LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Master’s Degree Programme in Energy Technology

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WASTEWATER TREATMENT AND DEINKING SLUDGE UTILIZATION POSSIBILITIES FOR ENERGY AND MATERIAL RECOVERY IN THE LENINGRAD REGION

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D.Sc. (Tech.)

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ABSTRACT

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Keywords: Wastewater treatment sludge, deinking sludge, pulp and paper industry, energy recovery, material recovery.

Operation of pulp and paper mills generates waste including wastewater treatment sludge and deinking sludge. Both sludge types are generated in large amounts and are mainly disposed of in landfills in the Leningrad Region resulting in environmental degradation.

The thesis was aimed at seeking new sustainable ways of sludge utilization. Two paper mills operating in the Leningrad Region and landfilling their sludge were identified: "SCA Hygiene Products Russia" and "Knauf". The former generates 150 t/day of deinking sludge, the latter – 145 t/day of secondary sludge.

Chemical analyses of deinking sludge were performed to assess applicability of sludge in construction materials production processes. Higher heating value on dry basis of both sludge types was determined to evaluate energy potential of sludge generated in the Leningrad Region.

Total energy output from sludge incineration was calculated. Deinking sludge could be utilized in the production process of "LSR-Cement" or "Slantsy Cement Plant Cesla" factories, and "Pobeda" and "Nikolsky" brick mills without exceeding current sludge management costs.

ACKNOWLEDGMENTS

Once started in October,
While being an exchange,
The story of my thesis
Has finishes month the same
(But only year later,
After the year twelve).

That time has flown faster,
Than someone can expect.
This always happens here,
At space of LUT.

For my well being here
I want to bestow them:
Asta Kujala (Kaarin)
For giving right a way
And numerous comments
You made to thesis mine.

With greatest size sincerety,
And heart, full of respect,
Professsor Horttanainen,
I want to thankyou you!
For sharing your knowledge
And efforts you have spent.

Isyanov Lev and Lena
From /εs//tiː//juː//piː//piː/,
My deepest credibility
Now goes straight to you.

The last in list of people
I show my gratitude,
But not the last important
I say big thank to you,
My darling lovey-dovey!

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LIST OF ABBREVIATIONS

AC	Ash Content
AD	Anaerobic Digestion
BAT	Best Available Techniques
BOD	Biochemical Oxygen Demand
CFBB	Circulating Fluidized Bed Boiler
COD	Chemical Oxygen Demand
DL	Direct Liquefaction
DS	Deinking sludge
DSC	Dry Solids Content
FBB	Fluidized Bed Boiler
FL	Federal Law
IPPC	Integrated Pollution Prevention and Control
LR	Leningrad Region
MC	Moisture Content
MHF	Multiple Hearth Furnace
PPI	Pulp and Paper Industry
RCF	Recycled Fibre
SCWG	Supercritical Water Gasification
SCWO	Supercritical Water Oxidation
StE	Sludge-to-Energy
TSS	Total Suspended Solids
WtE	Waste-to-Energy
WWTP	Wastewater Treatment Plant
WWTS	Wastewater Treatment Sludge

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1 INTRODUCTION

1.1 Background

The rate of goods consumption has increased in past and is expected to be rising in the future, especially in developing countries like BRIC[1] and VISTA[2] countries. Some of the products being consumed comprise an essential part of people's everyday life. Paper, especially tissue one, as well as cardboard and pulp, are examples of such products. Production of pulp in Europe was slightly increasing over the period of 1991-2011, while the production of paper and cardboard in European countries increased by 50% over the same period (Confederation of European Paper Industries, 2011). The production of pulp, paper and cardboard has grown in the Russian Federation as well (Federal State Statistics Service, 2013).

The production processes result in waste generation. In 2005, 11 million tonnes of solid waste, including 7.7 million tonnes of waste from recycled fibre (RCF) processing was generated during the production of 99.3 million tonnes of paper in Europe (Monte, et al., 2009). 15.2 million tonnes of pulp, paper, and board were produced in Russia in 2011 (Khasanova, 2012). Meanwhile, about 25% of all solid wastes generated in PPI and directed to landfills are wastewater treatment sludge (WWTS) and deinking sludge (DS) (Vuoristo, 2012).

Since 22 August 2012, the Russian Federation has been a member of the World Trade Organization (World trade organization, 2012) and, thus, to increase competitiveness of pulp and paper products produced in Russia on the international market level companies need to get certified to ISO 14001:2004 (Specialized Expertise Unit on Environmental Safety, 2012).

Nowadays, Russian legislation faces changes related to the environment and, thus, "Basics of state policy in the field of environmental development of Russia by 2030" were approved by the Russian President on April 30, 2012. (Russian Government, 2012) Relying on the chapter

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[1] BRIC – an acronym that refers to the countries of Brazil, Russia, India and China.

[2] VISTA – an acronym that refers to the countries of Vietnam, Indonesia, South Africa, Turkey and Argentina.

15 of the document, one of the mechanisms to ensure environmentally safe waste management is “phased implementation of the ban on landfilling of waste that have not been separated, mechanically or chemically treated, and waste that could be used as secondary raw materials (scrap-metal, paper, packaging materials, car tires, etc.)”. As it comes from the document, companies should seek for new ways to treat their waste materials before landfilling.

1.2 Statement of the problem

Being implemented many years ago, the waste management system in Russian companies is characterized with priority to waste landfilling rather than waste recovering. Nowadays, WWTS and DS are mostly landfilled in the Leningrad region. Exceptions are the cases where companies had suitable facilities and enough financial resources to implement sludge incineration. On contrary, approximately 96% of WWTS and 88% of DS are recovered in Finland and that is very positive experience towards sustainable development (Forest industries, 2008).

The problem of low sludge recovery rate is caused by absence of suitable equipment and finances, as well as by the lack of reliable information on sludge recycling technologies. Therefore, implementation of the study related to estimation of energy potential of sludge and its possible application in construction materials production could be used as a platform to switch from the waste management system where sludge in mainly landfilled to more sustainable ways of sludge utilization successfully applied in developed countries.

1.3 Objectives of the study

Subjects of the waste management, energy technology and sustainable development are linked within the thesis. When considering waste management, legislation aspects and waste treatment technologies will be reviewed. With the increasing demand on alternative energy sources, most feasible ways, as well as innovative ones, to get energy from WWTS and DS, including combustion, will be covered. Technologies required for sludge pretreatment before incineration will be discussed in the study as well.

Finally, the aim of the thesis is to show energy potential of WWTS and DS from pulp and paper industry (PPI) plants located in the Leningrad Region and technologies allowing energy recovery. In addition, applicability of DS and WWTS in construction materials production will be assessed. Energy potential calculations and selection of the construction material production process will be based on sludge properties and composition gained experimentally. Legislation aspects of sludge, as waste material, management will be included. Finally, transportation cost estimations will be given in the study.

1.4 Assumptions and delimitations

In any case, according to Bird (2008), during the operation of PPI plants, next types of solid waste are generated:

- Wastewater treatment plant (WWTP) residuals, including WWTS and DS;
- Boiler and furnace ash;
- Causticizing residues which include lime mud, lime slaker grits and green liquor dregs;
- Wood yard debris;
- Pulping and paper mill rejects.

However, the study scope does not cover other waste materials generated at PPI plants than WWTS and DS.

No possibilities to construct new facilities for sludge utilization will be examined, but only those already existing in the Leningrad Region. What relates to energy recovery option, some parameters are taken from literature sources and are assumptions.

2 PROPERTIES AND AMOUNTS OF SLUDGE GENERATED AT PULP AND PAPER MILLS

Various solid wastes and sludge are generated in the PPI at different production processes. Treatment of wastewater generated at pulping, papermaking, and deinking processes is the main source of WWTS and DS. WWTS is the largest waste stream generated at PPI plants by volume (Bird & Talberth, 2008). Composition and amount of sludge are strongly influenced by paper grade being produced, raw materials used by the process, the production and wastewater treatment technologies, as well as the paper quality (Monte, et al., 2009; Abubakr, et al., 1995).

2.1 Wastewater treatment sludge generation

Most commonly, a treatment plant includes both primary and secondary treatment stages installed one after another. The former is based on the sedimentation process mainly, but also can be implemented by a flotation method, the latter one is based on biological treatment preformed in either aerobic lagoons, activated sludge systems, anaerobic treatment or sequential biological treatment (aerobic-anaerobic or anaerobic-aerobic) systems. Moreover, tertiary treatment can take place in addition to the above mentioned treatment stages in countries with tight environmental regulations. (Bahar, et al., 2011; Abubakr, et al., 1995)

During the primary process, about 80% of total suspended solids (TSS) contained in wastewater entering the treatment process are transferred to WWTS (United States Environmental Protection Agency, 2004; Monte, et al., 2009). Inorganic part of WWTS is mainly present in the form of sand, while organic part is present as bark, fibre or other wood residuals.

During the biological treatment, soluble organic materials are converted to carbon dioxide, water and biomass by microorganisms present in active sludge and required for successful process implementation. The excess biomass is settled in the secondary clarifier where secondary sludge also known as biological sludge, biosolids or activated sludge, is generated (Bahar, et al., 2011, p. 8; Abubakr, et al., 1995). Also, depending on a certain treatment scheme applied at a certain mill, primary sludge and secondary could be either mixed together or collected separately. From the information above, it is seen that primary sludge consists of both organic and inorganic matter, while secondary WWTS is mainly organic materials.

WWTP residuals are the largest part of waste stream generated by PPI by volume. (Abubakr, et al., 1995) These residuals are presented by several types and their shares within all WWTP residuals are presented in Figure 1. The data presented in the figure is collected from PPI plants located in the USA (Bird & Talberth, 2008) and Italy (Boni, et al., 2003).

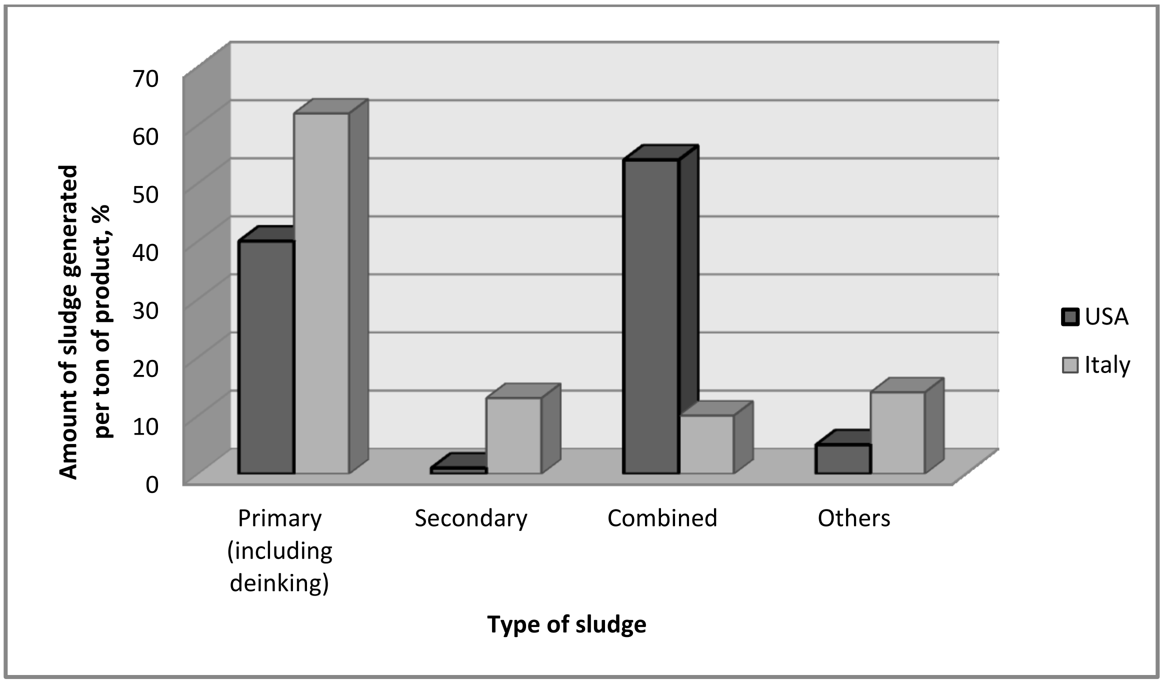


Figure 1. Percent distribution of sludge types produced by PPI plants (Bird & Talberth, 2008; Boni, et al., 2003).

The graph above shows that there is no certain tendency on how to collect sludge. Moreover, not all companies perform biological wastewater treatment on-site, and, thus, they do not have secondary sludge generated at all. Depending on sludge treatment and utilization method, separation of different sludge types, especially secondary sludge, could be beneficial. For example, if sludge is proposed to be used in the production of construction materials then the highest content of inorganic content is beneficial. Moreover, primary and secondary sludge types are of different nature and in the case of necessary pretreatment different sludge should be treated separately to achieve best possible results.

2.2 Deinking sludge generation

DS is generated as a result of recycled fibre production from recycled paper. In many cases deinking process is included in the production scheme since deinking enables increase of brightness and cleanliness of the material being produced. Froth flotation deinking process is mainly used in pulp and paper industry for selective deletion of ink particles only. Not only froth flotation is applied for ink removal during recycled fibre processing, but also wash deinking. That kind of deinking is more aimed at small particles removal, including fillers, coating materials, fines, and inks. However, froth flotation and wash deinking could be combined in the same production line so that the effect of unwanted materials removal is increased. In addition to deinking, de-ashing process is applied in tissue paper production for better removal of fines and fillers. (Kujala, 2012)

In case of deinking sludge, TSS can be categorized into organic matter, such as bark and fiber, and inorganic matter, such as, kaolin, clay, $CaCO_3$, TiO_2 that are resulting from coating materials and other chemicals used for paper production.

2.3 Sludge properties

Properties and nature of sludge, generated at PPI mills depend on the grade of the paper being manufactured, raw materials being used, fibre losses during the production process, as well as effectiveness of the wastewater treatment equipment. Generally, sludge can be characterized by following parameters:

- moisture content;
- ash content;
- heating value.
- loss of ignition;
- fiber length distribution;
- particle size distribution;
- viscosity and pH (Dahl, 2008).

Dahl (2008) and Abubakr (1995) provide information about chemical composition of different sludge types from various production processes. Also Gottsching (2000, p. 514) published the data about composition of DS. Information from these sources was gathered in Table 1. It is clear from the table that sludge composition varies even within the same production processes: dry solids content (DSC) of sludge from three Kraft pulp mills varies from 37.6 to 42.0%. In other words, different pretreatment methods are implemented at those mills. Not only solids content, but also ash content (AC) varies greatly.

Table 1. Composition of sludge from various pulp and paper processes (bark composition is given for comparison). (Dahl, 2008; Abubakr, et al., 1995; Gottsching, 2000)

Source/ Component	Elements content, %							Heating value on dry basis, MJ/kg
	Solids	Ash	C	H	S	O	N	
Kraft-pulp mill (2	37.6	7.1	55.2	6.4	1.0	26.0	4.4	24.1
Kraft-pulp mill(2	40.0	8.0	48.0	5.7	0.8	36.3	1.2	19.8
Pulp mill(2	42.0	4.9	51.6	5.7	0.9	29.3	0.9	21.5
Bleached pulp mill(2	33.4	1.9	48.7	6.6	0.2	42.4	0.2	20.1
Mixed sludge Paper mill(1	-	16.0	45.0	5.8	0.1	-	0.6	-
Mixed sludge Paper mill(4	-	9.6	45.9	6.5	0.7	9.6	3,7	18.9
Deinking sludge(2	42.0	20.2	28.8	3,5	0.2	18.8	0.5	12.0
Deinking sludge(2	42.0	14.0	31.1	4.4	0.2	30.1	0.9	12.2
Deinking sludge(4	-	*50.1*	*26.9*	*2.9*	*0.2*	*18.8*	*1.2*	*8.6*
Recycled paper mill(2	45.0	3,0	48.4	6.6	0.2	41.3	0.5	20.8
Recycled paper mill(2	50.5	2.8	48.6	6.4	0.3	41.6	0.4	20.6
Bark(2	54.0	3.5	48.0	6.0	0.1	42.1	0.3	20.3

(1 – taken from (Dahl, 2008);
(2 – taken from (Abubakr, et al., 1995);
(3 – taken from (Gottsching, 2000);
(4 – taken from (Niessen, 2002)

DS highlighted in *Italic* in the table above have the highest ash content. It means that more than a half of the sludge is incombustible inorganic matter. Along with that, carbon content of the sludge is the lowest between all sludge types. The parameters mentioned directly influence heating value - the major characteristic of sludge as a fuel. Therefore, even if DSC of deinking sludge is somewhat comparable to the rest sludge types or higher, heating values on dry basis are the lowest (from 8.6 to 12.2 MJ/kg).

The rest types of sludge have heating values comparable with bark. This comparison is given since co-firing of sludge with bark is relatively common technique for WWTS and DS utilization at PPI plants and will be described later. Pulp mill sludge generally has higher sulfur content than paper mill sludge and that should be taken into account when air pollution control system for sludge incineration plant is designed.

Monte, et al. (2009) provides information about heavy metals content (Table 2). Such information is needed to supports further decision about the way of sludge utilization, as well as to estimate the amount of heavy metals in emissions released into the atmosphere in the case of sludge incineration. In general terms, sludge contains smaller amounts of heavy metals compared to municipal solid waste (MSW) and, thus, the flue gas treatment system suitable for MSW incineration plants can be easily applied to sludge incineration process to comply with the regulations set on heavy metals emissions.

Table 2. Heavy metals content in different sludge types (bulk municipal solid waste composition is given for comparison). (Valkenburg et al, 2008; Monte, et al., 2009)

Source/ Component	Elements content on dry basis						
	Pb, mg/kg dry	Cd, mg/kg dry	Cr, mg/kg dry	Cu, mg/kg dry	Ni, mg/kg dry	Hg, mg/kg dry	Zn, mg/kg dry
Pulping – primary sludge	41	<0.7	24	238	6	0.1	141
Pulping – secondary sludge	22	<0.7	17	71	8	0.01	135
Deinking sludge from recovered paper	10-210	0.01-0.98	9-903	20-195	<10-31	0.1-0.9	34-1320
Municipal solid waste	50-350	1-35	8-240	35-750	1-150	0.1-2	85-500

Composition of inorganic part of deinking sludge, i.e. ash left after incineration, is presented in Table 3. It should be noted that composition of ash can vary depending on the raw materials used for recycled fibre production.

Table 3. Deinking sludge ash analysis. (CANMET. Energy technology centre, 2005)

Ash analysis, weight-%	**DS №1**	**DS №2**
Fe_2O_3	2.2	1.3
SiO^2	*28.6*	*40.9*
Al_2O_3	*43.4*	*22.9*
CaO	*4.6*	*25.8*
MgO	0.2	6.9
TiO_2	2.8	1.8
MnO	0.2	-
P_2O_5	5.4	-
Na_2O	3.6	0.2
K_2O	1.3	0.2
SO_3	4.1	-

As can be seen from the table, inorganic part of deinking sludge mainly consists of Si, Al, and Ca oxides. The rest elements are present in smaller concentrations. Si and Al are the main components of kaolin, while Ca is the main element of precipitated calcium carbonate. These materials are widely used in paper production that is further used for recycled fibre manufacturing. That composition will be required to assess applicability of deinking sludge in the production processes of different construction materials.

Some sludge properties, especially its aggregate state, depend on DSC of sludge as presented in Figure 2. Given DSC of sludge it is possible to determine sludge aggregate state (liquid/ solid) and structure. Moreover, heat conductivity of sludge is also displayed. As can be seen from the figure, sludge starts agglomerating at about 35% DSC, but only at DSC equal to 58% sludge is presented in the form of single granules. It worth mentioning, that the second zone borders can change depending on either absence, or presence of biological matter or fibers. All that should be taken into account when the pretreatment system is being chosen. (Degremont, 2007, pp. 1274-1275)

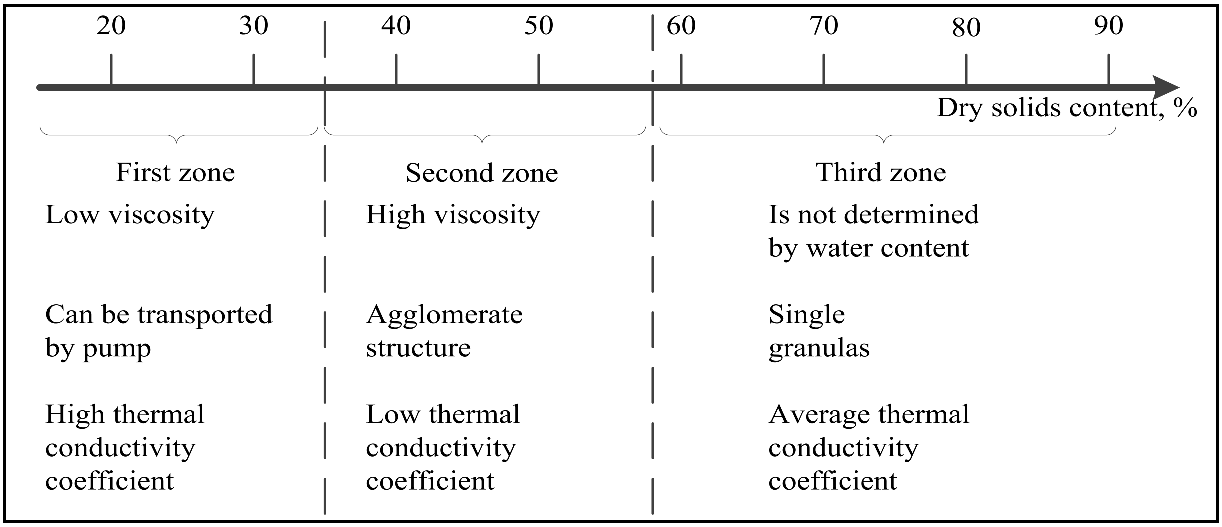


Figure 2. Relationship between the DCS and rheological properties of sludge. (Degremont, 2007, p. 1275)

2.4 Amounts of sludge produced

To evaluate the scale of the problem resulted from sludge landfilling and to select appropriate sludge utilization way, specific amount of sludge generation should be known. Volumes of sludge generated in several production processes could be found through specific rates of sludge generation presented in Table 4. Furthermore, generation rates of primary sludge only are shown in Table 5.

Table 4. Total amounts of sludge generated in several pulping and papermaking processes. (modified from Dahl, 2008; Xu & Lancaster, 2012).

Raw material	**Grade**	**Filler content**	**kg of sludge on dry basis/tonne of product**									
			10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**150**
Chemical pulp	Paper	Low	■	■	■	■						
Chemical pulp	Paper	High		■	■	■	■	■	■	■		
Mechanical pulp	Newsprint	Low	■	■	■	■	■					
Semichemical pulp	Corrugated board		■	■	■							
Recycled paper	*Tissue paper*	*Absence*			■	■	■	■	■	■	■	■
Recycled paper	Board		■	■	■							

Sludge generation rate depends on, firstly, raw material being used, secondly, type of the material being produced and, thirdly, filler content. The tendency observed from Table 4 is that use of virgin fibre does not lead to generation of high sludge volumes. However, in the case when the paper being produced has high filler content, amount of sludge generated increases even if virgin pulp is used in the production process. Use of recycled paper does not necessarily result in high amount of sludge, as in the case of board production. However, during manufacturing of tissue paper high amount of DS is generated (up to 150 kg dry solids/t of product). For the production of tissue paper, full removal of filler, inks and other additives present in recycled paper is required, while for the production of board it does not. Thus, the most important sludge generators are the companies producing tissue paper from recycled one.

Table 5. Amounts of primary sludge generated depending on the product being produced. (modified from Dahl, 2008).

Manufactured product	**kg of sludge on dry basis/tonne of product**								
	5	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**120**
Chemical pulp				■	■				
Mechanical pulp			■	■					
Semichemical pulp					■	■			
Recycled fibre								■	■
Paper and board	■	■							

Information in Table 5 is similar to the data presented in Table 4 with the main tendency about high sludge generation rate at mills producing recycled fibre. It can be proposed that recycled fibre was used for the production of tissue paper because of high amounts of sludge generated.

Once it becomes known how WWTS and DS are generated, their properties, factors affecting the properties and specific amounts of sludge generated, utilization possibilities of sludge can be examined with respect to sludge energy recovery and use of sludge in the construction materials production.

3 PRETREATMENT METHODS OF SLUDGE

This chapter is aimed at description of processes employed to give required properties to sludge so that sludge could be further utilized. Some of those properties are moisture content, stability and lack of pathogens in sludge. In accordance with GOST R 54535-2011 "Resource conservation. Wastewater treatment sludge. Requirements when disposed or used on landfills" (Federal Agency on Technical Regulation, 2012), which is valid and compulsory for implementation for all companies in Russia, DSC of sludge must be not less than 15 weight-% when sludge is disposed in landfills, and not less than 50 weight-% when sludge is used in landfills.

Diagileva (2012), Garg (2009), Degremont (2007, p. 1171) and Hynninen (1998, p.115) provide similar information on sludge handling methods, so information from these sources was compiled and presented in Figure 3. In addition, a typical route of sludge, generated in PPI, processing is indicated (Dahl, 2008).

In general case, sludge pretreatment consists of the following operations: thickening, conditioning, dewatering, drying and final utilization of sludge. Stabilization is not used to decrease moisture content of sludge and, thus, will not be described in the study. As it is shown in Figure 3, there is a great variety of sludge pretreatment methods exists and the selection of a real option depends on the situation.

3.1 Thickening

Thickening is a fundamental stage of sludge pretreatment in any case (Diagileva, et al., 2012). The most widespread thickening method is gravity thickening that does not imply installation of complex equipment. Normally, gravity thickening is implemented in clarifiers (see Appendix I). Once sludge has passed the clarifier, DSC increases from 0.3-3.0 to 7.0%. It worth mentioning that secondary sludge presented by excess biomass has higher resistance to dewatering and, therefore, final DSC of secondary sludge cannot be more than 3.0% in general (Hynninen, 1998, p. 115).

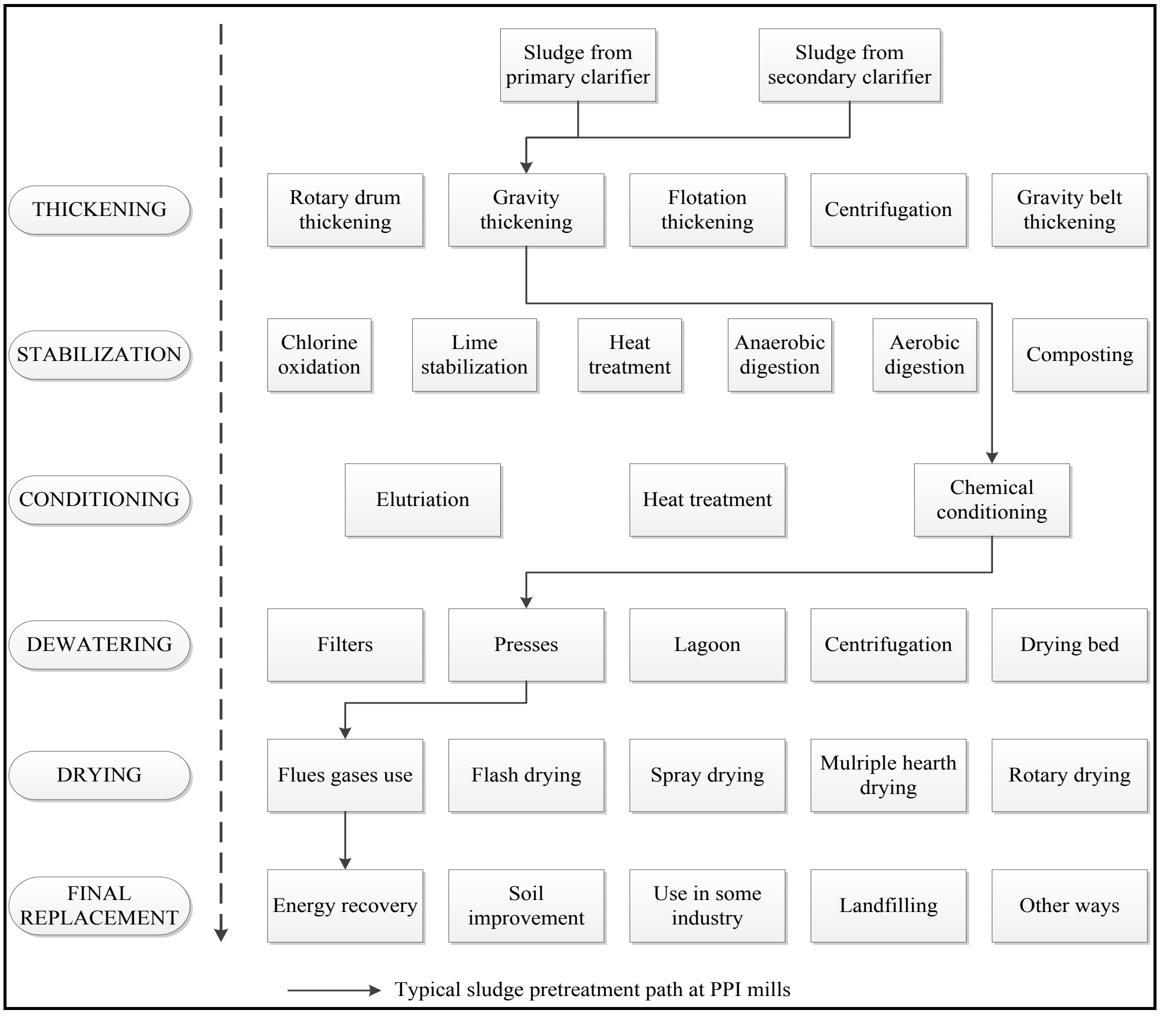


Figure 3. Stages of sludge handling process. (combined from Degremont, 2007; Diagileva, et al., 2012; Hynninen, 1998, p. 115; Garg, 2009).

The efficiency of sludge thickening is higher if thickening is done in a flotation unit (see Appendix II), while the most efficient thickening method is that in a gravity table (see Appendix III) or in a belt thickener (see Appendix IV). The latter one allows increase of sludge DSC to as high as 15.0%.

3.2 Conditioning

Conditioning is needed to ensure better water repulsion of sludge while being dewatered. Water-repellent properties of sludge are increased, since forms of water bonds are changed after conditioning. Thermal or reactant treatments are the most common ways to condition sludge at PPI mills. (Diagileva, et al., 2012, p. 87)

Reactant treatment that also refers to as chemical conditioning is used widely as a basic method. The best results could be gained when an inorganic salt and a polyelectrolyte are used together. Most frequently a combination of ferric chloride, aluminum oxides, and lime is applied as an inorganic salt. Amount of chemicals used is determined by simple analysis. Reagents are fed into a flocculation tank for 1-3 minutes to allow reaction with sludge. As a result, small solid particles contained in sludge coagulate into larger ones that are simpler to dewater. Cost of reagents on local market determines mainly the method application. Moreover, about 60-70% of used $FeCl_3$ and 80-90% of used $Ca(OH)_2$ pass into sludge, and consequently will influence composition of sludge generated. (Degremont, 2007, pp. 1192-1193; Hynninen, 1998, p. 115)

Thermal treatment could be implemented by a wet air oxidation method or by heat treatment. The former method is flameless oxidation at temperatures of 230-290 ^oC and pressure of about 8.3 MPa, while the latter one is done at temperatures of 180-200 ^oC and pressure level of 1-2 MPa. Heat treatment method is used more. When sludge is heated, water bound within the cell structure escapes from sludge and makes sludge easier to dewater. Sludge dewatering efficiency after thermal conditioning is higher, than that after chemical conditioning. However, cost of thermal conditioning is higher than that of chemical one. (Degremont, 2007, pp. 1196-1197)

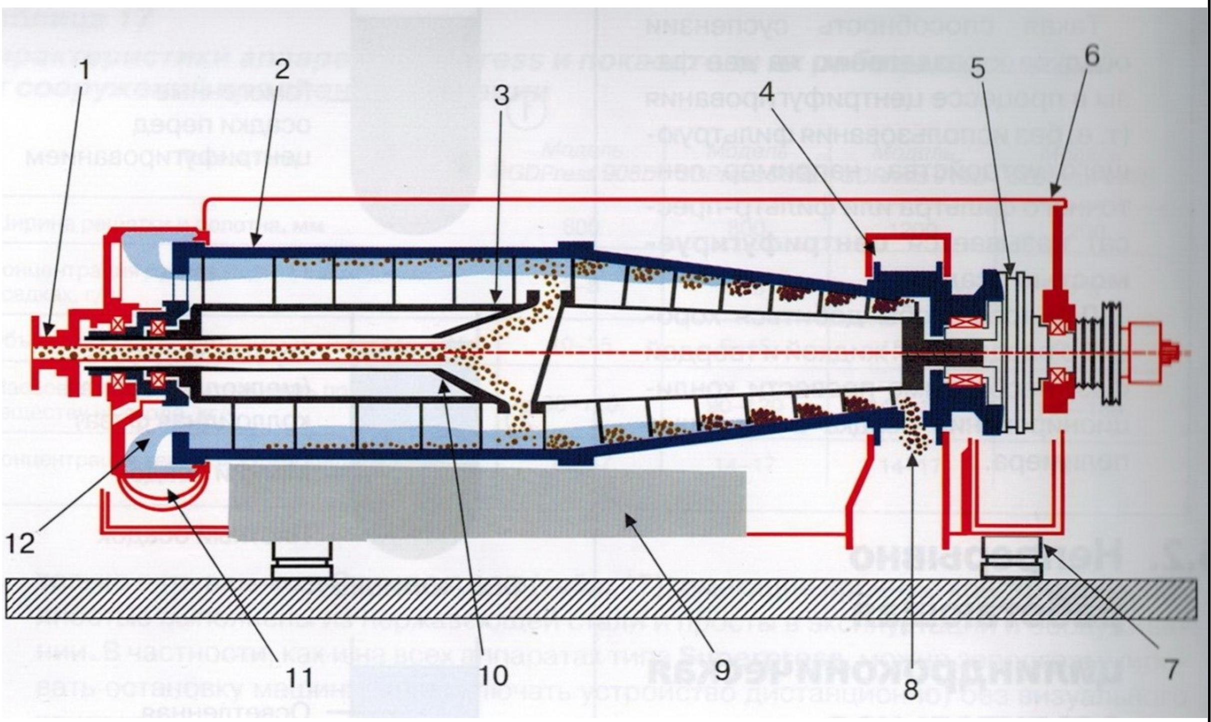
3.3 Dewatering

Dewatering is applied for enhanced water removal from sludge as required by legislation. Moreover, more effective dewatering leads to both environmental and economic benefits. Environmental benefits are reached due to sharp decrease in amounts of sludge disposed in landfills, if sludge is not processed further for energy or material recovery. Economic gains are expressed in terms of money saved from reduced amounts of sludge to be transported.

According to the reference document on Best Available Techniques (BAT) in the pulp and paper industry created by European commission (2001), biological sludge generated at secondary wastewater treatment stage has high resistance to dewatering and should be mixed with primary sludge in order to achieve higher dewatering efficiency. In addition, the document states that sludge should be both thickened and conditioned before being dewatered. Dewatering could be performed in several ways, and some of those are described below. (Garg, 2009)

3.3.1 Centrifuge

Out of all centrifuge types, most commonly applied technology in the wood processing industry is the solid bowl decanter also known as centrifuge. The centrifuge is presented in Figure 4.



1 – sludge inlet; 2 – rotor; 3 – screw; 4 – sedimentary box; 5 – differential gear; 6 – box body; 7 – shock damper; 8 – sludge outlet; 9 – basement; 10 – directional valve; 11 – drainhole; 12 – overfall.

Figure 4. Centrifuge. (Degremont, 2007).

Sludge to be dewatered (1) is sent to a directional valve (10) that distributes sludge evenly over the periphery of circle and forces sludge into space between a rotor (2) and a screw (3). Under centrifugal forces, sludge is pushed towards the rotor's inner wall and then is taken by the screw towards the discharge end of the centrifuge. Because of the differential gear (5) screw rotates a little faster than rotor what makes liquid/solid separation possible. Dewatered sludge is discharged at the end of the centrifuge (8).

Centrifuges show higher efficiency with both inorganic and conditioned sludge and lower with organic one because of specific nature of secondary sludge. Final DSC after sludge processing in centrifuges typically varies from 10 to 35% depending on sludge type and flocculants used for sludge conditioning. However, some advanced solid bowl decanters manufactured by Alfa Laval allow sludge dewatering up to 65% DSC (Alfa Laval, 2011). Specific energy consumption of a single centrifuge can vary from 20 to 60 kWh/tonne of sludge (Huber Technology, 2013). (CANMET. Energy technology centre, 2005; Hynninen, 1998, pp. 116-117)

3.3.2 Belt filter- press

Sludge dewatering in belt filter-presses is one of the common methods of sludge dewatering at PPI plants with many installations being used globally. A belt filter-press is presented in Figure 5.

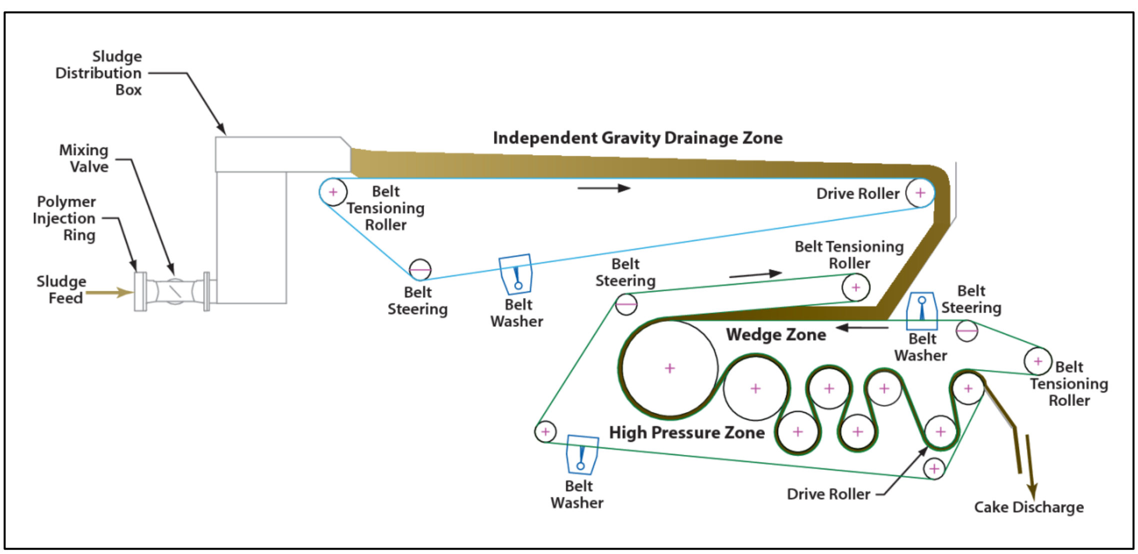


Figure 5. Belt filter-press. (Komline-Sanderson, 2010)

Conditioned sludge is distributed over the surface of a belt with the aid of sludge distribution box. Firstly, free water is removed by the gravity forces in the independent gravity drainage zone. Later, sludge is fed in between two belts, thus, being pressurized. Belts are moving then through a series of turning rolls of decreasing diameter. Eventually, dewatered sludge that is also called cake is discharged. Belts are washed in belt washers to recover filtrating ability.

Belt filter-presses were designed on the purpose of fibrous sludge dewatering, so fibre containing sludge can be treated at high efficiency. Moreover, such installations can be applied for primary and secondary sludge treatment, as well as their mixture. DSC of sludge processed in a belt filter-press varies in a range of 20-35%. Energy needed for treatment of one tonne of suspended particles contained in sludge is 10-25 kWh. (Degremont, 2007)

3.3.3 Screw press

Along with belt filter-presses, screw presses have found wide application around the world. A typical screw press is depicted in Figure 6.

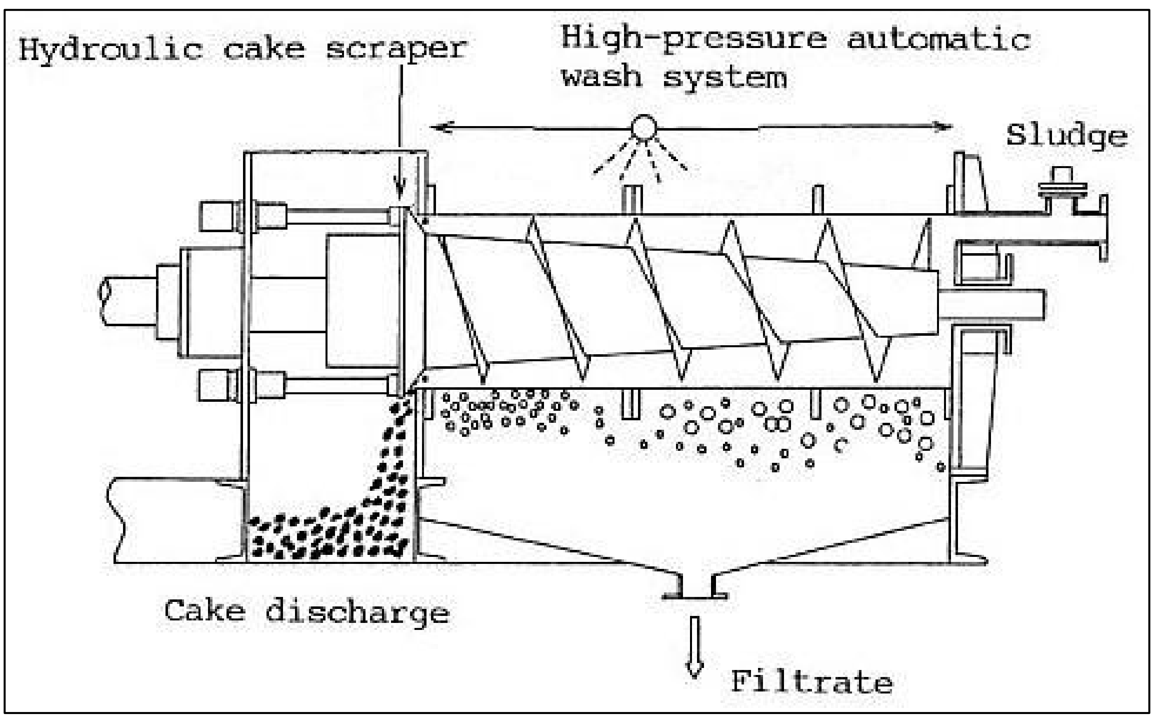


Figure 6. Screw press. (Organo Corporation, 2002)

Sludge fed into a screw press is transported along the length of the press because of the rotating screw. The screw shaft diameter increases over its length and, thus, increases pressure put on sludge. Because of that, water starts filtrating through a screen. Sludge discharging is regulated by the cake scraper that is used for prevention of uncontrolled sludge discharge. Gap size between the scraper and the screw is regulated so that efficiency of dewatering is maximum.

Screw presses show higher efficiency at primary sludge and DS treatment, while dewatering of secondary sludge is a questionable process because of slimy texture of secondary sludge. During normal operation of a screw press, final DSC of sludge can reach 30-50% depending on a sludge type and a conditioning method applied. Specific energy consumption of a screw press is 10-30 kWh/tonne of sludge (Huber Technology, 2013). (CANMET. Energy technology centre, 2005)

3.3.4 Chamber filter-press

Since chamber filter-presses have periodic mode of operation, their application is limited at PPI mills, however, amongst those already installed, high dewatering efficiency is obtained. A principal scheme of a chamber filter-press is shown in Figure 7.

A chamber filter-press is a set of vertical plates that are pressed against each other by a hydraulic press located at one end of the set. A filtration cycle includes closing of empty filter, filling the space between plates with sludge, pressing sludge between the plates by closure, purging the plates with compressed air. After that, moving head is drawn back and, as a result, filter cake falls down under its own weight. To recover filtrating ability of plates, washing after every 20-35 cycles is required.

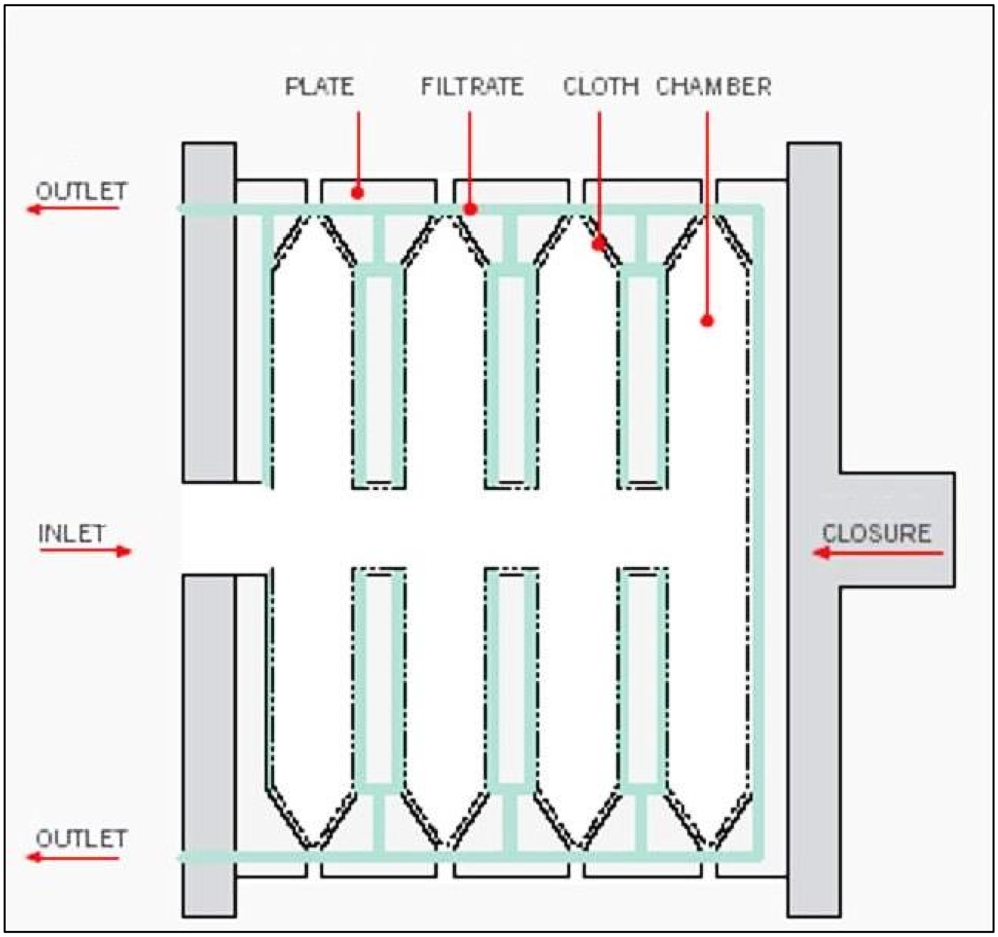


Figure 7. Chamber filter-press. (Lenntech, 2013)

Possible achievable DSC varies between 30-50%. One of the modifications of chamber filter-presses is a membrane chamber filter-press, which efficiency of dewatering is as high as 70% DSC at the end of the process. Drawbacks of the technology are its periodical work and high specific energy consumption of 30-90 kWh/tonne of sludge (Huber Technology, 2013).

3.4 Drying

Moisture content of dewatered sludge can be appropriate for sludge disposal, but not for energy or material recovery and, therefore, drying stage could be a necessary step in sludge pretreatment prior to its energy or material recovery. As it is shown in Figure 3, drying of sludge using flue gases from combustion process is a typical method, which can be done either at sludge generating mill premises, or at a receiving plant, especially, in sludge incineration plants. Fluidized bed dryers, rotary dryers, and multiple hearth dryers are considered to be effective for sludge drying.

3.4.1 Rotary dryer

An illustration of a rotary dryer is given in Figure 8. Sludge to be dried and air for drying are fed from the same end of the dryer, while air passes through a heater installed in the dryer. The inclined dryer slowly rotates moving sludge towards the discharge end of the dryer. Drying happens because of internal lifting flights of sludge that result in sludge tumbling through the warm air stream.

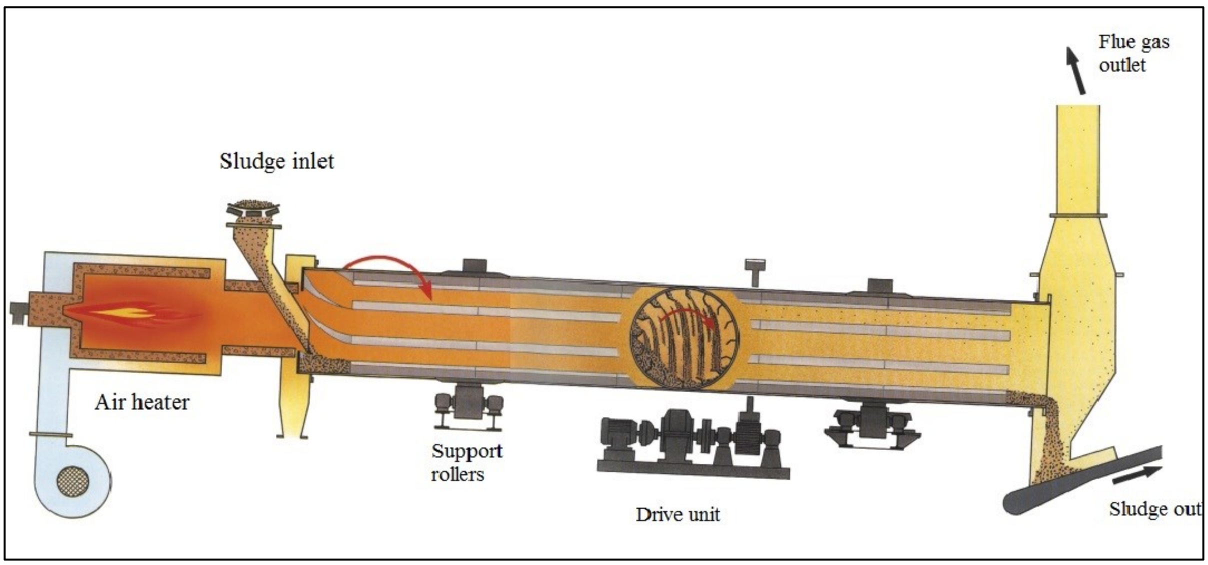


Figure 8. Rotary dryer. (GEA Process Engineering, 2013)

Rotary dryer could be either with direct or indirect contact of sludge and drying agent. If sludge drying is implemented in a rotary dryer with direct contact, then both sludge and drying agent are fed inside the dryer. In that case, hot exhaust gases are applied. When sludge is dried in a dryer with indirect contact, then drying agent is fed into a drum jacket, thus, preventing contact between sludge and the drying agent. In general terms, indirect dryers are better suited for drying of particles with low size and density and, therefore, rotary dryers with direct contact are more appropriate for deinking sludge drying. (CANMET. Energy technology centre, 2005)

3.4.2 Fluidized bed dryer

Fluidized bed dryers allow implementation of fast and even sludge drying at low temperatures enabling utilization of waste heat, such as low-pressure steam. An example of a fluidized bed dryer is presented in Figure 9.

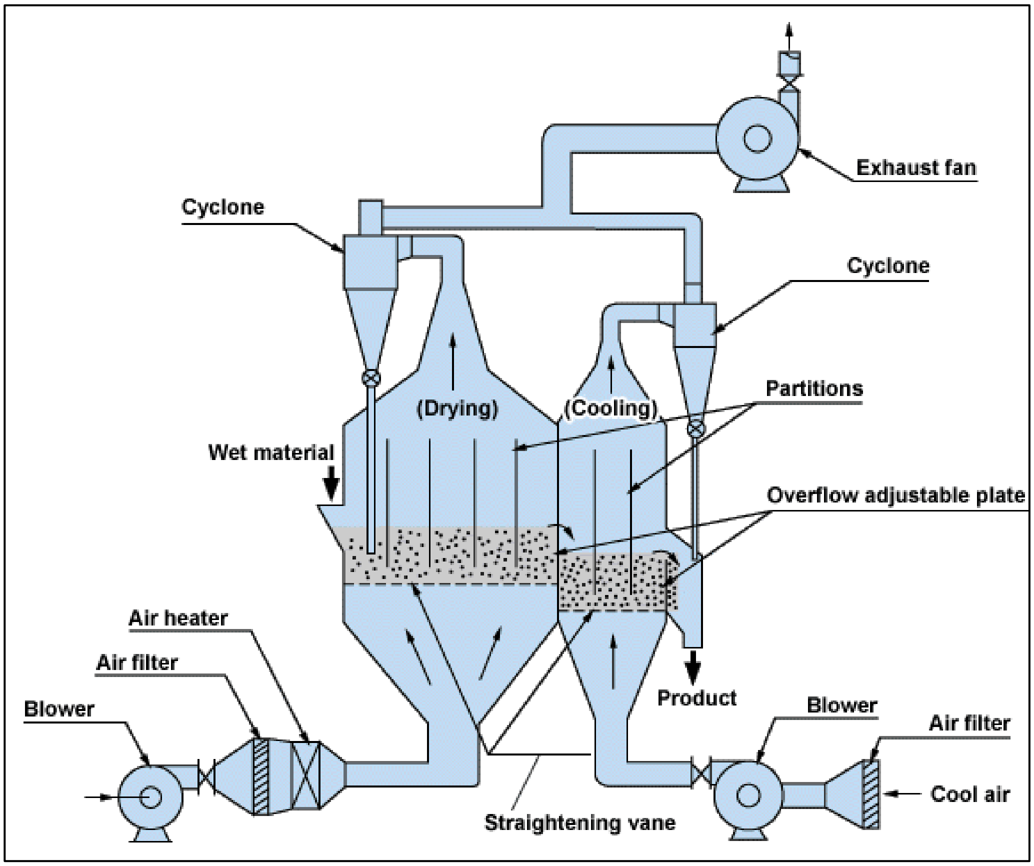


Figure 9. Horizontal multiple-chamber continuous fluid bed drying and cooling system. (Kurimoto, 1997)

Hot air coming from the bottom of the dryer through a straightening vane is used for heating up inert material, like sand, that later will contact with sludge enabling its drying. After sludge particles have been dried, they become lighter and overflow to a cooler. The most beneficial side of fluidized bed dryers is that almost all surface of sludge particles stays in contact with the drying agent. (CANMET. Energy technology centre, 2005)

3.4.3 Multiple hearth dryer

Creation of multiple hearth dryers was caused by the need of sewage sludge drying. Nevertheless, area of multiple hearth dryers application was extended to PPI mills since not much difference can be found in sludge properties important for drying. An ordinary multiple hearth dryer is illustrated in Figure 10.

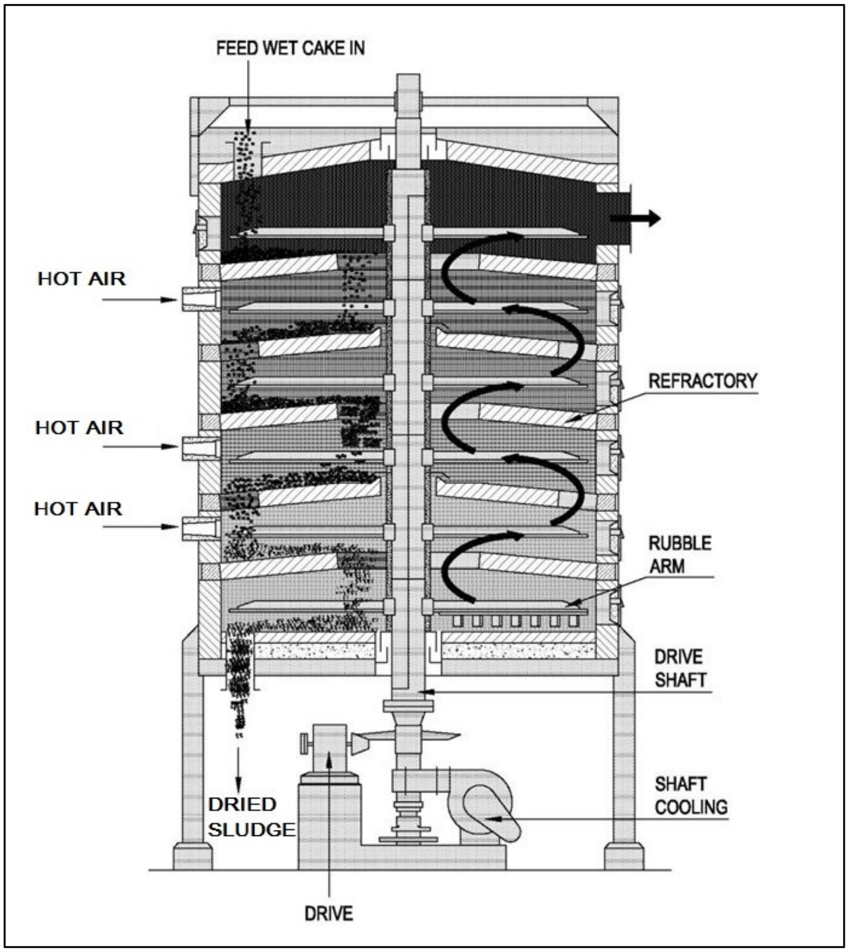


Figure 10. Multiple hearth dryer. (Adelaide Control Engineering, 2013)

Long residence time of sludge in the dryer allows effective drying of sludge by hot air blown inside. Direction of sludge movement and drying agent are displayed in the figure above.

With the furnace type development, a modification allowing combination of drying and incineration processes became more popular.

3.5 Summary of pretreatment methods

Comparison of sludge pretreatment methods is given in Figure 11. The methods are characterized by the range of DSC where each method can be applied. Gradient is given to show that there are no strict border values. As can be seen, there is no such DSC where no pretreatment method could be applied.

Thickening efficiency of different methods varies slightly. So, clarifiers have the lowest efficiency for sludge thickening amongst all methods mentioned in the study that equals to 7%. On contrary, belt thickeners are the most effective for sludge thickening with final DSC of sludge of 20%. Moreover, the range of belt thickener´s applicability is the widest.

What relates to dewatering, belt filter-presses are the least effective ones for sludge dewatering. Maximum achievable DSC of sludge after processing in a belt filter-press equals to 35%, while final DSC of sludge dewatered in a membrane chamber filter-press could be two times higher compared to a belt filter-press. Initial DSC of sludge fed into a screw press should not be less about 8% due to the design of the equipment.

Drying, regardless the method applied, is applied to achieve the highest feasible DSC. Final DSC should be economically justified and could be as high as 95%.

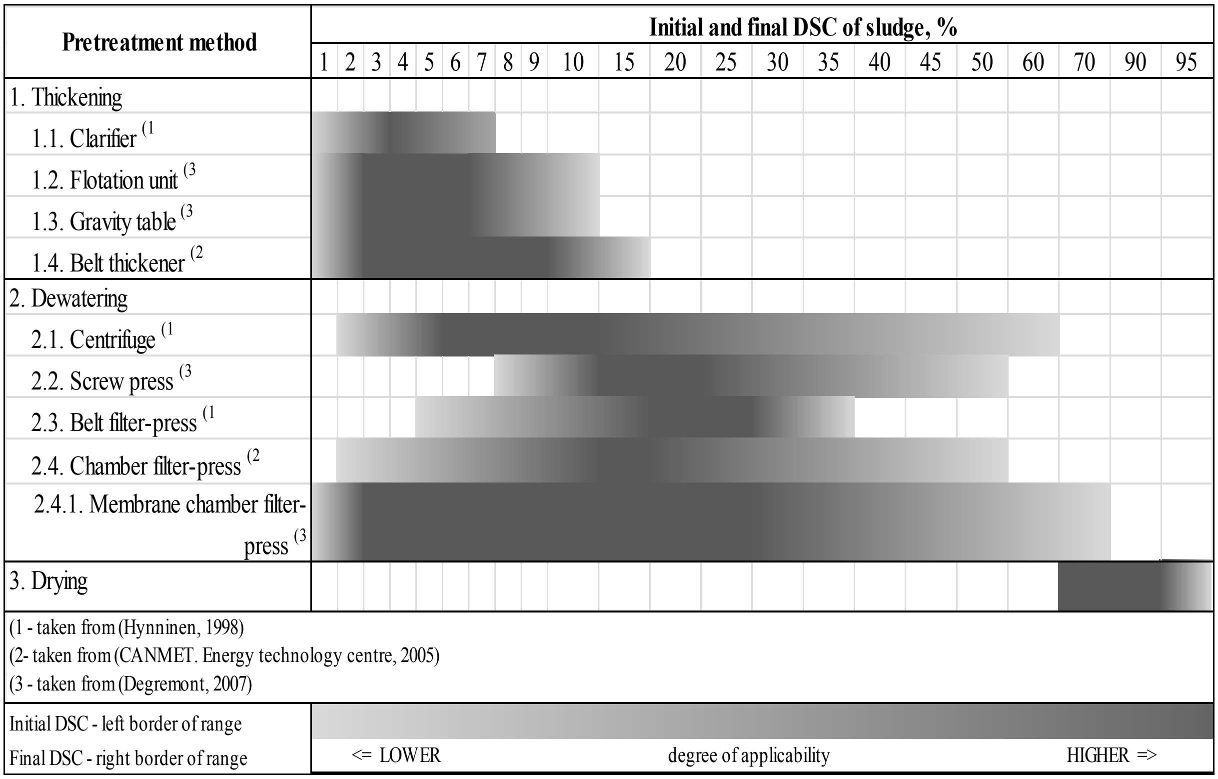


Figure 11. Comparison of pretreatment methods regarding initial and final DSC of sludge generated in PPI.

4 ENERGY RECOVERY

According to the Confederation of European Paper Industries (CEPI) [1] (2004b), it is possible to group all sludge treatment options as follows:

(1) reuse within the industry – reuse in the production process or use as an energy source at the mill;
(2) stabilization – composting and anaerobic digestion processes;
(3) land management – land restoration and landspreading;
(4) energy recovery – sludge incineration;
(5) construction materials – cement production and to lesser extent tile, brick and insulation production;
(6) other ways – animal bedding, cat litter.

Energy recovery and use on land are the most frequently used methods for sludge utilization. Popularity of each management option applied at pulp and paper mills of CEPI members is represented in Figure 12. Moreover, according to CEPI (2005a), during last twelve years energy recovery and use on land as utilization methods were constantly on top of all recovery options, while share of landfilled pulp and paper residues decreased by a factor of two.

Different sludge characteristics, such as given in chapter 2.3 and mainly moisture content, ash content, share of organic and inorganic parts and heating value determine a range of possible utilization ways. Since landfilling cannot be considered as a sustainable way of utilization, that method is not taken into the framework of the thesis. Land management is also outside of the thesis boundaries and will not be assessed.

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[1] CEPI - is a Brussels-based non-profit making organisation regrouping the European pulp and paper industry.

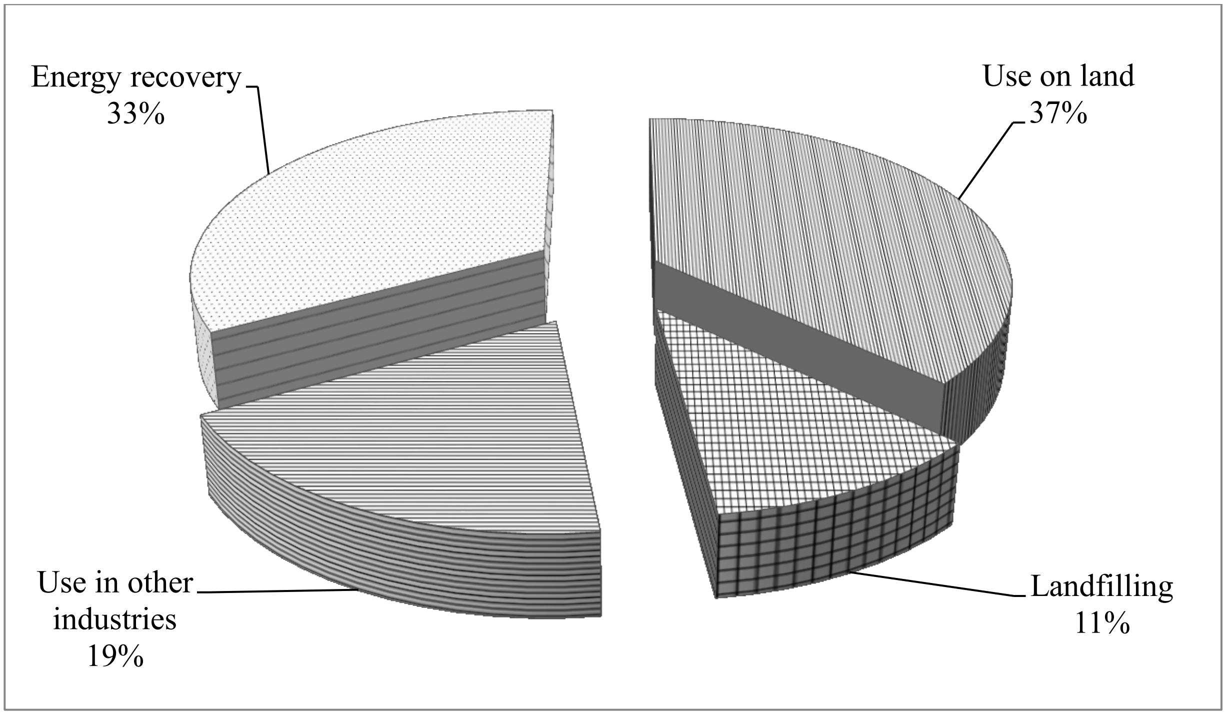

Figure 12. Sludge management options in practice. Average between CEPI countries in 2003. (CEPI, 2004b)

Any technology enabling conversion of chemical energy of sludge into heat and/or electricity refers to energy recovery technology. As it was mentioned in chapter 2, WWTS contains big share of organic matter such as fiber residues and excess biomass. All these organically based residues contributes to relatively high heating value of sludge on dry basis (Table 1) that is comparable to heating values of bark or waste paper. However, DS has much greater share of inorganic matter, and consequently has smaller heating value compared to WWTS. Nevertheless, sludge incineration is one of the most commonly applied sludge utilization method in European countries (Figure 12).

Energy recovery is beneficial for several reasons. Firstly, sludge incineration enables 80-90% reduction of sludge volume, in case of WWTS. Thus, main objective of waste-to-energy technologies, that also refer to as sludge-to-energy technologies in case of sludge incineration, is to significantly reduce environmental impact caused by amounts of sludge landfilled. Ash left after incineration is relatively inert and stable and, thus, might be used in other industries, if not landfilled. Applicability of ash is determined partly by the content of heavy metals. Hence, ash utilization is not considered in the thesis. Another beneficial side of energy recovery is transportation efficiency achieved by reduced amount of waste to be landfilled. Nevertheless, not all sludge incineration processes are energy efficient or economically viable due to high moisture content of DS and WWTS. Sometimes, additional energy sources are required to support combustion processes. Great variety of methods to utilize energy from sludge is known and applied nowadays (Figure 13). (Monte, et al., 2009)

The classification presented in Figure 13 is given initially for secondary sludge treatment only. However, the authors of the article (Xu & Lancaster, 2012) have not given explanation on why primary sludge is not acceptable. Most probably, classification is given for secondary sludge since incineration of secondary sludge is much wider used in comparison with DS. In the study it was assumed that both sludge types (WWTS and DS) could be treated according to the classification below. Moreover, Abubakr in his paper (1995) states that both sludge types could be successfully treated together with the same technologies and methods as given below.

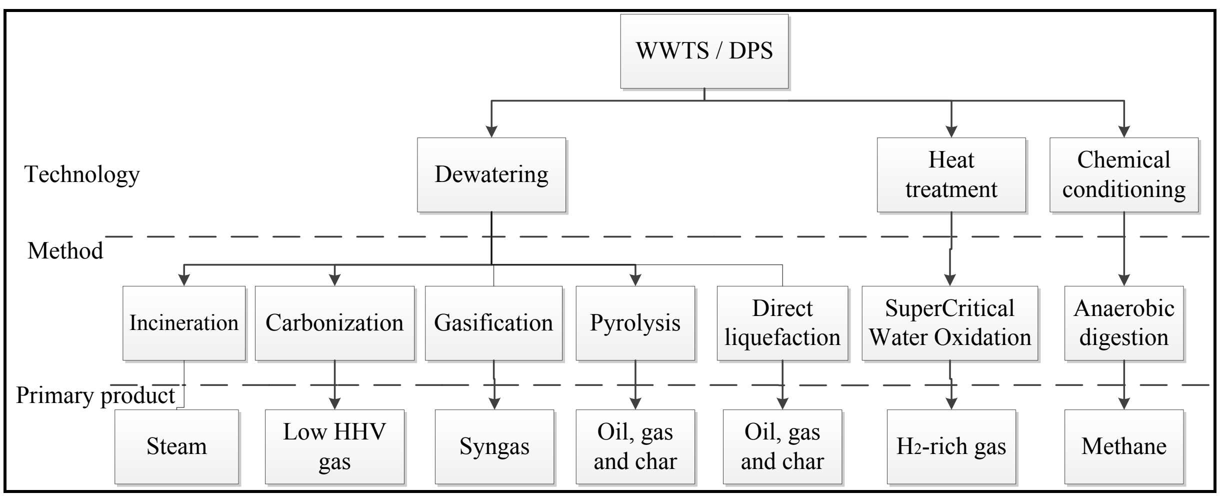

Figure 13. Energy recovery options for DS and WWTS. (modified from Xu & Lancaster, 2012)

4.1 Incineration

In the Reference Document on Best Available Techniques in the Pulp and Paper Industry (European commission, 2001) it is stated that residues generated in paper mills must be either recycled or recovered, including energy recovery, prior landfilling. To make simple assessment whether sludge can be incinerated alone without input of additional energy the fuel triangle is presented in Figure 14.

Relationship between ash content, moisture content and organic content of residues from paper mills including deinking sludge is illustrated. To maintain self-supporting incineration process, sludge should be not more than 50 weight-% moist, its AC should be less than 60 weight-%, and content of organic matter higher than 25 weight-%. DS has average moisture content of 50 weight-%, and average AC of 55% (Table 1) and, thus, such composition of sludge is difficult to be incinerated without additional fuel. Position of deinking sludge in the figure below is unexpected, since its water content varies between 10 - 20 weight-% and based on Figure 11, it can be concluded that sludge was dried prior to incineration. Nevertheless, first assumption about sludge behavior in combustion process can be done based on the figure below.

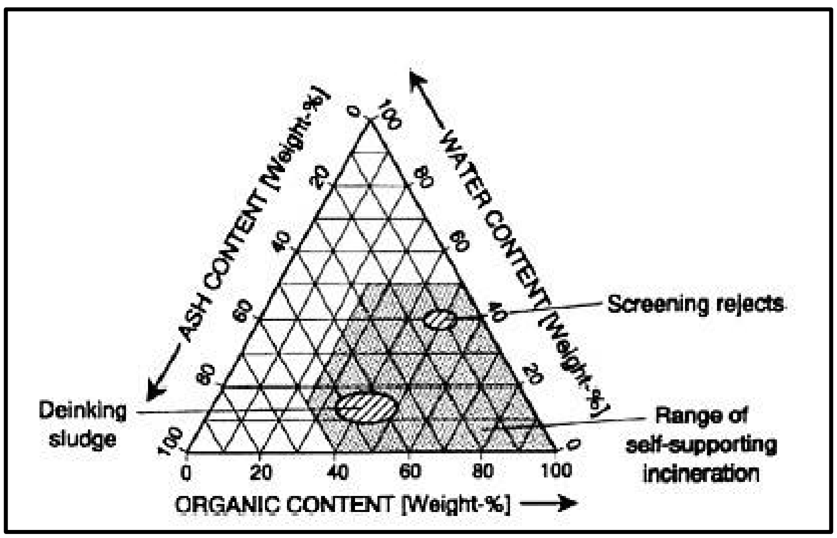

Figure 14. Tanner's diagram for residues generated in paper industry (European commission, 2001).

In case of sludge combustion, content of heavy metals, as well as alkali ones should be taken into account. Heavy metals will mostly influence flue gas treatment system, while alkali metals will affect the temperature of the process since they melt at relatively low temperatures generating agglomerates that block grates or cause defluidization. Concentration of heavy metals in sludge can be found in Table 2.

Grate type boilers, FBB, multiple hearth furnace or rotary kiln are applied for sludge combustion, while grate type boilers and FBB are the main types of technologies. (CANMET. Energy technology centre, 2005)

4.1.1 Grate type boiler

In pulp and paper industry, sludge incineration is commonly applied in co-combustion processes with bark and wood residues in already existing boilers (Abubakr, et al., 1995). Among all possible grate types, *travelling grate boilers* are the most popular for bark incineration (CANMET. Energy technology centre, 2005). This boiler type consists of a furnace with a bottom grate that is a metal belt conveyor carrying waste throughout the boiler. Many holes are made in the grate to supply and distribute combustion air to the combustion process. Ash is discharged as it goes out of the combustion zone. (CANMET. Energy technology centre, 2005; European commission, 2006)

Amount of sludge to be burned together with other residues (bark, chips) is determined by the particular boiler characteristics, sludge and bark properties. There is nothing to change with bark properties and not so much could be changed in the boiler design, whereas sludge characteristics, mostly moisture content, could be changed. Moisture of the fuel fed into the boiler strongly influences operation temperature. For example, moisture increase by 1% tends to 10^{o}C fall in the temperature. Abubakr (1995) provides next *methods that could compensate high moisture content of sludge*: (1) to raise the combustion air temperature by removing economizer surface area and by adding air heat transfer, (2) to increase the capacity of over-fire-air system, (3) better sludge dewatering, (4) to make more even sludge distribution with bark.

Design features of the travelling grate do not allow supply of air with temperature higher than approximately 230^{o}C what, in turn, limits amount of sludge to be added. Approximate bark moisture should not exceed 50 weight-% if no additional fuel is supplied. In such situation about 20% heat input from 60 weight-% moist sludge could be accommodated, but if moisture content of bark is 55 weight-% and higher, no sludge could be added. This problem is successfully solved in reciprocating or vibrating types of grate where temperature of air blown inside could reach up to 340^{o}C that results in increase of sludge amounts supplied to the boiler by 10%. *Often, in existing PPI plants with travelling grates installed in boilers 15-20 weight-% of fuel fed is sludge*. Larger amounts of sludge combusted lead to increased ash generation and to grate and boiler-tube fouling. (CANMET. Energy technology centre, 2005, p. 80)

4.1.2 Fluidized bed boiler

As it was mentioned above, sludge incineration process could be in some cases deficient due to sludge water content. *In fluidized bed technology moisture content is less problematic concern* due to more efficient thermal oxidation (Monte, et al., 2009). Moreover, fluidized bed boilers are intended to be the best option for new installations for sludge co-combustion. A schematic fluidized bed boiler is presented in Figure 15. (European commission, 2001, p. 189)

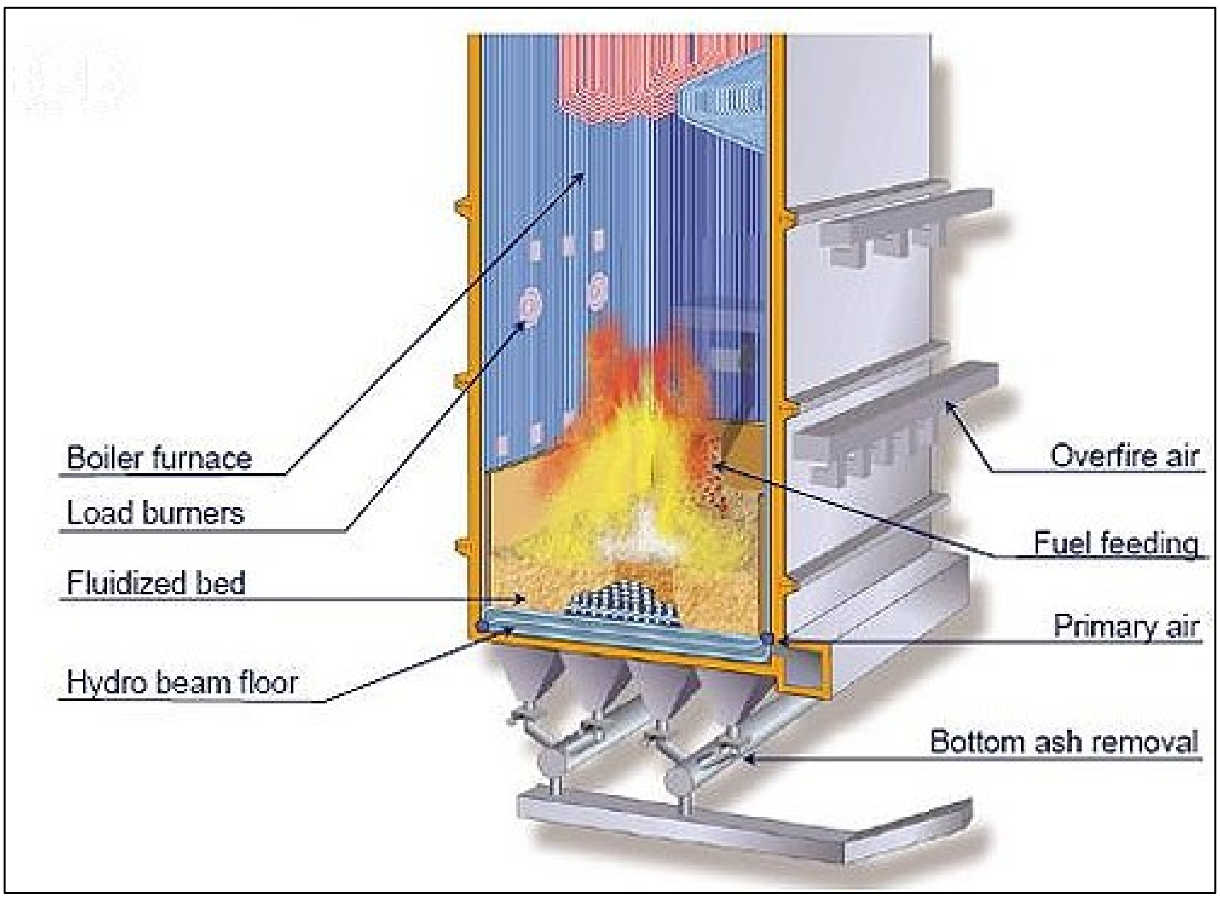

Figure 15. Fluidized bed boiler. (Power Technology, 2012)

In a fluidized bed boiler (FBB), a furnace is filled with inert material that could be classified sand or limestone to a depth of 0.6-1.2 m. Once air is blown inside from the bottom, the inert material starts bubbling or boiling to a height of 0.9-1.5 m. Usually air velocity is 2.4 m/s that allows bubbling without sand particles being blown out of the FBB. Air blown inside is preheated to 550°C only when the system starts. As fuel is spread into the bed material, evaporation begins. Then sludge rapidly absorbs heat and evaporates volatiles that ignite. Normal temperature for the bed material is 760-900°C. If the temperature is higher, problem with sand agglomeration arises, and if lower, CO emissions will increase. Secondary air should be used to increase flue gas temperature to the level required by the Directive 2000/76/EC on the incineration of waste (European Parliament and the Council of the European Union, 2000). (Abubakr, et al., 1995; CANMET. Energy technology centre, 2005, p. 83)

Use of inert material as a medium for incineration process enables combustion of high moisture sludge because the bed material acts as thermal storage. Another benefitial feature of FBB is energy transfer mechanism. In FBB, heat is transferred by conduction that is less sensitive to moisture content of the fuel (CANMET. Energy technology centre, 2005). In some cases sludge could even be burned alone if dewatered until desired moisture content. If moisture content of sludge is 58-62%, no supplementary energy is needed but at the same time no energy output will be. In that case the system is balanced in terms of energy input/output. If sludge is less moist, there is the need to install in-bed heat transfer surface to utilize energy from the process. (Abubakr, et al., 1995)

The problem with FBB can occur from *de-fluidization* that happens when inert material agglomerates and cannot be suspended by air blown inside. Such particles settle at the bottom and should be rejected. This fouling can happen, firstly, due to accumulation of large particles fed with the fuel and, secondly, because of the reaction of alkalis with alumina and silica resulting in formation of low melting point eutectics that agglomerate later. Nevertheless, there is the developed market of fluidized bed boilers. Companies provide not only new boilers, but also provide service for reconstruction of old grate boilers to FBB. It was proven that FBB can be used as a successful tool to recover energy potential from sludge. (CANMET. Energy technology centre, 2005, pp. 87-89)

If it is planned to incinerate sludge jointly with high heating value fuels, the need *to remove extra heat arises. This could be done in circulating fluidized bed boilers (CFBB)*. The operational mechanism differs slightly from FBB, especially by the mechanism of heat removal. Here, heat is removed with a portion of the bed material that will be cooled in a separate zone and then returned back to the process. The fuel is fed from the bottom of the CFBB and burns when contacts with the bed material. In such construction, more powerful cyclones are required to separate larger amounts of entrained sand. (CANMET. Energy technology centre, 2005; Abubakr, et al., 1995)

4.1.3 Rotary kiln

Rotary kiln consists of a rotating cylindrical vessel under a certain angle of inclination to allow waste movement under gravity force (Figure 16).

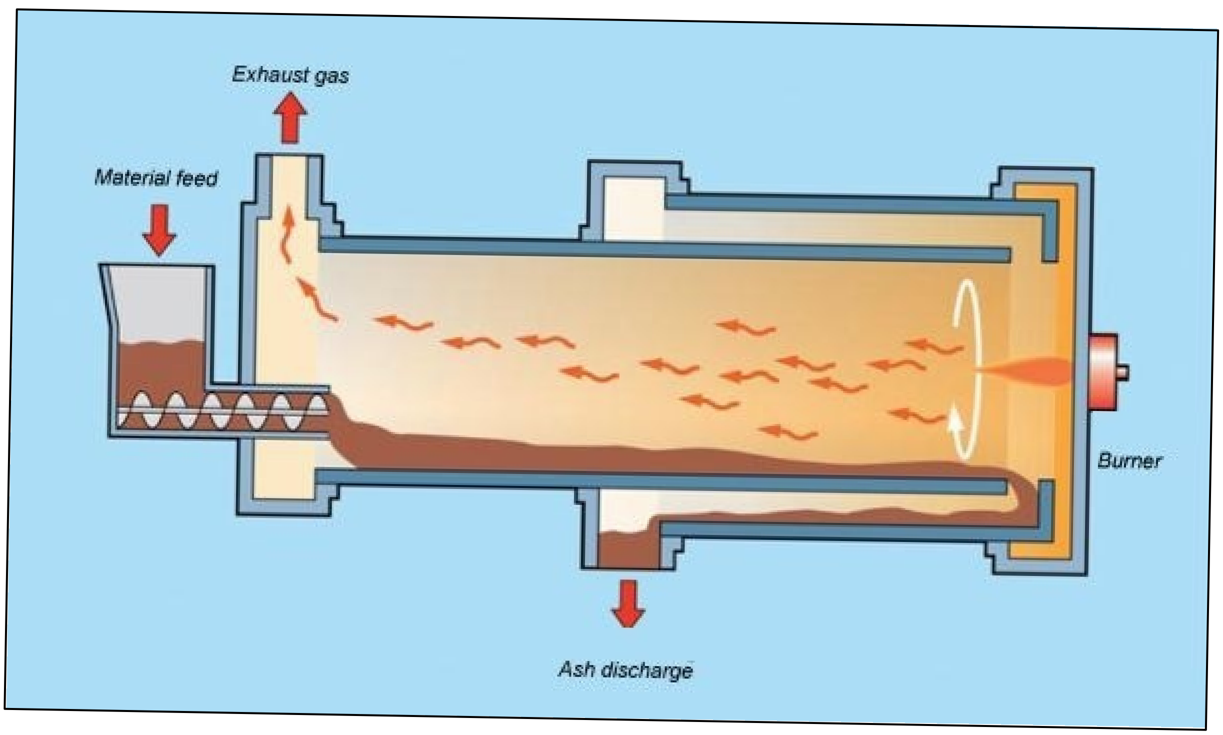

Figure 16. Rotary kiln. (Eisenmann, 2013)

The vessel is usually 10-15 m in length with the length/diameter ratio of 3-6. Generally, it takes from 30 to 90 minutes for waste to pass through the kiln and be burned. A post-combustion chamber is installed to increase destruction of toxic substances. Operational temperatures vary from 850 to 1300°C in the kiln and from 900 to 1200°C in the post-combustion chamber. (European commission, 2006)

4.1.4 Multiple hearth furnace

This type of equipment was mainly designed for sludge incineration (Figure 17). The description is given in (European commission, 2006) as follows: "the multiple hearth furnace consists of a cylindrical lined steel jacket, horizontal layers, and a rotating shaft with attached agitating arms. The furnace is lined with refractory bricks. The multiple hearth furnace also equipped with a start-up burner, sludge dosing mechanism, circulation-, sleeve shaft- and fresh air blowers." The sludge is fed on the top and air is blown from the bottom. (European commission, 2006)

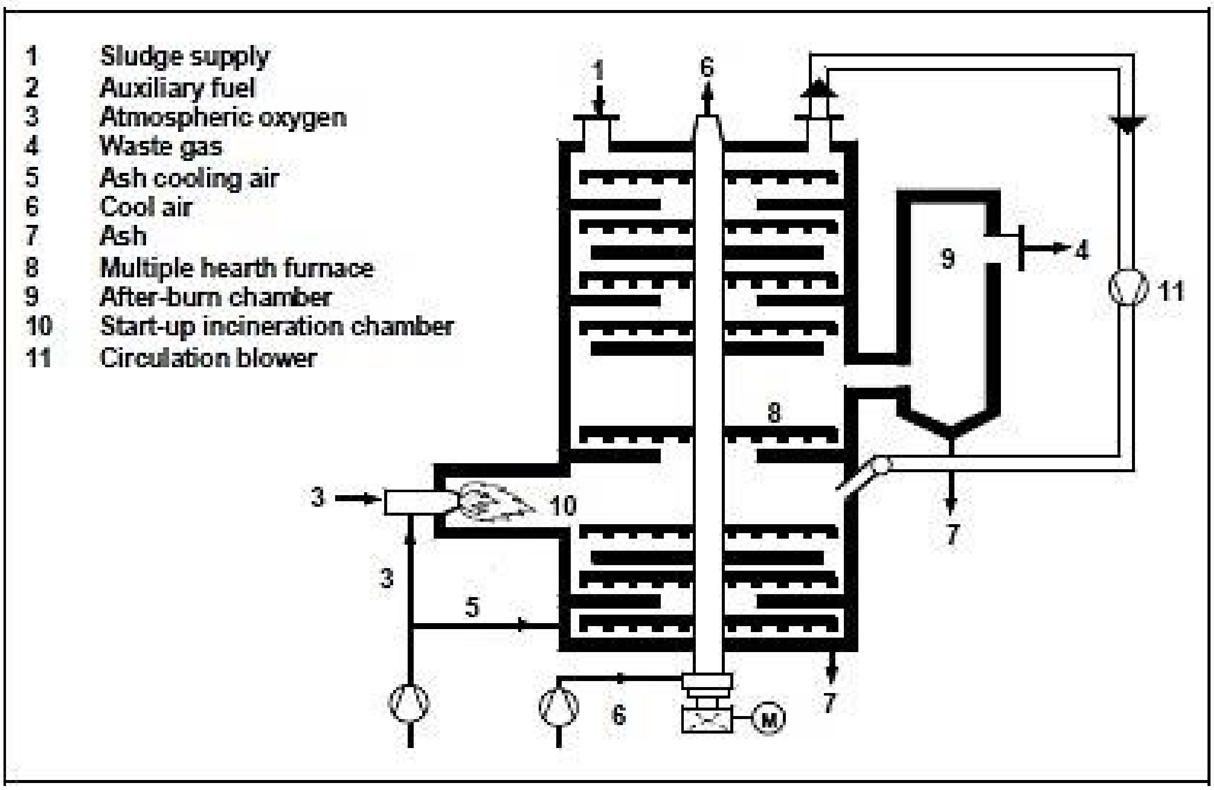

Figure 17. Multiple hearth furnace. (European commission, 2006)

Upper hearths are used as a drying zone where water evaporates from sludge fed. Operational temperature is not more than 980^{o}C because of the clinker generation at higher temperatures. One multiple hearth furnace (MHF) can process up to 12 tonnes per hour of sludge. (European commission, 2006)

4.2 Gasification

Gasification process is rarely used in the PPI nowadays, while the tendency is to increase the application of the process. Main technological barrier is that the process is difficult to understand and apply, while another challenge is the absence of information about WWTS and DS gasification process (CANMET. Energy technology centre, 2005, p. 94). However, the process becomes more and more popular because of *several benefits* gained: firstly, volume of flue gases and concentration of pollutants therein is lower than that of incineration process; secondly, *overall energy utilization efficiency of the process is higher*. Operating temperature of the process ranges between 900-1400^{o}C. (Xu & Lancaster, 2012)

Gasification process is a partial combustion of organic matter contained in the material being "combusted" to produce gases that can be used as fuel. Produced gas is called syngas or producer gas and consists mostly of N_2, CO_2, CO and to a lesser extent of H_2, and CH_2 (Xu & Lancaster, 2012). Calorific value of the produced syngas is not high and ranges between 3.7-9.7 MJ/Nm^3 if air or oxygen are used in the process (Monte, et al., 2009) (Xu & Lancaster, 2012). Syngas can be easily used in co-firing processes to generate steam or electricity. However, it needs clean-up from tars if used in gas turbines or micro-turbines. In addition to steam production, the producer gas can be liquefied to methanol as well as used for hydrogen production that, in turn, can be used in fuel cells. (Xu & Lancaster, 2012)

Unlike the incineration process, *gasification is much more dependent on fuel characteristics*. Main criterion for successful gasification is moisture content of the fuel. In general terms, it is possible to gasify sludge with 55 weight-% moisture, while it is recommended to dewater abd dry sludge up to only 10 weight-% moisture content to provide optimum efficiency of the process. Sludge moisture affects the reactor efficiency to negative side, as well as decreases the syngas quality. (CANMET. Energy technology centre, 2005, pp. 98-99)

With the development of waste-to-energy (WTE) technologies market, the range of equipment available expands. *Different configurations of already existing facilities and new emerging technologies are ready to be applied*. All gasification technologies can be grouped into the next categories: CFBB, FBB, fixed bed, updraft and downdraft, static and rotating beds. In recent times, plasma technology and supercritical water gasification (SCWG) technologies have risen in popularity. (Xu & Lancaster, 2012)

4.2.1 Plasma gasification

Mountouris (2008) investigated possibility of plasma gasification for sewage sludge utilization. In general terms, sewage sludge is mainly excess biomass, so it is similar to secondary sludge generated from wastewater treatment at PPI plants. Plasma gasification is applied to waste treatment in developed countries mainly. It was proven by Mountouris (2008) that gasification of 250 tonnes/day sludge with properties as given in Table 6 is energy efficient process.

Table 6. Sewage sludge composition and heating value in Psittalia. (modified from Mountouris, et al., 2008)

	Dry ash free,%	**Dry basis,%**	**As received,%**
C	54.8	37.6	12.0
H	8.0	5.5	1.8
O	33.4	22.9	7.3
N	3.8	2.6	0.8
S	0	0	0
MC	-	-	68(1
Ash	-	31.4	10.1
Sum	100	100	100
HHV (MJ/kg)	24.2	16.6	5.3
(1-moisture is given as expected to be after dewatering process			

The plasma gasification is implemented with the plasma torch, so there is almost no incineration process. The torch reaches temperature level of 3000°C that destroys all tars, char, dioxins (Xu & Lancaster, 2012). The plasma furnace is two electrodes between which electrical current is passed to generate the electric arc. The gas, usually air, becomes plasma when contacts with the arc. As a result, hydrogen, carbon monoxide and nitrogen are produced mainly. Ash left after the process is vitrified and is very stable and inert so that can be easily applied in the construction materials production. The syngas generated must be purified prior to energy recovery stage, since it still contains acid gases, suspended particles and moisture. (Mountouris, et al., 2008)

4.2.2 Supercritical water gasification

Supercritical water gasification (SCWG) is based on different physical and chemical properties of water above its critical point (374°C and 22.1 MPa). Almost complete biomass conversion into valuable fuel occurs because of the properties change. Main components of the fuel produced are hydrogen, methane and carbon dioxide. *The most beneficial side of SCWG process in case of sludge treatment is possibility to feed moist fuels (about 80 weight-% of moisture)*. Moreover, a small part of hydrogen produced after the process is generated from water itself making hydrogen production more efficient. (Gasafi, et al., 2008; Boukis, et al., 2002)

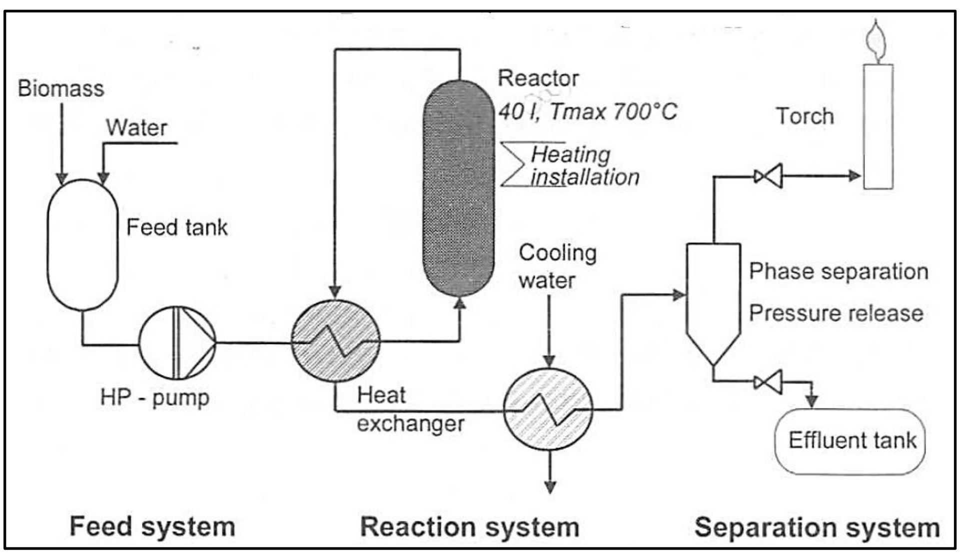

Figure 18. Simplified flowchart of the “Verena” pilot plant. (Boukis, et al., 2002)

Boukis, et al. (2002) in his paper provides a description of the process and a simplified flowsheet of a “Verena” pilot plant which capacity is 100t/h (Figure 18). Firstly, sludge is directed into the high pressure pump where sludge is pressurized up to 30 MPa. Also, the educt (conditioned sludge) is heated to 500-700°C in the gasification reactor. Due to special properties of supercritical water, gaseous components become soluble in water and leave the reactor as a homogeneous phase. Then, effluent from the reactor is cooled down enabling gaseous components to be separated from liquid. After it, the produced gas in cleaned from CO_2. In the pilot plant, wastewater generated is only treated from suspended solids and further discharged into a sewage system. If talking about deinking sludge, application to suspended solids left after the process must be found to make use of valuable inorganic compounds contained in sludge.

4.3 Supercritical water oxidation

Supercritical water oxidation (SCWO), as well as SCWG, is conducted at temperatures and pressures above the critical point of water. During SCWO, active oxidation takes place in order to convert organic substances to carbon dioxide, nitrogen and oxygen. Operational principle is given by Anders Gidner in his article (2001) and presented in Figure 19.

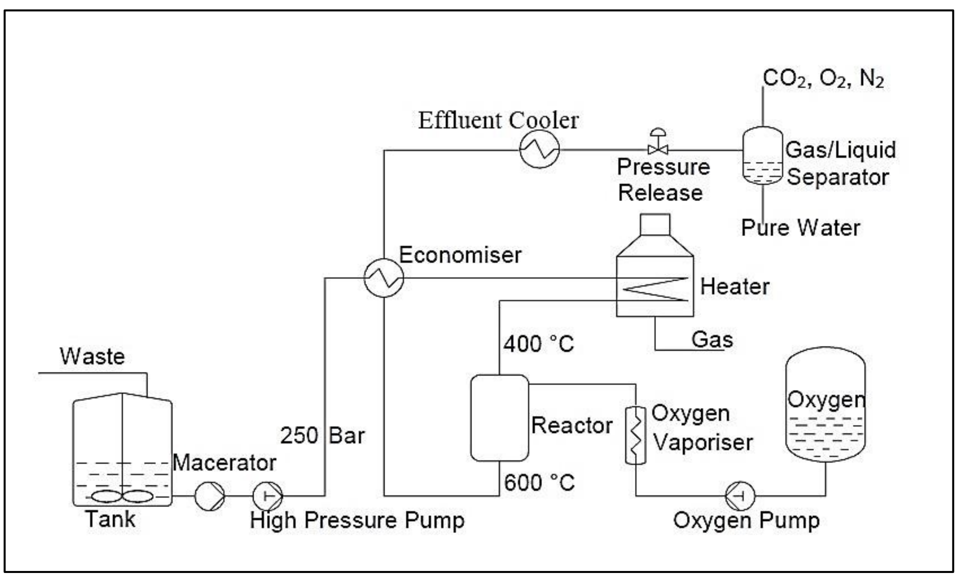

Figure 19. Flowchart of the SCWO pilot plant. (Gidner, et al., 2001).

Presented plant is designed to handle viscous sludge (waste in common). *Sludge to be treated does not need intensive dewatering. About 10% or less of solids could be contained in sludge prior to the treatment in the pilot plant*. A mechanical agitator is used to ensure even concentrations of sludge while fed to a high pressure pump. Also a macerator is used to prevent large particles flow to the pump. When sludge is sent to the pump it is pressurized to 25 MPa and then sludge is sent to an economizer where preheating happens. Sludge is heated up to 400°C in an economizer at normal operation conditions. At start up, or if concentration of organic matter is lower than 3%, a heater is needed for sludge preheating. Since heat is released during the oxidation process, outgoing effluent has temperature of 600°C that is maximum possible temperature for SCWO process (Xu & Lancaster, 2012). Heat is partially utilized in the economizer and fully in an effluent cooler. Final stage is the separation of gaseous phase from effluent.

Gidner, et al. (2001) states that deinking sludge processed in the pilot plant was successfully treated at temperatures of 540-580 °C. In addition, it becomes possible to utilize filler after the process. For example, the filler left after SCWO was successfully used in the production of newsprint paper in Sweden.

4.4 Pyrolysis

During the pyrolysis process, organic material is heated up to 400-800°C in anaerobic conditions to produce gas, char, oils. As it seen, no combustion process takes place, while little oxidation happens due to fuel oxygen content. *The fuel must be dewatered and even dried up to 80 weight-% of dry solids* (Monte, et al., 2009, p. 304). Also, the fuel should be rich in carbon. In the CANMET report (2005, p. 106) it is stated that there was no commercial pyrolysis system for utilization of energy potential of DS and WWTS. At the same time, Xu and Lancaster (2012) provide quite complete information on pyrolysis of secondary sludge from PPI plants, while Lou (2010) provides information on deinking sludge pyrolysis.

The pyrolysis process can be adjusted by operational temperature, heating rate and reaction time in order to select the product being produced. For example, char is produced mostly if the process is operated at low temperatures and low heating rates. The char has high heating value, if sludge is mostly organic, and can be used as a fuel, or can be activated to become activated carbon. In contrary, high oil generation rate is gained at high heating rate (temperature of 500°C and higher) and short residence time of sludge. As a result of such conditions, yield of approximately 70-75% of bio-oil with lower heating value of 16-19 MJ/kg can be reached. In addition, solid material left after DS pyrolysis can be recycled in paper production process (Lou, et al., 2010). Fast pyrolysis processes are implemented in FBB and CFBB or rotating cone reactors. (Xu & Lancaster, 2012)

To sum up, pyrolysis is the process enabling not only energy recovery, but also material recovery. Energy recovery is implemented through produced bio-oil utilization, and material recovery is done by recovering of solids left after the process. However, important issue is the requirements set on DSC of sludge that should be more than 80%.

4.5 Direct liquefaction

Direct liquefaction (DL) is a process performed in liquid phase at low temperature and high pressure. Catalysts are usually applied to increase reaction rate. The process product is bio-oil as that of the pyrolysis. The reason to apply DL process instead of pyrolysis is low quality of the product gas produced in the pyrolysis.

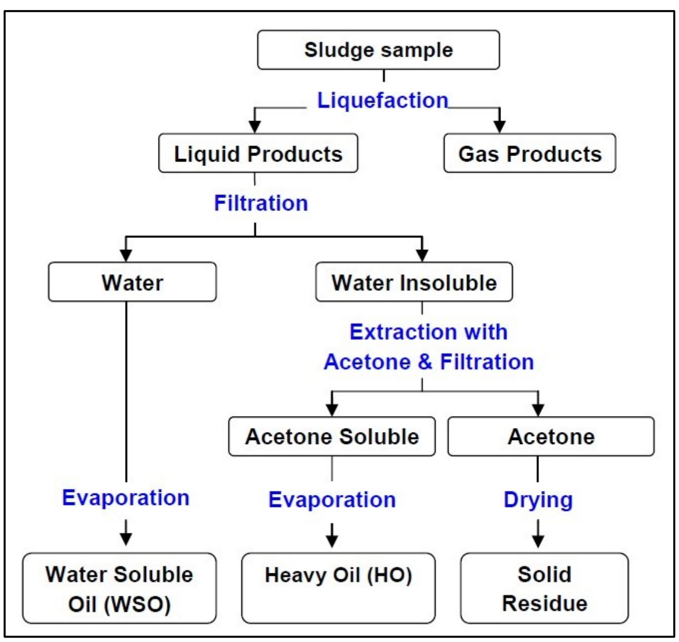

Figure 20. Outline of direct liquefaction process. (Xu & Lancaster, 2008)

Normal direct liquefaction process consists of several steps needed to convert biomass like sludge to liquid products. Those processes are: solvolysis, depolymerization, decarboxylation, dehydration and hydrogenolysis/hydrogenation (when hydrogen is present in liquefaction) followed one by one. Further processes are displayed in Figure 20. (Xu & Lancaster, 2008)

In the paper (Xu & Lancaster, 2008), sludge treatment was implemented at 250-380 ^{o}C and 15-120 min residence time in the atmosphere of N_2 or H_2. One note worth mentioning is that sludge was absolutely dried before treatment and that implies huge energy expenses in the industrial scale application. *The process was proven as energy deficient* and requires further development.

4.6 Anaerobic digestion

Anaerobic digestion (AD) is biological decomposition of biodegradable materials resulting in methane and carbon dioxide production. The majority of so called biogas produced is methane that has comparable to natural gas calorific value and can be used as biofuel. Even if the process itself is well known, there was no article found related to deinking sludge digestion. Most probably, the treatment of deinking sludge by anaerobic digestion is quite questionable because of its high inorganic content. After all, deinking sludge can possibly contain more toxic compounds that come from inks and other additives used in the printing industry.

Anaerobic digestion of WWTS that contains both primary and secondary sludge is not widely used as well, while some installations have been established. The major problem of anaerobic digestion of WWTS generated at PPI mills is long residence time of sludge in the digester (20-30 days). However, modern sludge preconditioning methods allow shortening of the residence time to only 7 days. Those pretreatment technologies include ultrasound treatment, thermal treatment, ozone oxidation, and mechanical degradation. All methods are aimed at destruction of cellulose walls in order to make them easier degradable. (Allan & Talat, 2007)

It was found that amount of sludge containing 38% of lignin can be reduced by 40%. Resulting biogas production was 0.5 m^3 biogas/kg sludge removed. Optimal performance of the digester was at sludge loading rate of 2.2 kg/m^3 day^{-1}. Produced biogas can be used as fuel for vehicles run of biogas, or in microturbines for electricity production. (Talat & Allan, 2006)

4.7 Comparison of waste-to-energy technologies

Comparison of the WTE technologies is based, firstly, on allowed dry solids content of sludge fed to the process, as a main parameter of sludge influencing thermal destruction process, and the temperature of the process, as one of the main parameters of WTE technology. Besides parameters mentioned, operating pressure and operating atmosphere are displayed in Figure 21.

As can be seen from the figure, use of additional fuel is not necessarily required. So, incineration of sludge with DSC more than 55% is energy efficient. Greater possibilities of self-supported combustion are in FBB that do not require additional energy when sludge with DSC exceeding 40% is combusted. In addition, sludge gasification process can be energy efficient.

To sum up, fluidized bed boiler has the widest range of possible self-supporting combustion process. It is achieved because of the energy transfer mechanism. The process is well-balanced at 58-62 weight-% MC of sludge. If DSC is higher than 62% then energy resulting from incineration should be removed from the system. If DSC is lower than 58% then either effective hot flue gas recycling system or addition of fuel is required. Moreover, if FBB is used, reliable prevention of dioxins and furans emission to atmosphere can be achieved.

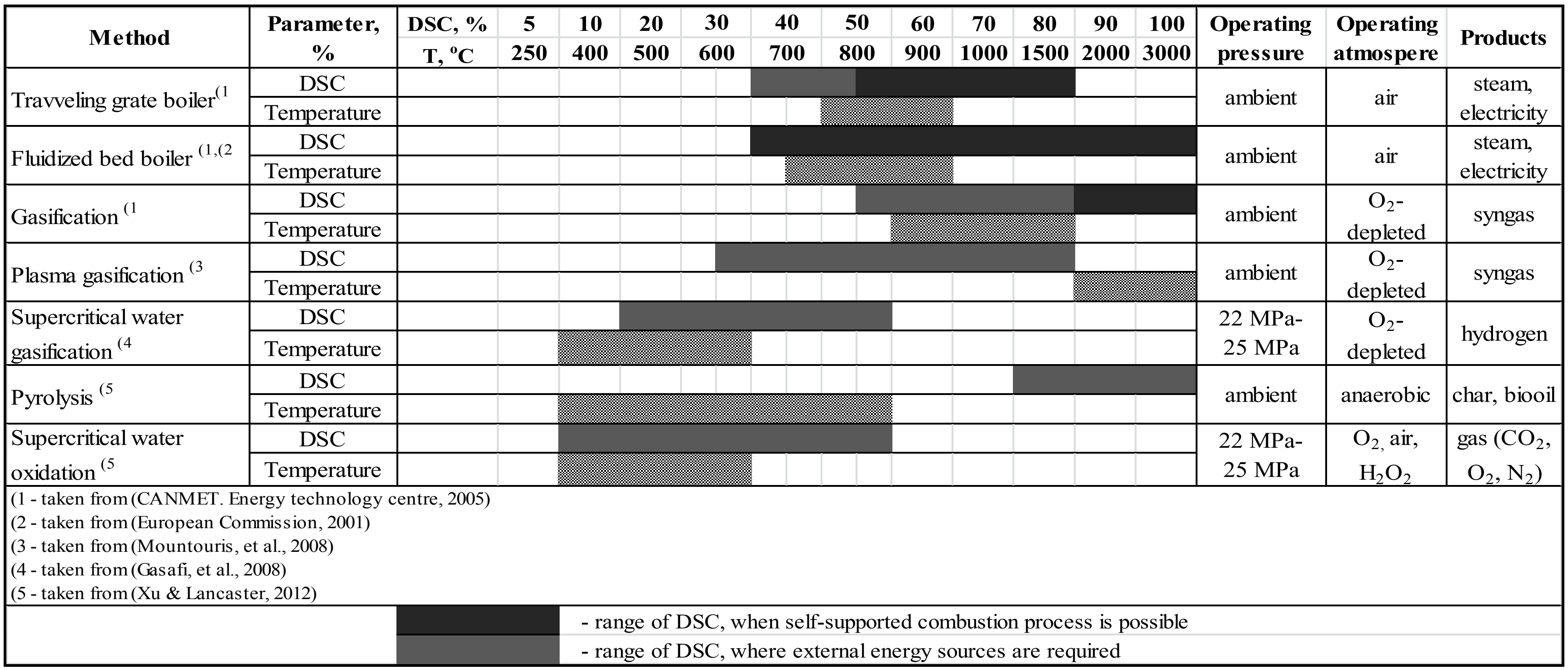

Figure 21. Comparison of WtE technologies.

5 MATERIAL RECOVERY

Application of WWTS and DS generated at paper mills in construction materials production, as well as reuse within the industry, is one of the possible ways to utilize sludge while seeking new environmentally-friendly sludge utilization options. It was proposed in the reference document of BAT for pulp and paper industry (European commission, 2001) to use sludge in brick production, cement industry, building industry, as well as for road construction. In addition to the options mentioned, following options seem to be possible: building board, glass or lightweight aggregate. Fire resistant products manufacturing with sludge is also possible. However, the selection of a real option is influenced by a number of factors.

The factor with the highest importance is competition of sludge with residues from other industries that could be potentially used in the same processes as sludge. In addition, costs of sludge transportation affect the choice of a real utilization option. Moreover, local availability of suitable processes can be a limiting factor. Thus, real applicability of sludge is not determined by a limited number of possibilities, but a current situation with existing mills ready to process this sludge. (European commission, 2001, pp. 384-385; Bird & Talberth, 2008)

5.1 Cement clinker

Addition of sludge into cement production process allows utilization of both energy and material content of sludge. Firstly, energy content of sludge is utilized in the process when sludge is calcined together with ordinary raw meal and, secondly, ash left becomes a part of cement clinker. DS is more appropriate for the process than WWTS due to its content of both organic and inorganic components. (European Commission, 2010, pp. 49-51,403).

Use of sludge in cement production process has benefits and drawback. Primary desired chemical elements for cement production are lime – CaO that comes from $CaCO_3$, silica - SiO_2, alumina - Al_2O_3, and iron. Thus, deinking sludge or its mixture with primary or secondary sludge can easily fulfill the need on those chemical elements listed in (European Commission, 2010). On the other hand, technological problems caused by sludge use could be, firstly, because of low heating value of sludge, if compared to heating value of conventional fuel used for cement production and, secondly, because of high MC.

As it was stated in chapter 3, DS is usually dewatered up to 50% MC, and WWTP up to 70% MC. Such sludge can be potentially used in a wet-method cement production process where raw materials are mixed with water before feeding to the kiln. Thus, that kind of sludge does not influence technological process in terms of water content. (LenTehStroy, 2013a)

However, dry-method cement production is more popular than the wet one and is considered to be the only method used for cement manufacturing in the future (LenTehStroy, 2013b). Sludge with 50% MC is not applicable for the dry-method cement production since can cause technological problems (Danilova, 2013) Thus, sludge requires further drying up to 5-25% MC. Drying processes used in PPI are described in chapter 3.4. In addition to the drying methods mentioned, sludge drying with waste heat generated at a pre-dryer of a cement kiln can be performed. (Hundebol, 1997)

Ernstbrunner and Fischau (1993) created a patent providing information on how to utilize moist DS in the dry-method cement production process. The dry-method cement production with a rotary kiln used for calcination has secondary combustion zone at the rotary kiln inlet enabling utilization of low-grade fuels as DS in order to replace a fraction of conventional fuel used for the process. The technique will tend to decreased primary energy consumption and decreased greenhouse gas emissions since mainly fossil fuels are used as primary energy sources in cement industry. However, sludge will not be of value in cement mills if the amount of energy required for water evaporation from sludge increases total energy consumption compared to that without sludge addition. (Ernstbrunner & Fischau, 1993)

Sludge was dried with hot flue gases generated in a rotary kiln from 50 to not more than 30% MC. Since DS contains short wood fibers, it has some energy potential that can contribute to decrease of the total energy consumption of a cement plant. Moreover, as sludge (especially DS) contains some inorganic materials, ash left after combustion of sludge is fully integrated into clinker substituting mineral matter that would be otherwise supplied from another source. Hence, ash resulting from sludge incineration causes less consumption of ordinary raw material for the production of standard cement clinker. (Ernstbrunner & Fischau, 1993)

Dry-method cement production process with sludge addition is shown in Figure 22. A key element of the production process is a rotary kiln (10), where only an inlet end (9) is displayed since there is no interest on the whole production process, but only those points related to sludge drying and its consequent feeding into the kiln. One of the innovative parts is to install a storage silo (1) equipped with a metering unit (2) connected with a metering conveyor (3) for wet sludge storage. Metering devices are used to adjust the rate of sludge addition according to the demand of the kiln. By passing through a gate (4), wet sludge is supplied into the drying facility (5), where a vibratory dryer or a drying drum is installed. Hot flue gases (5a) at the temperature of 350-370 ^{o}C are blown into the drying facility. Once DS is dried, it is sent to the gate (8) located close to the kiln by a system consisting of a worm conveyor (6) and a chute (7). The gate (8) is used for partial sludge addition to the rotary kiln. Predried sludge with MC of 30% is fed to the secondary combustion zone. By moving along the kiln's length, raw material is burnt, calcined and transformed into the clinker. (Ernstbrunner & Fischau, 1993)

Ordinary raw material, such as limestone and silicate mixtures, is introduced to the process through an inlet 11a. Firstly, raw meal is crushed in a drying-milling unit (11) that is connected with a flue gas treatment system (20). Particulate matter captured in flue gas cleaning equipment is sent to a silo by a conveyor worm (20'). Feeding from the silo located between the milling unit and a raw meal preheater (12) is implemented through a pass (12a). In the preheater, direct contact between raw meal and hot glue gases from the kiln occurs resulting in decreased moisture content of the raw meal and decreased temperature of flue gases. Then, flue gases are sent to both the drying-milling unit (approximately 80% of total flue gases generated), and to the sludge drying device (the rest amount of flue gases). (Ernstbrunner & Fischau, 1993)

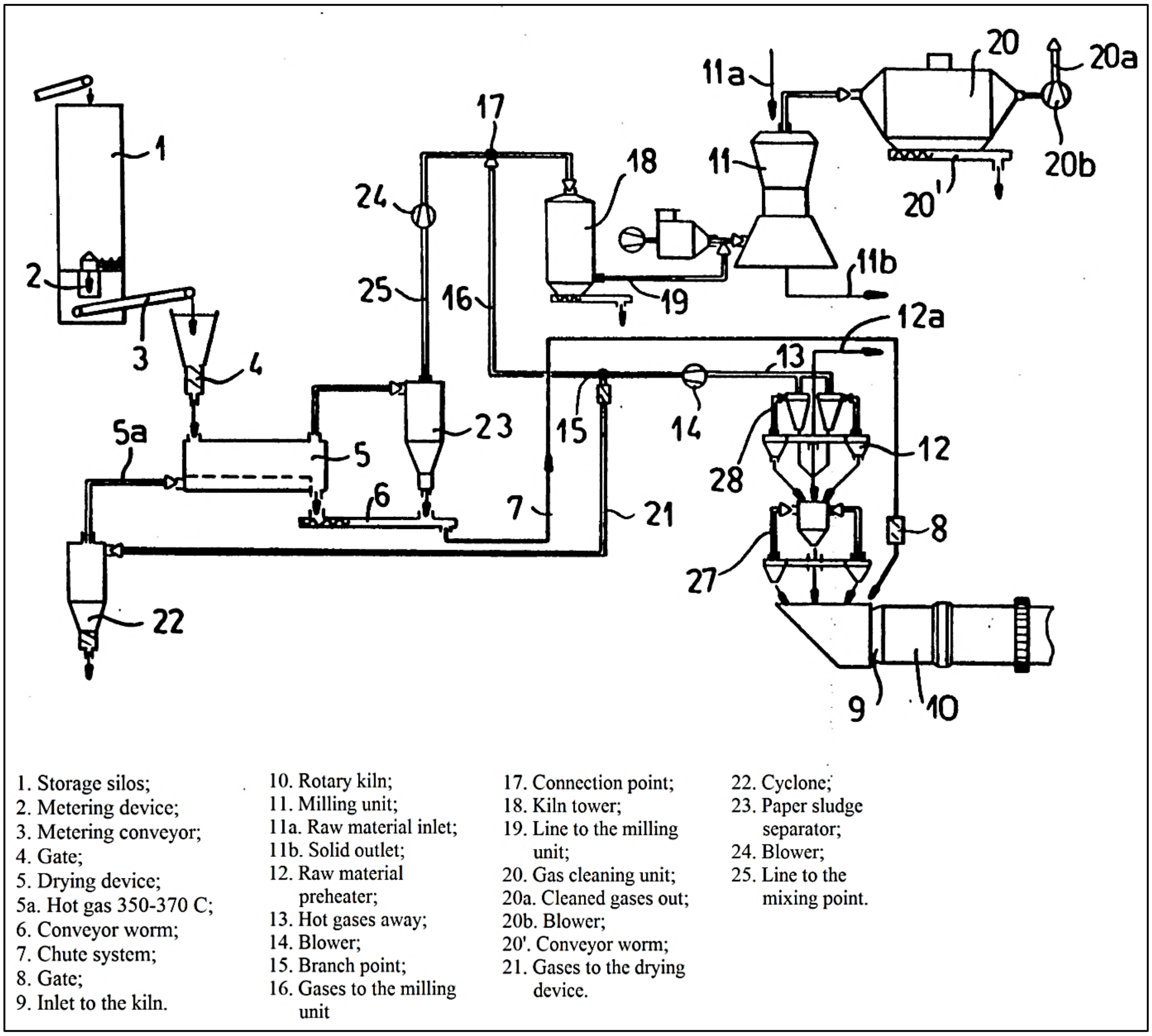

Figure 22. Flow-chart of cement production process with sludge addition. (Ernstbrunner & Fischau, 1993)

In the U.S patent (Hundebol, 1997) the author argues that the method of sludge drying with hot flue gases described above (Ernstbrunner & Fischau, 1993) results in large amounts of exhaust gases needed for drying which possibly may contain malodorous and toxic compounds. Thus, flue gases after the drying process need to be treated extensively before being released into the atmosphere. The author proposes the use of drying-milling units that are used widely in cement industry for sludge drying. The advantage is that the gas after drying is directed to the kiln where high temperatures enable effective destruction of those malodorous compounds, instead of emitting them to the atmosphere. Expected moisture content of DS before that process is 50-80%. (Hundebol, 1997)

Table 7. Raw meal analysis. (Ernstbrunner & Fischau, 1993)

Composition of raw meal	Without DS, weight-%	With DS, weight-%
SiO_2	13.8	13.4
Al_2O_3	3.7	3.6
Fe_2O_3	1.3	1.4
CaO	42.8	43.3
Silicate modulus	2.76	2.68
Lime standard	98.1	102.0

Based on the practical experience it was revealed that the ash resulting from DS incineration reduces the need for raw meal, used for high quality cement production as shown in Table 7. Heating value of absolutely dry sludge was 6.7 MJ/kg. Heat consumption without DS addition was about 3.6 MJ/kg of clinker produced, while with addition 3.3 MJ/kg of clinker produced. DS with following parameters was proven to be appropriate for the process: DSC – 34.3 to 51.8 weight-%, AC – 43.5 to 66.0 weight-%, heating value 5.5 to 8.6 MJ/kg. Ash resulting from the sludge incineration contained: 29% CaO, 2.5% MgO, 0.5% SO_3, 35% SiO_2, 32% Al_2O_3, and 1% Fe_2O_3. Cement kiln temperature stays at the same level as it was before and equals to 1500 ^{o}C. Ordinary raw meal composition is about 75% limestone, 20% clay, 5% quartz. Total amount of DS added is within 2-10% range. (Ernstbrunner & Fischau, 1993)

5.2 Ceramic products

Ceramic bricks that also refer to as clay bricks are mainly made of clay. Several authors claimed that DS can be utilized in the production of ceramic materials. The results of their claims diverge greatly. The reason could be that production processes differ in different sources. For example, behavior of ceramic bricks made of clay and DS was examined in (Radovenchik, et al., 2010; Demir , et al., 2005 and Sutcu & Akkurt, 2009). In all cases the results were mainly negative.

Radovenchik used DS with MC of 68%, AC of 10%. Amount of DS added varied from 0.5 to 6.0% (on dry basis). Increased amount of DS incorporated resulted in increased MC of furnace feed by 3.0% that consequently caused additional fuel use. However, due to increased porosity of the material produced less energy was required for its drying since atmospheric drying was more efficient. In addition, shrinkage rate that shows how much the material will be reduced in volume with time increases when more sludge is used. This fact causes problems since shape and dimensions of the material produced are not stable. Strength properties decreased dramatically (up to 62% shortage when 5.5% of sludge was added). The only positive result is decreased density of the material. (Radovenchik, et al., 2010)

Similar results were obtained by Demir , et al. (2005). In addition to parameters described above, water absorption ability of the material produced was analyzed. So, it was increased by 37% when 10% of DS was added. Increased water absorption capacity can, on one hand, improve setting of concrete with the bricks to make the construction stronger and, on another hand, increase weight of bricks.

Sutcu and Akkurt (2009) analyzed similar process with DS containing about 60% of inorganic metter and MC of 65%.The results showed that due to increased porosity of the material produced with 30% of sludge added, density of material and thermal conductivity decreased by 67% and 50% respectively. Moreover, mechanical properties of the material intended to be used in the construction industry decreased much. So, compressive strength of material where 30% of clay was substituted with DS was about eight times lower compared to material made of ordinary ingridients. (Sutcu & Akkurt, 2009)

High quality ceramics can be produced as stated in the patent (Treschev , et al., 2007). Following components and their volume-% were used: weak clay – 64-66, DS – 6-9, ferrous waste – 7-13, keramzite foam clay – 15-20. Composition of DS used is presented below. Moisture content of sludge was 60-80% and AC about 50%.

Table 8. Chemical composition of DS used in ceramics production. (modified from Treschev , et al., 2007)

Oxides content, weight-%					
SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	TiO_2
26-30	17-20	0.15-0.18	0.2-0.6	0.1-0.3	0.05-0.1

Several samples with different amounts of DS were prepared and tested. The results of the tests are shown in Table 9. As it is seen from the table, properties of samples 1, 2, 3 and 4 are better than that of the reference sample.

Table 9. Ceramic mass composition and properties of ready material. (modified from Treschev , et al., 2007)

Components (dried)	Sample numbers and their composition					Reference sample
	1	**2**	**3**	**4**	**5**	
Weak clay	68	66	65	64	64	70
DS	5.6	6	8	9	9.5	-
Sawdust	-	-	-	-	-	18
Ferrous slurry	-	-	-	-	-	12
Ferrous waste	12.4	13	9	7	6	-
Keramzite clay	14	15	18	20	20.5	-
Parameter tested						
Compressive strength, MPa	30.2	31.5	24.2	30.7	17.1	18.7
General shrinkage rate	8.0	8.12	8.75	9.00	9.27	12.4

To conclude, sludge could be used for the ceramics production without deterioration of final product if produced as stated in the patent (Treschev , et al., 2007). However, three other literature sources provided extensive information that incorporation of DS decreases properties of the final product. It could be so that the patent was not checked properly and does not work if really applied.

5.3 Pozzolanic material

Pozzolanic material or simply pozzolan is defined as "a siliceous or siliceous and aluminous material, which in itself possesses little or no cementing property, but will in a finely divided form - and in the presence of moisture - chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (Brunjes, 2008). Pozzolanic activity means to react with lime at normal conditions resulting in generation of viscous phases (MetaPro, 2011). Moreover, addition of 15% of pozzolan makes bonds with lime, thus, preventing bloom generation, that is known to be a problem in construction industry (Pozzolanic additives to cement, 2010). Hundebol in his patent (1994) described a process of pozzolanic material production. In the ways given in the patent, kaolinic fraction of DS is transformed into a pozzolanic material in an environmentally safe and economic way.

As stated in the patent, pozzolan is a material consisting of Al_2O_3, Fe_2O_3, SiO_2 or similar to those mentioned. The most obvious method of pozzolan production is thermal treatment in a long rotary kiln as described in a patent (Hundebol, 1997), however, malodorous gases can be generated, as well as external fuel will be required for the process. The scheme of pozzolan production is displayed in Figure 23. (Hundebol, 1994)

Wet DS is sent from a silo (7) by any applicable mean of transportation (a belt or a worm conveyor) to a dryer-crusher (1). At the same time, hot flue gases from a kiln system (3) via a duct (5) are supplied to the dryer-crusher in order to maintain sludge drying process. Dried sludge via a duct (9) is then directed to a separator (13) where solid particles are separated from gases that are sent then with a help of a fan (11) via a duct (27) to a cooler (25). Separated sludge is stored later in a silo (15) until it is used in the process. Feeding of sludge from the silo (15) to a burner (17) of the kiln system (3) is done by use of a screw conveyor, for example. The burner (17) is located inside the rotary kiln (21). Warm gases from the cooler (25) are used for incineration process, where they are heated up by heat generated during sludge combustion. Once exhaust gases are generated in the kiln, they are sent for treatment into a cyclone (23). Separated particles are sent back to the kiln, while exhaust gases are used again for DS drying. (Hundebol, 1994)

In the kiln, remained ash is led backward because of the rotation of the kiln and its inclination. Thus, direction of ash movement is opposite to the flame direction. Ash is sent below the flame and is being subjected to heat treatment under special conditions with maximum temperature of 700-850 ^{o}C. Next step is ash cooling in the cooler (25). The ready product that is often nodulized requires further grinding before being applied. It was assumed in the patent that the plant will be heat producing and a part of hot flue gases can be used for heat recovery in an economizer (41) with further glue gas treatment before releasing into the atmosphere. An electrostatic precipitator of a bag filter can be used for flue gas treatment. Amount of flue gases released is replaced with fresh air that is supplied through an air intake (10). (Hundebol, 1994)

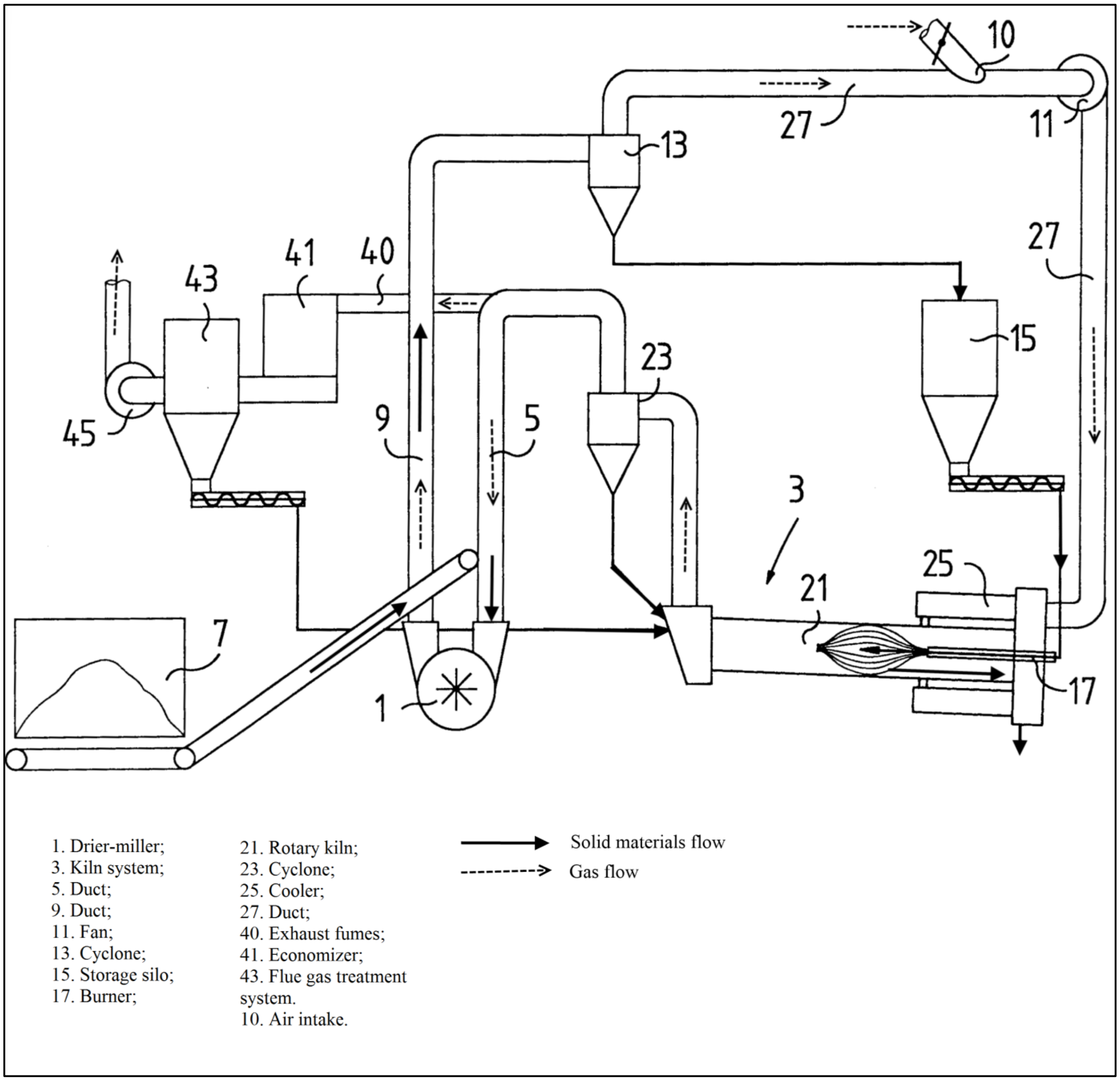

Figure 23. Flow-chart of pozzolan material production from DS. (Hundebol, 1994)

Biermann, et al. (1996) in his patent proposed the use of FBB for pozzolan material production at the same temperatures as in the previous patent to activate pozzolanic properties of DS. Utilization of DS in the production of pozzolanic material had positive influence on mortars properties prepared with sludge addition (Frias, et al., 2011).

5.4 Cement mortar

Cement mortar is based on organic filling material, produced from formation and solidification of a mixture consisting of Portland cement, DS, chemical additives, and water. For building blocks production from cement mortar, technical specification TU 69 USSR 82-84 "Building blocks made of cement mortar for farm building" was created in Ukraine. The material was classified as insulating concrete. (Pavel, 2008)

Average consumption of raw materials for the production of 1m^3 of building blocks is: Portland cement M400 – 230 kg, sludge (as absolutely dry solids) – 500 kg. Production of blocks is performed by blending of wet sludge with Portland cement without water. Compressing of the mixture produced in done at pressure of 0.08-0.12 MPa. Mode of solidification of blocks is natural or artificial drying. To prevent dried blocks from water absorption, its opened surface is recommended to be covered with repellent. (Pavel, 2008)

Pilot plant was established in Ukraine to produce such building blocks. To check real applicability of the blocks, two houses were built: one was built as a monolithic construction, and another one from small piece materials. Thermo technical properties of the houses were analyzed. Heat conductivity was equal to 0.2 W/(m·^{o}C) for material density of 600-650 kg/m^3, and 0.3 W/(m·^{o}C) for material density of 750-800 kg/ m^3. Heat protection was higher than required by legislation. It enabled to decrease thickness of the walls made of the blocks until 18 cm. (Pavel, 2008) In other words, application of sludge in cement mortar production was proven to be successful in terms of energy efficiency of the buildings made of the cement blocks.

5.5 Lightweight aggregate

Lightweight aggregate is a type of large sized aggregate used in the production of lightweight concrete products. Flow-chart of the production process is depicted in Figure 24. Firstly, required amount of DS is taken from a silo (1) and then is mixed together with cement in a mixer (2). Mixing is implemented in a thorough way. Well mixed blend is then sent to a pelletizing machine (3) where granules are produced. Last stage of the whole process is drying of the material produced at the temperature of 100-105 ^{o}C. (Liaw, et al., 1998)

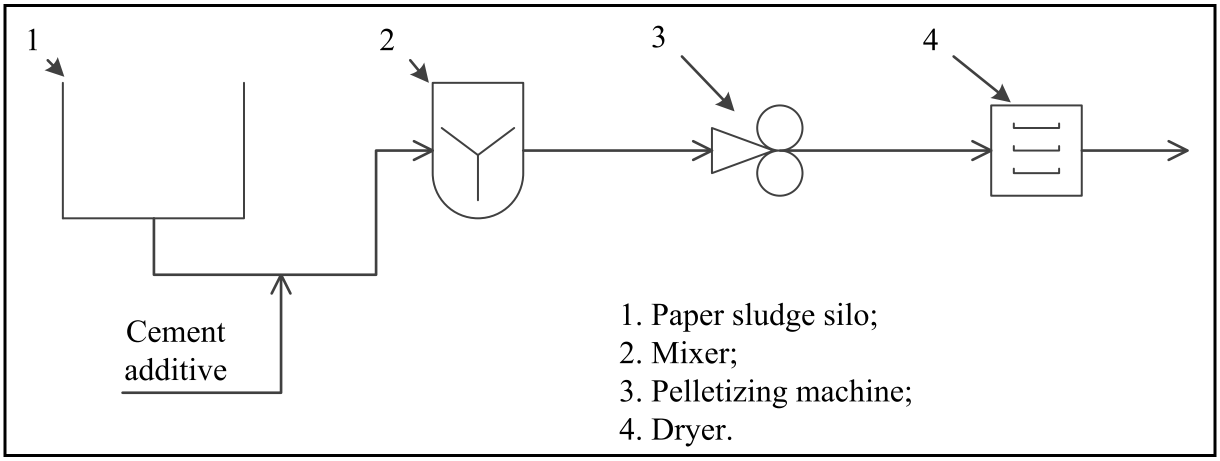

Figure 24. Flow-chart of lightweight aggregate production. (modified from Liaw, et al., 1998)

Chemical composition of DS utilized is presented in Table 10. Most probably, kaolin and talc were used as fillers in recycled paper processed in a paper mill where sludge was generated since amounts of SiO_2 and Al_2O_3 are the biggest. Relatively low content of calcium oxide was determined.

Table 10. Composition of sludge used for lightweight aggregate production (Liaw, et al., 1998).

	Average
Moisture content of sludge, %	75.40
Loss of ignition of dried sludge, %	70.11
AC, %	30.0
SiO_2	37.99
Al_2O_3	51.72
Fe_2O_3	3.04
CaO	5.09
MgO	3.10

Testing of the material produced included determination of volumetric specific gravity. The results from analyses showed that the best mixing time is about 10 minutes when any cement/DS ratio can be used for material production to obtain lightweight aggregate with volumetric density less than 1.0. If material has been mixed for 40 minutes then only cement/DS ratio less than 0.6 can be used. Thus, the longer raw meal is mixed, the more density of the material produced. (Liaw, et al., 1998)

Test bricks with dimensions of 40 cm·10 cm·10 cm were prepared using aggregate material produced from sludge. One brick weighted 5.4 kg that is 23% less compared to the one produced from concrete (7 kg). Compressive strength can reach 1780 psi, that is almost the same as set for loadbearing concrete masonry units in the Standard Specification for Concrete Brick (Hanson, 2009). To recapitulate, porosity of light-weight aggregate produced is lower, if mixing time is shorter. Moreover, incorporation of sludge has positive influence on light-weight aggregate produced because of decreased density, while compressive strength stays in acceptable limits.

5.6 Insulating material

Utilization of DS in the production of insulating material is described in (Cavaleri & Contu, 2011; Morozova & Shargatov, 2001; Zvyagina & Pushnoy , 1996). All authors offer different production ways and different insulation materials produced. Cavaleri & Contu (2011) describe production of thermal and/or acoustic insulation material in the form of flakes. It was stated that sludge containing long fibers is more appropriate for the production process. Presence of inorganic content decreases insulating properties of the material being produced. The production process is displayed in Figure 25. (Cavaleri & Contu, 2011)

DS with moisture content between 25-60% was used in the process. Firstly, sludge is stored in a silo (1), if needed. In addition to storage function, the silo is used as a mixing point where liquid additives, such as fungicides, flame retardants, and coloring agents are added to sludge, if required. Then the mixture is sent for drying process to a drying machine (2) and after that the mixture is hammered in a crusher (3) until its shape is flake-like. Also, powder additives can be added in the crusher, if required. (Cavaleri & Contu, 2011)

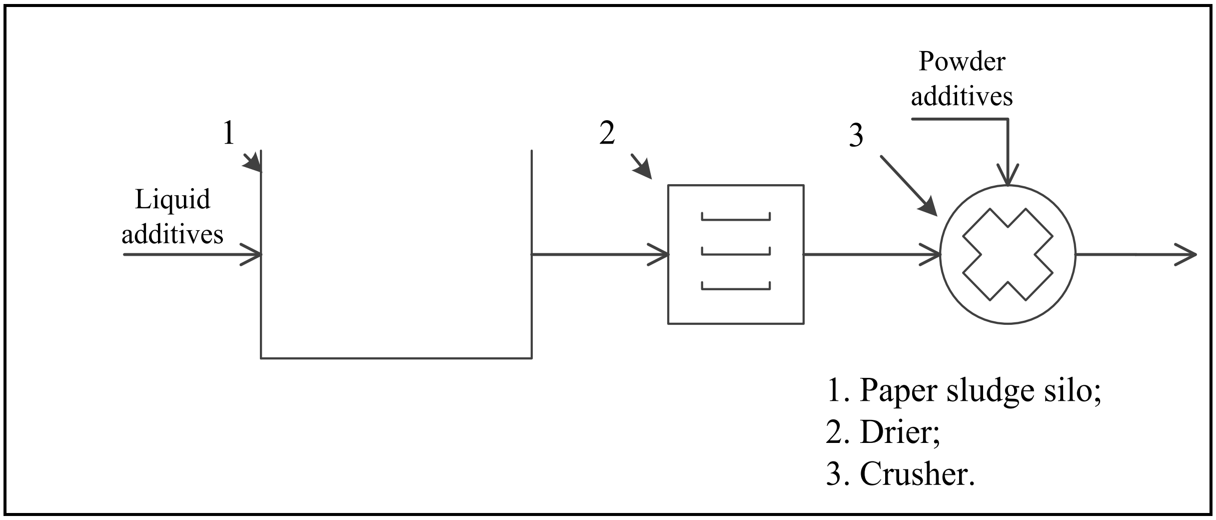

Figure 25. Production of flakes-like insulating material. (modified from Cavaleri & Contu, 2011).

Another way to produce insulating material from DS is to produce it in the form of boards. The material produced, as described in the patent (Morozova & Shargatov, 2001), can be used for manufacturing of wall panels used for thermal insulation of residential, industrial, and other buildings, as well as for thermal insulation of hot and cold water and steam pipelines. The raw meal is prepared in the following mixture ratio, weight-%: Portland cement M500 10-30, DS 60-80, plasticizing agent 0.05, solution for sludge impregnation in order to increase its fire resistance “Wuprotech” 1-3, foam-forming admixture to increase porosity of the ready material “Morpen” 1-3, water 4-6. DS used in the patent contained 7-9% of fiber (on dry basis). Production process of such material is shown in Figure 26. (Morozova & Shargatov, 2001)

DS from a silo (1) is mixed in a mixing unit (3) with Wuprotech stored in a vessel (2). Then DS is dewatered (4) in order to remove excess amounts of Wuprotech, which could be sent back to the process via a duct (5). Also, dewatered sludge is treated with a combination of cement wash and sodium glass in order to increase its fire-resistant properties. In a final mixing unit (6), water and Morpen are frothed well until strong foam is generated. Then, treated DS, as well as Portland cement and plasticizing agent, are added into the mixing unit (6) and mixed there during not more than 5 minutes. (Morozova & Shargatov, 2001)

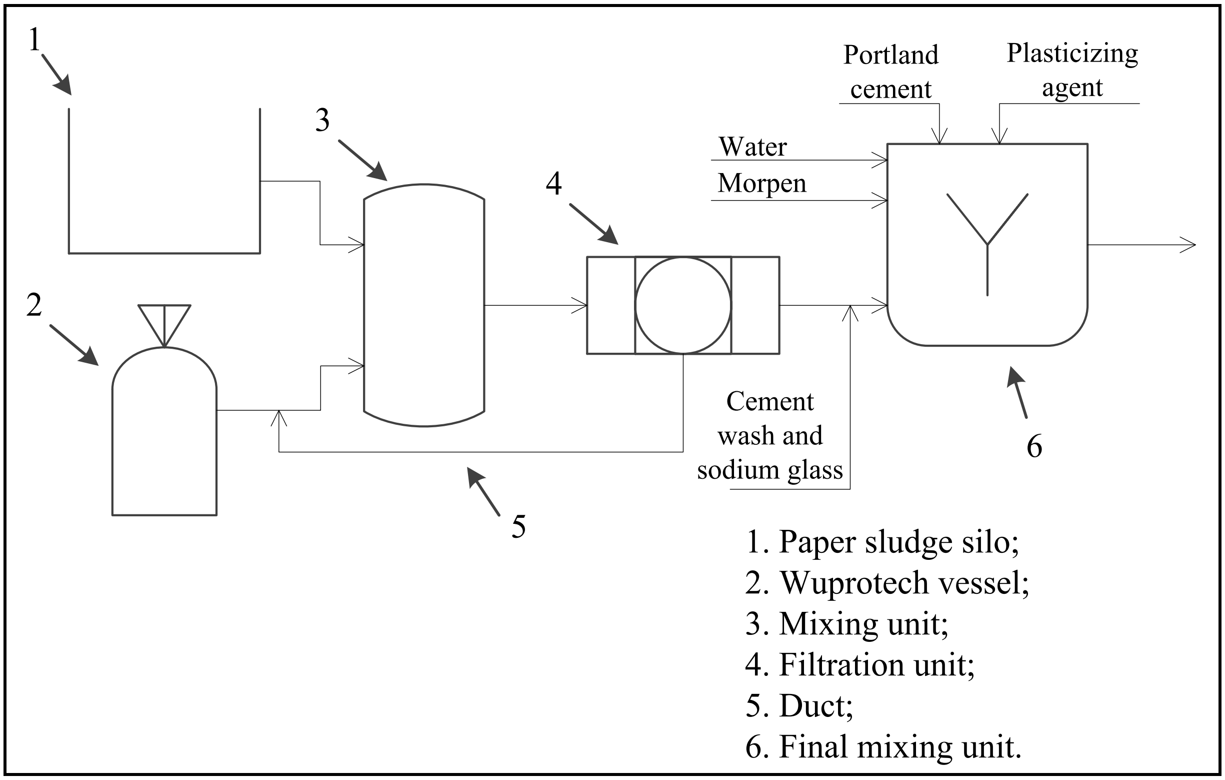

Figure 26. Production of raw construction mixture for manufacturing of insulating material. (Morozova & Shargatov, 2001)

Produced raw construction mixture then placed into forms or applied to any surface requiring insulating and dried at temperature of 50-60^{o}C for 10 hours. Several samples (with dimensions of 100mm·100mm·100mm and 150mm·150mm·150mm) made of the raw construction mixture were produced. Analyses of such samples have shown that the material produced from the mixture is nonflammable with thermal conductivity coefficient of 0.07-0.1 W/(m·^{o}C) at the temperature of 25^{o}C. (Morozova & Shargatov, 2001)

Another way of insulating material production is described in the patent (Zvyagina & Pushnoy , 1996). For the production of insulating material following components and their amounts in weight-% are required: cement – 22-30, granulated DS with density of 300-400 kg/m^3 – 56-66, and latex – 12-14. Instead of using foaming admixture as in previous case, dewatered until 40% moisture in press machine (2) DS is granulated by filters (3) as shown in Figure 27. After that, DS is dried in a rotary kiln (4) until moisture content of 5-10%. Dried sludge then is fed to a mortar-mixing unit where cement and latex are added as well. (Zvyagina & Pushnoy , 1996)

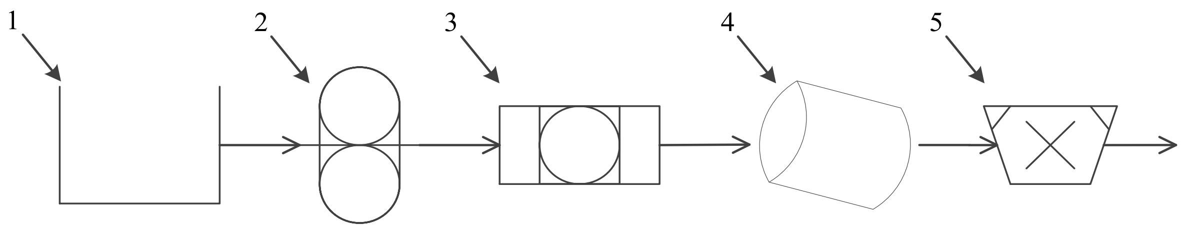

Figure 27. Production of insulating material from granulated DS. (Zvyagina & Pushnoy , 1996)

Lastly, the mixture formed is placed into forms under pressure of 1-2 kgf/cm^2 for 1 hour. Then, the pressure is removed and the material is left to stay for one day until being stripped. Thermal conductivity coefficient was determined for the samples with dimensions of 250mm·250mm·30mm. The coefficient was 0.07-0.08 W/(m·^{o}C). (Zvyagina & Pushnoy , 1996)

In general, DS can be widely used in the production of thermal and acoustic insulating material. Different production processes are known with different additives. Thermal conductivity coefficient for obtained materials was between 0.07-0.1 Wt//(m·^{o}C) that is somewhat similar or less than that of lightweight concrete (0.1-0.3 Wt//(m·^{o}C)) (The engineering toolbox, 2013).

5.7 Fiberboard

Softboard

Softboard is low density fibreboard made in the form of plate sheets of various dimensions. In the patent (Baibarisov, et al., 1994), softboards were produced with DS. Following components and their shares in weight-% (on dry basis) were used: DS – 8-12, sludge generated from wastewater treatment in the stock preparation unit of PPI or wood-processing factory – 68-79, sawdust with a fraction of less than 5 mm – 12-18, water repellant – 1-2.

Softboards were produced in accordance with the production process described in Figure 28, and the given composition had better bending strength, while the rest parameters stayed in permissible range stated in a valid in Russia State Standard (GOST 4598-86 "Fibre boards. Specifications", 1986). (Baibarisov, et al., 1994)

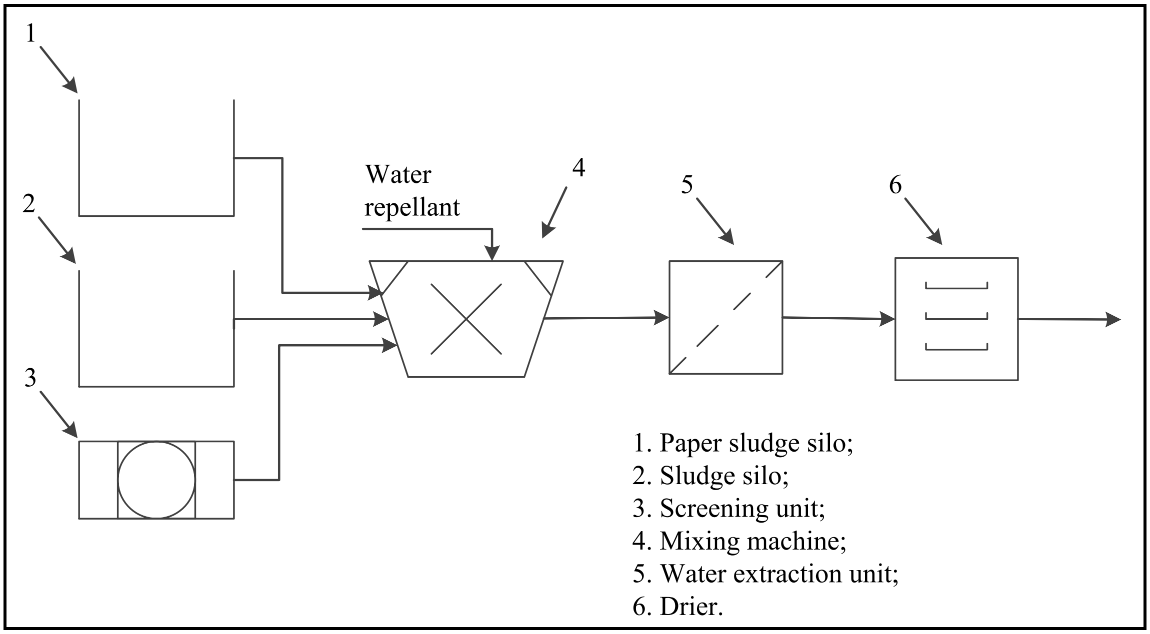

Figure 28. Softboard production process with DS addition. (Baibarisov, et al., 1994)

Firstly, DS from a silo (1), sludge generated in the stockpreparating unit of PPI or wood-processing mill from a silo (2), and screened sawdust from a silo (3) are mixed in a mixing unit (4) with water repellant (paraffin). After the mixing process the produced composition is injected into the press-mould, and then dewatered with vacuum (5). Last stage is to dry dewatered softboards in a drying facility (6). (Baibarisov, et al., 1994)

Hardboard

Hardboards are manufactured from low quality wood materials. Waste materials such as DS can also be in the process. In the patent (Denisov, et al., 2003), manufacturing process for the production of hardboard with sludge generated at PPI is described. Sludge used in the patent had following characteristics: weight fraction of fiber – 66%, weight fraction of other wood-based materials – 0.8%, weight fraction of inorganic part – 5.2%, weight fraction of secondary sludge – 27%, pH – 6.8. Following materials and their weight fractions were used in the production of hardboard in the patent: wood fiber – 68-88, sludge – 10-30%, resin – 1, paraffin – 1, sulfuric acid – 1. For the production of hardboard in the laboratory, all materials were blended and the mixture obtained was injected into mould, then dewatered until 55% MC and then presses at 185^{o}C for 8 minutes. Water absorption and swell value were slightly increasing with increasing share of sludge, but stated within the permissible range given in (GOST 4598-86 "Fibre boards. Specifications", 1986). (Denisov, et al., 2003)

To summarize what has been told before, incorporation of sludge into the production of soft- and hardboard makes slight changes to the final material, however, those changes lay within the acceptable range stated by the Governmental Standard valid in Russia.

5.8 Use in limekiln

Almost all Kraft-pulping mills are equipped with a system for lime recovering from lime sludge. Amount of lime sludge generated is 400 kg per tonne of pulp produced. Recovering is done in a limekiln that is a rotating drum kiln. Main reaction of the process is endothermic calcium carbonate decomposition. Heat consumption for lime sludge calcination is 10 MJ per 1 kg of calcined lime. (Milovidova, et al., 2010, p. 52)

Temperature of the process is about 1100-1300 ^{o}C, however optimal temperature of the process depends on inert additives content as presented in Table 11. Inert additives, especially silicates are melted at high temperatures and, thus, generate glass-like coating causing problems when lime is slaked. (Nepenin, 1990, p. 510)

Table 11. Optimal temperature of calcination process depending on inert additives content. (Nepenin, 1990, p. 510)

Inert additives content, %	High limit temperature, ^{o}C
3-5	1000-1300
5-8	950-1200
>8	950-975

Moisture content of lime sludge fed should not exceed 55% and content of Na_2O should be less than 1%. Otherwise, rings of lime will be generated on the kiln inner surface causing technological problems. Composition of lime sludge is given below. (Nepenin, 1990, p. 513)

Table 12. Composition of lime sludge fed into the limekiln. (Milovidova, et al., 2010, p. 108)

Element	Share, %
$CaCO_3$	>95
Na_2O	<0.2
SiO^{3-}	<0.2
Al	<0.5
Fe_xO_y	<0.5
$NaSO_4$	<0.01
CaO	<0.5

During the caustisizing and recovering, some part of CaO is lost. To cover the losses of CaO in the system, limestone is used. Amount of limestone used ranges from 10% to 15% of lime sludge fed into the process (Milovidova, et al., 2010, p. 74). Limestone is used since about 52 – 53% of limestone is CaO that is required for the process.

As of 2013, there was no scientific article available about DS utilization in a drum kiln. Nevertheless, DS is expected to be rich in calcium carbonate coming from paper filler and, thus, to be appropriate for the process. Content of calcium oxide that is generated as a result of calcium carbonate thermal decomposition is shown in Table 3.

5.9 Review of material recovery possibilities

Basically, all material recovery possibilities could be divided into three categories:

(1) inorganic materials requiring;
(2) fiber requiring;
(3) fiber and inorganic matter requiring.

For the production of cement clinker, pozzolanic material, ceramic products and for utilization in limekilns high inorganic content of DS is required. On contrary, for the production of insulating material, softboard, and hardboard, fiber is needed mostly. And lastly, in lightweight aggregate and cement mortar production both fiber and inorganic matter are utilized. WWTS is not recommended for utilization in construction materials production in terms of material recovery since that type of sludge does not contain any valuable inorganic substances or wood fibers.

Comparison of sludge material recovery options is presented in Appendix V. Information from real experiments with DS application as an additive was gathered so, that only main criteria of sludge used are presented, while the conditions and equipment used during the manufacturing processes can be found in the corresponding chapters of the study. Elements which presence in DS is highly recommended are given in Appendix V to make the selection of the real utilization way simpler.

Cement clinker production is extremely dependent on calcium oxide that comes from calcium carbonate. Moreover, availability of silica, alumina, and iron makes DS more applicable for the process. However, alkaline metals can cause problems in the kiln, so their content in DS should be maximally limited. That is why elements that should be avoided in DS are displayed in Appendix V as well. In addition, moisture content, as one of the crucial factors influencing possibility of sludge utilization, that DS should have before being used is presented.

6 LEGISLATION IN RUSSIA

In previous chapters, main focus of the thesis was on the technological aspect of sludge utilization. However, application of certain technologies must be in compliance with the current legislation of the Russian Federation. In this chapter, information on the legislation system on waste management in the Russian Federation, and the Leningrad Region particularly, will be provided.

The main legislative act regulating relations in the waste management sector in Russia is *the Federal Law dated 24.06.1998 №89-FL "On production and consumption waste"* (with changes and updates come into force on 23.09.2012) (Federal Law "On production and consumption waste" № 89, 1998). All waste regulations in Russia must follow principles of the 89-FL. The 89-FL has not been changed much since 2008 (Consultant plus, 2012). Main changes were related to the terminology used in the law. According to the last changes, waste with V class of hazard (almost non-hazard) are no longer classified as hazardous waste and their management should not be licensed, while management of waste that belong to I-IV classes of hazard (I – extremely hazard, II – high-hazard, III – relatively hazard, IV – low-hazard) is licensed. It worth mentioning that DS and WWTS usually are of IV or V hazard class.

One of the basic principles realized in the law is the payment for environment use. These payments are the compensation of damage caused by businesses to the environment. One of such fees is the waste disposal fee that is charged for waste disposal on landfills and depends on the waste type that are classified in accordance with *the Federal classification catalogue on waste* (Ministry of Natural Resources and Environmental Protection of the Russian Federation, 2002) that is a part of *the State waste inventory* (Order of Minprirodi of Russia №792, 2011). Most paper production waste refers to IV or V class of hazard. Pulp and paper mills should pay 37.5 eurocents/tonne of V hazard class waste generated (for comparison, disposal fee for I hazard class is 43 Euro), but still can be changed depending on the current situation (Klepach', et al., 2010, p. 59). This cost does not include disposal fee paid for sludge transportation and actual landfilling. V class hazardous waste are simpler to be handled (transported, stored etc.) in accordance with the item 30 of article 12 of *the Federal Law* *dated 04.05.2011 №99-FL "On licensing of certain types of activity"* (with changes and updates come into force on 01.01.2013) (Federal Law "On licensing of certaing types of activity" №99, 2011). In compliance with the item, only treatment and disposal of waste of I-IV class of hazard is licensed. It means that companies can avoid bureaucracy to get the license and can freely transport their waste.

Low waste disposal fee for V class waste, that are usually generated in large volumes and ease of its management tended to the situation when *waste landfilling is a major disposal practice*. In European countries, incentives or lower tax rates are practiced to support environmentally friendly technologies application. According to the 89-FL: "economic motivation of activities in waste management field is implemented by waste disposal fee reduction…, if implementation of technologies enabling waste reduction is done." (Federal Law "On production and consumption waste" № 89, 1998)

The most important event in the environment protection field in Russia in 2012 was approval of *"Basics of state policy in the field of environmental development of Russia by 2030"* by the President, Dmitri Medvedev, on 30th of April, 2012. (Russian Government, 2012). A lot of principles and mechanisms were described. Only those, related to the topic will be reproduced. Firstly, to reduce negative environmental impact following mechanisms are to be implemented: "b) reduction of … waste generation until the level corresponding to the analogical one gained in economically developed countries" and "z) implementation of the measures provided by the Climate doctrine of Russia…" Then, in the performance of environmentally safe waste management implementation so called mechanism "polluter pays" should be used. No information on real financial support is presented, but this information should be found in regional documents that are created to fulfill the Basics requirements.

Another driving force for modernization of equipment is *the Climate doctrine* (Russian Government., 2009), where federal bodies of state power are asked to develop financial mechanisms, including taxation system, contributing to mills improvement, as well as to intensification of renewable energy use. WWTS and DS are potential sources of renewable energy since contain biobased materials.

Item 1 of article 18 of *the Federal Law dated 04.05.1999 №96-FL "On atmosphere protection"* (revised on 25.06.2012) (Federal Law "On atmosphere protection" №96, 1999) prohibits waste incineration without special equipment applied. This equipment is given in *GOST R 54205-2010: "Resources conservation. Waste treatment. Best available techniques for improving energy efficiency on incineration" dated 01.01.2012* (GOST R 54205-2010, 2012). In general terms, the GOST is almost a translated copy of the Reference document on best available techniques for waste incineration (European commission, 2006). The best available technique for sludge incineration according to the GOST is FBB that is characterized with higher efficiency of incineration and small volumes of flue gases generated.

In 29.05.2012 the Government of Saint-Petersburg approved *the program "Regional target program on municipal solid and industrial waste management over the period 2012-2020"* (Saint-Petersburg resolution of 29.05.2012 N524, 2012). The objective of the program is "increase of environmental safety of citizens of Saint-Petersburg and reduction of damage to environment during management of production and consumption waste by modernization of existing in Saint-Petersburg system of waste collection, transportation and treatment." Waste composting was recognized as inefficient in economic and ecological terms so in the framework of the program next technologies will be implemented: (1) solid recovered fuel production (SRF) with possibilities to adjust its properties in order to fulfill customer's needs; (2) MSW utilization in reactors with plasma gasification technology being applied. First option is projected by a Greece company. The latter one will be based on reconstruction of current "Zavod MPBO-2". Both of them are aimed to treat MSW rather than industrial waste.

According to *the GOST R 54535-2011 dated 01.01.2013 "Resources saving. Sewage sludge. Requirements for waste dispose and use at landfills"* (2013), sludge can be landfilled if sludge is III-V class of hazard, contains not less than 15% DS and 20% of ash, has pH of 5.0-12.0, its chemical oxygen demand is 5000 mg-O_2/dm^3 and biochemical oxygen demand is 4000 mg-O_2/dm^3. Utilization of waste as a secondary raw material is prioritized more than landfilling. (GOST R 54535-2011, 2013)

7 PULP AND PAPER COMPANIES OF THE LENINGRAD REGION

In the current chapter, companies producing pulp, paper and cardboard and, as a result, generating sludge will be characterized. Characterization includes description of raw material used, type of commodities being produced at the companies and depiction of wastewater and sludge treatment processes applied at the companies. Results of chemical and thermotechnical analyses of sludge will be presented, where possible.

Information about following companies was gathered:

- “SCA Hygiene Products Russia”, Svetogorsk (SCA, 2013);
- “International paper”, Svetogorsk (International Paper, 2013);
- “Knauf”, Kommunar;
- “Syassky pulp and paper mill”, Syas (JSC "Syassky Pulp & Paper Mill", 2009).

Information for the chapter was obtained from either interviews with the companies’ representatives, or master’s theses from previous years written at Saint-Petersburg State Technological University of Plant Polymers.

7.1 “SCA Hygiene Products Russia”, Svetogorsk

SCA paper mill is located in Svetogorsk city in the north-west part of the LR (see Appendix VI). The factory produces tissue paper from recycled one. The fiber to the mill comes mainly from printing houses what makes the composition of recycled paper constant over the time. Production process includes a deinking unit resulting in generation of sludge in large volumes.

Sludge generation rate varies from 100 to 190 t/day with average sludge generation rate of 150 t/day. Sludge generation process is shown in Figure 29. Amount of sludge generated depends on the grammage of the tissue being produced (from 19 to 23 g/cm^2). High amount of sludge generated at the mill results from the requirements on tissue paper composition. The paper must not contain much additives to fulfill hygienic normative set legislation. The more the grammage is, the more sludge is generated. According to the environmental manager of the mill (Tunichenko, 2013), ash content of sludge and its MC does not change much with time and equal to approximately 60% and 50% respectively. Bulk density of sludge is 0.6 g/cm^3. Sludge is solid substance without leaking. Most part of sludge is sent for landfilling, while only a small fraction (about 15 tonnes/week) is supplied for cat litter production.

7.1.1 Deinking sludge generation process

Wastewater generated during stock preparation operations is mixed with flocculating agent and sent for treatment into a flotation unit (1). Wastewater generated at the papermaking machine is treated in a tilted plate flotation unit (2). Industrial wastewater from other equipment is treated in a flotation unit (3). Scum generated in flotation units (1), (2), (3) is collected in a scum tank (4) before further treatment.

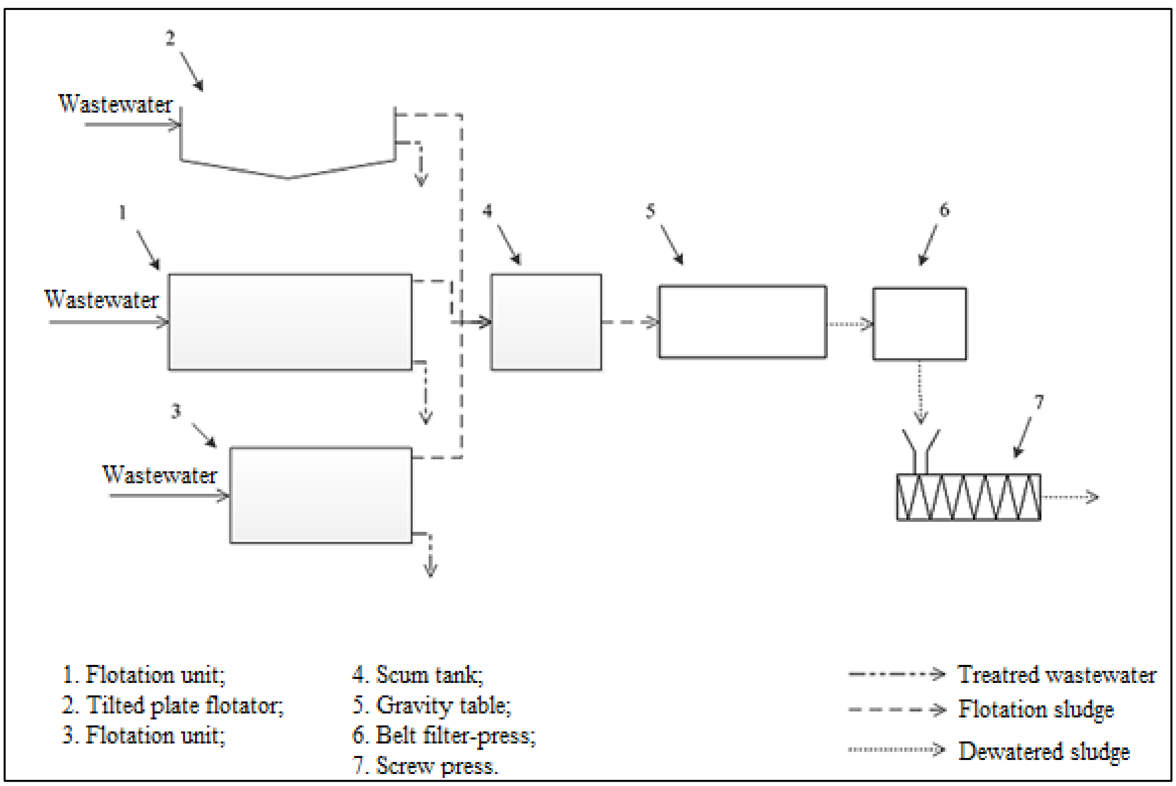

Figure 29. Flow-chart of wastewater and sludge treatment at “SCA Hygiene Products Russia” factory.

Scum that also refers to as flotation sludge is thickened in a gravity table (5) where MC of sludge decreases from 98-99 to 90%. After that, sludge is dewatered, firstly, in a belt filter-press (6) until MC of approximately 70% and, secondly, in a screw press (7) until final MC is about 50%.

7.1.2 Analyses of deinking sludge

Sludge sampled at SCA mill was analyzed to determine its heating value and chemical composition. Heating value analyses were performed in the laboratory of LUT Energy. Analyses were done with preliminary dried sludge. Moisture content of sludge in arrival conditions before heating value determination was 49.6%. Higher heating value on dry basis (HHV_d) was determined in a bomb calorimeter and the results of analyses are presented in Table 13. Standard deviation of the results is acceptable in accordance with the (GOST 147-95, 2010).

Table 13. Heating value of sludge sampled at "SCA Hygiene Products Russia".

Sample number	HHV_d, kJ/kg	LHV_d, MJ/kg	LHV_{ar}, MJ/kg
1.	7070	6.01	1.82
2.	7040		
3.	7070		
average	7060±14		

Lower heating value on dry basis was calculated as follows:

$$LHV_d = HHV_d - \left(l \cdot \frac{M_{H2}}{M_{H2}}\right) \cdot H = 7.06 - \left(2.441 \cdot \frac{18.015}{2.016}\right) \cdot \frac{4.8}{100} = 6.01 MJ/kg; \qquad (1)$$

where HHV_d – average higher heating value of dry material, MJ/kg;

l – latent heat of evaporation for H_2O (T=25 °C) = 2.441 MJ/kg;

M_{H2O} – molar mass of water from combustion of H2. g/mol;

M_{H2O} – molar mass of combusted hydrogen, g/mol;

H – decimal percents of hydrogen on a dry basis = 4.8%.

Hydrogen content is taken as an average from hydrogen content of tree deinking sludge types and two recycled paper mills presented in Table 1.

Lower heating value of sludge in arrival conditions was calculated as follows:

$$LHV_{ar} = LHV_d \cdot (1 - w_{H2O}) - l \cdot w_{H2O} =$$

$$6.01 \cdot (1 - 0.496) - 2.441 \cdot 0.496 = 1.82\ MJ/kg; \qquad (2)$$

where LHV_d – lower heating value of dry material, MJ/kg;

l – latent heat of evaporation for H_2O (T=25 ^oC) = 2.441 MJ/kg;

w_{H2O} – moisture content of sludge.

Chemical analyses of the sludge were performed in the accredited laboratory of the Federal State Unitary Enterprise “All-Russian Research Institute of metrology named after D. I. Mendeleev” and the results are given in Table 14.

Amount of elements is presented on dry basis. High share of calcium (15.51 weight-%) compared to the rest elements presented demonstrates availability of $Ca(CO_3)$ in sludge generated at the mill. It is also noticeable that the content of aluminum is higher than share of the rest elements from the list and equals to 3.2 weight-%. Presence of sodium and potassium, alkaline metals, is negligible and accounts less than 0.09 weight-%.

Table 14. Chemical composition of sludge sampled at "SCA Hygiene Products Russia".

No	Measured component	Analysis method	Measurement results				
			S1	S2	S3	S4	Average
1.	Moisture content (mass fraction of weight loos while drying) at 105 ^oC, %	Gravimetrical	47.8	48.3	47.9	46.8	47.7±0.55
2.	Ash content. Measured at 1050^{o}C, based on the dry matter, %		42.9	42.9	42.8	42.8	42.85±0.05
3.	Weight content of carbon, based on the dry matter, % C total C organic C inorganic	Infrared spectrometric	 24.0 18.97 5.04	 24.3 19.2 5.10	 24.4 18.97 5.40	 25.2 19.75 5.44	 24.5±0.44 19.22±0.32 5.25±0.18
4.	Calcium, %	Atomic emissive with inductively coupled plasma	15.32	15.78	14.99	15.95	15.51±0.38
5.	Aluminum, %		3.36	3.45	2.97	3.02	3.2±0.21
6.	Iron, %		0.127	0.126	0.117	0.116	0.12±0.01
7.	Magnesium, %		0.24	0.23	0.022	0.22	0.18±0.09
8.	Sodium, %		<0.0005	<0.0005	<0.0005	<0.0005	0.0005
9.	Potassium, %		0.093	0.064	0.068	0.056	0.07±0.01
10.	Cobalt, mg/kg		<0.5	<0.5	<0.5	<0.5	0.5
11.	Nickel, mg/kg		<0.5	<0.5	<0.5	<0.5	0.5
12.	Lead, mg/kg		<0.5	<0.5	<0.5	<0.5	0.5
13.	Cadmium, mg/kg		<0.5	<0.5	<0.5	<0.5	0.5
14.	Cupper, mg/kg		85.9	83.1	82.6	83.0	83.65±1.31
15.	Zink, mg/kg		22.8	23.9	26.1	20.9	23.43±1.88
16.	Manganese, mg/kg		66.7	66.4	64.9	63.3	65.33±1.35
17.	Chrome, mg/kg		10.37	10.40	10.79	8.95	10.13±0.7
18.	Arsenic, mg/kg		<0.5	<0.5	<0.5	<0.5	0.5
19.	Titan, mg/kg		110	139	98.9	92.0	109.98±17.9

7.2 "International Paper", Svetogorsk

Factory is located in Svetogorsk (see Appendix VI) and leases a part of its land to "SCA Hygiene Products Russia". The company produces mainly Kraft-pulp and chemi-thermomechanical pulp. Feedstock for the production process is virgin wood only. Wastewater at the factory is treated as shown in Figure 30. No information about chemical composition or thermotechnical properties of sludge was obtained. It can be assumed that sludge has properties similar to those shown in Table 1 in first two rows.

7.2.1 Wastewater treatment sludge generation process

Wastewater generated during Kraft-pulp production process, is sent, firstly, to a primary clarifier (1) for suspended solids precipitation, and then to an aerotank (2) for biological treatment. Activated sludge is separated from treated wastewater in a secondary clarifier (3). At the same time, wastewater generated during chemi-thermomechanical pulping is treated in a flotation unit (4) where suspended solids are separated. Then wastewater is biologically treated in an aerotank (5). Activated sludge is separated in a flotation unit (6). A part of activated sludge is returned back to the aerotanks, while the rest sludge that is called excess biomass is thickened in a flotation unit (7) together with primary sludge, from the clarifier (1) and the flotation unit (4). MC of excess biomass to be thickened is about 99%, while after thickening MC is reduced to 95-97%. Compacted sludge is dewatered in a membrane chamber filter-press (8) until final MC is approximately 60-70%. In such conditions dewatered sludge is combusted in a multi-fuel boiler used for energy production.

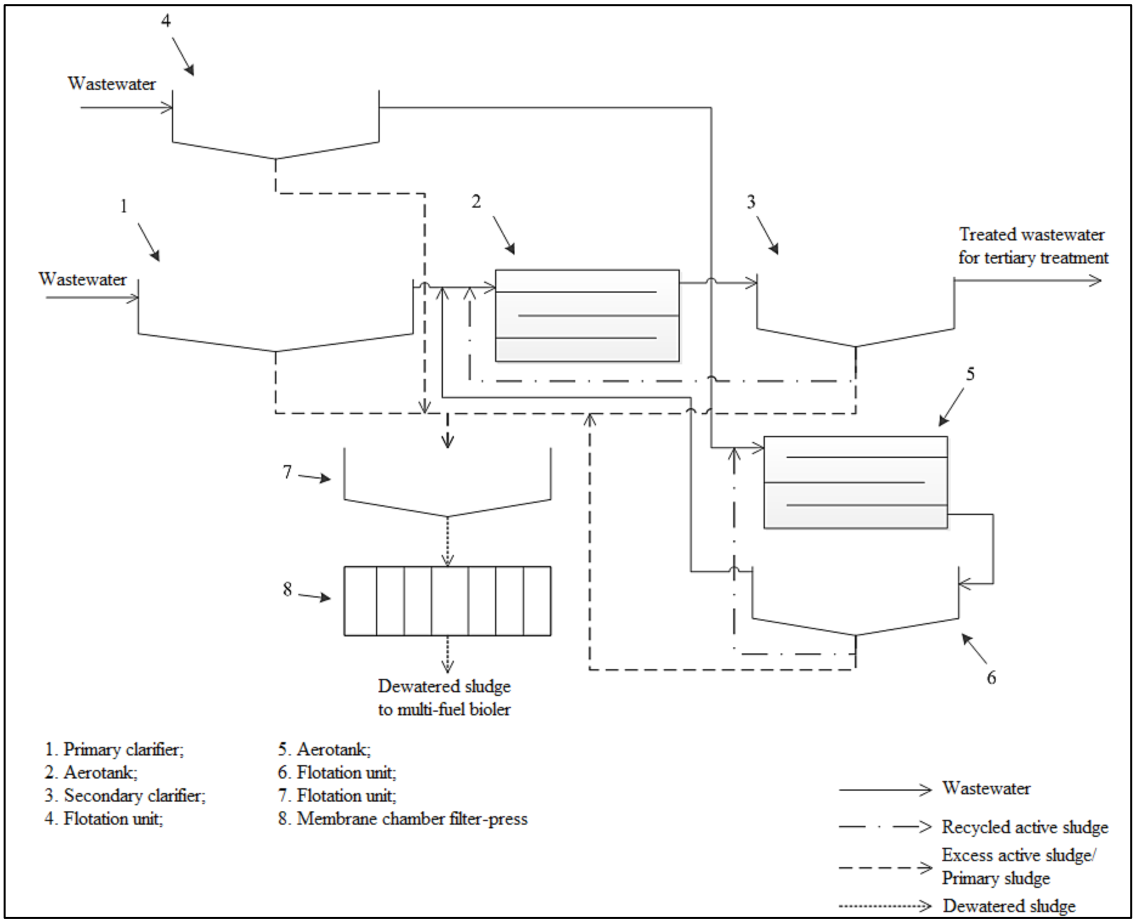

Figure 30. Flow-chart of wastewater and sludge treatment at “International Paper” mill.

7.3 “Knauf”, Kommunar

The mill located in Kommunar (see Appendix VI) manufactures cardboard that is used in the production of construction materials mainly, while some smaller quantity is used for packaging production. The mill uses from 85 to 100% recycled fiber depending on the type of cardboard being produced. Amount of primary sludge generated daily at the mill is 36 tonnes, while the amount of mixed sludge from biological treatment plant is 145 tonnes/day.

Primary sludge is generated at the stage of fine screening where recycled fibers are treated from polyethylene left. Moreover, short fiber is lost during the process. Waste generated is sent to dewatering and then stored at the mill until being transported to landfill. In addition to that, a flotation unit is installed in there for recycled water treatment. Major component separated during wastewater treatment is short fiber. Fiber separated is dewatered together with other waste flow described before. Composition and properties of primary sludge are presented below.

Table 15. Composition of primary sludge generated at "Knauf" factory.

Parameter	Share
MC, %	65
Fiber, %	92
SiO_2, %	6.37
Polyethylene, %	1.14
Polypropylene, %	0.29
Polyvinylchlorid, %	0.2

Thus, primary sludge generated consists mainly of fiber with some minor addition of silica oxide. Its aggregate state is solid. No calcium is present in sludge. Heating value of sludge is unknown.

7.3.1 Wastewater treatment sludge generation process

Secondary sludge generated at the mill is of more importance since its volumes are large. Sludge is generated at the biological treatment plant, which flow-chart is depicted in Figure 31.

Wastewater generated in the production process is, firstly, mixed with flocculants to increase separation efficiency and then is treated from suspended solids in a sand separator (1). After sand is removed, wastewater flow is sent to a primary clarifier (2) where large enough particles are precipitated under gravity force. Sediments generate sludge that is directed to a sludge thickener (7) for further treatment. Next, clarified wastewater enters a first stage aerotank (3) where biological treatment takes place. Microorganisms use organic matter contained in wastewater as feedstock for growth and reproduction. Thus, biochemical oxygen demand is decreased, while amount of biomass in the system increased. Biomass is separated in a secondary clarifier (4) and wastewater flow is directed to a second stage aerotank (5) where the same process takes place. Biologically treated wastewater is, finally, sent for tertiary treatment before being reused or discharged to a water basin.

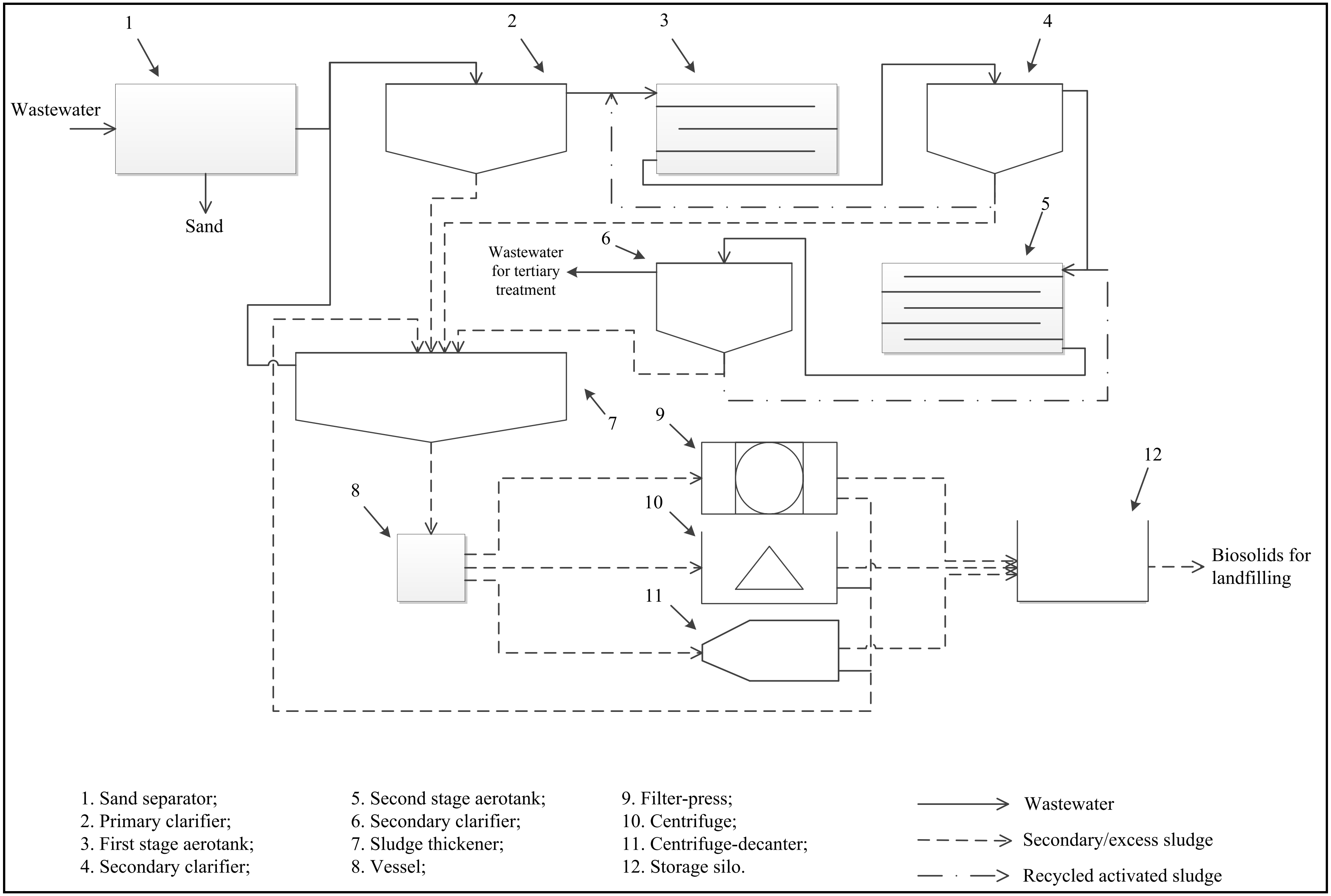

Figure 31. Secondary sludge generation process at "Knauf" factory.

A part of biomass separated in the clarifiers (4) and (6) is send back to the aerotanks (3) and (5) respectively, while the rest excess biomass is subjected to further treatment in the sludge thickener. Secondary sludge is compacted in the thickener until its moisture content is 97%. Supernatant generated is sent back to the primary clarifier. Compacted secondary sludge is sent then for dewatering into a filter-press (9), a centrifuge (10), or a centrifuge-decanter (11). Dewatered sludge that also refers to as biosolids has MC of about 70%. It is stored in a silo until being landfilled.

7.3.2 Analyses of sludge

Composition of sludge and its characteristics are presented in Table 16. Content of all chemical substances is presented on dry basis.

Table 16. Properties of secondary sludge generated at “Knauf” factory.

Parameter	Amount
MC, %	70.1
Organic matter, %	78.6
SiO_2, %	18.71
Oil product, %	0.14
Fe, %	0.20
PO^{3-}, %	2.27
Cu, mg/kg	204.01
Zn, mg/kg	113.71
Pb, mg/kg	153.85
Cd, mg/kg	0.33
Co, mg/kg	10.37
Ni, mg/kg	50.17
Mn, mg/kg	163.88
Cr, mg/kg	30.10
HHV_d, MJ/kg	9,91
LHV_{ar}, MJ/kg	1,17

Similarly to primary sludge, secondary sludge is rich in organic matter. However, organic matter presented is mostly excess biomass. This determines relatively high heating value of sludge on dry basis, while high MC makes it unacceptably low for incineration without pretreatment. Inorganic content is presented mainly by silica oxide.

7.4 “Syassky pulp and paper mill”, Syas’

The pulp mill is located in Syas’stroy city (see Appendix VI) and produces sulfite pulp, chemical-mechanical pulp, wrapping paper, and tissue paper. The mill uses only virgin fiber for the production processes. Thus, no deinking unit is installed. Wastewater treatment plant flow-chart is illustrated in Figure 32.

7.4.1 Wastewater treatment sludge generation process

All wastewater generated in the production processes is collected together for the treatment. Wastewater is mixed with flocculants for enhancing sedimentation process in a sand separator (1) and a primary clarifier (2). Primary sludge is thickened in a sludge thickener (5) with further flocculants addition. After it, sludge is dewatered in a separator (6) until its MC is approximately 60 %. Dewatered sludge is stored in a silo (7) before being used as a ready product according to Technical Specifications 5711-023-43508418-2008.

Clarified wastewater is biologically treated in an aerotank (3). Mixture of biomass and wastewater is separated in a secondary clarifier (4). Wastewater is directed for tertiary treatment before being discharged, while a part of biomass is reused in the aerotank. The rest biomass is compacted in a sludge thickener (8). Compacted biomass is blended with flocculants before being treated further in a belt thickener (9) and a belt filter-press (10) until its MC is 70-72%. Sludge is stored in a silo (11) before being used as a ready commodity according to Technical Specifications 9291-018-43508418-2004.

Therefore, no sludge generated at the mill is landfilled. The only case sludge is landfilled is when sludge does not correspond to the requirements set on it. There was no information provided about sludge utilizer. However, it can be concluded based on Appendix VI that primary sludge can be used in insulating material, hard- and softboard production processes. Use of sludge for cement clinker, pozzolan material, and ceramics production is unlikely. The information presented was gathered in 2010.

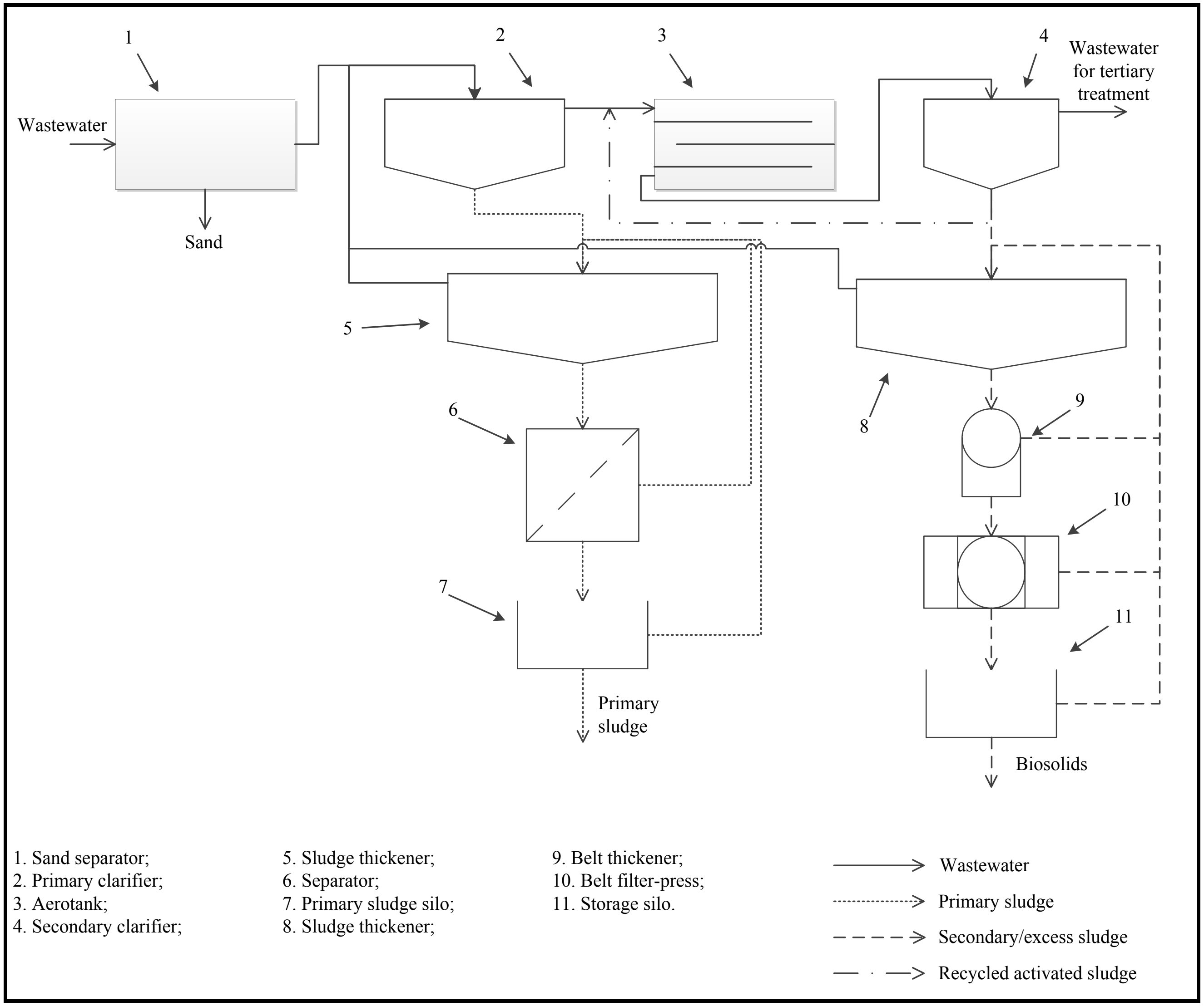

Figure 32. Sludge generation processes at “Syassky pulp and paper mill”.

7.5 Preliminary conclusions of pulp and paper companies

WWTS generated at both “International paper” and “Syassky” mills is not landfilled, but used for energy or material recovery. WWTS and DS generated at “SCA Hygiene Products Russia” and “Knauf” mills is landfilled. Sludge generated at the factories has high moisture content and, as a result, low heating values, what limits possibilities of sludge energy recovery without use of additional fuel. Furthermore, DS generated at “SCA Hygiene Products Russia” mill has ash content of 42.9%. In other words, about a half of sludge will become ash after incineration. Ash, consequently, requires further utilization. However, use of deinking sludge generated at “SCA Hygiene Products Russia” in construction materials production, like cement or bricks, is advised.

8 ENERGY AND MATERIAL RECOVERY POSSIBILITIES IN THE LENINRGAD REGION

Energy recovery sub-chapter will be based on the thermotechnical properties of sludge generated at "SCA Hygiene Products Russia" (Table 13 and Table 14) and "Knauf" factories (Table 15). Amount of sludge generated and used in the calculations is 150 t/day for the former factory, and 145 t/day for the latter one. These amounts are average amounts of sludge generated at the companies. Lecture material used in the course "Energy recovery from solid waste" (Horttanainen, 2012) will be used as a basis for the calculations.

Material recovery sub-chapter will introduce the study of DS, generated at "SCA Hygiene Products Russia" paper mill, utilization possibilities in existing companies of the Leningrad Region only. The rest sludge types either are not appropriate for material recovery, like WWTS from biological treatment plant at "Knauf" factory, or their quantity is negligible, like primary sludge from the same company.

8.1 Energy recovery

Grate boiler and fluidized bed boiler techniques will be analyzed within the study as potential energy recovery options. Following calculations will be related to incineration of deinking sludge generated at "SCA Hygiene Products Russia" mill in fluidized bed boiler. Calculations for grate boiler and sludge generated at "Knauf" factory are the same with appropriate changes in some parameters as will be noticed further. Firstly, annual amount of energy enclosed in sludge generated at "SCA Hygiene Products Russia" is calculated:

$$E_s = LHV_{ar} \cdot q_s = 1.82 \cdot 150\ 000 \cdot 365 = 99\ 645\ 000\ \ MJ/a; \qquad (3)$$

where LHV_{ar} – lower heating value of sludge in arrival conditions, MJ/ kg;
q_s – annual amount of sludge generated, kg.

LHV_{ar} for sludge from "Knauf" is 1.17 MJ/kg and q_s is 145 000 t/day.

Thus, energy potential of sludge equals to 100 TJ/a (=27.7 GWh/a).

Annual electricity production (gross, no transfer losses are included):

$$E_{EL} = \eta_{EEP} \cdot E_s = 25\% \cdot 27.7 = 6.9\ GWh/a; \quad (4)$$

where η_{EEP} – assumed efficiency of electricity production at WtE plant (Eurelectric, 2003) (η_{EEP} for GB is assumed to be 25%);

E_s – annual energy potential of sludge, GWh/a.

District heat production (gross, no transfer losses are included):

$$E_{DH} = \frac{E_{EL}}{PtH} = \frac{7.8}{0.45} = 15.4\ GWh/a; \quad (5)$$

where PtH – assumed power-to-heat ratio (Energy-AN Consulting, 2010); (PtH for GB is assumed to be 0.42).

Total boiler energy output:

$$E_{NET} = E_{EL} + E_{DH} = 6.9 + 15.4 = 22.3\ GWh/a. \quad (6)$$

Boiler efficiency:

$$\eta_{TOT} = \frac{E_{NET}}{E_S} = \frac{22.3}{27.7} = 81\%. \quad (7)$$

Electricity output:

$$\Phi_{EL} = \frac{E_{EL}}{t_{APL}} = \frac{6.9}{7800} = 0.89\ MW; \quad (8)$$

where t_{APL} – incineration plant availability (annual peak load), h/a; (t_{APL} for GB is assumed to be 8000 h/a).

District heat output:

$$\Phi_{DH} = \frac{E_{DH}}{t_{APL}} = \frac{15.4}{7800} = 1.97\ MW. \quad (9)$$

Total energy output:

$$\Phi_{NET} = \Phi_{EL} + \Phi_{DH} = 0.89 + 1.97 = 2.86\ MW. \quad (10)$$

The results of the calculations are combined in the Table 17.

Table 17. Characteristics of GF and FBB for incineration of both DS generated at "SCA Hygiene Products Russia" and WWTS generated at "Knauf".

Parameter	Eq. No	Unit	"SCA Hygiene Products Russia"		"Knauf"		Total	
			GF	FBB	GF	FBB	GF	FBB
E_s	3	GWh/a	27.7		17.2		44.9	
E_{EL}	4	GWh/a	6.9	6.9	4.3	4.3	11.2	11.2
E_{DH}	5	GWh/a	16.5	15.4	10.2	9.6	26.7	24.9
E_{NET}	6	GWh/a	23.4	22.3	14.5	13.9	37.9	36.2
η_{TOT}	7		85%	81%	85%	81%	85%	81%
η_{EEP}			25%	25%	25%	25%	25%	25%
PtH			0.42	0.45	0.42	0.45	0.42	0.45
Φ_{EL}	8	MW	0.9	0.9	0.5	0.6	1.4	1.4
Φ_{DH}	9	MW	2.1	2.0	1.3	1.2	3.3	3.3
Φ_{TOT}	10	MW	2.9	2.9	1.8	1.8	4.7	4.6

The calculations show that FBB has higher total output compared to GF boiler. Mainly due to higher efficiency of electricity production.

During sludge heating value determination, it was found that moist sludge cannot be combusted alone without additional fuel. Therefore, sludge must be either dried before single combustion, or co-combusted with other waste from PPI. Since the framework of the study does not assess possibilities for new installations construction, only co-combustion could be analyzed.

As for co-combustion, both mills do not have their own boiler where co-combustion could be implemented. Along with the problem caused by high moisture content, other problems, such as high amount of ash left after incineration and flue gas treatment still must be solved.

DS has 40% ash content. It means that almost a half of sludge will be left after the combustion process. Moreover, since the major reason for combustion is to decrease amount of sludge landfilled, incineration is not the best way to utilize such type of sludge. Another drawback of combustion is that flue gas treatment equipment installed in already existing combustion plant should be replaced with more efficient one, because the amount of flue gases to be treated will increase 5 times if compare bark and deinking sludge incineration (see

Appendix VII). In addition, the potential of grate and tube-fouling of boilers will rise with sludge addition (CANMET. Energy technology centre, 2005, p. 82).

Summing up what has been said, energy recovery of WWTS from “Knauf” factory is the only way to treat sludge, if not landfilled, since application of WWTS in construction material production is not possible. Incineration of DS in arrival conditions sounds problematic, so use of sludge in construction materials production should be assessed.

8.2 Material recovery

DS generated at “SCA Hygiene Products Russia” can be used as raw material for cement clinker, ceramic and pozzolanic materials production. The last option is difficult to examine since the product is usually produced at cement mills. Moreover, pozzolanic material is used as an additive so amount of pozzolanic used totally is expected to be low.

8.2.1 Cement production

Cement production industry is developing fast in Northwestern Federal District of Russia where the LR is located. Manufacturing of different cement types increased by 64% from 2.3 million tonnes in 2009 to 3.6 million tonnes in 2011 (FSSS, 2013e). Furthermore, about 80% of all cement produced in Northwestern Federal District in 2009 was produced in the LR (Rosbalt, 2010). All over the Leningrad Region, cement is produced in following three mills mainly: “LSR-Cement”, “Slantsy cement plant Cesla”, and “Pikalyovsky cement plant”. Joint production capacity of the mills is 5.6 million tonnes of cement annualy.

Dry method

“LSR-Cement”

Installed capacity of the mill is 1.86 million tonnes with possibility to install a new more production line. Most of raw materials come to the mill from the area not further than 30 km. (LSR-Cement, 2013) The mill is located in about 350 km from DS generating mill (Appendix VI), thus, making sludge transportation process significant. In addition, problems can arise when DS sludge is added, because dry method is used for cement production at the mill

(Danilova, 2013). Basically, high moisture content of DS is the reason for potential technological problems.

To produce 1000 kg of cement by dry method, 1214kg of raw materials is needed (European Commission, 2010, p. 44). Thus, for the production of 1.860.000 tonnes of cement at “LSP-Cement” plant, 2.258.040 tonnes of raw materials is required. It means that 64 tonnes of DS ash daily generated at paper mill producing tissue paper accounts for only 1% of total raw material consumed by “LSP-Cement”.

“Slantsy cement plant Cesla”

The mill is located in the same city as “LSR-Cement” mill is. Installed capacity of the mill is 1.4 million tonnes, where real one is 0.8 million tonnes (Internet portal "Cement", 2013a). The mill has dry method production process. It can be expected that the same sludge type can cause similar problems in the production process.

According to the Reference Document on Best Available Techniques in Cement, Lime and Magnesium Oxide manufacturing industries (European Commission, 2010), rotary kilns can be equipped with a preheater. Thus, use of preheater would considerably decrease amount of water in sludge. It is illustrated in Figure 22 how preliminary drying of sludge can be implemented at a cement plant.

For manufacturing of 800.000 tonnes of cement at “Slantsy cement plant Cesla” plant 971.200 tonnes of raw materials is consumed. Thus, 64 tonnes of DS ash for “SCA Hygiene Products Russia” accounts for only 2.4% of total raw material consumed by “Slantsy cement plant Cesla”. According to Ernstbrunner & Fischau (1993), share of DS fed to the process can vary from 2-10%.

Wet method

“Pikalyovsky cement plant”

The production process is based on the wet process. DS with high MC can be theoretically supplied to the process without causing technological problems. Real annual production capacity of the plant is 2.7 million tonnes of cement (Internet portal "Cement", 2013b).

Amount of raw material used in the wet process does not change compared to the dry one (European Commission, 2010, pp. 44-46). Thus, it can be estimated that amount of DS generated at paper mill producing tissue paper accounts for 1.7% of raw material consumed in the mill. However, the mill is located in 442 km distance from the sludge generating mill (see Appendix VI) what makes sludge utilization at Pikalyovsky cement plant not feasible because of high transportation costs.

8.2.2 Ceramic bricks

Production of ceramic bricks is presented in the LR mainly by “Pobeda LSR” brick corporation. The corporation is presented by three factories located in the LR. Location of two of them is depicted in Appendix VI and the distance from them to “SCA Hygiene Products Russia” is 220 km and 230 km. Joint production capacity of all factories is 290 000 000 standard bricks equivalent annually (Vespo Group, 2013). A weight of one standard brick equivalent is about 1.8 kg (Midland Brickipedia, 2008). Thus, total weigh of produced bricks is 522 000 tonnes. To produce bricks, clay and loam are used mainly, so that, to manufacture 1000 kg of bricks 1200 kg of clay and loam is required. Consequently, for the production of 522 000 tonnes of bricks 626 400 tonnes of raw materials is needed. It means that amount of DS ash generated annually equals to 3.7% of total raw material consumed by three factories. In other words, amount of DS ash is relatively small compared to ordinary ram meal consumption.

9 TRANSPORTATION OF SLUDGE

Transportation of sludge to the potential sludge utilizer is considered to be one of the biggest concerns in sludge management in the Leningrad Region. Previous attempt to send sludge to the construction material production process has ruined, particularly, because of high transportation fee. Within the current study, research on possibilities to decrease the transportation fee was carried out, as well as on possibility for new transportation way by railroad.

Sludge generated at “SCA Hygiene Products Russia” was an example in calculations, since only that sludge type is mostly suitable for utilization in construction material production. As of now, sludge generating company pays approximately 20 €/t for sludge transportation to landfill and actual disposal. The maximum amount of money the company is ready to spend for sludge transportation and disposal is 45 €/t.

Sludge transportation in trucks can be done by any waste transportation company, eg. “Ecotrans”. Contacts with “Ecotrans” during spring 2013 resulted in following data: sludge transportation fee could be decreased to 0.053 €/(t·km). Taking that data as the basis for calculations, it could be stated that the maximum distance for sludge transportation without surpassing the current utilization fee (20 €/t) is 377 km (one way for sludge transportation only) without possibility to pay gate fee to the potential sludge utilizer. If amount of money for sludge utilization is 45 €/t then the distance increases to 849 km without possibility to pay gate fee to potential sludge utilizer.

Estimation of railroad transportation was implemented through personal communications with the representatives of the JSC “Russian Railways”. Transportation of sludge has never been implemented in the Russian Federation by railroad and, thus, there is, firstly, the need of special carriage requirements development. Once the requirements have been approved, transportation becomes possible. The prices were estimated based on waste wood (basically sawdust, ships, bark) transportation. If sludge is transported in wagons that are owned by either sludge producer or sludge utilizer, then prices for sludge transportation are following depending on the wagon type: open-box wagon – 0.062 €/(t·km), chip wagon – 0.045 €/(t·km).

Transportation will happen during several days (in average 5 days, but can vary greatly) and, thus, buffer zone is required to make sludge supply to any production process reliable. It worth mentioning that the price included only services related to transportation process itself, and does not cover sludge loading/uploading, wagons rent prices, development of the carriage requirements for new transportation commodity. Especially because of the absence of the requirements on transportation, comparison with sludge transportation in trucks becomes impossible.

Economic evaluation of sludge transportation in trucks and possible profit of "SCA Hygiene Products Russia" obtained if sludge is not landfilled but utilized in other industry are shown in Table 18.

Table 18. Economic evaluation of sludge management based on transportation costs over one year timeframe.

Destination point	**Distance, km**	**Transportation fee, M€**	**Profit, M€**	**Money Limit*, M€**
"LSR-Cement"	350	1.02	0.07	1.09
"Slantsy Cement Plant Cesla"	350	1.02	0.07	1.09
"Pobeda Brick Mill"	220	0.64	0.45	1.09
"Nikolsky Brick Mill"	230	0.67	0.42	1.09
-	377	1.09	0	1.09
"Pikalevsky Cement Plant"	440	1.23	-0.19	1.09
* - money limit means amount of money currently spent on sludge transportation and disposal.				

As can be concluded from the table, the most profitable sludge utilization way taking into account only transportation is to supply sludge for bricks production mills located in Kolpino and Nikolskoe. By doing that, "SCA Hygiene Products Russia" will save as much as 0.45 M€/a. Sludge transportation to "Pikalevsky Cement Plant" is viable since sludge generating company is ready to spend as much as 45 €/t, but requires additional payment of 0.19 M€/a.

10 CONCLUSIONS AND RECOMMENDATIONS

Literature review has shown that the amount of sludge generated from wastewater treatment at pulp and paper mills essentially depends on the raw materials being consumed and the commodity being manufactured. Two paper mills located in the Leningrad Region, namely, “SCA Hygiene Products Russia” and “Knauf”, landfill their sludge. The amount of sludge landfilled daily is 150 tonnes of deinking sludge and 145 tonnes of secondary one respectively.

At PPI plants located in the LR, following equipment is used for WWTS and DS treatment: gravity tables, flotation units, clarifiers, belt thickeners, belt filter-presses, centrifuges, membrane chamber filter-presses and screw presses. The equipment is the same as used in European countries and advised by the reference document on BAT in pulp and paper industry. In order to enhance sludge dewatering, it is recommended to install centrifuges and membrane chamber-filter presses enabling final MC of sludge less than 30%.

Based on energy recovery experience of the European Union it is concluded that rotary kilns, multiple hearth furnace and fluidized bed boilers are used for sludge incineration. Therewith, FBB is the most perspective way of sludge incineration since allows full utilization of sludge energy potential. If sludge generated at paper mills located in the Leningrad Region would be incinerated, then total energy output was 4.6 MW. However, to produce the same amount of energy, amount of flue gases will be 5 times more from sludge incineration than if bark would be combusted alone.

Based on literature review and chemical analysis of DS it was proven that sludge most successfully can be utilized in cement, ceramics, lightweight aggregate and fiberboard production. Sludge can be potentially utilized in cement mills “LSR-Cement”, “Slantsy Cement Plant Cesla” and brick mills “Nikolsky Brick Mill” and “Pobeda Brick Mill”.

To summarize, theoretical and practical experience shows availability of technologies for sludge pretreatment and further Sludge-to-Energy recovery, as well as presence of factories suitable for material recovery in the Leningrad Region from environmental and economic aspects of sustainability to prevent sludge landfilling.

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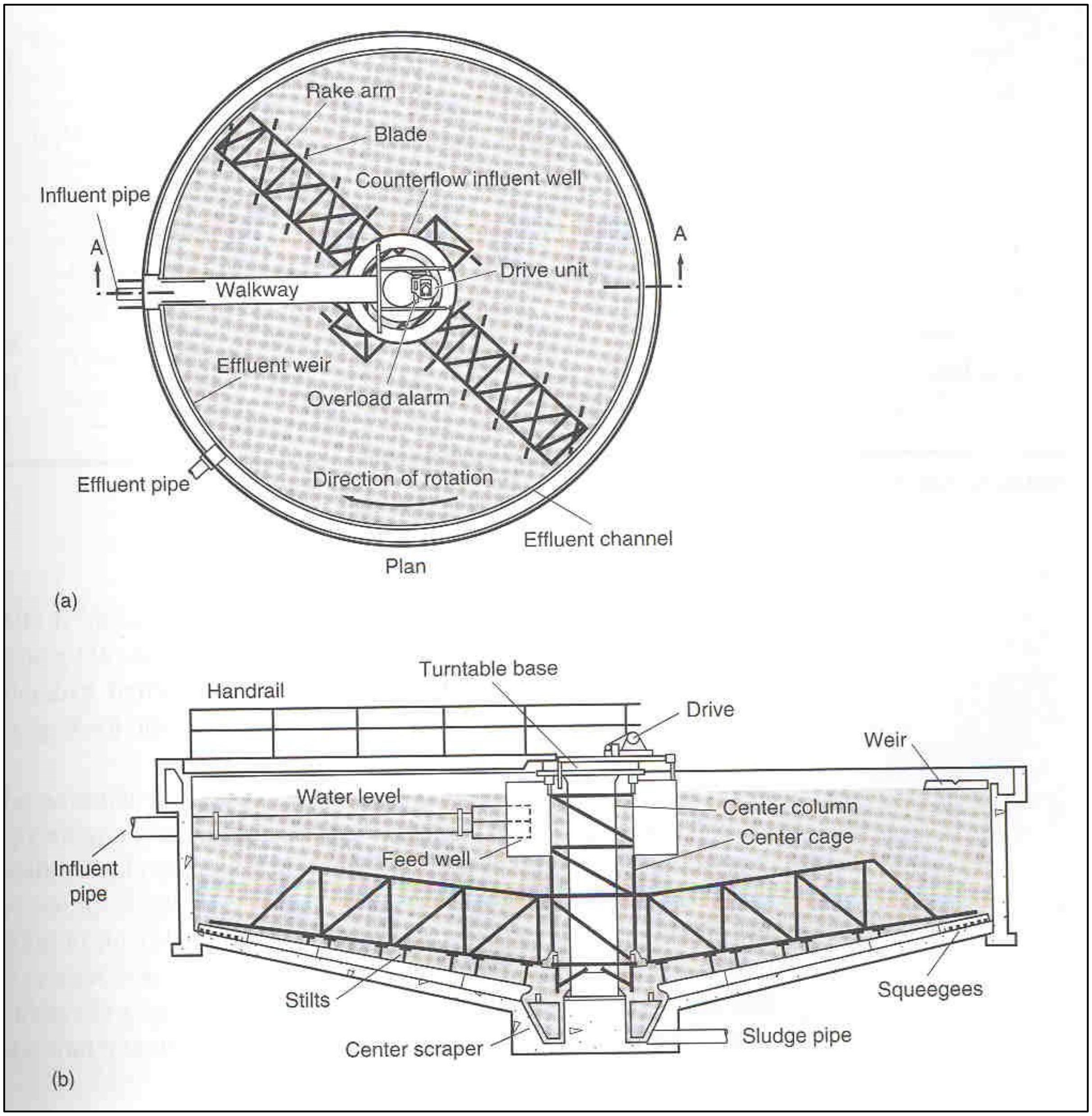
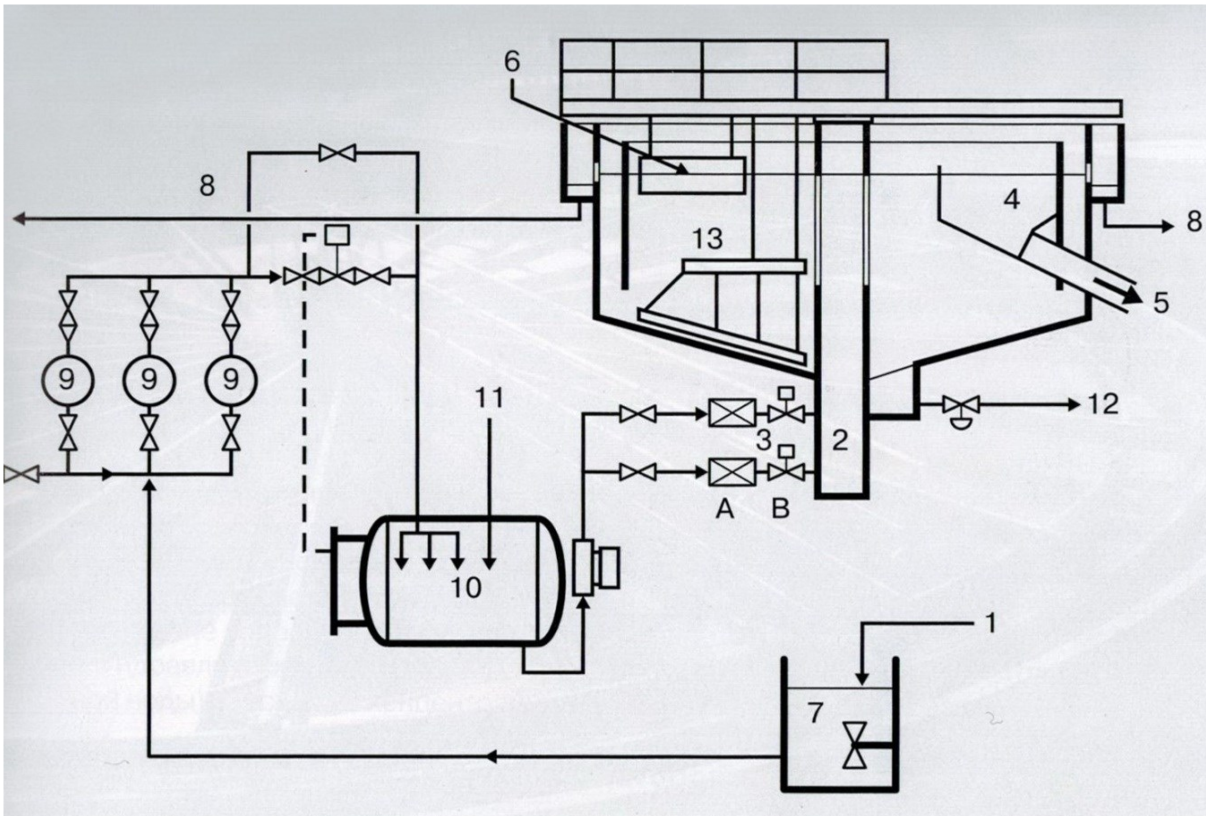
APPENDIX I. Clarifier.



Source: Wastewater Engineering: Treatment and Reuse, by Metcalf & Eddy, Inc. George Tchobanoglous Franklin Burton H. David Stensel, 2003.

Sludge thickening is implemented due to vertical stilts, which removes air containing in sludge while rotating slowly. Sludge suspended at the bottom of the clarifier is transported with the aid of blades also called scrapers to the centre of the clarifier from where thickened sludge is removed.

APPENDIX II. Flotation unit.

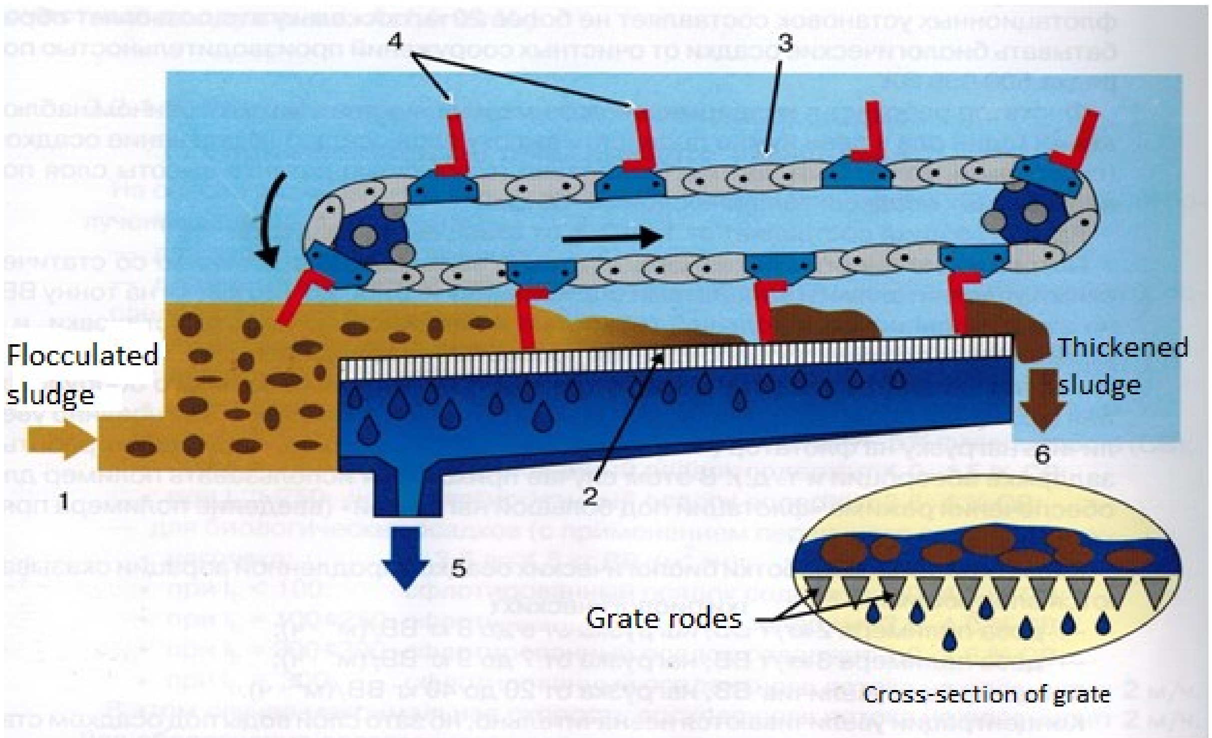


1 – sludge inlet; 2 – low-pressure chamber; 3 – pressure lowering system; 4 – sludge outlet; 5 – pipe; 6 – surface scrapers; 7 – vessel; 8 – treated water outlet; 9 – pressurizing pumps; 10 –saturation vessel; 11 – compressed air; 12 – bottom residues.

Source: Degremont, 2007. Liquid sludge treatment. In: G. Bakasova, M. Volgina, L. Reshetnikova

Sludge generated during wastewater treatment is sent to a saturation vessel, where compressed air is fed as well. In the saturation vessel air dissolution takes place and at then saturated with air sludge is fed to a flotation unit´s low-pressure chamber system through pressure lowering system. Due to sharp decrease in pressure air bubbles start generating from saturated sludge. Bubbles, while moving upwards generate flotoflakes with sludge particles. Flotoflakes are collected from the surface by the surface scrapers and sent for the further treatment.

APPENDIX III. Gravity table.

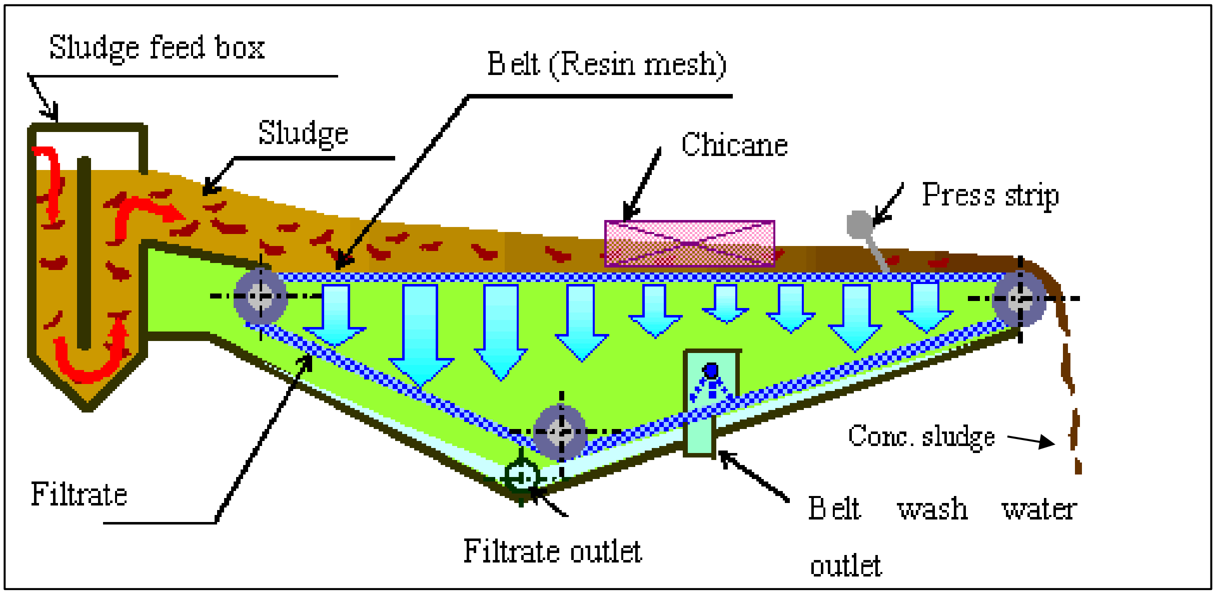


1 – sludge inlet; 2 – grate; 3 – chain belt; 4 – scrapers; 5 – filtrate; 6 – thickened sludge output.

Source: Degremont, 2007. Liquid sludge treatment. In: G. Bakasova, M. Volgina, L. Reshetnikova

Sludge, preliminary mixed with flocculants, is fed onto the grate, equipped with rods installed over a certain distance from each other so that there are intervals between them. Free water contained in sludge starts draining through the interval made in the grate. While moving towards the discharge end of the system with the help of scrapers, sludge is thickened. Thus, amount of free water in sludge is reduced when sludge is discharged.

APPENDIX IV. Belt thickener.



Source: Ministry of the Environment, Japan. Global Environment Centre Foundation. http://www.gec.jp/water/data/water_29-4.html.

Sludge is fed onto the surface of the belt. Since the belt has meshes distributed over the length of the belt, free water contained in sludge drains through the belt. To increase efficiency of the process, a chicane is installed. The chicane is used for sludge overturn what makes water separation more efficient and, consequently, sludge dryer. At the last stage of the process sludge is slightly pressurized by a press strip. Once sludge passed through the machine, it is discharged for further treatment as concentrated sludge.

APPENDIX V. Comparison of material recovery possibilities.

Produced material	**Required elements**	**Unwanted elements**	**Properties of sludge used in reference material**	**Composition of sludge used in reference material**	**Maximum MC allowed, %**
Cement clinker	$Ca(CO)_3$; SiO_2; Al_2O_3; Iron. [1]	Alkaline metals.	DSC: 48.2 - 65.7%; AC: 43.5 - 66.0%; Heating value: 5.5 - 8.6 MJ/kg (on dry basis). [2]	Ash left composition: CaO – 29%; MgO – 2.5%; SO_3 – 0.5%; SiO_2 – 35%; Al_2O_3 – 32%; Fe_2O_3 – 1%. [2]	50% in wet production method. [3] 5-25% in dry production method.
Pozzolanic material	Kaolin [4]		Organic content – 32.34%; Calcite – 45.27%; Kaolinite – 13.67%. [5]	CaO – 25.43%; SiO_2 – 10.79%; Al_2O_3 – 6.82%; MgO – 0.86%; Fe_2O_3 – 0.46%; SO_3 – 0.33%; TiO_2 – 0.28%; Na_2O – 0.13%; K_2O_4 – 0.24%; P_2O_3 – 0.13%. [5]	The lower, the better, but whatever in solid shape is applicable.
Ceramic products		Alkaline metals.	MC: 68%; AC: 10%; Inorganic matter: 60%. [6]	SiO_2 – 26-30%; Al_2O_3 – 17-20%; CaO – 0.15-0.18%; MgO – 0.2-0.6%; Fe_2O_3 – 0.1-0.3%; TiO_2 – 0.05-0.1%. [7]	Could be 45-65%

continued on next page

Appendix V continued

Recovery in limekiln	$Ca(CO)_3$ [8	Alkaline metals, especially silicates and Na. [9	No experimental results found		Not more than 55% [9
Insulating material	Long fiber[10	High inorganic matter content	Not stated in the reference material		25% - 60% [10
Softboard	Long fiber	High inorganic matter content	Not stated in the reference material		
Hardboard	Long fiber	High inorganic matter content	Fiber: 66 w-%; Inorganic matter: 5.2 w-%; Secondary sludge: 27 w-%; pH – 6.8.	Not stated in the reference material	Sludge moisture should be around 40-55%
Cement mortar	Fiber as filling material for pores generation. Inorganic matter for strength properties		Not stated in the reference material		Sludge is mixed with other materials, so MC defines amount of water required for the process

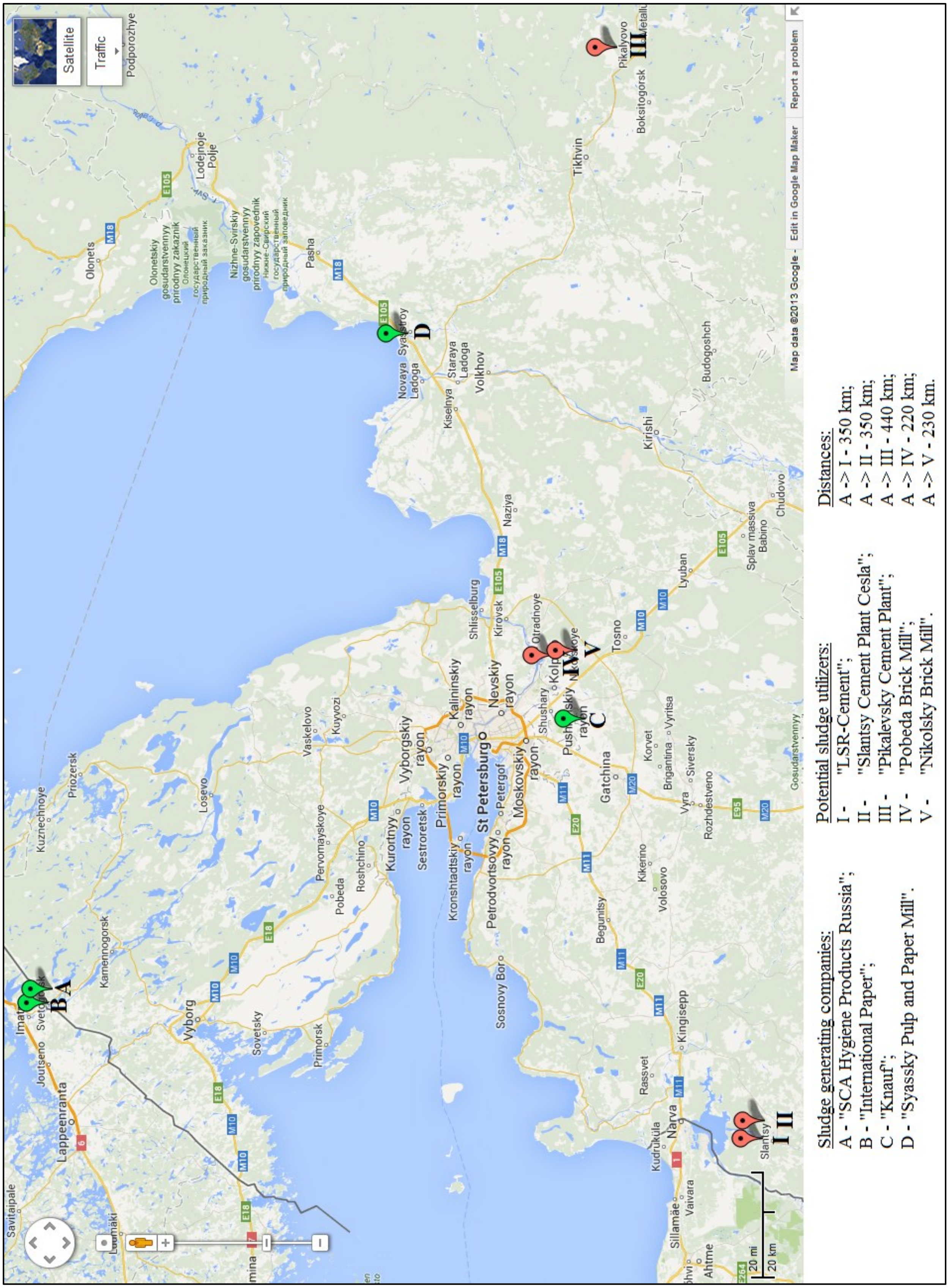
continued on next page

Appendix V continued

Light-weight aggregate	Mostly fiber as filling material for pores generation. Some inorganic matter for strength properties [(11]		MC: 75.5%; LOI: 70.11%; AC: 30%. [(11]	SiO_2 – 37.99% Al_2O_3 – 51.72%; Fe_2O_3 – 3.04%; CaO – 5.09%; MgO – 3.10%. [(11]	Sludge is mixed with other materials, so MC defines amount of water required for the process

(1 – taken from (European Commission, 2010);
(2 – taken from (Ernstbrunner & Fischau, 1993);
(3 – taken from (LenTehStroy, 2013a);
(4 – taken from (Hundebol, 1997);
(5 – taken from (Frias, et al., 2011);
(6 – taken from (Radovenchik, et al., 2010);
(7 – taken from (Treschev , et al., 2007);
(8 – taken from (Milovidova, et al., 2010);
(9 – taken from (Nepenin, 1990);
(10 – taken from (Cavaleri & Contu, 2011);
(11 – taken from (Liaw, et al., 1998).

APPENDIX VI. Map of the Leningrad Region.



APPENDIX VII. Calculation of flue gases.

Appendix VII. Table 1. Initial data for calculations.

Content of elements, weight-%	Deinking sludge*	Bark (Abubakr, et al., 1995)**
C	12.8	32.9
H	2.6	4.1
O	13.9	28.8
N	0.6	0.2
S	0	0.1
MC	47.7	31.5
AC	22.4	2.4
Total	100%	100%
LHV_{ar}, MJ/kg	1.82	9.13
* - content of elements in deinking sludge, except MC and AC, has not been determined, but assumed as average based on the data presented in Table 1. ** - content of elements for bark is initially given on dry basis, but was transformed on as received basis.		

The calculations of amounts of flue gases generated as a result of bark or DS incineration is based on the data presented in Appendix VII. Table 1. The results of calculations are shown in Appendix VII. Table 2 and Appendix VII. Table 3 for deinking sludge and bark respectively.

To generate the same amount of energy from deinking sludge and bark with heating values of 1.82 and 9.13 MJ/kg respectively, approximately 5 times more deinking sludge need to be burned. Thus, amount of flue gases generated from deinking sludge and bark combustion to generated equal amount of energy is 11.7 m^3 and 4.1 m^3 respectively.

Appendix VII. Table 2. Amount of flue gases generated from incineration of 1kg of deinking sludge.

Deinking sludge					Flue gas component				
Component	m, g	M, g/mol	N, mol	O2-demand, mol	CO2	SO2	H2O	N2	O2
C	128	12	10,67	10,67	10,67				
H2	26	2	12,80	6,40			12,80		
O2	139	32	4,35	-4,35					
N2	6	28	0,21					0,21	
S	0	32	0,00	0,00		0,00			
MC	477	18	26,50				26,50		
AC	224								
Sum	1000			12,71	10,67	0,00	39,30	0,21	
Combustion air (stoichiometric)									
N2 from comb air (N2=79/21*No2)								47,83	
H2O from comb air (Nh2o=R*(No2+Nn2))							0,60		
Excess air									
O2									1,27
N2								4,78	
H2O							0,06		
Sum					10,67	0,00	39,96	52,82	1,27

Flue gas component	N, mol	Vm, m3/kmol	V wet, m3	% (vol.)	V dry, m3	% (vol.)
CO2	10,67	22,26	0,24	10,1	0,24	16,4
O2	1,27	22,39	0,03	1,2	0,03	2,0
N2	52,82	22,4	1,18	50,5	1,18	81,7
SO2	0,00	21,98	0,00	0,0	0,00	0,0
H2O	39,96	22,4	0,90	38,2		
Sum			2,34	100 %	1,45	100 %

Appendix VII. Table 3. Amount of flue gases generated from incineration of 1kg of bark.

Bark					Flue gas component				
Component	m, g	M, g/mol	N, mol	O2-demand, mol	CO2	SO2	H2O	N2	O2
C	329	12	27,42	27,42	27,42				
H2	41	2	20,50	10,25			20,50		
O2	288	32	9,00	-9,00					
N2	2	28	0,07					0,07	
S	1	32	0,03	0,03		0,03			
H2O	315	18	17,50				17,50		
ash	24								
sum	1000			28,70	27,42	0,03	38,00	0,07	
Combustion air (stoichiometric)									
N2 from comb air (N2=79/21*No2)								107,96	
H2O from comb air (Nh2o=R*(No2+Nn2))							1,35		
Excess air									
O2									1,43
N2								5,40	
H2O							0,07		
Sum					27,42	0,03	39,42	113,43	1,43

Flue gas component	N, mol	Vm, m3/mol	V wet, m3	% (vol.)	V dry, m3	% (vol.)
CO2	27,42	22,26	0,6103	26,0	0,6103	42,1
O2	1,43	22,39	0,0321	1,4	0,0321	2,2
N2	113,43	22,4	2,5408	108,4	2,5408	175,3
SO2	0,03	21,98	0,0007	0,0	0,0007	0,0
H2O	39,42	22,4	0,8830	37,7		
Sum			4,0669	100 %	3,1839	100 %