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# Perspective Methods of Sewage Sludge Utilisation for Energy Production

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# PERSPECTIVE METHODS OF SEWAGE SLUDGE UTILISATION FOR ENERGY PRODUCTION

# PERSPEKTIVNÍ METODY ENERGETICKÉHO VYUŽITÍ ČISTÍRENSKÝCH KALŮ

SHORT VERSION OF PHD THESIS

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sewage sludge, advanced dewatering, sludge incineration, pollutants generation, disintegration of stabilized sludge

**Klíčová slova**

čistírenský kal, zlepšení odvodnitelnosti, spalování kalu, tvorba polutantů, dezintegrace stabilizovaného kalu

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# 1 INTRODUCTION

Sewage sludge is a versatile biofuel that is available in every urban area of the world. Due to its origin, the utilization in mono-combustion and co-firing, is subject to legal requirements regarding the incineration of waste, which sets more stringent requirements for the air emissions and treatment conditions. Furthermore, its constituent parts and fluctuating composition (ash content, chlorine, sulfur, heavy metals and water content) make sludge a complex biofuel that requires knowledge of its properties to identify bottlenecks and opportunities in its processing.

The processing of sewage sludge represents a relatively broad range of interests, towards which attention is devoted not only from the operators of wastewater treatment plants (WWTPs), but also by various research institutions. From the operators' point of view, one can name the effort to reduce the sludge production to a minimum and with it the reduction of expenses for sludge disposal or to increase the production of biogas from the WWTP and, with it, to reach the self-sufficiency on energy.

In research institutions, the material properties and the possibilities of its utilization are both investigated. One can find contributions on the rheological behavior of different types of sludges ([1], [2] and [3]), nutrient content utilized by crops ([4] and [5]), or contributions monitoring diverse pollutants contained in sludges ([6] and [7]). From the point of view of utilization, attention is paid to the possibilities of increased biogas production from anaerobic stabilization, the issue of sludge incineration and sludge drying respectively. One can find studies on the possibilities of phosphorous recovery from sludge, which can possibly be used for fertilizer production [8]. Moreover, attention is paid to improving the composting process and the production of so called fuel compost.

# 2 GOALS AND OWERVIEW OF THE THESIS

Although, during doctoral studies, attention was paid to several topics, which are related to the processing of sludge, this short version of the PhD thesis summarizes only two relatively independent research fields. The first is the issue of sludge incineration, where the focus is given to the pollutants in the sludge. Due to the components contained in sludge, the incineration products arising from the incineration are different compared to the emissions from the incineration of fossil fuel and knowledge is required for the design and rating of sludge incineration plants. Conducted experimental sludge incineration tests under addition of limestone aimed at evaluating the influence of alkali on the distribution of pollutants in the combustion products. The experiment was carried out in a fluidized bed reactor and the arising flue gas and ashes were analyzed. Sulfur dioxide is the component, for which the most distinctive change was expected. The components nitrous oxides, hydrogen halides and persistent organic pollutants were tracked additionally. Furthermore, attention was drawn to heavy metals.

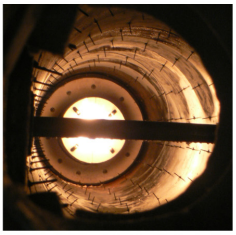
The second outstanding chapter in this work is the influence of sludge disintegration on its dewaterability. Currently, disintegration is primarily used to increase biogas production where the destruction of the microorganisms' cell walls makes the cell content available to fermentation bacteria. An obstacle for efficient sludge processing is the high water content ranging from 70 % to 84 % in dewatered sludge. The high water content affects the treatment costs and constrains the possibilities of waste to energy applications. For an efficient utilization, low water content is desired. From this reason, the possibility of using disintegration to increase the dewaterability of sludge was studied in laboratory scale and, based on the results, a operational scale unit was designed and its benefits in a possible application on a WWTP was assessed.

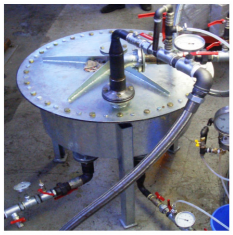
During the study period, next to those topics mentioned before, further studies and field experiments have been conducted (see Figure 1). The activities targeted at improving sludge processing for its subsequent utilization and comprised of:

- Rheological study of the flow behavior of different types of sludges [P1].
- Design and testing of an experimental heat exchanger for flue gas-sludge applications. Determined results of heat transfer and flow behavior have been compared with values from CFD-Analysis using experimentally determined material properties [P6].
- Operational scale dewatering experiments of aerobic stabilized sewage sludge. The experiments aimed at studying the impacts of flocculant consumption and centrifuge load on the quality of dewatered sludge and centrate [P19].
- Operational scale dewatering experiments of digested sewage sludge at different temperatures.
- Development and performance tests on a helical water-sludge heat exchanger for sludge heating. Based on the results of measurement, the calculation relations for calculation of heat transfer coefficient and pressure drop have been corrected [9].

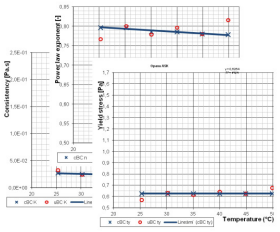
**Total Scope of Activities**

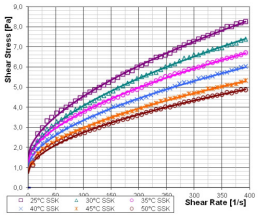
- Sludge heating
  Testing of heat exchanger for water-sludge and flue gas-sludge applications



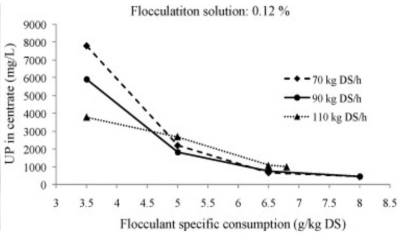


- Material properties of sludge
  Study of the rheological behaviour, density and heat capacity of sludge




- Dewatering tests
  Determination of impacts of flocculant consumption on sludge and centrate properties and impact of temperature on TS after dewatering




- Solar sludge drying
  Design of a experimental unit for experiments in the field of solar sludge drying

**Presented Scope of Activities**

- Sludge disintegration
  Outcome of thermal and thermo- chemical methods for improved dewatering

- Sludge incineration
  Influence of alkali addition into the incineration reactor on the emissions generation and distribution

**Figure 1** Scope of activities

# 3 EMISSIONS GENERATED BY SLUDGE INCINERATION

The generation of emissions from the incineration of dried sludge was evaluated, and the influence of alkali on the generated emission was investigated.

## 3.1 EXPERIMENTAL PROCEDURE

Dried digested sludge was incinerated in a bubbling fluidized bed reactor that is 93.6 mm in diameter and 980 mm in height. The experiments can be classified in long-term experiments (experiment 1 and 2), where fuel A and B was used, and short-term experiments (experiments 3 and 4), where fuel C was used. The influence of limestone was investigated in experiment 2 and 4. The long-term experiments 1 and 2 were conducted in order to provide sufficient sampling time for polychlorinated dibenzodioxins and dibenzofurans (PCDD/F) and persistent organic pollutants (POP) measurements, where the sampling time was 6 h. During measurements 1 and 2, hydrogen halides and heavy metals (HM) were also measured, where samplings took place three times. The short-term experiments 3 and 4 served for tracking the emissions of hydrogen halides and $SO_2$ by means of absorption (only one sampling) and continuous tracking of NO, $NO_2$, and $SO_2$.

## 3.2 RESULTS

The change in pollutants' emissions for each pollutant class is summarized in Figure 2. However, the change in pollutants' emissions requires careful consideration - the reduction of polychlorinated biphenyls (PCB) is determined from concentrations which are close to the limit of determination. Thus, the reduction cannot be taken for granted and is discussed in the following. The PCDD/F emissions are not listed as the concentration was below the limit of determination. The addition of limestone achieved the highest pollutants' reduction for sulfuric compounds, which could be reduced by 61 %. The downside of limestone addition is a higher production of nitrogen oxides, resulting in an increase of $NO_x$ emissions.

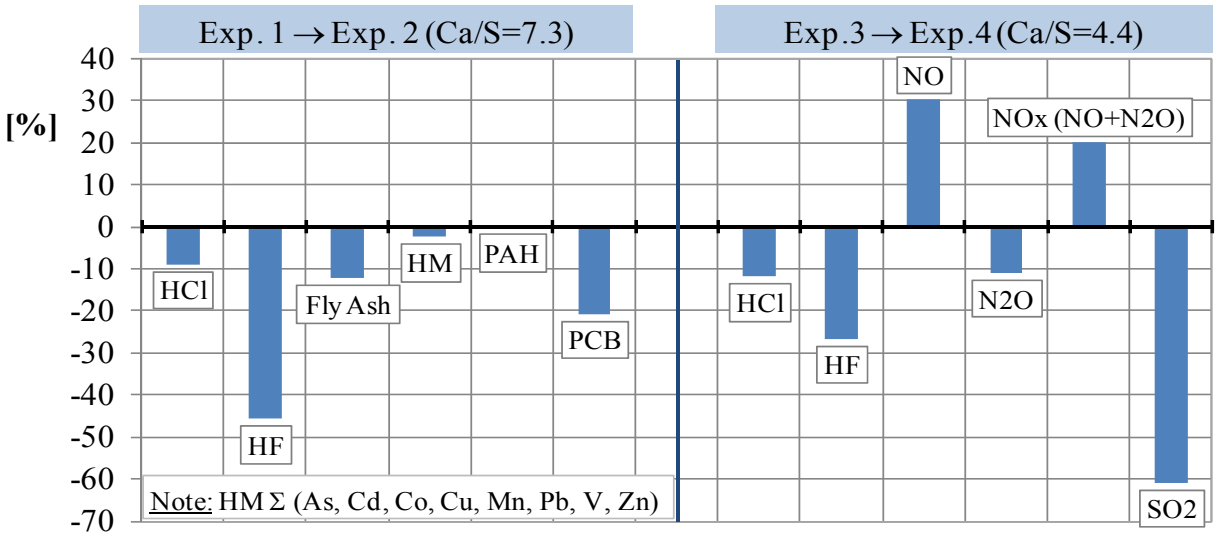



**Figure 2** Change of emissions in conducted experiments

### 3.2.1 Nitrogen Compounds

Sludge counts among biofuels containing high amount of nitrogen and produces emissions high in nitrogen oxide. The concentrations of NO and $N_2O$ in flue gas were measured within this work. The conversion of fuel-N to NO-N and $N_2O$-N results from the organic nitrogen content in fuel and depends on the composition of sludge ash serving as bed material.

The addition of limestone at an Ca/N ratio of 2.5 (Ca/S = 4.4) increased the fuel-N to NO-N conversion. In accomplished measurements, the conversion is relatively high and amounts to 10.3 % and 13.5 % where limestone was added. Limestone decreased the conversion of fuel-N to $N_2O$-N. For the incineration of sludge (exp. 3), 3.4 % of the fuel-N was converted to $N_2O$-N. Under addition of limestone (exp. 4), the conversion was amounted to 3.0 %.

### 3.2.2 Sulfur Dioxide

The amount of sulfur contained in fuel (1.39 waf.%) yields a calculated $SO_2$ concentration of 2656 $mg/m_N^3$ at 11 vol.% $O_2$ (for 100 % conversion). The measured concentration during sludge incineration (exp. 3) was considerably lower amounting to 1290 $mg/m_N^3$ at 11 vol.% $O_2$. This represents 49 % of sulfur contained in fuel. The low $SO_2$ yield in the flue gas is the result of CaO contained in sludge ash, which captures approximately 50 % of the sulfur contained in fuel. The Ca/S ratio, naturally given was 4.8. The addition of limestone in experiment 4 (Ca/S = 4.4 %) reduced the $SO_2$ concentration in flue gas to 460 $mg/m_N^3$ at 11 vol.% $O_2$, representing 19 % of sulfur contained in fuel. From the sulfur balance of experiment 3 and 4 follows, as a result of limestone addition, a $SO_2$ capture of 61 %.

### 3.2.3 Hydrogen Halides

The reaction of CaO with HCl is constrained by the temperature dependency of the equilibrium concentration [10]. For the capture of chlorine using limestone, the equilibrium concentration is higher than 1000 $mg/m^3$ at conditions in the fluidized bed (T = 860 °C). In experiments, a minor reduction of chlorine in the flue gas was observed. The capture of chlorine was independent from the limestone dosage and amounted to approximately 10 % during experiments. The capture is likely to take place downstream the head of the reactor, where the flue gas was at temperature between 510 and 230 °C.

The reduction of fluorine emissions goes along with the amount of limestone used in the particular experiment. Comparing experiment 1 and 2, (Ca/S: 7.3), the chlorine emissions were reduced by 45.8 %. For experiment 3 and 4 (Ca/S: 4.4), the reduction in fluorine amounted to 27 %.

### 3.2.4 Polychlorinated Dibenzodioxins and Dibenzofurans

Polychlorinated Dibenzodioxins and Dibenzofurans (Dioxins and furans) were not detected in conducted experiments. Thus, from the conducted experiments, the influence of limestone on the production of dioxins and furans cannot be judged. The upperbound concentrations suggest a PCDD/F concentration below 390 pg/$m_N^3$ representing a toxic equivalent (expressed as 2,3,7,8-TCDD) of 36 pg/$m_N^3$ (values at 11 vol.% $O_2$).

### 3.2.5 Polycyclic Aromatic Hydrocarbons

The sum of measured polyaromatic hydrocarbons (PAH) concentrations in flue gas amounts to 25.5 µg/$m_N^3$ at 11 vol.% $O_2$. The addition of limestone gave a concentration of 27 µg/$m_N^3$ at 11 vol.% $O_2$. The total production in both experiments is 180 µg PAH/kg of dry fuel. The addition of limestone did not influence the PAH emissions. This finding is supported by [11], where no influence could be determined in co-firing of sludge.

### 3.2.6 Polychlorinated Biphenyls

The PCB emissions from sludge incineration do not depend on the addition of limestone. The dominant PCBs in the flue gas stream are tri-PCB, tetra-PCB and hexa-PCB. The concentrations of PCB 156, which represents the only detected dioxin-like PCB, were considerable low amounting to approximately 2 ng/$m_N^3$ at 11 vol.% $O_2$. The sum of isomeric PCBs produced in the combustion experiments amounts to approximately 5.5 µg/kg dry fuel.

### 3.2.7 Fly Ash

Fly ash emission increased within the experiments due to attrition in the ash bed. The measured concentrations at 11 vol.% $O_2$ average 129 mg/$m_N^3$ in experiment 1 (no additive) and 108 mg/$m_N^3$ in experiment 2 (addition of limestone). The change in concentration is probably the result of the different fuel composition (ash and volatile fraction).

### 3.2.8 Heavy Metals

The major part of heavy metals was detected in the ash fraction. The minor part of HM contained in fuel is transferred into the flue gas. For the heavy metals As, Cd, Co, Cu, Mn, Pb, V and Zn, a consistent balancing was possible for the mass streams of the incineration process. The transfer of these HMs from the fuel into the flue gas averaged 2.5 %. The addition of limestone decreased the average yield of HM marginally to 2.4 %.

### 3.2.9 Legal Aspects

The incineration of sludge falls into the category of waste incineration, which is subject to stringent air emissions requirements, where the standard is set by legal regulations regarding the incineration of waste [12]. Experiments conducted on emissions generation aimed to identify bottlenecks and possibilities of emissions' reduction in sludge incineration. The addition of limestone influences the concentrations of $SO_2$ and HF positively (✔), for $NO_x$ negatively (✘) and the other emissions remain unchanged (-). For the evaluation of legal aspects, the air emissions concentrations determined in experiments are compared with legal requirements (see Table 1). It is obvious, that compliance with limit values cannot be reached and additional flue gas treatment is required to primarily reduce the concentration of $SO_2$, HCl, HF, heavy metals and dust.

**Table 1** Determined pollutants' concentrations and limit values

| | Limit Value | Sludge Incineration *Fuel A/C* | Alkali Addition *Fuel B/C+Limest.* | Effectiveness of Limestone |
|---|---|---|---|---|
| Carbon monoxide [$mg/m_N^3$] | 50 | 9.2 | 8.2 | - |
| Dioxins and Furans [$ng/m_N^3$] | 0.1 | < 0.036 | < 0.028 | - |
| Heavy metals Σ (As, Co, Cr, Cu, Mn, Ni, Pb, Sb, V) [$\mu g/m_N^3$] | 500 | 1867 ♦ | 1769 ♦ | - |
| Heavy metals Σ (Cd, Tl) [$\mu g/m_N^3$] | 50 | 5.5 ♣ | 4.7 ♣ | - |
| HCl [$mg/m_N^3$] | 10 | 80 | 72 | - |
| HF [$mg/m_N^3$] | 1 | 17.1 | 8.4 | ✔ |
| $NO_x$ expressed as $NO_2$ [$mg/m_N^3$] | 200 | 2894 ♠ | 3103 ♠ | ✘ |
| $SO_2$ [$mg/m_N^3$] | 50 | 1290 | 460 | ✔ |
| Total dust [$mg/m_N^3$] | 10 | 129 | 108 | - |

Note: Concentrations are given at normal conditions and 11 vol.% oxygen in dry exhaust gas
♦ Comprising of As, Co, Cu, Mn, Pb, V, Zn ♣ Comprising of Cd ♠ Including $N_2O$

# 4 SLUDGE DISINTEGRATION

Currently, disintegration methods are applied to increase the biogas production in fermentation or in case of operational problems (floating and bulking sludge). In order to increase biogas production, waste activated sludge is disintegrated. Here, mainly mechanical disintegration methods e.g. ball mill, ultrasound and lysate-thickening centrifuge are used.

Disintegration of stabilized sludge before dewatering influences the dewaterability of sludge ([13] and [14]). Here, during disintegration the sludge flakes are disrupted and bound water becomes available for gravitational means of dewatering. The increase in total solids (TS) concentration in dewatered sludge goes along with the reduction of water contained in dewatered sludge. This reduces the total amount of sludge for disposal and increases the possibilities of sludge utilization in waste to energy as less water needs to be evaporated by drying or during incineration.

For the design of a suitable disintegration process for improved dewatering, experiments were conducted. The experiments were aimed at collecting data for process design and the evaluation of impacts on the centrate after dewatering.

## 4.1 METHODS AND MATERIALS USED FOR EXPERIMENTS

The impact of thermo-chemical treatment of sludge on its dewaterability was assessed in laboratory measurements. For this purpose, a laboratory-scale disintegration unit was designed and used in experimental work (see Figure 3). The disintegration unit is built as a double jacket vessel designed to operate under pressure or atmospheric conditions and can hold up to 2.7 L of sludge. The admissible pressure is 1 MPa at an operating temperature of 180 °C.

**Figure 3** Disintegration unit used in experiments

## 4.2 INFLUENCE OF THERMO-CHEMICAL DISINTEGRATION ON WWTP OPERATION

In experiments, NaOH was used as an agent in thermo-chemical treatment. The treatment conditions were selected 110 °C for 30 min at 0.5 MPa. Based on indicative measurements, the NaOH amount was adjusted to 100 g/kg of sludge solids and the polymer flocculant Ciba ZETAG 8185 was used in dewatering experiments. The flocculant dosage for untreated samples amounted to 6 g/kg sludge solids. For disintegrated samples, a higher flocculent dosage was selected (8 g/kg sludge solids).

### 4.2.1 Attainable Total Solid Concentration under Operational Conditions

The experimentally determined total solid concentration using a beaker centrifuge is considerably lower in comparison with TS concentration attained in operational-scale using a dewatering centrifuge or filter press. Transferring experimentally determined results to operational-scale was subject to research summarized in [15] and [16]. The lab-scale dewatering conditions for this work were chosen 1000×g for 5 min. For these conditions, the dependency of operational results on experimental results is given by Equation (4-1) [16].

$$TS_{op-scale} = 2.35 \cdot TS_{lab-scale} + 1.49 \qquad (4\text{-}1)$$

where $TS_{op\text{-}scale}$ = total solid concentration attained under operational conditions [%]
$TS_{lab\text{-}scale}$ = total solid concentration attained under laboratory conditions [%]

### 4.2.2 Sludge Dewaterability and Centrate Composition

The total solid concentration of digested liquid sludge used in experiments amounted to 3.1 %. The results of total solids after dewatering in lab-scale, and in operational-scale are given in Table 2. The dewatering tests, conducted at 1000×g over a period of 5 min, suggest an increase by seven percentage points in operational-scale. This corresponds to a reduction of 25 % for the disposal of dewatered sludge.

**Table 2** Total solid concentration of thermo-chemically treated sludge

| | TS IN LAB-SCALE ♦ *[%]* | TS IN OPERATIONAL-SCALE ♣ *[%]* |
|---|---|---|
| Untreated sludge cake | 8.3 | 21.0 |
| Treated sludge cake | 11.3 | 28.1 |

♦ Average of three samplings; ♣ Proposed by Equation (4-1)

The centrate properties were determined in an accredited laboratory. The protocol of measurement is listed in [17]. The amount of total solids in centrate ranged between 1540 mg/kg in untreated, and 9850 mg/kg in treated sample. For treated

samples, the chemical oxygen demand (COD) was in the range of 9000 mg/l. The COD in the untreated sludge amounted to 1500 mg/l, which corresponds to operational data given in [18]. Sludge disintegration has minor influence on the ammonium concentrations in centrate. The concentrations determined in experiments amount to 1062 mg/l in treated, and 1031 mg/l in untreated centrate.

**Table 3** Centrate properties of thermo-chemically treated sludge

| | UNTREATED SLUDGE | TREATED SLUDGE |
|---|---|---|
| $COD_{Cr}$ [mg/l] | 1500 | 8700 |
| Undissolved solids [mg/l] | 330 | 3720 |
| Total solids [mg/kg] | 1540 | 9850 |
| pH [-] | 8.0 | 9.2 |
| $NH_4$ [mg/l] | 1031 | 1062 |
| $NO_3$ [mg/l] | < 0.20 | 1.58 |
| $NO_2$ [mg/l] | 0.13 | 1.09 |
| Total nitrogen [mg/l] | 844 | 1319 |

### 4.2.3 Additional Load on the WWTP

Dewatering of disintegrated sludge causes a higher pollution in centrate. Treatment of this water is accomplished in the biological treatment stage of the wastewater treatment plant. The additional oxygen demand depends on the concentration of carbonaceous organic pollutants and the nitrogenous compounds ($NH_4^+$ and $NO_3^-$) in the centrate. The oxygen consumption is calculated from the pollutants' reductions ($S_0$-S) given in Table 4, where the outflow concentrations (S)of the biological treatment stage were selected according to operational data [18] and the biological oxygen demand ($BOD_5$) is determined from the measured COD, where the $BOD_5$/COD ratio was 0.5.

**Table 4** Pollution reduction ($S_0$-S) used in the calculation of oxygen requirement

| | UNTREATED CENTRATE | TREATED CENTRATE |
|---|---|---|
| $BOD_5$ [mg/l] | 745 | 4345 |
| $N\text{-}NH_4^+$ [mg/l] | 796 | 821 |
| $N\text{-}NO_3^-$ [mg/l] | -11.2 | -10.8 |
| $N\text{-}NO_2^-$ [mg/l] | -0.5 | -0.2 |

The total oxygen consumption amounts to 1.72 g/l for untreated, and 4.57 g/l for treated centrate (see Table 5).

The consumption of electricity for the supply of air into the aeration tanks is influenced by the aeration efficiency (AE), which is defined as the ratio of the oxygen amount and the input power of the aerator and includes losses by transmission and frequency converter. The AE used in this work amounts 1.23 kg $O_2$/kWh and was evaluated for an existing WWTP with a capacity higher than 1,000,000 PE. The calculated values are given in Table 5.

The additional energy consumption for the treatment of centrate in the biological treatment stage is given by the difference of the specific energy consumptions of treated and untreated centrate and amounts to 2309 Wh/m³.

**Table 5** Oxygen consumption of centrate in the aeration process

| | UNTREATED CENTRATE | TREATED CENTRATE |
|---|---|---|
| Total oxygen consumption [g/l] | 1.72 | 4.57 |
| Electricity consumption [Wh/m$^3$] | 1406 | 3715 |

## 4.3 DISINTEGRATION PROCESS FOR ENHANCED DEWATERING

In order to improve dewatering, disintegration is integrated between digestion and dewatering unit as shown in Figure 4.

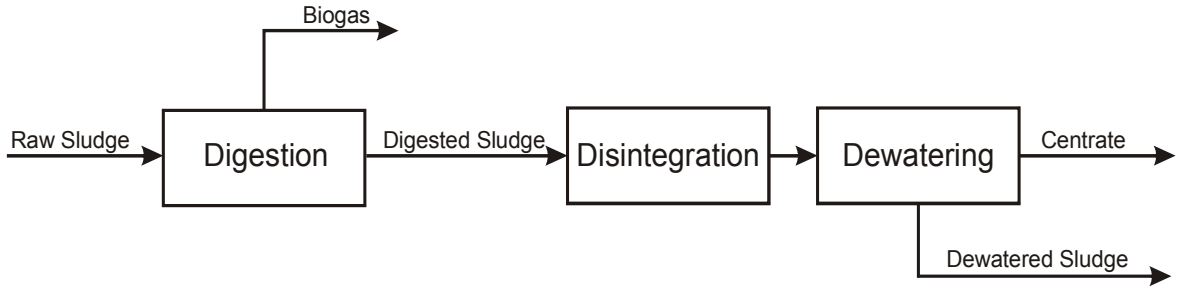



**Figure 4** Flow diagram of sludge management for enhanced dewatering

The considered process of thermo-chemical disintegration is rated for a liquid sludge amount of 10.8 t/d containing 4 % of solids. The resulting amount of total solids (432 kg/d) refers to a WWTP capacity of 10,000 PE.

The disintegration process, as shown in Figure 5, is operated continuously and consists of the disintegration unit and a heat exchanger which recovers heat from the hot sludge, and thus raises the temperature of cold sludge from 10 to 50 °C. Further increase in temperature is accomplished in the disintegration unit. Prior to leaving the system, disintegrated sludge is recooled in the heat recovery.

For operational use of thermo-chemical disintegration, liquid agent is used to ease its handling. The considered specific dosage of NaOH 50% into the sludge corresponds to the concentrations used in conducted experiments (described in Section 4.2) and amounts to 0.2 kg/kg TS. The temperature level for disintegration is selected according to conducted experiments (described in Section 4.2).

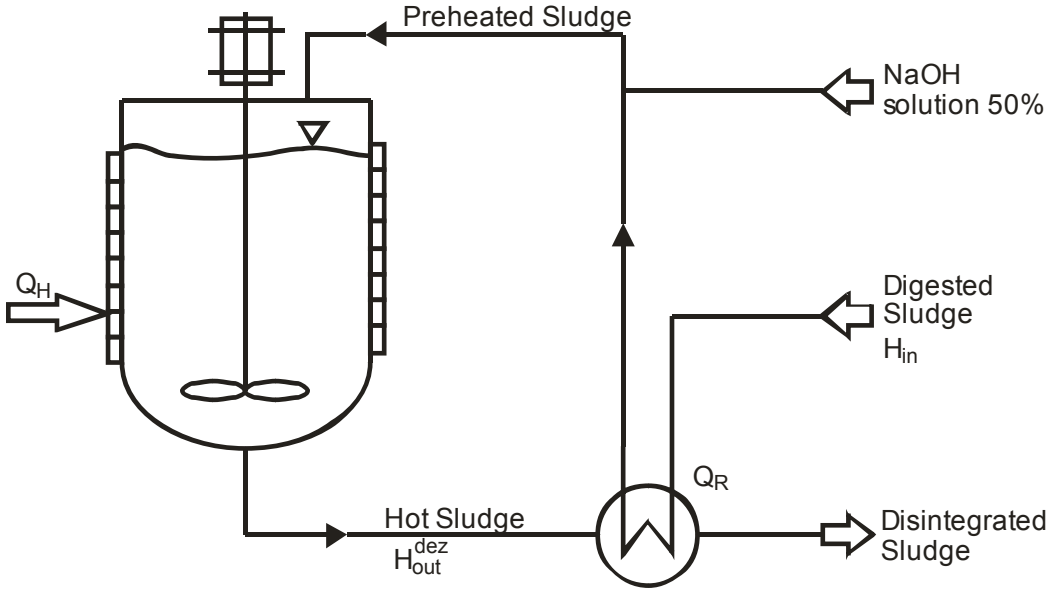



**Figure 5** Flow diagram of disintegration process

### 4.3.1 Heat and Mass Balance

The flow rates after disintegration and conventional treatment is shown in Table 6. According to disintegration measurements (described in Section 4.2.1), an increase in solid concentration in the dewatered sludge from 21.0 % to 28.0 % can be expected. The amount of dewatered sludge decreases by 25 % and the amount of centrate increases by 6 %.

**Table 6** Mass streams in sludge handling process

| | CONVENTIONAL | DISINTEGRATION |
|---|---|---|
| ***inlet*** | | |
| Digested sludge [kg/d] | 10 800 | |
| Total sludge solids [kg/d] | 432 | |
| NaOH solution 50 % [kg/d] | - | 86.4 |
| ***outlet*** | | |
| TS in dewatered sludge [%] | 21.0 | 28.0 |
| Dewatered sludge [kg/d] | 2057 | 1543 |
| Centrate [kg/d] | 8743 | 9257 |

In terms of heat balance, the disintegration unit (Figure 5) can be described as shown in Equation (4-2).

$$H_{out}^{dez} = Q_H + H_{in} + Q_R \quad [J] \qquad (4\text{-}2)$$

where $H_{in}$ = enthalpy of digested sludge [J]
$Q_R$ = recovered heat in heat exchanger [J]
$Q_H$ = required additional heat supplied by heat transfer medium [J]
$H_{out}^{dez}$ = enthalpy of hot sludge [J]

The heat exchanger recovers a daily heat amount of 1.74 GJ from the hot sludge leaving the disintegration unit and reduces the amount of required heat to 2.66 GJ/d. Table 7 summarizes the heat streams and temperatures.

**Table 7** Heat fluxes and temperatures in disintegration process

| | HEAT FLUX *[MJ/d]* | STREAM TEMPERATURE *[°C]* |
|---|---|---|
| Digested sludge $H_{in}$ | 440 | 10 |
| Required additional heat $Q_H$ | 2658 | - |
| Recovered heat in heat exchanger $Q_R$ | 1737 | - |
| Hot sludge $H_{out, dez}$ | 4835 | 110 |
| Preheated sludge | - | 49.5 |
| Disintegrated sludge | - | 70.5 |

For sludge digestion, waste heat from the incineration of biogas can be supplied to the disintegration process. With respect to the amount of available waste heat from biogas utilization, the heat demand of the disintegration process ($Q_H$) is covered by internal sources or has to be acquired in the form of natural gas.

### 4.3.2 Economical Evaluation

The major part of sludge, produced in the Czech Republic is disposed of in agriculture and composting. As a result, the costs for disposal are relatively low and range from approximately 450 to 600 CZK/t. For the following economical evaluation, the costs are assumed 500 CZK/t.

Capital costs for the disintegration unit account for approximately 1085 thousand CZK and include a stirred pressure vessel, heat exchanger, burner for the heat transfer medium, dosage system for the chemical agent, project engineering and expenses for construction. The costs for the disintegration vessel and heat exchanger are determined based on the material costs of used steel. The material costs for the used agents remain unconsidered in this evaluation as the application allows to use a suitable chemical agent of low purity at low cost.

The produced centrate has an adverse influence on the cost-effectiveness of the process as it requires more oxygen for its cleaning in the aeration process (discussed in Section 4.2.3). The resulting increase in electricity consumption depends on the amount of produced centrate and amounts to 21.85 kWh/d for a TS increase from 21 to 28 % after dewatering. Additional electricity consumption is caused by the stirring of the disintegration unit and summarized in Table 8.

**Table 8** Additional electricity consumption caused by disintegration

| | |
|---|---|
| Vessel mixer [kWh/d] | 3.1 |
| Additional blower consumption [kW/m³ of centrate] | 2.3 |
| Electricity costs [CZK/kWh] | 2.5 |

For TS concentrations determined in experiments, the payback period amounts to at least 15 y (in case the heat demand of the disintegration process is completely covered by waste heat) and probably exceeds the lifetime of the equipment. The payback period depends highly on the amount of acquired heat. For covering 5 % of the required heat by natural gas, the payback period is prolonged to 20 y. As shown in Figure 6, where the plumb line marks the TS concentration obtained from experiments for a increase in TS concentration from 21 to 28 %.

Analyzing the types of costs and savings (capital costs, electricity costs and savings from sludge disposal) shows that the capital costs highly influence the economy of the process. For a final TS concentrations of 28 % and covering the heat demand by waste heat, the daily capital costs are a fourfold of the costs for electricity and thus strongly influence the payback period (see Figure 7).

Due to the long payback period, the influence of increasing sludge disposal costs should be taken into account. During recent years, the fee for landfilling of sludge has risen by 5 %/y. Thus, the price adjustment for sludge disposal by the private sector can be expected to be in the same magnitude. For a 5 % p.a. increase in disposal costs, and TS increase from 21 to 28 %, the payback period will be reduced by 4 y and amounts to 11 y - see Figure 8, where the plumb lines mark the operation period after which the savings cover the total expenses.

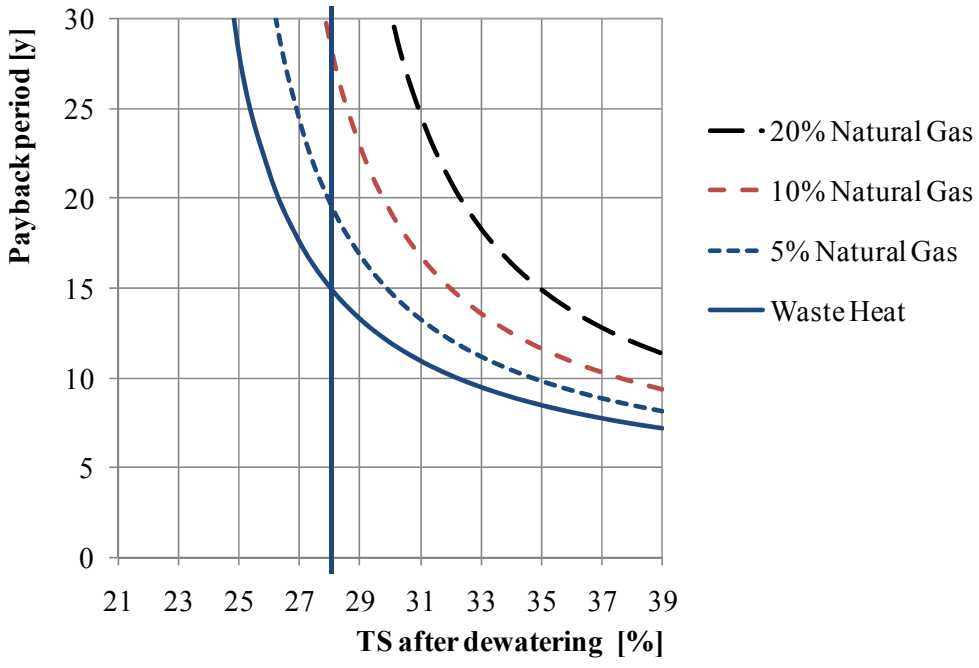



**Figure 6** Payback period depending on attained TS and amount of acquired heat

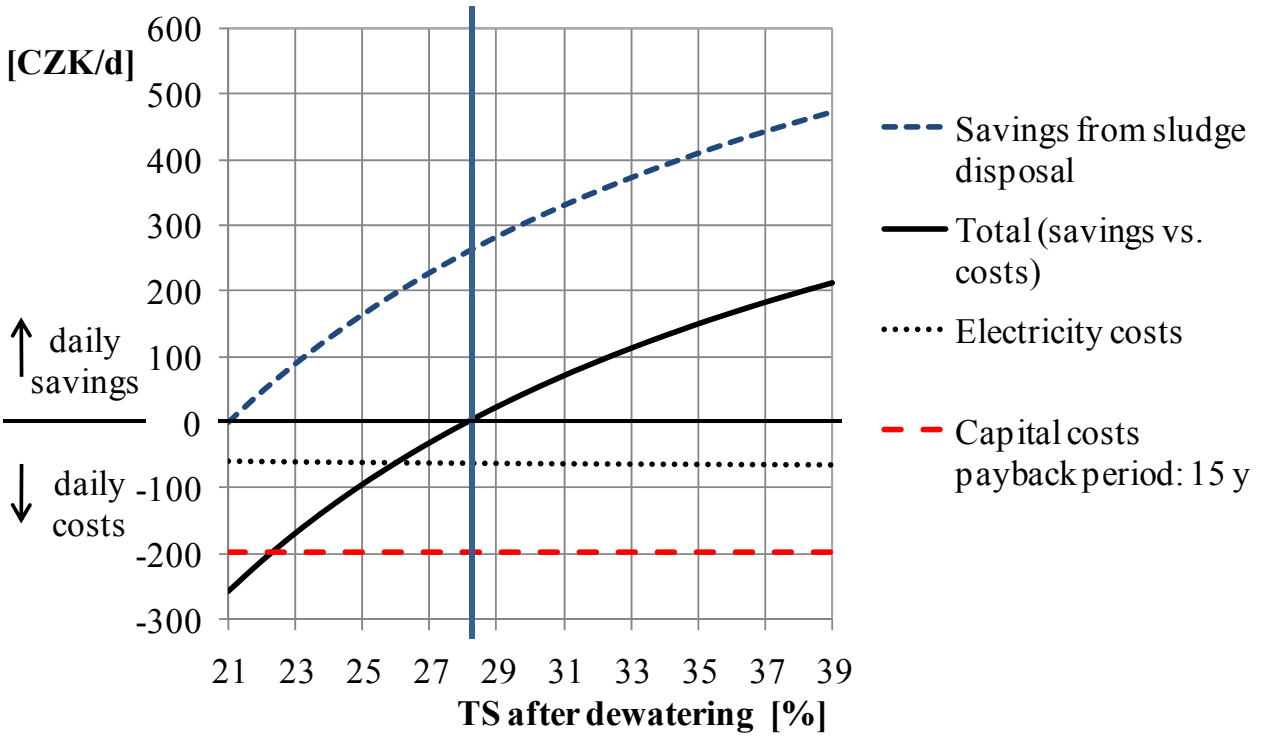



**Figure 7** Daily costs and savings of disintegration for a 15 y payback period

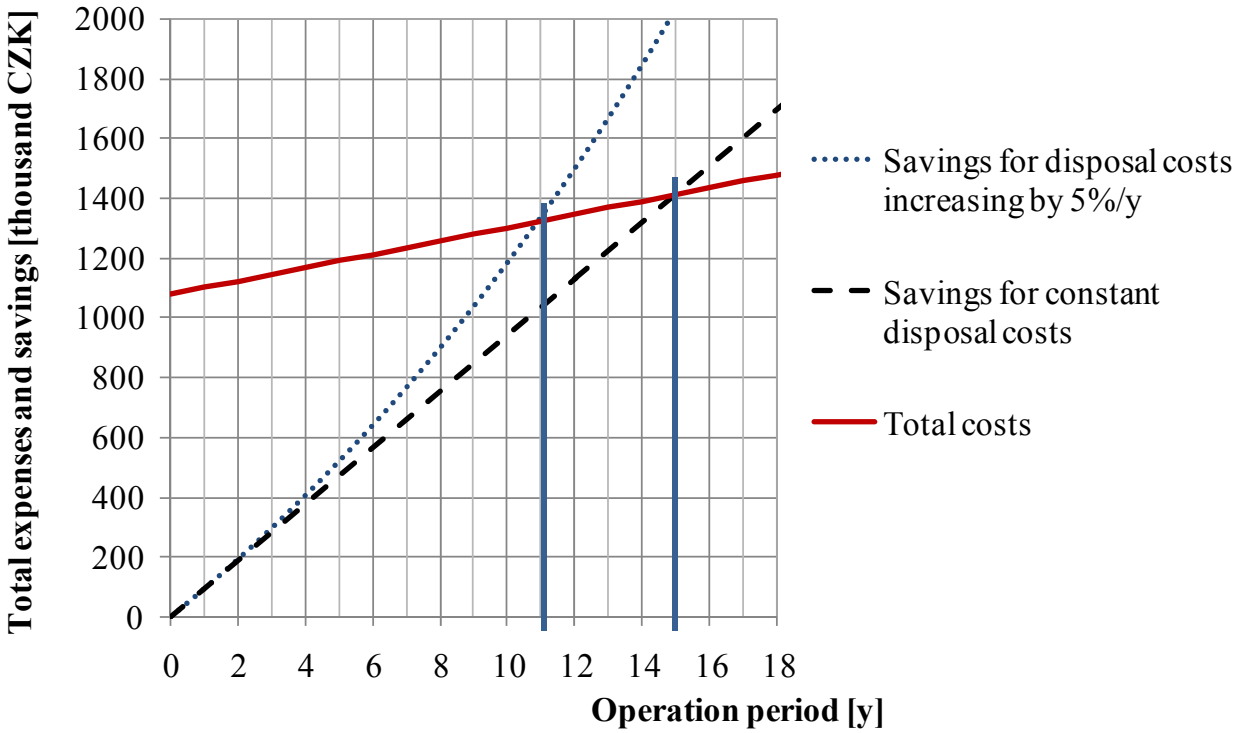



**Figure 8** Total expenses and savings for constant and increasing disposal costs

### 4.3.3 Discussion

Disintegration of digested sludge offers a convenient way of improving sludge dewaterability, and thus reducing its disposal costs. However, the costs (especially the capital costs) strongly impair its economy and the payback over the lifetime cannot be taken for granted.

The efforts undertaken for sludge disintegration should not only be seen as the reduction of waste for disposal, but also as an improvement of sludge quality. Thermo-chemical disintegration use similar process parameters as required for the sanitation of sewage sludges generated in the processing of animal by-products not intended for human consumption (e.g. from slaughterhouses). Here, the suggested disintegration process could provide a capable method to produce a harmless material fulfilling corresponding legal requirements. Moreover, the reduction of the water contained in dewatered sludge improves the possibilities of sludge utilization in incineration.

# 5 CONCLUSION

The incineration of sludge in waste to energy applications falls into the stringent legal frame of waste incineration and their operation is constrained by the low calorific value of sludge and contaminants contained in sludge solids. For the improvement of sludge incineration processes, knowledge of sludge properties, emissions generation and the possibilities of water reduction in the sludge is required. This short version of PhD thesis on the processing of sewage sludge in waste to energy applications is, devoted to sludge disintegration for improved dewatering and the experimental study of emissions in fluidized bed incineration, where the influence of alkali addition is examined.

The energy production from the incineration of sludge solids is constrained by the material properties of sludge – mainly the high water content, which usually ranges between 70 and 84 % after dewatering. As a means of reducing the water content, thermo-chemical disintegration of stabilized sewage sludge before dewatering is considered within this thesis. For this process, the outcome is a reduction of the water content in sludge and a higher pollution concentration in the centrate. Experiments conducted on a laboratory scale suggest a reduction in the water content from 79 % to 72 % after dewatering. The comparison of costs (costs for additional centrate treatment and capital costs for the disintegration unit) with the savings from the reduction of sludge disposal costs result in a long payback period, which probably exceeds the lifetime of the equipment. However, sludge which underlies legal requirements of sludge sanitation can be treated appropriately using the disintegration process considered in this thesis. Furthermore, the water content is reduced and the possibility of its utilization in incineration is improved. Testing the dewaterability of sludge for further agents, as for example salts, in thermo-chemical disintegration, can widen the possible range of suitable agents. Investigating the influence of further agents, which are favorably waste or by-products from

production or other processes, can reveal the influence of the agent's oxidation state, treatment temperature, retention time and pressure on the dewaterability of sludge.

In incineration, the contaminants of dried sludge result in air emissions exceeding the allowed limit values, making comprehensive flue gas treatment mandatory. Experiments were conducted in sludge incineration with the aim of determining the behavior of the gaseous pollutants generated and heavy metals contained in sludge, and the influence of limestone on the distribution of pollutants was also investigated. Using dried sludge (TS = 91.5 %), the experiments confirmed that the addition of limestone into the incineration reactor cannot replace the flue gas treatment. The addition of limestone reduced the emissions of $SO_2$ and HF and increased the $NO_x$ emissions. The utilization of semi-wet sludge (TS = 31 %) in incineration is in favor of reducing $NO_x$ emissions as reported by [19]. However, with respect to the experimental incineration apparatus, this could not be verified in own measurements as the apparatus is appropriate for dry fuel only. Using a mixture of semi-wet sludge and hydrated lime (as it is used in the treatment of dewatered sludge) can possibly limit the $NO_x$ emissions and reduce the emissions of acidic substances.

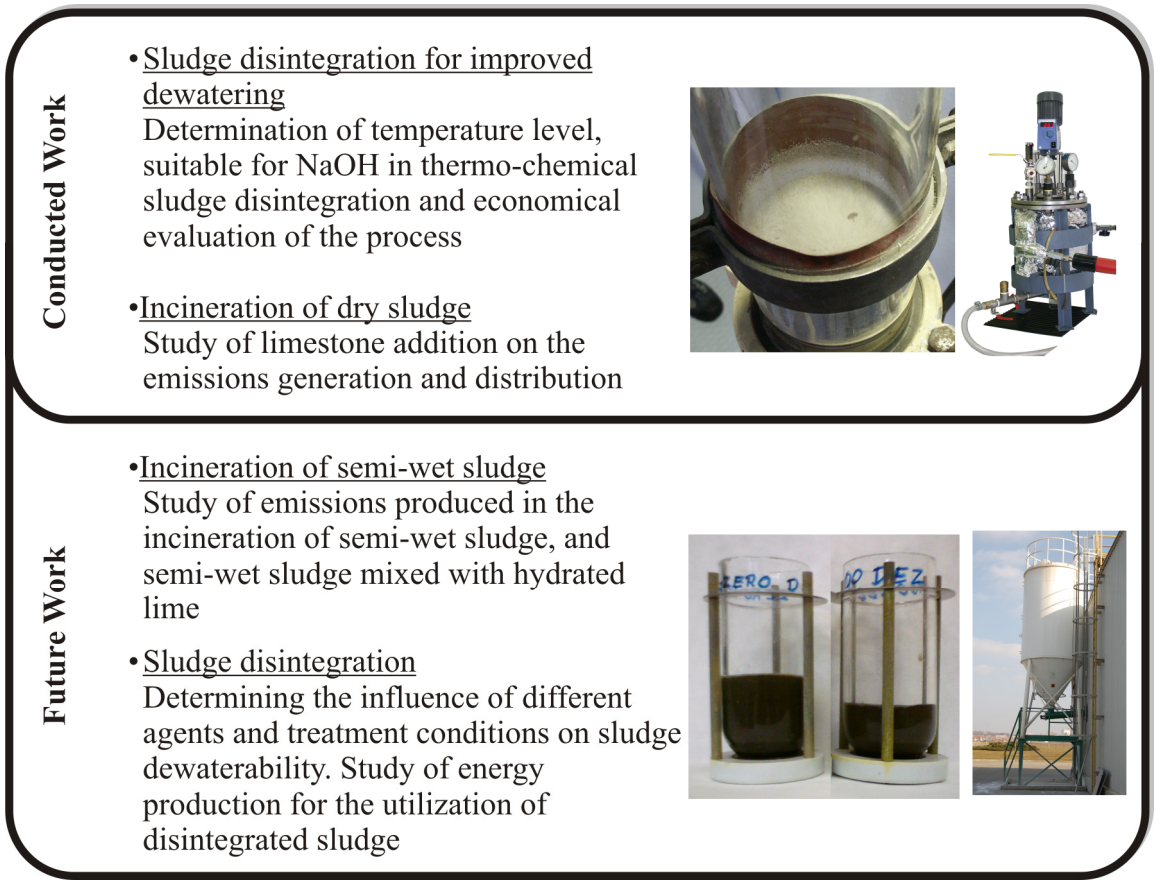



**Figure 9** Future activities

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# CURRICULUM VITAE


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## ABSTRACT

This short version of PhD thesis on the processing of sewage sludge in waste to energy applications is devoted to sludge disintegration for improved dewatering and the experimental study of emissions produced in incineration, where the influence of alkali addition was examined. The incineration of dried sludge was done in a fluidized bed reactor and the production of air emissions and distribution of heavy metals was studied. The thermo-chemical disintegration of stabilized sewage sludge, elaborated in the second main chapter, aims at reducing the water content of sludge after dewatering. Experiments conducted in laboratory-scale aimed at identifying a suitable temperature level and required dosage of chemical agent. In the following, a basic economical evaluation is described, where the savings are determined from savings in sludge disposal.

## ABSTRAKT

Tato zkrácená verze dizertační práce o energetickém využití čistírenských kalů je věnována desintegraci kalu vedoucí k zvýšení obsahu sušiny po odvodnění a experimentálnímu zkoumání tvorby emisí při spalování kalu, kde byl posuzován vliv přídavku alkálie. Spalování vysušeného kalu proběhlo ve fluidní vrstvě, byla zkoumána produkce škodlivin a distribuce těžkých kovů. Druhá ucelená část práce je věnována termochemické desintegraci stabilizovaného kalu, přičemž byl experimentálně vyhodnocován vliv na obsah vody v odvodněném kalu. Provedené experimenty sloužily k detekci vhodné teploty a dávky chemikálie. Výsledky experimentů byly rovně podkladem pro ekonomickou bilanci, která je založena na úsporách za likvidaci menšího množství kalu.