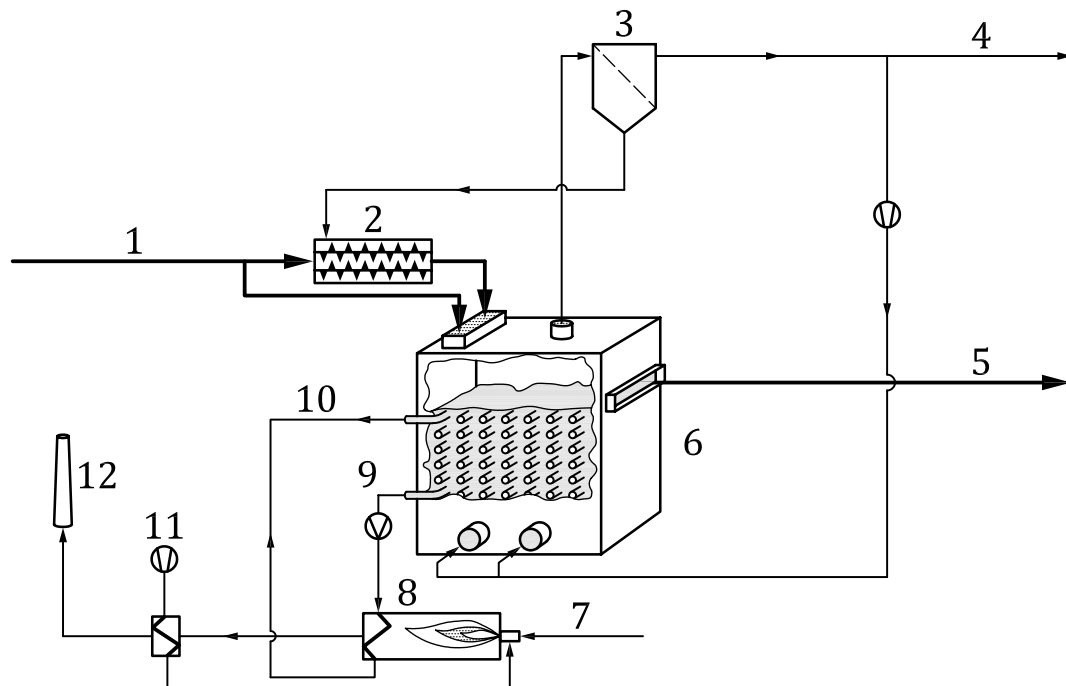
Key

1	heating medium (oil or stream)	9	chopper
2	re-heater	10	thin film evaporator
3	air fan	11	belt dryer
4	condensates	12	heat recovery (vapour)
5	heat export	13	air cooler
6	sizer	14	condenser
7	granules	15	air exhaust
8	sludge pump	16	post-condenser

Figure 4 — Belt dryer system

In drum dryer, the dewatered sludge with a dry solid content in the range of 20 % to 35 % is introduced via appropriate feeding devices into a revolving drying drum. The material flows away from the entry point through the drum internals which can largely vary. The drum dryer can be single pass or multi-pass. The residence time in the dryer depends on drum speed, drum inclination, flow rate of the drying gas and the storage device of the drum end.

The belt dryer is a lower temperature system compared to a rotary drum system. In contrast to the rotary drum system, the thermal fluid used is hot water or flue gas supplied to air heat exchanger. The belt drying system distributes dewatered sludge as a thick layer (4 cm to 15 cm) onto a horizontal perforated belt moving slowly to offer a high surface area exposure to the hot air. The sludge can be introduced and shaped by an extruder before entering the belt zone to increase again the exposure. The drying area can be divided into several sections equipped with air inlets to control at best the temperature in the range of 90 °C to 150 °C. The lower temperature belt drying system can utilize lower grade waste heat in addition to high temperature waste heat. Belt drying systems can have multiple belts to help minimizing the unit volume size. The rate of air recirculation is commonly over 90 %. The gentle sludge flow on the belt limits the dust generation. The condensate produced is extracted. [Figure 4](#) shows a mixed arrangement in which the main hot air belt dryer is preceded by a thin layer drier. The indirect method is used to condense the vapour emitted during the first drying stage and the vapour's latent heat is recovered for use in heating the hot air loop acting as the second stage heat exchange fluid. This greatly reduces the dryer's energy consumption compared to other drying technologies.



Key

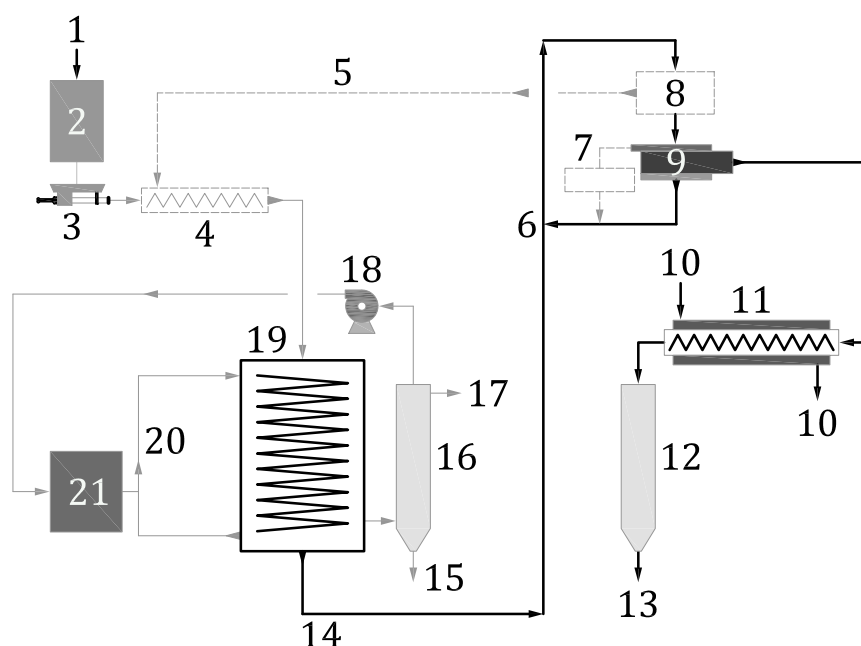
- 1 dewatered sludge
- 2 mixer
- 3 solids separator
- 4 exhaust vapour treatment
- 5 dried sludge
- 6 fluidized bed dryer
- 7 oil/gas
- 8 burner
- 9 condensate
- 10 steam
- 11 air feed
- 12 exhaust gas

Figure 5 — Fluidized bed dryer system

Other dryers using convection are of fluidized-bed type (see [Figure 5](#)). These operate on the basis of an upward air flow passing through the bulk of sludge. Dewatered sludge is directly fed into the fluidized bed first filled with dry granules. Fluidization gas is uniformly blown over the cross-section of the dryer generating a fluidized bed of dry granulates which are mixed at the same time. The granules become free-floating and at the same time mixed thoroughly. Granulation occurs upon water evaporation and particle movement in the dryer. The fluidized bed dryer itself consists of three main sections: a wind box with a gas distribution plate, a middle section which holds the heat exchanger immersed in the fluidized bed, a top dryer hood which separates particles lifted from the layer with the fluidization gas. This may partly deagglomerate the solid and turns it into a fine powder. The gas leaves the dryer carrying the evaporated water and the fine powder. The fine powder is separated in the cyclone and the evaporated water is condensed out of the gas stream in a scrubber-condenser. The dust is fed to a mixer with the inlet dewatered sludge. The dryer operates in a closed inert gas loop. The heat exchanger transfers all the required heat for evaporating the water coming along with the wet sludge. Steam or thermal oil is the usual transfer medium. The dry granules leave the fluidized bed unit through the discharge opening.

7.2.2 Indirect dryers

Systems that primarily use conduction for heat transfer are referred to as “indirect” dryers. In indirect dryers, metal walls separate the wet sludge from the heat transfer medium which can be steam, hot water or oil heated in a boiler fired with fossil fuel or biomass. The sludge is mechanically moved through the dryer. Its temperature is raised by contact with the heat exchange surfaces. Some types of indirect dryers are able to handle viscous fluids so that recycling of dry material is not required. Following the dryer, the material handling equipment is similar to that used in the direct system. The three main technologies used are: disc, paddle and thin film dryers. For all, a rotor whose design is key serves for sludge conveying. The specific energy consumption varies from 800 kWh to 1 000 kWh per ton of evaporated water with a specific evaporation rate more important than for convective drying. This range of dryer provide an evaporating capacity of up to 4 000 kg/h. A schematic diagram of a typical paddle drying system is shown in [Figures 6 and 7](#).



Key

1	wet cake from dewatering system	12	storage silo
2	feed bin	13	dried biosolids
3	feed pump	14	dry solids
4	mixer	15	condensate
5	recycled dry solids	16	condenser
6	dry solids	17	cooling water
7	crusher	18	fan
8	separation hopper	19	indirect dryer
9	screen	20	steam or thermal fluid
10	water	21	heater
11	product cooler		

Figure 6 — Typical paddle drying system

In the disc dryer, the rotor consists of a shaft with hollow discs shaped as plates and equipped with transport paddles. The discs are heated by thermal fluid injected into the rotor axis and distributed across the disks. The combined action of disc and stirring paddles ensures an excellent heat transfer and a slow progression of the sludge. Wiper and paddles are required to clean the disc surface. To avoid clogging, a part of the dry sludge might be mixed with the inlet dewatered sludge.