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ANALYSIS OF SLUDGE PRETREATMENTS FOR CONVENTIONAL ANAEROBIC DIGESTION WASTEWATER TREATMENT PLANTS

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This thesis is dedicated to my family and to my loving wife and best friend, Rachaël. Their endless love, support, and encouragement enabled me to tackle and accomplish this and the infinite tasks I habitually undertake. I am greatly indebted to Rachaël for the sacrifices she made in time and in energy to help me balance these undertakings in the two years of our union. I look forward and am privileged to pursue a life's worth of ambitious opportunities by her side.

NOMENCLATURE

AS	Activated Sludge
AD	Anaerobic Digestion
AMWD	Apparent Molecular Weight Distribution
BT	Biodegradibility Test (or Biotreatment in PretrAD)
BOD	Biochemical Oxygen Demand (kg/m^3)
BPT	Biogas Production Test
C_{pamb}	Heat Flow Coefficients for Ambient Air ($kJ \cdot m/m^2 \cdot d \cdot °C$)
C_{pfc}	Heat Flow Coefficients for Floating Cover ($kJ \cdot m/m^2 \cdot d \cdot °C$)
C_{psur}	Heat Flow Coefficients for Surface Material ($kJ \cdot m/m^2 \cdot d \cdot °C$)
C_p	Heat Transfer Coefficients for Sludge ($kJ/kg \cdot °C$)
CH_4	Methane
CH_{4Equiv}	Equivalent of Methane Per Volume of Biogas
CH	Conventional Heating
CHC	Controlled Hydrodynamic Cavitation
CM	Chemical
COD	Chemical Oxygen Demand (kg/m^3)
$COD_{MTADi,e}$	COD Influent or Effluent to the Anaerobic Digester (kg/m^3)
$COD_{MTADtoCH4}$	COD Exiting as CH_4 from the Anaerobic Digester (kg/m^3)
$COD_{MTADtoVSS}$	COD Exiting as VSS from the Anaerobic Digester (kg/m^3)
CST	Capillary Suction Time
DE	Dewatering
DS	Dissolved Solids
E_{EI}	Total Input Electrical Energy (kWh/d)
E_{EMI}	Input Electrical Mixing Energy (kWh/d)
E_{EPI}	Input Electrical Pumping Energy (kWh/d)
$E_{HL1,2}$	Electical Heating Energy Losses for SPT (1) and MTAD (2) (kWh/d)
$E_{HN1,2}$	Electical Heating Energy Needs for SPT (1) and MTAD (2) (kWh/d)
$E_{HR1,2}$	Electical Heating Energy Recovery for SPT (1) and MTAD (2) (kWh/d)
E_{spec}	Specific Energy ($kJ/kg \cdot °C$)
E_{sup}	Supplied Energy

EC	Energy Conversion
EP	Electricty Price ($/kWH)
F:M	Food to Microorganism Ratio (g BOD_5/d·g MLVSS)
FSR	Full-Scale Reactor
GSP	Grid Sell Price ($/kWh)
H_{bg}	Height of Anaerobic Digester Below Ground (m)
H_e	Height of Anaerobic Digester Exposed (m)
H_i	Height of Anaerobic Digester Insulated (m)
HPH	High Pressure Homogenizer
HRT	Hydraulic Residence Time
IE	Inhabitant Equivalents
JST	Jet Smash Technique
LC	Lysate Centrifuge
LSR	Lab-Scale Reactor
MAD	Mesophilic Anaerobic Digestion
MLTSS	Mixed Liquor Total Suspended Solids (kg/m^3)
MLVSS	Mixed Liquor Total Volatile Solids (kg/m^3)
MTAD	Mesophilic or Thermophilic Anaerobic Digestion
M_{TSS}	Mass of Total Suspended Solids (kg/d)
MWH	Microwave Heating
OR	Overflow Rate (m^3/m^2·d)
OZ	Ozone
P_c	Percent Capture (%)
P_d	Percent Dedicated Flow (%)
P_f	Percent Flow (%)
P_{HL}	Percent Heat Loss (%)
P_{hrae}	Percent Heat Recovered Application Efficiency (%)
P_r	Percent Removal (%)
PC	Primary Clarification or Sedimentation
PretrAD	Name for Constructed Model
PSR	Pilot-Scale Reactor

PS	Primary Sludge
PT	Preliminary Treatment
Q_{ab} or Q_{abc}	Flow (m^3/d, see Flow Nomenclature Legend)
$Q_{BTi,e}$	Biotreatment Flow (Influent, Effluent) (m^3/d)
$Q_{DEi,e}$	Dewaterer Flow (Influent, Effluent) (m^3/d)
Q_{DEr}	Dewaterer Recycle Flow (m^3/d)
$Q_{DEsludge}$	Dewaterer Sludge Cake Flow (m^3/d)
$Q_{DEPC,BT}$	Dewaterer Recycle Flow Directed to PC or BT (m^3/d)
Q_{ECi}	Energy Conversion Influent Flow (m^3/d)
Q_{ECCH4}	Energy Conversion Influent Methane Flow (m^3/d)
$Q_{MTADi,e}$	Anaerobic Digester Flow (Influent, Effluent) (m^3/d)
$Q_{MTADbio}$	Anaerobic Digester Biogas Flow (m^3/d)
$Q_{MTADPC,BT}$	Anaerobic Digester Supernatant Flow Directed to PC or BT (m^3/d)
$Q_{PCi,e,u}$	Primary Clarifier Flow (Influent, Effluent, Underflow) (m^3/d)
$Q_{PTi,e}$	Preliminary Treatment Flow (Influent, Effluent) (m^3/d)
$Q_{RFi,e}$	Raw Feed Flow (Influent, Effluent) (m^3/d)
$Q_{SCi,e,u}$	Secondary Clarifier Flow (Influent, Effluent, Underflow) (m^3/d)
Q_{SCw}	Secondary Clarifier WAS Flow (m^3/d)
Q_{SCr}/Q_{BTi}	Recycle Ratio
$Q_{SDi,e}$	Sludge Disposal (Influent, Effluent) (m^3/d)
$Q_{SPTi,e}$	Sludge Pretreatment Flow (Influent, Effluent) (m^3/d)
$Q_{SPTtreated}$	Portion of SPT Influent that is Treated (m^3/d)
$Q_{SPTuntreated}$	Portion of SPT Influent that is Untreated (m^3/d)
$Q_{THi,e}$	Thickener Flow (Influent, Effluent) (m^3/d)
$Q_{THPC,BT}$	Thickener Recycle Flow Directed tp PC or BT (m^3/d)
RF	Raw Feed
S_g	Specific Gravity (unitless)
SC	Secondary Clarification or Sedimentation
SBM	Stirred Ball Mill
SD	Sludge Disposal
SGH	Shear Gap Homogenizer

SPT	Sludge Pre-treatment
SRT	Sludge Retention Time
SVI	Sludge Volume Index (mL/g)
$T°_{RFi}$	Temperature of Raw Feed Influent (°C)
$T°_{i1,2,3}$	Temperature Influent to SPT (1), MTAD (2), and DE (3) (°C)
$T°_{e1,2,3}$	Temperature Effluent to SPT (1), MTAD (2), and DE (3) (°C)
T,p,s,BOD_5	Total, Particulate or Soluble 5-d Biochemical Oxygen Demand (kg/m^3)
T,p,s,COD	Total, Particulate or Soluble Chemical Oxygen Demand (kg/m^3)
TAD	Thermophilic Anaerobic Digestion
TH	Thickening
TC	Thermochemical
TS	Total Solids
TSSi,e	Total Suspended Solids (Influent, Effluent) (kg/m^3)
TWAS	Thickened Waste Activated Sludge
UD,SD	Subscripts referring to User, Supplier Data for Pumping and Mixing
UDV	User Defined Value
ULT	Ultrasound
V_{BT}	Volume of the Biotreatment Unit (m^3)
V_{MTAD}	Volume of the Anaerobic Digester (m^3)
$V_{MTADbio}$	Volume Occupied by 1 Mole of Biogas (m^3)
VFA	Volatile Fatty Acids
VS	Volatile Solids
VSS	Volatile Suspended Solids (kg/m^3)
WAS	Waste Activated Sludge
WW	Wastewater
WWTP	Wastewater Treatment Plant
X	Concentration Variable for COD, BOD_5, and TSS (kg/m^3)
Y_{net}	Biomass Net Yield (kg TSS/kg BOD_5)
ρ	Density (kg/m^3)
ρ_w	Density of Water (kg/m^3)
θ_x, SRT	Solids Retention Time (d)

θ_d, HRT	Hydraulic Retention Time (d)

Flow Nomenclature Legend

"Q_{ab}" or "Q_{abc}"	a – Process Step	b – Stream or Direction
Example - Q_{PTi}	Preliminary Treatment	Influent
Example – Q_{SCe}	Secondary Clarification	Effluent
Example - Q_{THPC}	THickening	Recycles to Primary Clarification
Example - Q_{PCSPT}	Primary Clarification	Directed to Sludge Pretreatment
Example - $Q_{MTADuSPT}$	Anaerobic Digestion Underflow with SPT (**c - with SPT**)	

ABSTRACT

Pretreatment of primary sludge, waste activated sludge, and comingled sludges has become of substantial interest for the improvement of the rate limiting hydrolysis step during anaerobic digestion. As primary sludges are already easily degraded, waste activated sludges provide the most noticeable improvements in anaerobic digestion (AD) as a result of sludge pretreatment (SPT). A vast literature and theory review was conducted to establish high-potential treatment and result ranges. The average wastewater compositions for total chemical oxygen demand (COD) and total solids (TS) were 16-43 and 13-40 g/L, respectively. Sludge pretreatment percent solids solubilisation ranges for all common SPT technologies were 13-42% for both particulate COD and total suspended solids (TSS). Subsequent anaerobic digestion enhancement ranges were percent reductions in total COD and TS of 24-55 and 22-46%, respectively, as well as biogas production increases of 9-43%. The ranges shown here were fairly representative of those observed for all SPTs. Additional SPT technology information for full-scale design was also gathered.

A MS Excel spreadsheet wastewater treatment plant model (referred to herein as PretrAD) capable of comparing control and SPT incorporation scenarios was created. The PretrAD output was verified against a third party commercial model. PretrAD allows the user to input data on performance of all unit processes found in a typical biotreatment wastewater treatment plant (WWTP). Various return flow paths and other attributes of a WWTP can be specified and provide versatility and comprehensiveness. A database of typical performance data for all unit processes was compiled and used in PretrAD and for comparing performance of WWTPs with and without SPT.

The stirred ball mill, high pressure homogenizer, and ultrasound technologies were mechanical processes with sufficient comparable data for inclusion in PretrAD. Conventional heating and microwave heating technologies were included as thermal processes. Alkaline and ozone technologies were included as chemical processes. Finally, the common conventional heating + alkaline (thermochemical) technology was also included alongside a purely financial assessment of a proposed microwave heating + alkaline technology incorporation scenarios.

PretrAD was then used to evaluate treatment benefits by varying a number of performance parameters with and without SPT. Operating parameters that were changed were normal and low heat recoveries at the anaerobic digester, normal and doubled sludge disposal distances, low-peak influent flow regimes, and low to high SPT energy demands (evaluated with identical solubilisation results). Control and SPT scenarios were performed for all variables and both mesophilic and thermophilic AD.

Overall net WWTP treatment costs based on energy inputs and recoveries along with chemical inputs were compared for the various scenarios. It was found that an all average influent flow regime represented (within 5%) all annual flow regime combinations of low, average, and high flows and their associated quality variations. Following the basic comparisons of control and SPT scenarios, additional runs were conducted with increases of 25 and 50% for the energy demands of each SPT.

Mesophilic AD scenarios always had lower final costs than thermophilic AD scenarios under identical treatment parameters. Practical (cost-effective) and impractical (higher than control costs) scenarios were found for all SPTs except thermal and thermochemical processes. Thermal and thermochemical processes were always practical and always impractical, respectively, when compared to control scenarios using identical conditions. When different scenario conditions were compared, both thermal SPTs were deemed impractical when high cost results were compared to low cost results.

Solids loadings and heat recoveries were the most cost-influential variables of PretrAD. Other important qualitative results were not incorporated into the evaluation. They include but are not limited to dewatering improvements, pathogen reduction, anaerobic digester vessel size reduction, and hydraulic residence time reductions for the anaerobic digester. Inclusion of these parameters could render some SPTs practical for scenarios where they were deemed impractical on a pure cost of treatment basis. Furthermore, full-scale incorporation drawbacks such as additional unit costs, operation and maintenance demands, and actual throughput capacities could render some practical scenarios impractical.

The constructed PretrAD model has been proven effective for the rapid determination of treatment plant costs related to SPT incorporation. A tool such as this is vital for the site-specific analysis of SPT technologies.

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CHAPTER 1

Introduction

1.0 PROBLEM DEFINITION

Municipal wastewater treatment plants (WWTPs) using anaerobic digestion (AD) processes to treat primary and secondary/waste activated sludges (PS, WAS) are common-place. Advantages to AD use in place of aerobic digestion are well known and include waste conversion to methane, low nutrient needs, and no oxygen requirement. Production of methane, a valuable fuel, benefits sludge handling/disposal by solids reduction and energy demands by cogeneration. As populations grow and sludge land-use policies become more stringent WWTPs can experience difficulties performing within environmental and financial constraints.

Hydrolysis of organic matter is considered to be the rate-limiting step in WAS degradation. Sludge pretreatment (SPT) incorporation may thus be a suitable process upgrade for WWTPs experiencing disproportionately high sludge handling/disposal costs, treating wastes of low biodegradability, and/or generating minimal daily biogas. Sludge pretreatment processes include mechanical, thermal, chemical, biological treatments, and combinations of these. Their use further hydrolyses the sludge feed. Firstly, improved sludge digestibility in turn increases the rate of and overall biogas production (i.e., increased energy production). Secondly, residual solids which must be ultimately disposed in a landfill are reduced. Thirdly, a smaller AD vessel or treatment of additional comingled sludge may be possible due to the improvement in the AD rate. Sludge pretreatment does not render nondegradable solids degradable but only accelerates the rate at which degradable solids will be digested. Since there is potential to achieve identical treatment guidelines within a shorter AD residence time, there will be an optimal vessel size to maximize overall benefits.

These benefits must however, be weighed against a number of cost and/or energy inputs for the SPT. Operational and maintenance (O&M) costs of all SPTs likely include additional pumping, mixing, and/or chemical costs. The vessel requirement and energetic input for hydrolysis by each SPT type must also be considered. Since the efficacy of SPT tends to rise with the feed sludge solids concentration, various means and costs of concentrating the sludge must be evaluated.

A comprehensive analysis of all ramifications of SPT prior to and following AD is the goal of this thesis. The compilation of all available literature results for SPT working ranges and subsequent treatment improvements ranges was performed. The creation of a conventional WWTP model including optional SPT incorporation based in Microsoft Excel was deemed necessary to perform the proposed task. Though many variables affect SPT and AD performances and few full-scale results are available, a tool such as this could guide designers through comparison and/or demonstrate feasibility of SPT through environmental/financial impacts, all of which will be reported in US dollars.

1.1 RESEARCH OBJECTIVES AND SCOPE

The primary objective of this research was to assess the full-scale suitability of SPTs to conventional WWTPs using mesophilic or thermophilic AD (MTAD). Suitability of SPT incorporation was based on energy and financial demands for their use. More than 150 studies pertinent to this research were available and the creation of a model to efficiently analyse SPT using these results was immediately the most desirable approach.

Once the model (referred to herein as PretrAD) was complete, permutations of unit operations excluding SPT (i.e., control scenarios/results/costs/demands) were performed. These results were then compared to those obtained using identical feeds and treatment specifications in Plan-It STOAT (a third party commercial software package advertised as "A planning tool for rapid evaluation of wastewater treatment plant design and configuration options"). PretrAD performed satisfactorily and permutations including SPT (i.e., SPT scenarios/results/costs/demands) were initiated. Raw feed (RF) settings were varied to assess the impacts of low to peak flows and low to high solids loadings.

Scenarios with SPT incorporation were varied to compare low to high energy uses for individual SPTs and obtain overall suitability scenarios for them. PretrAD was built to provide key output tables and plots for the user. These and other comparative plots were generated for the purposes of this research.

1.2 THESIS ORGANIZATION

This study evaluated energy and financial impacts of SPT incorporation in conventional MTAD WWTPs to assess their full-scale suitability.

Chapter 2 is composed of a thorough summary of the literature gathered for this research. The focus is on SPT treatment settings as well as qualitative and quantitative control and SPT AD results. Full-scale facility results are given alongside an evaluation performed by the US EPA. Summary tables for WW compositions tested, SPT working and results ranges, and AD treatment improvement ranges were given for all SPTs. These ranges were applied to PretrAD for the evaluation of SPT incorporation.

Chapter 3 presents equipment theory for the conceptualization and actual full-scale design of SPTs where sufficient information was found. The approach to design equations provided in PretrAD for certain SPTs follows in the next Chapter.

Chapter 4 provides the model walkthrough, design, and equations. PretrAD is successfully compared to Plan-It STOAT for flow and solids handling validations.

Chapter 5 shows the control and SPT scenario results. Trends and working ranges are discussed. Optimal conditions and preferred processes are listed.

The final chapter of this research, Chapter 6, presents conclusions on the established results and recommendations are made for future runs and PretrAD improvements.

Appendix A contains the referenced low-high default values provided to the user in PretrAD. Appendix B contains the additional and necessary Plan-It STOAT design, explanations, and equations used for PretrAD validation. Appendix C contains a guide to all raw data and PretrAD output files that are available electronically.

CHAPTER 2

Literature Review and Full-Scale Facilities

2.0 INTRODUCTION

Anaerobic digestion (AD) has long been used for waste stabilization. The biodegradable matter in the waste is primarily converted to insoluble methane and carbon dioxide [20]. Methane is a useful end product that can be utilized for the WWTP or elsewhere as an energy source [20]. Reductions in sludge mass, no oxygen requirement, low nutrient requirements, and an improvement in dewatering properties are other main benefits of AD [4, 20]. Drawbacks to AD include sensitivity to shock loads and toxic materials [17]. A lengthy hydraulic residence time (HRT or θ) is also needed to complete the four stages of AD: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Conventional digesters, as shown in Fig. 2.1a, are typically operated at an HRT of 20-30 d to complete the degradation [17, 20]. Many layouts, such as an upflow anaerobic sludge blanket reactor, an anaerobic clarigester, a fluidized bed reactor, and an anaerobic contact digester are possible [20]. The latter is shown in Fig. 2.1b and provides a shorter HRT.

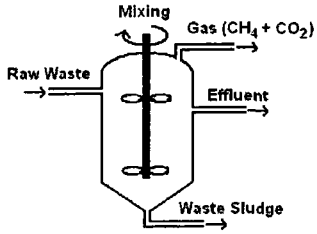


Figure 2.1a Conventional digester

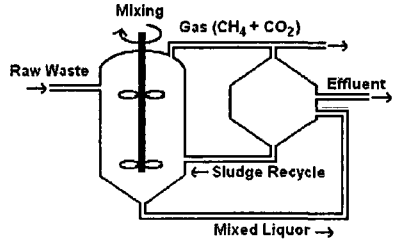


Figure 2.1b Anaerobic contact digester

A reduction in AD HRT can be achieved by selecting an optimal PS:WAS ratio, although this is difficult to achieve [20]. The HRT can also be reduced by operating under thermophilic conditions [thermophilic AD (TAD)] [20]. Average TAD temperature is 55°C compared to 35°C for mesophilic AD (MAD). Methane production is typically increased in TAD and the HRT is generally lower because intrinsic cell activities occur at an improved rate [20]. Lower energy requirements and a better process are however benefits to MAD [20]. For either operating condition (MTAD), organic matter hydrolysis

is identified as the rate-limiting stage in WAS degradation [1-4]. Sludge pretreatments can be utilized to ameliorate AD performance by lysing sludge cells and releasing extracellular and intracellular matter [2, 3]. This matter is now more accessible to the anaerobic microorganism consortium [1, 2]. Mechanical (grinding, pulverizing, and cavitation), thermal, chemical, biological, and combinations of these processes make up the five SPT categories. Under optimal conditions each process demonstrates a seemingly worthwhile improvement in solids reductions and rate of biogas production [1-20]. While dewaterability may be improved, methane content in the biogas is typically not improved [1-20].

In the papers reviewed herein, lab-scale reactors (LSRs) are responsible for almost all results obtained. Some pilot-scale reactor (PSR) studies were found. For both types it is often underlined that more extensive research is needed to ascertain the level of benefit that would be gained by applying the results under full-scale conditions [3, 9, 14]. Benefits such as increased methane production that can serve as an energy source and reduced power requirements can be negligible or nullified by drawbacks present in full-scale reactors (FSR) [3, 9, 14, 17]. Also losses in energy capture or delivery of energy captured are significant reductions associated with improved biogas yields. The goal of this thesis is to determine the likely full-scale observable benefits and drawbacks to many of the SPT processes.

General observations from LSR, PSR, and FSR facilities are made in the respective SPT sections below. They consist of particulate matter disintegration, digestion improvements, and common or atypical trends as observed by the authors. Following the mechanical, thermal, chemical, and thermochemical sections, a quantitative summary is provided and the data which were deemed to be sufficiently comparable for all SPT processes are tabulated. A qualitative results summary for all SPTs (those where sufficient studies were found) is given in Section 2.8. As will be shown, insufficient enzymatic SPT processes were available and a summary is not provided for the biological process section. Studies evaluating shear gap homogenization and lysate centrifugation were also insufficient and summaries are not given.

2.0 DATA COLLECTION

Three principal obstacles were responsible for the complexity of the data collection process. The first being that many of the studies were not conducted in a similar fashion. That is to say, sample volumes, treatment times, treatment inputs, AD parameters, and observed optimal scenarios differed. It certainly wasn't expected that all studies would have been performed with identical methods, but it was assumed that most would be performed with the intention of establishing SPT potential beyond a single lab-scale experiment. The second significant obstacle was that some studies, though thoroughly informative and having promising results, did not provide sufficient quantitative data (e.g., wastewater compositions and digestion parameters) to discern the working ranges. The third time-consuming obstacle was the effort required to discern treatment improvements based on graphical data and any unit conversions to those listed in the summary tables of Sections 2.2-6. An attempt was made to ascertain the actual (experimental) results from the at times difficult to interpret (published literature) results. This may, however, have lead to some minor discrepancies between values listed herein and those of the respective authors' work.

A Microsoft Excel Workbook was created to list all the conditions of each study. This was done under the assumption that sufficient comparative data were available. The literature data, however, were not as easily discernable or as analogous as necessary. It was thus almost immediately observed that direct comparisons could not be made and that only, where sufficient similar treatment inputs and subsequent improvements were found, could SPT working ranges be established. This meant that a formulaic analysis defining fixed digestion improvements based on specific hydrolysis results could not be made. Working ranges and potential improvements were however, gathered and subsequently incorporated into PretrAD's default values worksheet. The comparative evaluation (tabulated summaries) is shown in Sections 2.2-6 with each SPT having three tables. The first table describes the referenced (left-most column) WW composition and SPT input ranges. The second table describes the SPT result ranges and the subsequent AD improvement ranges.

Ratios for comingled PS and WAS are not given in the working ranges tables as they typically varied from 0:100 to 100:0 (PS:WAS) and no conclusive remarks could be made as to how they relate to SPT effects on subsequent AD improvements (e.g., solids reductions and enhanced biogas production). It has been shown however, that subjecting PS, which is already highly biodegradable) to SPT typically yields minimal (as compared to WAS) or no digestion improvements [5, 7]. It can thus be assumed that regardless of the PS:WAS ratio evaluated, the WAS fraction led to the most significant improvements in AD.

2.2 MECHANICAL PROCESSES

One of the benefits of mechanical processes is that chemicals are not required, thus reducing effluent sludge mass and costs [1]. Mechanical methods include stirred ball mills (SBMs), high pressure homogenizers (HPHs), ultrasound (ULT), shear gap homogenizers (SGHs), and lysate centrifuges (LCs).

Steel, ceramic or glass grinding beads can be used in SBMs where agitator discs, in a cylindrical chamber, create rotational movement that disrupts cell membranes by shear and pressure stresses. Drawbacks to this process include clogging and erosion in the chamber as well as friction losses [11, 21]. High pressure homogenization works by compressing sludge up to pressures of 90 MPa and subsequently directing the sludge through a homogenising valve [11, 21]. The surrounding pressure thus becomes lower than the vapour pressure of the sludge and the sludge's velocity increases significantly [11, 21]. The cell membranes in the sludge are disrupted by shear, turbulence, and cavitation stresses as the sludge collides against an impaction ring [11, 21]. Drawbacks to this process include minimal pathogenic reduction, clogging, and erosion in the pump and valve [11]. Ultrasonic homogenization provides hydrolysis by cavitation and localized heating and pressures. A sonotrode is immersed in the sample sludge and only relatively short contact times (1-25 min) are needed. Drawbacks to this process are energy demand and fouling. Shear gap homogenization is performed inside a stationary cylindrical casing in which a rotor spins at speeds up to 24,000 rpm [11, 22]. Cell membranes are disrupted

by shear stresses [11, 22]. Drawbacks to SGH include low sludge disintegration and erosion [11, 22].

2.2.1 Stirred Ball Mill

Kopp et al. (1997) studied the effects of mechanical disintegration on AD and dewaterability by means of a SBM, ultrasound, a HPH, and a SGH [22]. Their goals were to improve AD as well as reduce the amount of sludge to be disposed. They stated that sludge dewatering characteristics are affected by particle size distribution, presence of colloidal particles, surface charges, and volatile suspended solids (VSS) content. It was also stated that the application of mechanical SPT disrupts cell walls in minutes instead of days. Soluble chemical oxygen demand (sCOD) increased from 34 to 93% of total COD (TCOD) using HPH SPT for specific energy (E_{spec}) inputs of 1,000 to 9,000 kJ/kg suspended solids (SS), respectively. Energy stored divided by the unit mass describes E_{spec} and is shown in Equation 2.1. This E_{spec} evaluation can be performed for all mechanical SPTs and for MWH.

$$E_{spec} = \frac{(P \cdot t)}{(V \cdot TS_0)} \qquad 2.1$$

Where: P is power input, t is contact/exposure time, V is sample volume, and TS_0 is initial solids concentration

For a E_{spec} of 1,000 to 12,000 kJ/kg SS, SBM and SGH were capable of increasing COD solubilisation from 42 and 10%, respectively to 89 and 34%, respectively. Solubilisation of VSS was also monitored. Immobilized sludge was evaluated at 4 d MAD HRTs for SBM and HPH SPTs and compared to the control run (at 34%), they achieved 41 and 57.5% VSS solubilisation, respectively.

Sludge in suspension was also evaluated. Increasing the HRT from 4 to 15 d increased the VSS solubilisation from 22.5 to 52% and 27 to 54% for control and SBM runs, respectively. Shear gap homogenization was the only mechanical SPT to not achieve a high degree of cell disintegration. The HPH was the most effective (90% disintegration) when energy consumption alone (6,000 kJ/kg SS) is considered. Long grinding times and high agitator speeds using a SBM were needed to achieve the best

disintegration results. Ultrasound homogenization required the commonly found E_{spec} of approximately 14,000 kJ/kg SS to achieve disintegration of about 90% and equal to that of SBM SPT at 11,500 kJ/kg SS. An increase up to 5% of the sludge's SS content improved the observed disintegration (up to 60%) at low E_{spec} input (2,000 kJ/kg SS). Anaerobic digestion using untreated and pretreated sludge was evaluated. The impact of mechanical SPT on the degree of anaerobic degradation and biosolids dewaterability was found to be more significant at shorter HRTs. For HRTs above 15 d, similar degrees of degradation were achieved for control and pretreated samples. It is thus observed that shorter digestion times can be achieved. Immobilisation was shown to be effective at minimizing wash out of the anaerobic microorganism consortium when operating at short MAD retention times.

Dewaterability, as assessed by polymerization and lab-scale centrifugation, was marked by percent improvement of 1.3% at a 4 d MAD HRT for HPH SPT and by 0.7% at a 15 d MAD HRT. Polymer demand was increased by 18 and 5% for the runs conducted at MAD HRTs of 4 and 15 d. The authors point to the floc and colloid destruction that occurred during SPT as the reason for the polymer demand increase. Though it was not presented, a rough calculation of energy-consumption and costs was said to illustrate the viability of SPT incorporation into a WWTP based on the energy gains from improved biogas production.

A study comparing SBM and a high speed cutting mill was performed by Baier et al. (1997) [23]. Foregoing SPT restricts the amount of available intracellular material for AD and thus limits degradation of domestic WAS to approximately 55%. The authors chose not to evaluate chemical SPT as they suggest its main purpose is to fully stabilize sludge and does not present itself as an upgrade to an existing WWTP. Distillery slops, brewery residues, WAS, aerobically digested WAS, and anaerobically digested sludge were evaluated. The SBM consisted of a 300 mL chamber with revolution speeds set at 2,000, 3,200, and 4,200 rpm. Glass and zirconium balls with diameters of 0.2-0.25 mm (fine) and 1-1.5 mm (coarse) were used. The fine balls were more effective for disintegration but only significantly more effective with WAS. Sludge pretreatment runs were continuous and operated for 9 min on average. Revolution speed and ball diameter

were found to influence disintegration more than ball composition. Sludge content also influenced the disintegration. Soluble COD rose by a factor of 10-15 and 3-3.5 for the WAS containing less COD and dissolved solids and for the thicker sludge, respectively. The high speed cutting mill with cutting speeds set at 2,000 and 16,000 rpm required a water cooled chamber. Poor results were obtained with all sludge samples using the cutting mill. Up to 16% COD solubilisation was obtained for WAS using the cutting mill but this result was mostly attributed to the relatively high temperatures (60-90°C) occurring due to milling. The SBM had more significant results. Initial sCOD contents of 5.5 and 1%, respectively, characterized WAS from aerobic digestion SRTs of 5 and 7 d, respectively. Improvements to 17 and 13% were observed for the WAS with 5 and 7 d SRTs, respectively. Aerobically digested sludge, combined (PS+WAS) thickened sludge, and non-thickened anaerobically digested sludges had sCOD contents of around 6.5, 3, and 1%, respectively. For the same sequence as above, the initial sCOD content was 1.8, 0.5 and 2%. Brewery and distillery sCOD contents improved from 46 and 41% to 60 and 77%, respectively. Incorporation of mechanical SPT led to a 10% increase in biogas production for WAS in 1 L MAD reactors for an HRT of 20 d. The related volatile solids (VS) reduction for WAS in the LSRs improved from 40 to 60%. A rough estimate of SPT energy consumption was found to be 1-1.25 kW/m^3 sludge/d. The authors stated that FSR verifications of this estimate need to be performed.

2.2.2 High Pressure Homogenizer

Mechanical, thermal, and oxidative SPT processes were compared by Camacho et al. (2002). Kady Biolysis™ is introduced as a return activated sludge mechanical SPT which promotes cell lysis. A HPH was used at pressures of 30, 50, and 70 MPa for 1, 2, 5, and 10 passes. The authors found that SPT for more than 2 passes was necessary for cell disruption. Soluble COD for a sludge sample containing 1-1.5 g total suspended solids (TSS)/L increased from about 17 to 49% for E_{spec} of 1,000 to 15,000 kJ/kg TSS, respectively. A sludge sample containing 41 g TSS/L had sCOD improve from 15 to 28% of TCOD for E_{spec} of 50 to 250 kJ/kg TSS, respectively. In regards to power consumption and the solubilisation effect of SPT without subsequent AD, mechanical SPT was found

more suitable than thermal SPT. It was underlined that incorporation of the SPTs into a WWTP is necessary to prove the observed benefits.

Camacho et al. (2002) continued their previous work with a feasibility study incorporating HPH SPT for WAS into an aerobic digestion PSR [25]. For the purpose of this project only the SPT results are considered. Sludge treatment and disposal is said to account for up to 60% of operating costs. As such, disintegration at pressures of 30 and 70 MPa was performed to evaluate the alleviation of these costs in terms of increased particulate COD (pCOD) solubilisation and AD stabilization. Sludge pretreatment improved pCOD solubilisation linearly with respect to the number of passes in the HPH. For 7 passes at 30 and 70 MPa, pCOD solubilisation reached 18 and 33%, respectively. A limiting value of 60% pCOD solubilisation was found for 10 passes at either 50 or 70 MPa.

A HPH SPT was evaluated by Machnicka et al. (2005) for the purposes of AD improvement by pretreated WAS and/or foam addition [37]. The unit performed at 10 MPa and a 3 min contact time to treat 25 L of WAS through a 1.2 mm nozzle. Overall contact times of 15, 30, and 60 minutes were chosen and as such, 5, 10, and 20 passes were performed. An AD HRT of 14 d for WAS digestion at 30°C was observed. Concentrations of sCOD were improved by 200 to 300% for contact times of 15 and 60 min, respectively. An 81% improvement in biogas production was obtained when 20% pretreated sludge was digested with the WAS for an HRT of 14 d. When 20 and 40% foam additions were also considered, biogas percent improvements were 460-610%. Ultrasound SPT was also evaluated. Little information was given but it was said that organic matter and phosphate release (610% improvement) from SPT cell lysis was improved with this technology. The authors state that hydrolysis disintegrates the poly-P phosphate storage of the cells and it enters the liquid as depolymerised phosphates (PO_4^{3-}) [37].

Wook Nah et al. (2000) tested HPH technology in PSRs with a 2 m^3 mesophilic anaerobic digester at 15 d HRT [51]. The HRT was reduced to 6 d with SPT and no significant negative process efficiency and effluent quality effects were observed.

Thickened WAS (TWAS) was pretreated at 5 MPa with a 2.5 mm nozzle and stored in a 1 m^3 tank to promote continuous AD operation. An agitator was used to maintain the completely mixed status of the pretreated TWAS. The characteristics of the sludge prior to SPT were 14-18 g/L TS and 10-12 g/L VS. The process schematic is shown in Fig. 2.2. The TWAS was sieved (1) for a size of 2.5 mm, stored (2), and added to the SPT unit (5). The pretreated TWAS was again stored (8) and fed to the continuous MAD unit (10).

The quantitative effects on sCOD, soluble protein, and SS concentrations are shown in Fig. 2.4 (as adapted from [51]). It is clear that particulate matter is reduced (SS by 5%) and sCOD concentrations are increased from 250 to 750 mg/L. An increase in total dissolved solids and a decrease in pCOD are observed because, though minor mineralization may occur, there is no significant loss of matter during the homogenization process.

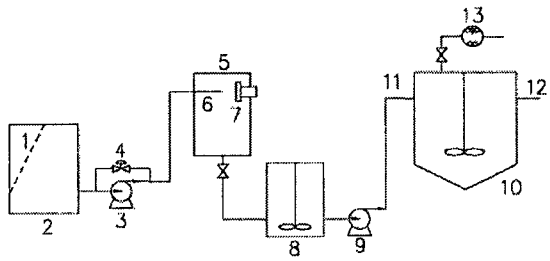


Figure 2.2 HPH process incorporation schematic (adapted: [51])

Homogenization results are depicted by microphotographs (magnification × 400) in Fig. 2.3 (as adapted from [51]).

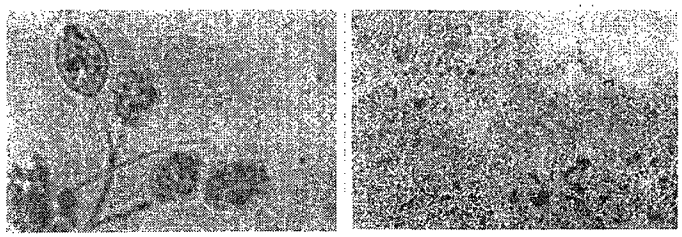


Figure 2.3 Microphotograph (magnification × 400) of TWAS prior to (left) and following SPT (right) (adapted: [51])

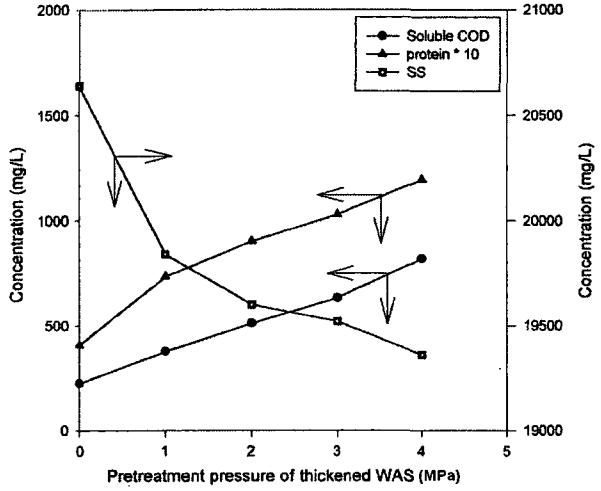


Figure 2.4 Particulate matter solubilisation and intracellular matter lysis (adapted: [51])

Organic carbon and sCOD availability increased by 500-700%. Soluble proteins were increased by about 250%. Alkalinity, NH_3-N and total phosphorous (TP) increased by about 20%. The alkalinity results primarily from the presence of hydroxides, carbonates, and bicarbonates due to calcium, magnesium, and ammonia. Phosphates can also contribute to alkalinity and thus, the additional releases of both NH_3-N and TP improve alkalinity which in turn, helps stabilize the digestion process. The study did not evaluate a control run and instead compared VS reductions and biogas productions to those expected for AD HRTs of 20-30 d. This comparison showed an improvement of 6 and 34% for VS reduction and biogas production, respectively. The authors did note a slight increase in VFA concentrations at shorter HRTs but no dramatic pH changes were observed [51].

Controlled hydrodynamic cavitation (CHC) was, as far as could be understood, quite similar to HPH and is thus described here from a study by Nicholas et al. (2008)

[113]. The process was described as seeking to promote sufficient cavitation whilst also harnessing the kinetic energy input. It was listed as being successfully implemented for over 17 years for the treatment of cooling water based on its bacteria eradication effect. The unit is depicted in Fig. 2.5 (as adapted from [113]).

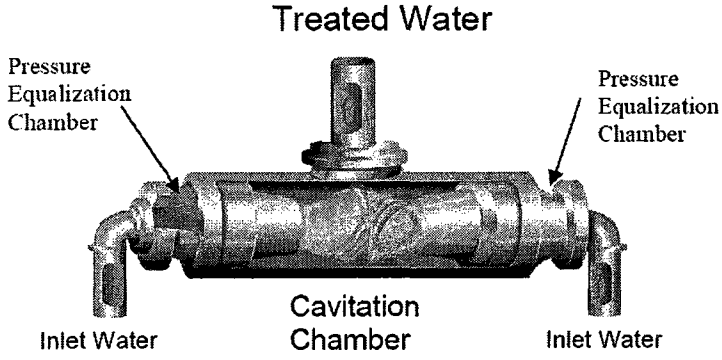


Figure 2.5 CHC unit showing collisions at high pressures (adapted: [113])

A close-up graphical layout of the process is shown in Fig. 2.6 As the process closely resembles HPH and ULT in terms of cavitation, the formation and collapse of bubbles will not be explained here.

Small changes in TCOD were observed due to minimal oxidation occurrence. Increases in sCOD by 160 and 360% after 15 and 50 passes, respectively, were observed. Reductions (17%) in TSS were observed and particle size averages lowered from 60 to 20 microns. An 80% improvement in size uniformity was noted. Finally, dewatering was listed as being improved by a 20-40% decrease of water in the cake solids.

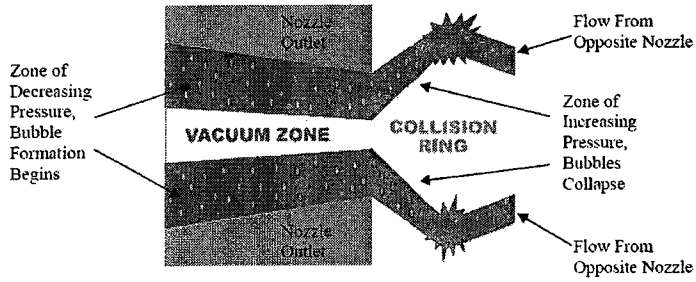


Figure 2.6 Cavitation process as a result of bubble formation and violent collapse (adapted: [113])

A technical study was performed for HPH by Onyeche (2004) at full-scale and is explained in the section on those facilities [101]. Two MicroSludge^{TM} studies were

available and represent the combination of HPH and CM SPTs. They are also described in the full-scale facilities section (Section 2.7) and again in the brief SPT equipment theory of Chapter 3 [83, 101, 153].

2.2.3 Ultrasound

Ultrasonic treatment is said to not only improve methane generation but also to allow reduction in HRT [2]. Ultrasound frequency and E_{spec} have typically been studied for their effect on COD solubilisation and biogas production. Low frequencies (<100 kHz) are thought to promote mechanical and physical degradation while high frequencies promote sonochemical effects [1]. TAD conditions are said to enhance the biogas and methane production rates compared to MAD conditions and were therefore selected for enhanced organic matter removal following ULT SPT [1].

Ultrasonic SPT was evaluated by Benabdallah El-Hadj et al. (2007) for the specific removal of naphthalene and pyrene under MTAD conditions [1]. They found that frequencies in the range of 20-40 kHz are optimal for the promotion of mechanical degradation. Higher frequencies however, promote disintegration of particulate matter into smaller more soluble matter which benefits the stabilization of WAS. Certain polycyclic aromatic hydrocarbons, such as naphthalene, are primarily hydrophobic but are rendered water soluble by ultrasonication. Biogas production was improved when E_{spec} was increased from 0 to 11,000 kJ/kg TS. However, increasing from 11,000 to 15,000 kJ/kg TS did not significantly improve biogas yield. Also, biogas production and COD removal were improved under both MAD and TAD with SPT. Improvement values under MAD were almost double those under TAD. Methane content in the biogas was the same for both conditions. The authors summarized their study by selecting an optimal E_{spec} of 11,000 kJ/kg TS under both MTAD. They also specified that TAD, being highly efficient, does not benefit as noticeably from ULT SPT.

Benabdallah El-Hadj et al. (2007) and Bougrier et al. (2005) found that E_{spec} inputs lower than 3,000 kJ/kg TS did not impact biogas production from the particulate fraction of the sludge even though the solids concentration decreased [1, 2]. The latter authors also observed the biogas production from the soluble fraction of the sludge

increased with an increase in E_{spec}. A minimum increase of 25% in biogas production was observed with ULT SPT. It was also found that particulate matter was 97% responsible for biogas production in untreated sludge and only 60% responsible in pretreated sludge. Ultrasound thus effectively converts the particulate matter to soluble species which now contribute to approximately 40% of the biogas production. The soluble fraction was also observed to be three times higher in pretreated sludge at 7,000 kJ/kg TS. The authors observed that at 3,000 kJ/kg TS the biogas volume produced was of the same order of magnitude for both the particulate and soluble fractions. Organic matter, pCOD, and nitrogen solubilisation are all said to increase with an increase in E_{spec}. Though unverified, the method used brought the conclusion that at <1,000 kJ/kg TS, floc size is reduced and that an increase in E_{spec} would then "break" flocs or cells. In contrast to Benabdallah El-Hadj et al. (2007), a supplied energy higher than 7,000 kJ/kg TS is not recommended because it yielded no further improvement in biogas production.

One study by Stuckey et al. (1984), as outlined in the introduction to this article by Climent et al. (2007), found that biogas and methane production are higher under MAD conditions for both untreated and treated sludges [3]. Valo et al. (2004) found improved COD solubilisation by 25 and 60% for WAS pretreated at temperatures of 130 and 170°C, respectively [10]. The authors also reported increments of 21 and 45% in biogas production for 130 and 170°C pretreated samples, respectively. Ultrasound SPT was studied alongside high and low temperature thermal SPTs and microwave SPT for WAS used under TAD. Temperature in the SPT unit as well as contact time was varied for optimality. Results for other SPTs are handled in their respective sections. Ultrasound SPT using a 300 W ultrasonic homogenizer was applied for treatment times of 10-987 s to obtain E_{spec} values in the range of 1,000 to 100,000 kJ/kg TS. Although the authors also found that the degree of disintegration is greater with E_{spec} below 20,000 kJ/kg TS they selected 40,000 kJ/kg TS for optimal SPT of WAS. It is stated that Tiehm et al. (1997) lowered treatment time to 64 s by using a high performance ultrasound at 3.6 kW. The authors did not observe an increase in biogas production with ULT SPT. In fact, only low temperature thermal SPT was responsible for an increase in biogas production. It was hypothesized that TAD conditions accelerate the hydrolysis step to a point where SPT

effects are concealed. Low temperature thermal SPT is also said to enhance the activity of thermophilic bacteria. Climent et al. (2007) conclude with the comment that an accurate economic study including all the factors implied in FSR operation (e.g., thermal inertia, maintenance of digester temperature, and possible uses of residual heat) to balance all the possible benefits and drawbacks of SPT should be performed.

Kim et al. (2003) evaluated the effects of thermal, chemical, ultrasonic (discussed herein), and thermochemical SPTs on WAS [4]. As in the previous works, the methane fraction (~70%) of the biogas remained constant while the amount of biogas produced increased. Ultrasonic SPT was responsible for an approximate increase of 20% in biogas production from MAD as evaluated using a gas sampling port affixed to the 1 L LSR. All SPTs are said to reduce the impact of the rate-limiting step and thus, WAS AD was improved.

2.2.4 Shear Gap Homogenizer and Lysate Centrifuge

These two technologies show low but similar potential to improve AD by sludge hydrolysis as all other SPTs. Insufficient literature information was found however, on either technology.

Shear gap homogenization was reviewed by Kopp et al. (1997) alongside ULT, SBM, and HPH [22]. For SBM, ULT, and SGH, contact times of 1-60 min were employed for E_{spec} ranging from 8,000-20,000 kJ/kg SS. The SPT comparison in terms of disintegration (solubilisation) and E_{spec} is shown in Fig. 2.7. Higher disintegration rates as compared to ULT for similar E_{spec} are shown for HPH and SBM. Comparable results were however, not found in the literature. Additional HPH and SBM studies used WW working ranges and obtained solubilisation results that were similar to those for ULT evaluations. The established ranges used in PretrAD are shown in Tables 2.1-6. It is clear that higher energy inputs are needed with SGH to achieve similar pCOD solubilisations. It is also likely that this research illustrated low SGH potential and was from this point forward of significantly less interest. Based on energy input and solubilisation results, the authors pursued AD with only HPH and SBM SPTs.

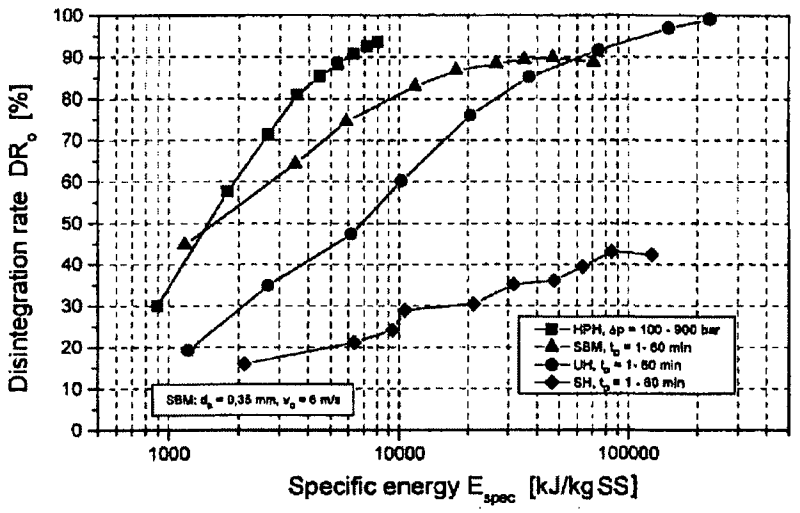


Figure 2.7 Degree of solubilisation by HPH, SBM, ULT (UH), and SGH (SH)

A single article investigating lysate centrifugation in a LSR was found in the literature review. Insufficient information was listed for discussion here. Three full-scale facilities employing this process were evaluated and the discussion is found in Section 2.7.

2.2.5 Mechanical SPT Summary

Energy demands for desired hydrolysis by SBM and HPH were found to be relatively similar. Though ULT seems to require higher E_{spec} for equivalent disintegration, subsequent digestion improvements were, in almost every study, found to be lower when SBM and HPH were used. As such, ULT was typically the preferred process prescribed by the authors. Shear gap homogenization was not found in the literature to a sufficient extent to warrant further evaluation. Though FSR LC studies are investigated in Section 2.7, both it and SGH cannot be summarized adequately.

Wastewater composition ranges, SPT working ranges, SPT results, and AD improvement ranges are listed below for ULT, SBM, and HPH in the same manner as they will be listed for each of the thermal, chemical, and thermochemical SPT summaries. It is clear that not all rows of the summary tables are complete for all references. These data, though they may be available, could not be determined from the referenced study. A minor margin of error must be assumed for any of the data that were represented graphically. The data here are intended for use as a full-scale design guide

with the model constructed for this research. An average and potentially low primary energy input value was selected for all SPTs and used in Runs 1-4 to be described in Chapter 5. Runs 1a to 2b were then conducted with reasonable (within the working ranges established) 25 and 50% energy input for SPT increases. It is important to note that some references that were excluded from the summary tables due to insufficient overall information were still considered in the establishment of certain ranges (e.g., WW composition but not AD improvements). For instance, though Table 2.1 lists 2 values below 15 g/L, the TCOD range for WW composition of ULT studies was selected as 15-45 g/L. The established ranges describe the average and likely results that exclude potential outlier observations. The ranges are listed directly below the summary tables and a table listing all excluded references is also given below the all summary tables.

At times, sufficient VSS data were not available and are thus not shown in the summary tables. The logical reduction from TSS values according to VSS/TSS relationships (0.6-0.9) for PS and WAS has been made to provide ranges (below the summary tables) for all variables evaluated in the literature [160].

The AD improvements are given for control and SPT incorporation conditions. The terminology used throughout this thesis to represent WWTP runs with and without SPT will now be described. Runs without SPT are labelled 'Control'. Incorporation runs (with SPT) are labelled 'SPT'. This was done to clearly define the control (i.e., initial) results and/or costs from the SPT (i.e., incorporation scheme) results and/or costs.

Wastewater composition ranges and SPT working ranges for ULT are shown in Table 2.1.

Table 2.1 ULT WW composition and working ranges

	WW Composition (All terms in g/L except SRT in d)						Energy Use			
Ref.:	BT θ_x[1]	TCOD	TS	VS	TSS	VSS	Power (W)	t (h)	V (L)	E_{spec} (kJ/kg TS)
[1]		45	30	23			70	0.03-0.09	0.05	0-15,000
[2]			19	16			225	0.01-0.18	0.5	0-15,000
[3]			38-49	28-38	36-46	28-36	300	0.003-0.278	0.08	1,000-100,000
[4]		27.7	38	26				0.17-2.00		
[22]	3				8-15					1,000-100,000
[23]							3,600	0.017		
[60]		5.4	8.2				110	0.33-2.00	0.25	63,000-386,000
[92]		9.9		7.3	9.9			0.5	0.1	9,000
[107]		15	10-38				200	0.008-0.333	0.05	3,200-128,000
[135]			4	3			1,500			1,250-1,950
[140]		22			0.8	0.6	500	0.017-1.000		

[1]BT represents biotreatment and θ_x represents SRT as shown in the nomenclature

TCOD (15-45 g/L), TS (10-40 g/L), VS (7-28 g/L), TSS (8-32 g/L), VSS (6-22 g/L)

ULT power (100-300 W), t (0.017-0.33 h), V (0.05-0.1 L), E_{spec} (4,000-25,000 kJ/kg TS)

Ultrasound homogenization hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.2. Some authors noted optimal SPT working range settings.

Table 2.2 ULT hydrolysis result ranges and AD improvements

Ref.	Solubilisation (%)			Optimal Settings	MTAD (d and °C)			Reductions (%)						Biogas Prod.
	pCOD	TSS	VSS	kJ/kg TS	$\theta_{Control}$	θ_{SPT}	T	TCOD		TS		VS		% Impr.
								Control	SPT	Control	SPT	Control	SPT	
[1]	28-32	30-52	30-44	11,000	20		35	44	52	23	26	42	47	16
[1]					15		55	49	53	24	26	46	49	31
[2]	4-36	4-31	5-34	7,000	16		35	25	28-41					12-60
[3]			26	40,000	32		55							0
[4]	10-17				7		37	55	40			21	39	21
[22]					15		35		20-90					
[23]					22		37					45.8	50.3	
[23]					16		37						49.3	12
[23]					8		37						44.3	37
[60]	20													
[92]	30	26											24	
[107]	30													25
[135]					15		35					55	54-58	-4-+7
[140]	24													

pCOD solubilisation (10-30%), TSS solubilisation (10-50%), VSS solubilisation (8-40%)

Control and SPT TCOD reductions (20-50% and 20-60%), TS reductions (20-30% and 22-34%), VS reductions (25-50% and 25-55%)

Biogas production improvement (5-35%)

Wastewater composition ranges and SPT working ranges for SBM are shown in Table 2.3. Stirred ball milling hydrolysis result ranges, and subsequent AD improvements are outlined in Table 2.4.

Table 2.3 SBM WW composition and working ranges

	WW Composition (d and g/L)						Energy Use			
Ref.:	BT θ_x	TCOD	TS	VS	TSS	VSS	Speed (rpm)	t (h)	V (L)	E_{spec} (kJ/kg TS)
[22]	3				8-15					1,000-70,000
[23]	5	20.2	0.02	0.07						
[23]	7	6.3	0.04	0.07			2,000-4,200	0.15	0.3	
[56]							1,100	0.33	3	5,000-35,000

TCOD (10-30 g/L), TS (10-35 g/L), VS (8-30 g/L), TSS (8-32 g/L), VSS (6-25 g/L)

SBM speed (1,000-4,000 rpm), t (0.08-0.5 h), V (0.05-1 L), E_{spec} (3,000-40,000 kJ/kg TS)

Table 2.4 SBM hydrolysis result ranges and AD improvements

	Solubilisation (%)			MTAD (d and °C)			Reductions (%)						Biogas Prod.
Ref.	pCOD	TSS	VSS	$\theta_{Control}$	θ_{SPT}	T	TCOD		TS		VS		% Impr.
							Control	SPT	Control	SPT	Control	SPT	
[22]				4		35		45-90			38	42	
[23]	10-14					35	51	53			38	57	10-15
[56]	10-24									2-89			

pCOD solubilisation (10-40%), TSS solubilisation (10-40%), VSS solubilisation (10-40%)

Control and SPT TCOD reductions (20-55% and 20-60%), TS reductions (20-30% and 20-40%), VS reductions (20-50% and 25-55%)

Biogas production improvement (5-35%)

Wastewater composition ranges and SPT working ranges for HPH are shown in Table 2.5. High pressure homogenization hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.6. References that were considered for the ranges establishment shown below the above tables are listed in Table 2.7.

Table 2.5 HPH WW composition and working ranges

	WW Composition (d and g/L)						Energy Use			
Ref.:	BT θ_x	TCOD	TS	VS	TSS	VSS	P (MPa)	t (h)	V (L)	E_{spec} (kJ/kg TS)
[6]			45				60			
[22]	3				8-15					800-8,000
[51]			16	11			3	0.017	30	

TCOD (10-30 g/L), TS (10-40 g/L), VS (8-35 g/L), TSS (8-25 g/L), VSS (6-20 g/L)

HPH MPa (10-90 MPa), t (0.017-0.5 h), V (0.05-1 L), E_{spec} (2,000-20,000 kJ/kg TS)

Table 2.6 HPH hydrolysis result ranges and AD improvements

	Solubilisation (%)			MTAD (d and °C)			Reductions (%)						Biogas Prod.
Ref.	pCOD	TSS	VSS	$\theta_{Control}$	θ_{SPT}	T	TCOD		TS		VS		% Impr.
							Control	SPT	Control	SPT	Control	SPT	
[6]				20		36		30-94				7	18
[22]				4		35					38	58	
[51]	27	7		13	6	35					30	30	

pCOD solubilisation (10-40%), TSS solubilisation (10-40%), VSS solubilisation (10-40%)

Control and SPT TCOD reductions (20-55% and 20-60%), TS reductions (20-30% and 20-45%), VS reductions (20-50% and 25-60%)

Biogas production improvement (5-35%)

Table 2.7 Mechanical SPT studies without sufficient, comparable or discernable data

	References
ULT	[34],[38],[46],[59],[64],[70],[87],[134]
SBM	[34],[38]
HPH	[26],[27],[32],[34],[37],[38],[104],[113]

2.3 THERMAL PROCESSES

Temperatures required for thermal SPTs typically range from 60-180°C [3]. Sludge pretreatments heating sludges to less than 100°C are considered to be low temperature [3]. Over 100°C temperatures are considered high and are induced by either heat exchangers or steam injection [3]. These thermal SPTs are known as conventional heating (CH) or microwave heating (MWH) processes. An increase in energy demand is said to be balanced by higher sludge biodegradability and by the use of sludge residual heat to maintain the temperature in the digester [3]. Dewaterability and pathogen reduction are also increased and result in reduced sludge disposal costs and signify improved sludge stabilization [4].

2.3.1 Conventional Heating

Gavala et al. (2003) sought to determine the optimal SPT duration and temperature under CH for both MAD and TAD of PS and WAS separately [8]. They found that optimizing these two variables depends on the ratio of PS to WAS. A SPT temperature setting of 70°C and an AD HRT of 20 d were used. Methane production rates for MAD decreased by 10 to 18% when PS was first subjected to SPT at contact times of 1, 2, 4, and 7 d. When WAS was used under identical MAD and SPT conditions, methane production rates increased from 43-145% for the same SPT durations. The SPT period of 4 d showed the lowest and highest methane production rates for both PS and WAS, respectively. Thermophilic AD methane production rates for PS were found to increase by 64-77% for 1 and 2 d SPT periods and increase by 33-50% for 4 and 7 d SPT periods. For WAS, an increase was observed in TAD methane production rates from 4-58% for the 1, 2, 4, and 7 d SPT contact times. This can be explained by the beneficial influence of WAS hydrolysis compared to PS hydrolysis. The hydrolysis yields for different sludge types following CH SPT are shown in Fig. 2.8 (as adapted from [33]). Shorter biotreatment (BT) SRTs provided improved hydrolysis yields because longer SRTs already degrade (by lipids and carbohydrates release) the sludge extensively [44].

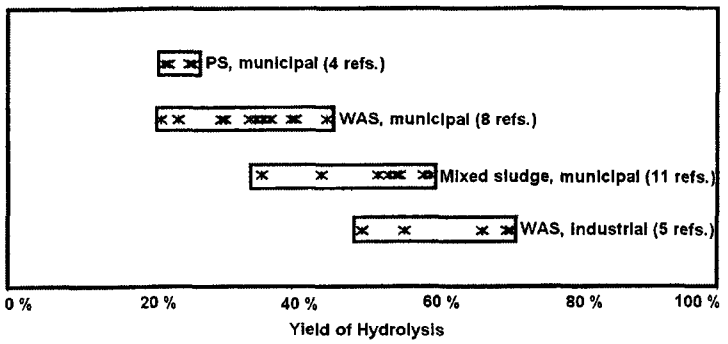


Figure 2.8 Hydrolysis influence on different sludge types (adapted: [33])

The following is a further evaluation of the aforementioned Climent et al. (2007) study [3]. High temperature, low temperature, and MWH SPT results will now be discussed. Duration and temperature were altered for both high and low scenarios. Optimal conditions were found for high temperature SPT at 134°C and 90 min with a biogas production of 0.030 L/d. Low temperature SPT conditions were set at 70°C and 9 h and provided a subsequent biogas production of 0.027 L/d. These conditions were deemed optimal. An optimal E_{spec} (40,000 kJ/kg SS) for MWH was found and subsequently biogas production improved by 50% (compared to the control) and was observed at 0.030 L/d. It was also determined that the low temperature scenario was the only scenario in which biogas production was increased under thermophilic conditions.

A PSR CH feasibility study was performed by Pérez-Elvira et al. (2008) [100]. A pilot-scale plant at a WWTP in Spain was used to determine the scale-up feasibility. Three runs were conducted with identical volumes (10 L) of PS, WAS, and a mixture of both. Sludge pretreatment was set at 170°C by steam injection for a 0.5 h contact time. The highest percent VS reductions were observed when WAS hydrolysis provided a 64% disintegration of particulate matter. A short energy analysis was performed and showed that at a SPT WAS feed of 3% TS and with biogas recovery, 61 kWh/ton sludge would be required to achieve enhanced AD. As done in PretrAD, energy integration (recovery) was needed. Though some data are given on unit (boiler and steam engine) efficiencies, they will not be listed here because they are highly variable. Furthermore, their study's energy balance is highly specific to their treatment conditions and parameters incorporated into their analysis. Also, daily sludge volumes treated significantly impact energy considerations. The main point here is to grasp the pilot-scale feasibility and full-

scale potential. Thicker (7-8% TS) sludges could be anaerobically digested largely due to the favourable viscosity. More biogas (40%) was produced during an almost 50% reduction in AD HRT. A 246 kW energy surplus (based on ~1.7 g COD/g VSS and ~0.225 m^3 CH_4/kg VSS) was noted with respect to conventional processes. Finally, Class A biosolids could be achieved and only 42% of the initial biosolids production was observed after incorporation of SPT [100].

A CH (CAMBI) simulation using a developed BioWin™ toolkit for full-scale design was explored by Wett et al. (2009) [143]. The constructed toolkit permits cost calculations for AD and CH to be performed in the context of a complete advanced wastewater treatment plant (AWTP). The Blue Plains AWTP in Washington, DC is said to be the largest AWTP in the world. It separates the treatment of sludges (PS, WAS, nitrification, and blended). The results shown in the study were conducted in accordance with the sludge characteristics of that facility. They were conducted at pilot-scale with 2 MAD reactors operating at 15 and 20 d HRTs. A feed volume of 1 L influent sludge was replaced with hydrolysed sludge and the impacts were simulated with the BioWin™ ASDM model. Solubilisation rate was altered to achieve 30-40% sCOD following hydrolysis. The proposed incorporation schematic developed for the toolkit is shown in Fig. 2.9 (as adapted from [143]).

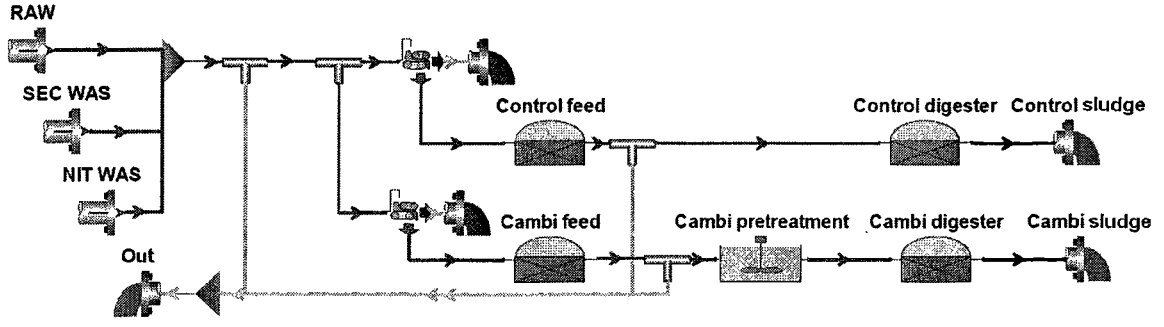


Figure 2.9 Integration and control schematics including AD units (adapted: [143])

As mentioned by the authors, a series of tests and pilots cannot definitively asses the full-scale effect of CAMBI CH incorporation. Their results proved the importance of the holistic approach used in this thesis for the addition of SPT into a WWTP where large changes in liquid and solids flows are observed. Results were not compared to control

status but both HRTs were compared. With identical sCOD percentages being fed to the 2 digesters, the HRT of 15 d provided a 22% biogas production improvement. Strangely, a 4.5% decrease in solids reduction (in terms of COD) was observed. An appropriate explanation for this observation was not provided [143].

2.3.2 Microwave Heating

Microwave heating (MWH) has been studied as an alternative to CH. Energy requirements, reaction times, and methane yield are all said to improve under MWH [5]. Microwave irradiation corresponds to 1×10^{-3}-1 m wavelengths in the electromagnetic spectrum with equivalent frequencies of 300-3×10^{6} MHz, respectively [5]. For the heating or drying of thin substances, frequencies of 2,450 MHz with correspondingly short wavelengths (0.12 m) are adequate. If deep penetration into materials is required, frequencies of 900 MHz with correspondingly long wavelengths (0.37 m) and energy outputs of up to 100 kW are used [5]. MWH is thought to not only lyse cells by the thermal effect (as in CH) – heat generated by the rotation of dipole molecules under the oscillating electrical field of a microwave – but also by the "athermal effect" – possible breakage of hydrogen bonds due to the polarized components of the macromolecules re-aligning with the poles of the electromagnetic field [5]. This effect is thought to explain cell lysis that has been observed to occur at temperatures lower than the cell thermal death point [5]. However, contradicting studies have found both improved and unimproved lysis following MWH. Factors affecting MWH are sludge density and viscosity [5]. Sludge boiling point is the limit for the E_{spec} applied. It is thus important to consider hot spots and consequently, limit E_{spec} [3, 5].

Eskicioglu et al. (2007) utilized thickened WAS (TWAS) and mimicked heating rates of CH up to temperatures of 50, 75, and 96°C to evaluate the presence and significance of athermal effects [5]. The SPT step was followed by MAD. It was found that identical heating profiles generated similar sCOD/TCOD ratios for both heating methods at each SPT temperature. Slower heating rates and consequently longer heating times increased the SCOD/TCOD ratios for both heating methods. Under MWH and CH NH_3-N concentrations increased in the samples at each SPT temperature. This occurrence

was assumed to be a result of improved hydrolysis of substrate containing organic nitrogen. Results show that with acclimated and non-acclimated inoculums, biogas production for MWH compared to CH is 6 and 5% higher, respectively. The occurrence of athermal effects was thus validated by biogas production but not by WAS solubilisation.

A study by Woo et al. (2000) found no improvement in cell lysis or destruction using MWH in place of CH. The use of MWH is stipulated here to increase the susceptibility of cells to lysis when undergoing AD. Biochemical methane potential (BMP) tests illustrated typical methane content ranges of 55-73% and 61-73% for acclimated and non-acclimated inoculums, respectively. As in other SPT studies, the methane (CH_4) yield from the batch mesophilic digester was within the range of 0.49-0.75 L CH_4/g VS removed.

In a previous study by Eskicioglu et al. (2006) where apparent molecular weight (AMW) and size distribution were the primary objectives, sCOD values were found to increase by approximately 361, and 143% with CH and MWH, respectively [7]. As is typically found when MWH is not ramped up to produce temperature increases similar to CH temperature increase rates, greater WAS solubilisation is observed with CH. The conclusion is that the longer heating time needed to reach the desired temperature causes superior solubilisation. Biogas production, as assessed by BMP test, increased by approximately 475 and 211% for CH and MWH, respectively. The authors also concluded by suggesting that the SPT of supernatants containing both particulate and soluble fractions can lead to a reduction in required digester volume and an increase in waste stabilization. Thermal SPT can thus potentially render the sludge safe for use as fertilizer.

Park et al. (2004) found that increasing microwave irradiation resulted in up to a 22% increase in sCOD [9]. Mesophilic conditions were used for tests at HRTs of 8, 10, 12, and 15 d. Average daily biogas production decreased from approximately 240 mL/L/d to 117 mL/L/d for the HRT sequence. Methane production and COD removal were 79 and 64% higher than without MWH SPT, respectively. The authors maintain that

technical and economical aspects to SPT selection for full-scale conventional digestion processes must be considered. A qualitative analysis of capital and operation and maintenance (O&M) costs was given which compares mechanical, thermal, chemical, and microwave SPT processes. They specify that applying any of the SPTs to a WWTP is only cost-effective if the WWTP is experiencing over-loaded digesters, low sludge biodegradability, and/or high disposal costs. Microwave irradiation is directly compared to ultrasonication where 120 min are needed with double the E_{spec} to obtain equivalent disintegration after only 7 min of MWH irradiation. The MAD HRT was reduced from 15 to 8 d without hindering the AD process.

2.3.3 Thermal SPT Summary

Subjecting a portion of the sludge ultimately sent to the digester to a hydrolysis process by heating mimics temperature-phased AD. Overall rate of hydrolysis is improved and heat can be recovered. The AD HRT required was thus observed to be reduced and digestion improvements included important increases in biogas production. As a result of high heat exposures, both CH and MWH can provide greater pathogen reduction but also cause undesirable odours. Time required to reach these elevated temperatures and then maintain them may constrain hydrolysis levels and the fraction of sludge that can be pretreated. Most of these drawbacks might however be mitigated, thus making SPT feasible. This is further explained by the full-scale SPT facilities review in Section 2.7.

Wastewater composition ranges and SPT working ranges for CH are shown in Table 2.8.

Table 2.8 CH WW composition and working ranges

	WW Composition (d and g/L)						Energy Use		
Ref.:	BT θ_x	TCOD	TS	VS	TSS	VSS	Temp. (°C)	t (h)	V (L)
[3]			38-49	28-38	36-46	28-36	110-134	0.33-1.5	0.5
[3]			38-49	28-38	36-46	28-36	70	9-72	0.5
[4]		27.7	38	26			121	0.5	
[6]			45				80-121	1.0	
[7]	5	60-81	59	41			96		1.0
[8]							70	24-168	0.04
[10]		17	17	12			130-170	0.5-1.0	0.0007
[13]							121	0.5	
[15]		56	31				140	0.5	0.3
[16]		9			6.6	5.7	130	0.08	
[28]							121	1.0	
[58]		61			38	31	90	24	
[61]		56	39	37			90-200	0.33-0.66	0.3
[70]		11	10	7	9	7	130-170	0.017	
[74]		10			9	5	70	48	0.5
[78]	15		7.5				175	0.66	230
[102]							140-200	0.66-1	
[126]		30	27	21			50-65	48	0.6

TCOD (15-55 g/L), TS (15-50 g/L), VS (12-45 g/L), TSS (10-40 g/L), VSS (8-35 g/L)
CH temperature (70-140 °C), t (0.017-1 h), V (0.05-0.5 L)

Conventional heating hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.9. Some authors noted optimal SPT working range settings. A negative to a positive range is sometimes shown for the biogas improvement (right-most column). In these cases, the authors found percent reductions and improvements in biogas production.

Table 2.9 CH hydrolysis result ranges and AD improvements

Ref.	Solubilisation (%) pCOD	TSS	VSS	Optimal Settings kJ/kg TS	MTAD (d and °C) $\theta_{Control}$	θ_{SPT}	T	Reductions (%) TCOD Control	TCOD SPT	TS Control	TS SPT	VS Control	VS SPT	Biogas Prod. % Impr.
[3]			16-85	134, 1.5	32		55							0
[3]			32-47	70, 9.0	32		55							-10-+58
[4]	18			121, 0.5	7		37	55	37			21	32	32
[6]				121,1.0									+4-6	16-21
[7]	24				23				+3.5					475
[8]					20		37							-7-+16
[8]					20		37							20-26
[8]					20		55							38-86
[8]					20		55							-6-+5
[10]	23-58	20-46		170, 1	20		35	44	71	27	59	35	67	64
[28]					30		35	66	54	67	63	72	66	80
[58]					30		37	52	51			48	50	10-51
[70]														36-50
[74]					13		55					6	43	38
[78]	12	16			11		35		46	40				
[78]	12	16			3		35				65	44	54	25
[102]	40-50			180,1	20		35							80
[126]							35							

pCOD solubilisation (10-45%), TSS solubilisation (15-40%), VSS solubilisation (15-40%)

Control and SPT TCOD reductions (40-60% and 45-65%), TS reductions (25-60% and 25-65%), VS reductions (25-60% and 25-65%)

Biogas production improvement (5-40%)

Wastewater composition ranges and SPT working ranges for MWH are shown in Table 2.10. Microwave heating hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.11. Some authors noted optimal SPT working range settings.

Table 2.10 MWH WW composition and working ranges

	WW Composition (d and g/L)						Energy Use			
Ref.:	BT θ_x	TCOD	TS	VS	TSS	VSS	P (W)	t (h)	V (L)	E_{spec} (kJ/kg TS)
[3]			38-49	28-38	36-46	28-36	400-800	0.05-0.17	0.5	520-13,000
[5]	5	46-67	46-55	31-37			1250	0.08-1.00	0.1	7,500-90,000
[7]	5	60-81	59	41			1250			
[9]			30	19			700	0.05-0.25	0.5	8,400-42,000
[119]	5		5-12				0-1250	0.36-0.55	0.28	

TCOD (40-65 g/L), TS (20-45 g/L), VS (15-35 g/L), TSS (15-40 g/L), VSS (10-35 g/L)

MWH power (700-1,250 W), t (0.05-0.5 h), V (0.1-0.5 L), E_{spec} (4,000-25,000 kJ/kg TS), temperature (50-100 °C)

Table 2.11 MWH hydrolysis result ranges and AD improvements

Ref.	Solubilisation (%) pCOD	TSS	VSS	Optimal Settings kJ/kg TS	MTAD (d and °C) $\theta_{Control}$	θ_{SPT}	T	Reductions (%) TCOD Control	TCOD SPT	TS Control	TS SPT	VS Control	VS SPT	Biogas Prod. % Impr.
[3]			4-13	13,000			55							-9
[5]	8-16			45,000-95,000	15		35							4-16
[7]	8				23				+4.6					211
[9]	8-20				15	8	35	14	24			23	26	30
[119]					21		35							13-31

pCOD solubilisation (5-25%), TSS solubilisation (5-25%), VSS solubilisation (5-20%)

Control and SPT TCOD reductions (10-20% and 10-25%), TS reductions (20-30% and 20-35%), VS reductions (20-30% and 20-35%)

Biogas production improvement (5-30%)

References that were considered for the ranges establishment shown below the above tables are listed in Table 2.12.

Table 2.12 Thermal SPT studies without sufficient, comparable or discernable data

	References
CH	[24],[26],[32],[94],[146],[148],[155]
MWH	[118]

2.4 CHEMICAL PROCESSES

Acids and minerals, alkaline, and ozone SPTs can be used to degrade complex organic compounds [11]. Acids and alkali both work at low temperatures [11]. Alkaline (CM) SPT is performed by increasing the sludge pH to 12 and sustaining it for duration of up to 24 h [11]. Complex organics such as polycyclic aromatic hydrocarbons, lipids, and proteins are hydrolysed into smaller and more soluble compounds [11]. Alkaline hydrolysis requires low energy input, solubilises COD effectively, and provides good sludge dewaterability [11, 18]. Desired bacteria can be harmed however and chemical addition speeds up equipment corrosion and fouling [11]. Also, some of the soluble compounds that are formed are not biodegradable [11, 18]. Ozone (O_3) can be used in place of alkali and requires no salt or chemical additions [11, 14, 17]. During ozone SPT (OZ), it is important to only partly hydrolyse the complex organics to avoid the formation of non-degradable compounds [11]. Dewaterability is improved but the energy input is high and metal impurities need to be removed [11, 14, 17].

2.4.1 Acid

Pilot-scale peroxidation of sewage sludge was investigated by Neyens et al. (2003) [29]. Anaerobic digestion of pretreated sludge was not evaluated. The oxidation process uses hydrogen peroxide (H_2O_2) and ferrous iron (Fe^{2+}) in a well-known reaction dubbed Fenton's reagent. Iron catalyses H_2O_2 dissociation which in turn produces reactive hydroxyl radicals. Ferric ions are also produced via Fe^{2+} and hydroxyl interactions and these proceed to dissociate H_2O_2 and HO_2' radicals. Finally, organics can be oxidised through the abstraction of protons and these organic radicals can again be oxidised. With no reagent limitations, organics can be entirely converted to CO_2, water, and salts. It is mentioned that though Fenton's reagent is well known, a complete correlation to enhanced sludge properties for digestion is not yet established. The SPT schematic is shown in Fig. 2.10 (as adapted from [29]).

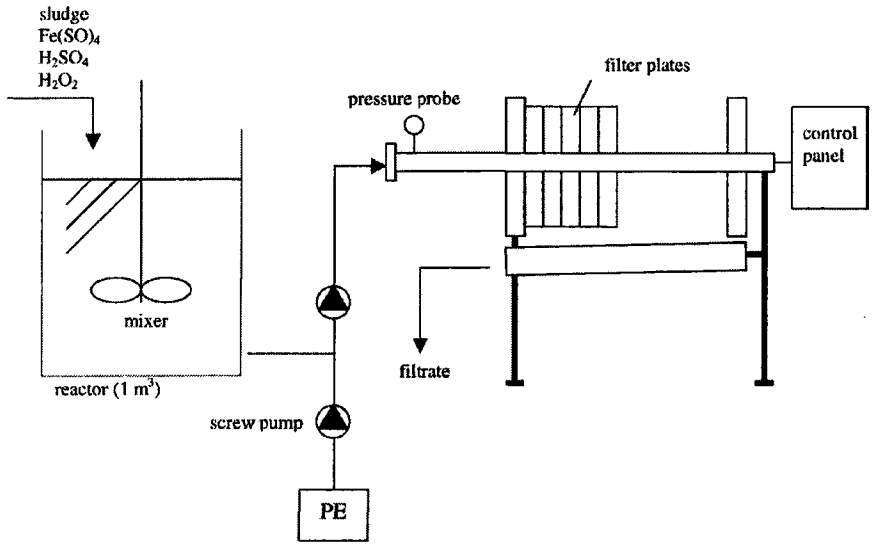


Figure 2.10 Fenton's peroxidation SPT setup (adapted: [29])

Various emulsion polyelectrolytes as shown by the PE box were tested to enhance the flocculation of treated sludge. Untreated sludge was fed to the SPT unit at a dried solids content of 6% and subjected to H_2SO_4 (pH adjustment to 3), Fe^{2+} in the form of $FeSO_4$, and H_2O_2. Ambient temperatures and pressures are maintained along with 100 rpm agitation. Gaseous CO_2 and small organic molecules are emitted and the contact time was stopped when gases were no longer emitted (1-1.5 h). The pH is adjusted to neutral (6-8) after treatment with $Ca(OH_2)$.

Optimal SPT parameters were found to be 5 g H_2O_2/kg DS with 1.67 g Fe^{2+} ions/kg DS at a pH of 3 (by 145 g H_2SO_4/kg DS) and a contact time of 1 h. A chemical feed of 55.6 g $Ca(OH)_2$/kg DS was needed to neutralise the pH. The most promising polyelectrolyte was 'K 111 L' (an acrylamide/adame-quat with 30% cationic and 100% branching strengths). A 30% reduction and 30% increase were then observed for sludge volume and percent DS content in the dewatered cake, respectively. This was described as a reduction in drying energy, on a per inhabitant equivalent (IE) basis, from 457 kJ/IE·d to 88.4 kJ/IE·d for 90% cake solids. Higher nitrogen concentrations and unfortunately, higher heavy metal releases were observed. With a WWTP serving 300,000 IE, fixed, equipment, and maintenance costs were estimated at $73,000/yr, $58,000/yr, and $15,000/yr, respectively. With savings at the dewatering stage, a net gain

of $1,380,000/yr or $200/ton DS was calculated. Peroxidation incorporation was deemed beneficial [29, 30, 99].

Lu et al. (2003) evaluated Fenton's reagent impact on dewaterability of WAS [48]. Digestion was not considered in this study but as in the previous one by Neyen et al. (2003), dewaterability was improved. The addition of 6 g/L Fe^{2+} and 3 g/L H_2O_2 to a WAS of 8.3 g SS/L at an initial pH of 6.14 resulted in a subsequent 10% increase in cake solids content. Beakers (0.5 L) were used with 0.1 L sludge samples at a contact time of 0.5 h. Organic carbon in the cake solids was not significantly affected [48].

Cacho Rivero et al. (2006) studied CH, acid, and a combined CH-acid process for the enhancement of MAD by WAS hydrolysis [58]. Their second reactor configuration consisted of single-stage digestion with a 30 d HRT and the use of 2 g H_2O_2/g VSS. To minimize foaming and improve contact time (up to 24 h) in the SPT vessel, a 6 h peroxide addition was employed for the SPT of 30 g VSS/L WAS. Removals of VSS for the control and acid incorporation treatments were 48 and 63%, respectively. This resulted in a 65% biogas production improvement. An 11% pCOD solubilisation and a reduction in fecal coliforms from 3.6×10^4 to 6.8×10^3 MPN/g DS were achieved. The MPN method is a statistical analysis that provides the Most Probable Number value for fecal coliforms. Class B biosolids designation (less than 2,000 MPN/g DS) was awarded to both the control and the SPT sludge [58]. Biosolids classifications are discussed in Section 2.7.

2.4.2 Alkaline

Lin et al. (1997) completed a study on the alkaline solubilisation of WAS for the enhancement of AD [18]. A single-stage, high-rate, semi-continuous LSR at MAD conditions was used and the HRT was lowered from 20-7.5 d. It was stated that chemical SPT is more efficient and cost-effective at ambient temperature as compared to thermal and thermochemical SPTs. A summary of improvements in digester performances was given and illustrates the percent increases for the 20, 13, 10, and 7.5 d HRT. At 20, 10, and 7.5 d , reactor D, which was pretreated with 20 meq/ L NaOH for a feed containing 2% TS, showed the most significant improvements. The higher percent increase in VS

and COD reductions, as well as gas production was more evident after 7.5 d. After 20 d, the overall improvement in performance was less noticeable. For 20 and 7.5 d the respective percent increases in VS and COD removals as well as gas production were 29, 20, and 98% and 133, 123, and 286%, respectively. For an AD HRT of 13 d, COD and VS removals were lower for reactor D than they were for the control test with no SPT. No explanation was given. Dewaterability was also tested and the pretreated sludge improved by up to 200% in capillary suction time (CST) filterability tests.

Moeller-Chávez et al. (2002) evaluated both alkaline and thermal SPTs separately for PS hydrolysis [28]. A subsequent addition of 0.0-0.2% yeast extract for the enhancement of AD was also tested. The results shown below will be for alkaline treatment alone. Mesophilic AD with a 30 d HRT was used to observe COD, TSS, and VSS removals. Biogas productions were computed with the BMP test. The CM process consisted of a NaOH concentration maintained at 40 g/L to reach a pH of 10 during a 1 h contact time. Hydrochloric acid (HCl) was used to neutralise the pH. A decrease in COD, TSS, and VSS removals was actually observed with SPT incorporation compared to the control runs. Strangely, a 25% improvement in biogas productions was also observed. The authors suggest the significant initial degradability of PS as being responsible for low additional solids reductions but provide no explanation with respect to biogas improvements. Results were not deemed to be statistically significant with respect to either performance decreases or increases [28].

Alkaline and acid SPTs were studied by Chen et al. (2007) [43]. Results for the CM treatment will be discussed but in some cases, also compared to acidification. WAS characteristics were 14, 11, 13, and 0.04 g/L for TSS, VSS, TCOD, and sCOD, respectively. Proteins and carbohydrates were said to account for 90% of the VSS. Sludge pretreatment was conducted at ambient temperatures in 13.5 L reactors that were stirred at speeds of 80 rpm. The pH was altered from 6.8 to ranges of 4-11 by adding 80 g/L NaOH or 71 g/L HCl. Alkaline SPT showed the highest solubilisation results (8 g/L sCOD) at a pH of 11 as compared to 1.9 g/L at a pH of 4. Acidification did increase sCOD by approximately 0.6 g/L. The protein concentrations at higher pH and for the control runs were 1.75 and 0.25 g/L, respectively. Phosphorous and nitrogen (PO_4^{3-}-P

and NH^{4+}-N) were substantially released into the soluble phase and removal was now deemed simplified by means of phosphorous precipitation and ammonia stripping. Acidification solubilised phosphorous and nitrogen to an even greater extent. Concentrations of these after CM and a 14 d AD HRT were 300% higher than control values. Biogas productions were highest without SPT incorporation [43].

2.4.3 Ozone

The impact of OZ on AD for the enhancement of biogas production and sludge reduction was investigated by Bougrier et al. (2007) [14]. Settling, odour, and viscosity improved following SPT with ozone. Dosage should be evaluated based on the purposes of the process but when dosage was elevated to 0.5 g O_3/g TS, 20% COD mineralization can occur. Different doses were used in their tests and it was found that a dose of 0.15 g O_3/g TS resulted in the highest percent increase (37%) in pCOD solubilisation. Biogas production at this ozone dosage was approximately 244% higher than that of the WAS without SPT. The authors explain that at slightly higher ozone dosage (0.18 g O_3/g TS) biogas production is only increased by 191% due to the formation of refractory compounds or more acidic conditions. They conclude that OZ should be economically compared to biogas production and other SPTs to effectively optimize performance and costs in a full-scale facility.

Ozone was used as SPT for AD of an unspecified mixture of PS and WAS [17]. Weemaes et al. (2000) found that ozonation was optimal at a dosage of 0.10 g O_3/g COD and that it led to sludge oxidation and solubilisation of 38 and 29%, respectively. Higher dosages were found to have a less pronounced effect. Methane production was increased by 180%. In this study, ozonation was found to have a negative effect on the dewaterability of the sludge prior to AD. Following AD, the impact was nullified. The authors emphasize that their results stem from non-adapted microbial communities in static batch tests. They then underline that continuous digestion tests with microbial communities adapted to oxidized sludge as a feed substrate need to be performed to obtain more realistic and reproducible results.

2.4.4 Chemical SPT Summary

Acid, alkaline and ozone hydrolysis have been evaluated in the literature. All processes are capable of hydrolysis to different extents. Both CM and OZ provide desirable LSR digestion improvements and CST test dewaterability impacts. Drawbacks to CM include SPT contact time, chemical costs, pH correction costs (to return to desirable digestion values after hydrolysis), and increases in sludge due to chemical addition. Drawbacks to OZ include high energy demands for O_3 generation and the potential to degrade sludges by ozonation to undesirable levels. Too few articles were found with regards to acid SPT to validate its inclusion in PretrAD. The same was found for LC and will be shown for the enzymatic (ENZ) SPT. From this point forward, CM will be used to solely represent alkaline SPT.

Wastewater composition ranges and SPT working ranges for CM are shown in Table 2.13. Chemical (alkaline) hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.14. A negative to a positive range is sometimes shown for the biogas improvement (right-most column). In these cases, the authors found percent reductions and improvements in biogas production.

Table 2.13 CM WW composition and working ranges

	WW Composition (d and g/L)						**Energy Use**		
Ref.:	BT θ_x	TCOD	TS	VS	TSS	VSS	Dose (kg/m^3)	t (h)	V (L)
[4]		27.7	38	26			0-21		
[10]		17	17	12			1.7-3.7		
[13]							7		
[15]		56	31				0-26.1		
[16]		9			6.6	5.7			
[18]	3						0.8-1.6		241
[28]							40.0	1	
[43]		13.4			13.8	10.8		48-480	
[61]		56	39	37			260	0.5	

TCOD (15-50 g/L), TS (15-40 g/L), VS (12-35 g/L), TSS (10-25 g/L), VSS (8-20 g/L)
CM dose (1-5 kg/m^3), t (0.05-1 h), V (0.5-1 L), pH adjustment (10-12)

Table 2.14 CM hydrolysis result ranges and AD improvements

Ref.	Solubilisation (%)			MTAD (d and °C)			Reductions (%)						Biogas Prod.
	pCOD	TSS	VSS	$\theta_{Control}$	θ_{SPT}	T	TCOD		TS		VS		% Impr.
							Control	SPT	Control	SPT	Control	SPT	
[4]	18-42			7		37	55	42			21	30	13
[10]	7-29	6		20		35							0
[15]	58-60												−12-+28
[18]	30-51			20		35	39	47			35	36-42	36
[18]	30-51			7.5		35	21	38			19	19-26	90
[28]							66	54	67	61	72	66	30
[43]	36-43			2									
[43]	36-43			20									

pCOD solubilisation (15-40%), TSS solubilisation (10-30%), VSS solubilisation (10-30%)

Control and SPT TCOD reductions (30-60% and 30-60%), TS reductions (25-60% and 25-60%), VS reductions (25-60% and 25-60%)

Biogas production improvement (5-30%)

Wastewater composition ranges and SPT working ranges for OZ are shown in Table 2.15.

Table 2.15 OZ WW composition and working ranges

Ref.	WW Composition (d and g/L)						Energy Use		
	BT θ_x	TCOD	TS	VS	TSS	VSS	Dose (kg/m^3)	t (h)	V (L)
[14]		18			16	14	0.2-3	0.017-0.75	0.3
[17]		8			10	6	0.35-1.10	1-3	15

TCOD (10-25 g/L), TS (10-25 g/L), VS (8-20 g/L), TSS (10-20 g/L), VSS (8-15 g/L)

OZ dose (2.5-10 kg/m^3), t (0.017-1 h), V (0. 5-1 L)

Ozone hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.16.

Table 2.16 OZ hydrolysis result ranges and AD improvements

	Solubilisation (%)			**MTAD (d and °C)**			**Reductions (%)**						**Biogas Prod.**
Ref.	pCOD	TSS	VSS	$\theta_{Control}$	θ_{SPT}	T	TCOD		TS		VS		% Impr.
							Control	SPT	Control	SPT	Control	SPT	
[14]	46	47											14-144
[17]	58	59	67	30		33	36	47-64					70-120

pCOD solubilisation (20-55%), TSS solubilisation (20-55%), VSS solubilisation (20-55%)

Control and SPT TCOD reductions (20-50% and 25-55%), TS reductions (20-50% and 25-55%), VS reductions (20-50% and 25-55%)

Biogas production improvement (20-80%)

References that were considered for the ranges establishment shown below the above tables are listed in Table 2.17.

Table 2.17 Chemical SPT studies without sufficient, comparable or discernable data

	References
CM	[29],[30]
OZ	[25],[26],[147]

2.5 BIOLOGICAL PROCESS

Biological SPT could be labelled hydrolysis enhancement and be performed using excess optimal aerobic and acidogenic bacteria [13]. The bacteria are thought to secrete extracellular enzymes such as proteases and amylases that improve solubilisation [11]. It could also be performed using enzymes to catalyze cell degradation [6]. Enzymes are of particular interest as they can be found within the intracellular matrix which can be easily released through the use of other SPT processes [11]. Drawbacks to enzymatic SPT include high cost and strong odours.

2.5.1 Enzyme

Barjenbruch et al. (2003) evaluated the effects of enzymatic, mechanical, and thermal SPT on foaming within the digester, reload of sludge liquor, sanitization, and dewaterability [32]. The disintegration achieved by SPT is known to benefit the WW treatment train by, among others, improving settling performance of both the bulking and floating sludge as well as by reducing foaming. Hydrophobicity of the sludge is thought to contribute to foaming but by employing the BATH test (material adhesion to hydrocarbons), the authors found that no correlation could in fact be made. Foaming was found to decrease minimally by enzymatic, mechanical, and low-temperature (90°C) thermal SPT. High-temperature (121°C) thermal SPT was responsible for a complete reduction of foaming. It was concluded that foam production depends on the ratio of exo-polymer substances as opposed to the filament structure of the sludge. Enzyme SPT improved VSS removal (1.5%) and biogas production (12.5%) the least compared to the other SPTs. Dewaterability was improved most significantly by enzymatic SPT. A 26% decrease in CST was observed. High-temperature thermal and HPH SPTs increased CST by 10% each whereas low-temperature thermal SPT decreased suction time by 6%. The authors suggested that the trend signified that dewatering is enhanced with sludges containing a smaller ratio of fine particles. Sanitization was markedly improved with regards to *Escherichia coli* reductions following SPT. The 20 d AD HRT provided negligible improvement in these reductions and thus it was assumed that the positive impact on sanitization is outweighed by the PS:WAS ratio (40:60). The authors

concluded by justifying the further evaluation of enzymatic SPT based on simple handling and its positive effect on AD.

Park et al. (2005) studied thermochemical and biological hydrolysis and their ability to enhance AD [13]. Two three-staged LSR digestion systems were used. The first, second, and third stage consisted of SPT hydrolysis, the acidogenic process, and the methanogenic process, respectively. To perform the biological hydrolysis, a 5 L reactor was used in which WAS is agitated at a speed of 150 rpm and hydrolyzed at 30°C by aerobic bacteria (*Cellulomonas uda* KCCM 12156 and *C. biazotea* KCCM 40760). In the acidogenic process, *Clostridium butyricum* KCCM 35433 was utilized to promote the production of volatile fatty acids (VFA). This process was performed in a 10 L reactor agitated at a speed of 100 rpm and maintained at a temperature of 37°C. The methanogenic process was performed in a 20 L reactor agitated at a speed of 50 rpm and maintained at a temperature of 41°C. Rumen microorganisms were used to promote methane production. The retention times for the first, second, and third stages were 3, 6, and 12 d, respectively. Solubilisation of pCOD increased from 8% in the control to 88% and 24% in the thermochemical and biologicial SPT runs, respectively. Volatile solids (VS) reduction increased from 32.3% in the control run to 77.5% and 75% in the thermochemical and biologicial SPT runs, respectively. Biogas production was observed at 0.29, 0.52, and 0.43 L/g VS for the control, thermochemical, and biological runs, respectively. Following the same sequence, methane content in the biogas was found to be 70.2, 79.5, and 75.3%, respectively. Although thermochemical hydrolysis was a quicker and more efficient SPT than biological hydrolysis, the latter was concluded to involve lower maintenance costs. When treating a small quantity of WAS quickly, thermochemical SPT was recommended. When treating WAS on a large-scale and cost is of importance, biological SPT was recommended.

2.5.2 Biological SPT Summary

Incorporation of ENZ in PretrAD was not justified by the potential improvement results for the 2 studies discussed above. These results varied significantly and no direct comparison could be made with the other ENZ studies evaluated.

2.6 COMBINED PROCESSES

Joining SPT processes together can yield the benefits of each process [11]. One example of thermochemical SPT is the acidification (to a pH of 1-2) of the sludge after thickening followed by high temperature hydrolysis (140°C, 30-40 min) [11]. This is known as the Krepro-process and the sludge is solubilised up to 40% [11]. This sludge solution's pH is corrected upwards (from a pH of 1-2 to a pH of 3) with ferric salts and alkali and is centrifuged to separate out the dissolved heavy metals and organic fibrous particles [11].

2.6.1 Thermochemical

The following is the continuance of the earlier discussion on the study by Kim et al. (2003) [4]. The chemical and thermochemical SPT results will now be evaluated. For the chemical SPT, sodium hydroxide (NaOH), potassium hydroxide (KOH), magnesium hydroxide ($Mg(OH)_2$), and calcium hydroxide ($Ca(OH)_2$) were used at ambient temperature and pCOD solubilisation results were 39.8, 36.6, 10.8, and 15.3%, respectively. The results for thermochemical SPT, involving the same sequence of alkaline agents with optimal temperature and duration of 121°C for 30 min, were 51.8, 47.8, 18.3, and 17.1%, respectively. These results marked an improvement from the control where only 8% pCOD solubilisation was observed. An optimal agent and dosage was also selected as NaOH at 7 g/L. Reductions in VS and increases in biogas production after MAD for 7 d were 30 and 46% as well as 13.4 and 37.8% increases for chemical and thermochemical SPTs, respectively. Biogas production and VS reduction for the control after MAD for 7 d were 2,500 L/m^3 WAS and 20%, respectively.

Valo et al. (2004) conducted a study on thermal, chemical, and thermochemical SPT followed by continuous AD [10]. The most beneficial SPT observed in terms of biogas production was thermochemical. At treatment temperatures of either 170°C with a pH of 12 or at 130°C with a pH of 10 which were found to be optimal, pCOD solubilisation reached 83 and 58%, respectively. Variations in temperature, not pH, were found to more strongly affect their results. These solubilisations were higher than the thermal SPT observations of approximately 60 and 31%, respectively. Potassium

hydroxide was selected as the optimal alkaline agent as the authors found from previous studies that it is more efficient in AD than NaOH. To increase the pH to 10 and 12, dosages of 1.68 and 3.65 g KOH/L were used. For the complete trial (SPT and AD), the optimal temperature of 130°C was selected with a pH of 10. The increases in COD removal and biogas production were 37 and 92%, respectively. The authors concluded that in terms of full-scale operation, thermal SPT would clearly be the more advantageous process as no chemicals are needed and the WAS is more significantly reduced.

A study on the hydrolysis kinetics and solubilisation of WAS as a result of thermal-alkaline SPT was performed by Vlyssides et al. (2004) [12]. Low temperatures were used (50-90°C) with increased pH in the range of 8-11. It was found that hydrolysis can be categorized into two stages. The first stage was noted as the rapid hydrolysis stage where VSS solubilisation represents 64-85% of the total VSS solubilisation observed after a 10 h SPT contact time. The first stage lasted 1 and 8 h for pH adjustments to 8 or 9 and 10 or 11, respectively. Solubilisation was thus, most improved at a pH of 11 and a temperature of 90°C. Methane production when SPT was incorporated prior to TAD was recorded at 0.28 L CH_4/kg VSS. No further information (control values or digestion parameters) was given.

Park et al. (2005) investigated the efficiency of thermochemical and biological hydrolysis [13]. The former will be evaluated herein and showed the most significant improvements. Reductions of COD and VS were measured at 88.9 and 77.5%, respectively. Methane yield was found to be 0.52 m^3/kg VS (520 L CH_4/kg VS). A three-stage continuous digester was utilized for the tests. The first stage of the digester handled the hydrolysis step and the second and third stages handled the acidogenic and methanogenic steps, respectively. This digester was found to be preferable when results were compared to those of single and two-stage continuous digesters. Mention of costs was made in the conclusion whereby thermochemical is preferred over biological SPT for its efficacy and speed of treatment. Costs however, are higher due to the chemicals and heat required. Biological hydrolysis was promoted for FSR treatment based on lowest overall costs.

In this study by Penaud et al. (1999), pH was said to be the primary contributor to improved COD solubilisation and VS reduction [15]. Thermochemical SPT was found to be optimal at 140°C for 30 min whereby heating thus enhanced the effects of NaOH addition. A dosage past 5 g Na/L did not increase pCOD solubilisation without the additional incorporation of thermal SPT. Including thermal SPT, a dosage of 26.1 g Na/L led to 85% solubilised pCOD, whereby 5 g Na/L led to 80% solubilised pCOD. Other alkaline agents were tested [KOH, $Mg(OH)_2$, and $Ca(OH)_2$] and showed similar pCOD solubilisation results.

2.6.2 Thermochemical SPT Summary

Studies for both CM and CH have been classified as TC. To incorporate both SPTs,energy and cost demands are, in essence, doubled. Where authors have briefly evaluated cost impacts of the incorporation of a single SPT unit (e.g., ULT, MWH or OZ), subsequent improvements were at times insufficient. As such, subsequent improvements would also need to be doubled to recover the demands of two SPT uses. Conventional heating however, conceptually replaces a portion of the heating that would otherwise be performed in the digester. Thus, improvements as a result of TC incorporation need be higher than a single SPT unit but may not necessarily need to be doubled.

As shown in the literature review, both CH and CM can be strong hydrolysis processes. Since the pretreated sludge can either only reach certain hydrolysis levels or must not reach specific levels due to undesirable effects (e.g., increased foaming and/or sludge boiling), limits to SPT use exist. These limits translate to the minimal increases in subsequent improvements when TC is compared to CH.

Literature values for TC (i.e., CH+CM) SPTs are listed below. Wastewater compositions and working ranges are those for CH and CM separately and can thus be found by following the noted references of Tables 2.18 and correlating them to the tables for CH and CM SPTs. A cost analysis of MWH+CM was conducted using PretrAD. For all instances of TC labelling however, only CH+CM are being referenced. In Chapter 5, TC(MWH) reflects a MWH+CM SPT and cost combination.

Thermochemical (CH+CM) hydrolysis result ranges and subsequent AD improvements are outlined in Table 2.18.

Table 2.18 TC hydrolysis result ranges and AD improvements

Ref.	Solubilisation (%)			Optimal Settings	MTAD (d and °C)			Reductions (%)						Biogas Prod.
								TCOD		TS		VS		
	pCOD	TSS	VSS	kJ/kg TS	$\theta_{Control}$	θ_{SPT}	T	Control	SPT	Control	SPT	Control	SPT	% Impr.
[4]	35-85			121, 0.5, 7.0	7		37	55	61			21	46	38
[10]	20-43			130, 1, 3.7	20		35	44	60	27	36	35	60	80
[13]	88							56	89				78	
[15]	72-84		15	140, 0.5, 5										-19-+38
[16]	53	48	50		8	8	37	32	54	32	8	39	9	200
[16]	53	48	50		8	6	37	20	26	8	-5	11	0.5	982
[61]	37-76			140, 0.5										

pCOD solubilisation (25-60%), TSS solubilisation (25-60%), VSS solubilisation (20-50%)

Control and SPT TCOD reductions (25-55% and 25-60%), TS reductions (15-30% and 15-30%), VS reductions (15-35% and 15-50%)

Biogas production improvement (25-60%)

References that were considered for the ranges establishment shown below the above tables are listed in Table 2.19.

Table 2.19 Combined SPT studies without sufficient, comparable or discernable data

	References
TC	[12], [19],[127]

2.7 FULL-SCALE FACILITIES

Assessments for SPT incorporation into full-scale facilities were found. A dozen studies highlighted the use of mechanical, thermal, chemical, and combined processes. The following is a discussion of their experiences with respect to benefits and drawbacks of SPT use. Some results will be outlined but the focus herein is to provide an overview of primarily qualitative effects. This was done because the variability of operational characteristics at each full-scale facility was very high, cannot be adequately compared, and SPT operation with respect to each WWTP and lab-scale methodologies was significantly altered to achieve beneficial use.

Kepp et al. (2000) reported on a 5-year CAMBI CH facility, as will be mentioned below based on the US EPA fact sheets, that was first attempted in Norway [33]. Dewatered sludge (PS:WAS:Dewatered solids = 33:33:33, 10-12% DS) is heated by steam and as a result, 50% of the digester volume is no longer required, 60% stabilisation is achieved (based on COD to CH_4 conversion), and pathogen reduction is 100%. The pressure differences created by the elevated SPT temperatures sterilize and lyse the cells. This study remarks on the Porteous process (a CH technology) that was incorporated at many sites worldwide and has since been virtually eliminated due to odour and economic concerns. The CAMBI process heats sludge to 130-180°C for a 0.5 h contact time. Cell lysis reduces particle size which in turn was noted as a positive change in viscosity such that 12% DS can be digested as effectively as PS with 5-6% DS. The authors mention that a higher sludge concentration can now be fed to the digester and that buffering capacity and digestion stability are improved. Dewaterability using the Porteous process showed 20-25% increases in percent cake DS while 60-80% increases are reported for the CAMBI process. Optimums are mentioned at 150-165°C with 10 min contact times. A contact time of 30 min had insignificantly better results. As the steam is internally recycled, the patented process is said to produce no localized overheating and substantially avoid scaling. Odour problems are minimized by the closed system combining SPT and MAD. The MAD HRT was reduced from 20 to 17 d, solids reductions improved from 30 to 46%, and sludge disposal was thus decreased from 9×10^6 to 4.37×10^6 kg. Electricity production was increased by 20%. Stabilized biosolids

nutrient levels were 10 and 20% higher for nitrogen and phosphorous, respectively. A schematic of the CAMBI process at the Norway WWTP is shown in Fig. 2.11 (as adapted from [33]).

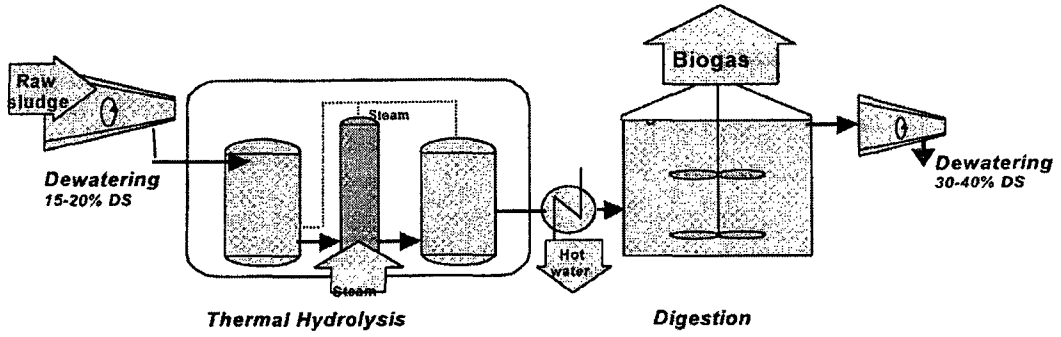


Figure 2.11 CAMBI treatment incorporation train (adapted: [33])

Incorporation of ULT SPT was demonstrated at a Singapore water reclamation plant and evaluated by Xie et al. (2007) [36]. The facility includes two 5,000 m^3 egg-shaped digesters receiving commingled sludge at a PS:TWAS ratio of 33:66. Solids concentrations for PS and TWAS are solids of 1-2 and 2-4%, respectively. Biogas production as a result of SPT use increased by up to 45% and VSS reduction was thus assumed to be improved by up to 30% when optimal conditions were used. Almost negligible solubilisation levels were achieved with the use of 5×6 kW sonotrodes treating 8.33 m^3 sludge/h at contact times of 1.5 s. Biogas production was however, observed to be consistently more than 200 m^3/d above that of the control digester and reflects a 15-58% improvement after a 30 d MAD HRT. Biosolids nutrient levels were not affected. A brief energy analysis was conducted and showed that 288 kWh/d would be required to provide a 2.2 kWh/m^3 gain from biogas conversion. The 288 kWh/d value is substantially lower than that found in the runs that were made for this thesis. The specific run inputs and results are given in Chapter 4 and 5. Hydrolysis contact time and the 25% difference in treated flows explain the large discrepancy. PretrAD found an average 4.2 kWh/m^3 gain from biogas conversion. Insufficient information is listed in the paper to evaluate the difference between these findings. Regardless, if potential gains from biogas conversions are lower than those established, ULT use would simply hold less potential. This will be

discussed further in the Chapter 5 [36]. The plant logistics and energy conversion for ultrasonication for the Singapore facility is shown in Fig. 2.12 (as adapted from [36]).

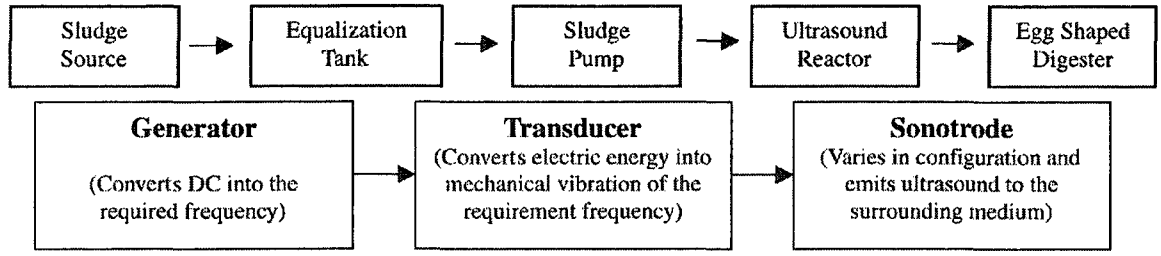


Figure 2.12 ULT incorporation and ultrasound generation from direct current electricity (adapted: [36])

Zábranská et al. (2006) evaluated the integration of lysate centrifugation technology in 3 WWTPs [49]. Biogas productions and COD reductions were found to range from 15-26 and 48-49%, respectively. Sludge disintegration (i.e., solubilisation) is achieved by the disintegrating gear mounted at the end of the TWAS flow. Centrate quality is therefore unaffected and high throughputs can be achieved. As mentioned in many studies, higher solubilisations occur with younger WAS (shorter aerobic digestion SRTs) and improved AD results are found with shorter AD HRTs. As was found in this research, "sometimes certain data (required for the economic and energetic balance evaluation) are not accessible in sufficient quantity and reliability". One full-scale plant listed 2 mesophilic digesters with 4,400 m^3 capacities and 40 d MAD HRT treat the WW from the 100,000 IE Liberec, Czech Republic. An SPT throughput of 39 m^3/h and rotational speed of 3,140 rpm was used. Solubilisations of pCOD (9-18%) and biogas production improvements of 26% were observed. Positive effects on viscosity were again seen and resulted in the ability to thicken WAS to 9-11% TS as opposed to 6% TS without clogging of pumps. A significantly smaller WWTP (70,000 IE) in Germany with 2 digesters of 1,800 m^3 and 35 d MAD HRTs incorporated LC at a throughput of 12 m^3/h and rotational speed of 2,250 rpm. Solubilisations of 9-11% and biogas production improvements of 15% were observed. A plant serving 650,000 IE in Aachen-Soers, Germany showed a 15% improvement in biogas production and a subsequent 2,410 kWh/d energy gain from the 1,128 m^3 biogas/d. This reflects another 2.13 kWh/m^3 biogas conversion value and effectively represents a 7,691 kJ/m^3 heating or electrical value.

Results from this thesis, shown in Chapters 4 and 5, found a different but commonly used 33-35,000 kJ/m^3 methane heating value that was adjusted for losses due to conversion efficiencies. For heating and electrical conversions they were 25,575 and 11,935 kJ/m^3 (75% and 35% efficiencies), respectively. Thus, both the above studies seem to have used meagre ~7,700 kJ/m^3 biogas conversion values. Explanations were not provided [49].

Ozonation was studied at a full-scale facility for 2 years and explained by Yasui et al. (2005) [77]. This small facility employs 2×1,125 m^3 mesophilic anaerobic digesters and produced 10,000 ton/y dewatered sludge cake. Ozone dosage was set at 24 kg O_3/d for low throughputs of 22-44 m^3/d. An 88% VSS reduction was noted alongside a 30% improvement in biogas production with a positive impact on sludge cake dewaterability (20 to 32% solids). Biosolids productions were reduced by 51-82%. The high VSS reductions were said to also contribute to lower drying and incineration costs during sludge handling. The schematic for OZ incorporation at this facility is shown in Fig. 2.13 (as adapted from [77]).

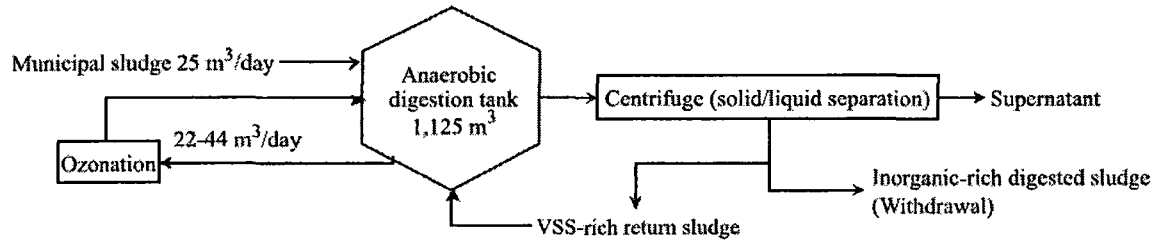


Figure 2.13 OZ incorporation for digested sludge treatment (adapted: [77])

A WWTP serving 1,000,000 IE was selected for the scenarios evaluated by PretrAD and the entire WAS flow was subjected to SPT. As such, more than 650% of the WAS pretreated in the study by Yasui et al. (2005) was pretreated in the model. The potential to incorporate substantial treatment by SPT is thus shown to be limited. Digestion improvements however, may be sufficient without significant WAS SPT. PretrAD allows the user to specify TSS and VSS reductions in the digester and for the runs conducted, a 15% reduction in biosolids production was observed. If this were increased as it was observed at the full-scale facility with OZ SPT, OZ incorporation potential would become more positive. More is shown on OZ incorporation potential in Chapter 5.

Three facilities were investigated in a study by Winter (2002) [90]. At all three WWTPs biogas productions and solids reductions were improved by approximately 20%. The first two pilot-scale facilities incorporated SBM to treat TWAS. The first was noted as treating TSS and VSS concentrations of 25 and 17 g/L. The mesophilic anaerobic digester had a 17-18 d HRT. Storage tanks were included to ensure continuous feed of pretreated TWAS (12-30 m^3/d). The SBM operates at a motor rating of 37 kW, speed of 15 m/s, grinding chamber void volume of about 15% (the remainder was occupied by various grinding beads). Certain parameters were varied to find optimal conditions. Sludge flows (0.45-1.3 m^3/h), TSS concentrations (5-25 g/L), and bead diameters (150-250 and 600-800 μm) were varied. Lower sludge flows increase contact times and subsequently E_{spec} inputs. Higher solubilisations are achieved. SBM efficiency was also noted to improve with smaller diameter beads. Solubilisations of pCOD were observed as 25% (low E_{spec}) and 60% (higher E_{spec}). The third facility incorporated OZ and was run as a batch process with doses of 0.06 kg O_3/kg SS. Average pCOD solubilisations of 30% were observed. For the SBM facilities, polymer demand and dewaterability were not significantly affected. Gains that included disposal costs reductions (35-79%), thermal energy recoveries, and electrical energy recoveries were calculated and were found to meet incorporation demands exactly. Additional results for the OZ facility were not yet available. The incorporation schematic alongside the control treatment schematic is shown in Fig. 2.14 (as adapted from [90]).

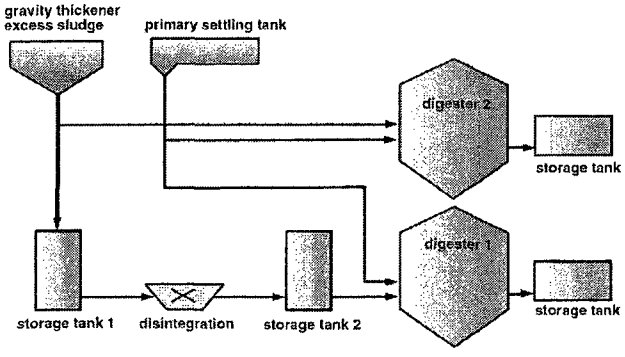


Figure 2.14 Control and SPT incorporation schematics for the SBM pilot facility (adapted: [90])

High pressure homogenization was incorporated into a WWTP in Germany handling WW from a population of 30-40,000 IE. Its impacts were reported by Onyeche

(2004) [101]. The plant produces 60 m^3/d of sludge which was concentrated to 40 g/L from an initial 18 g/L. Digested TWAS from the two-stage MAD process is then macerated to prevent clogging of the homogeniser valve. A throughput of 2.7 m^3/h was used with a pressure of 15 MPa. Biogas production was measured separately by LSRs to avoid the biogas contributions of untreated PS and WAS. A graphical energy balance was also provided to depict break-even energy use over a 9 week period but these results were unclear. An average energy consumption of 0.2 kWh/kg sludge produced was however noted. The schematic describing the operation is shown in Fig. 2.15 (as adapted from [101]).

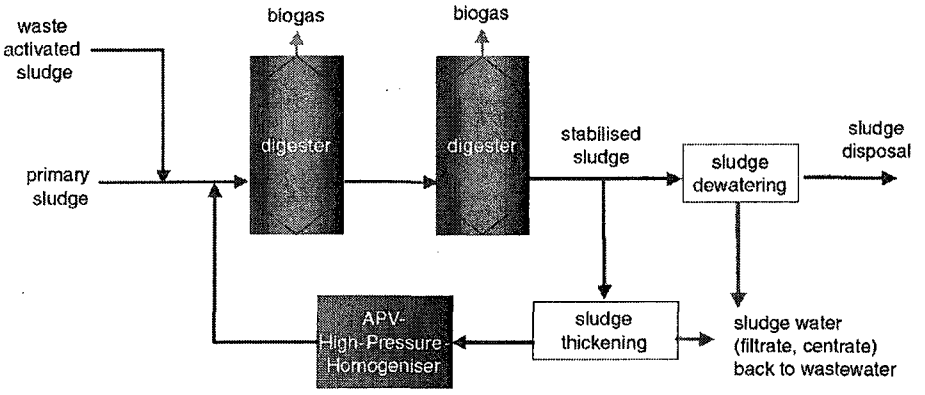


Figure 2.15 HPH integration for two-phase digested TWAS SPT (adapted: [101])

Optimal results were found at low pressures (15-20 MPa) where 30% more energy could be gained from the additional biogas production. Biosolids were reduced by 23%. These were said to promote digester cost investment reductions (lower volume requirements) and operational time and energy for digested sludge dewatering [101].

Full-scale MicroSludge^{TM} (HPH and CM) facilities are discussed below and in the Chapter 3 when SPT equipment theory is given [83, 153].

2.7.1 US EPA Fact Sheets and Biosolids Classifications

The US EPA performed an evaluation on emerging technologies for biosolids management [167]. It is shown here to outline some of the full-scale technologies available and to establish the level of current and common information regarding SPTs. More stringent sludge handling and disposal regulations in both the US and EU have

promoted SPT research as a means of attaining directive targets. Those of the EU are fairly similar to those of the US and biosolids disposal was projected to resemble that of the US by 2005 [69, 111]. As such, only the US regulations will be discussed below.

Technologies have been classified as established, innovative, and embryonic. An established technology was defined as a widely used technology (more than 25 facilities in the US). Innovative refers to a technology that meets 1 of 4 criteria: tested at full-scale in the US, implemented in the US for less than 5 yrs, have some level of beneficial use or established overseas with some level of beneficial use in the US. Embryonic technologies were those that were solely in the lab-scale developmental stage in the US (whether or not they've reached the pilot or full-scale stage overseas). For example, as shown in Fig. 2.16 (as adapted from 'Table 2.1' of the review), chemical and heat conditioning, two common-place technologies are deemed established whereas enzyme conditioning is deemed embryonic.

Established	Innovative	Embryonic
Chemical Conditioning Heat Conditioning	Cell Destruction ▪ Chemical (MicroSludge™) ▪ Ultrasonic	Cell Destruction ▪ Biological (BIODIET®) Electrocoagulation Enzyme Conditioning

Figure 2.16 State of development of conditioning technologies (adapted: [167])

Their study stated that 'comparative criteria are general attributes that the technology may possess relative to the attributes of established technologies'. Such criteria included impacts on other processes, complexity, emissions, beneficial uses, energy demand, and environmental footprint.

Potential benefits of the innovative and embryonic technologies are given and compared to established technologies in Fig. 2.17 (as adapted from 'Fig. 1.1' of the review). Though the US EPA separated the Microsludge™, ULT, and ENZ processes from the CAMBI CH process, they are both considered in the review as technologies with the primary incorporation benefits of enhanced AD by sludge hydrolysis. As shown, Microsludge™, ULT, and the CAMBI processes are thought to be of relatively low cost

when compared to the established thermal and alkaline conditioning methods. Solids reduction is an improvement all processes share. Based on pathogen reduction, the CAMBI process also produces Class A biosolids.

Technology and Advancement(s)	Potential Benefit* as Compared to Established Technologies					
	Low Capital Cost	Low Annual Costs	Reduces Solids or Thickens	Produces Class A Biosolids	Reduces Odor	Beneficial Use (Non Agriculture)
Chapter 2 Conditioning						
Established						
Chemical Conditioning						
Heat Conditioning						
Innovative						
Cell Destruction						
Chemical (Microsludge™)		●	●			
Ultrasonic		●	●			
Embryonic						
Enzyme Conditioning			●			
Chapter 4 Stabilization						
Established						
Alkaline Stabilization						
Innovative						
Anaerobic Digestion						
Thermal Hydrolysis (CAMBI Process)	●	●	●	●		

Figure 2.17 Summary and comparison f biosolids technologies to established processes (adapted: [167])

For all innovative and embryonic technologies listed in the review (regardless of US EPA Chapter classification), a 1-2 page report was given. The report outlined the primary technology objectives, state of development, full-scale example, sample costs, and vendor(s) name(s). The ULT, Microsludge™, ENZ, and CAMBI processes are summarized here based on those reports.

Ultrasound technology objectives were listed as including the increased rate of AD by sludge hydrolysis, sludge settling improvement, denitrification facilitation, and biogas production ameliorations. Two full-scale examples include the sewage works

plant in Sweden (2002) and the Mangere WWTP in New Zealand (2005). Available cost information is based on a 19,000-30,000 m^3/d treatment facility where only 30% of the sludge is subjected to SPT. Capital costs were reported as $265,000. Costs for O&M were reported as $10-20,000/yr and include labour, parts, and power consumptions. The listed vendor was EIMCO® Water Technologies.

MicroSludge™ is explained in Chapter 3 and as such, objectives, development status, and treatment process will not be explained here. Available cost information and vendor name are discussed. For the handling of 190 m^3/d of WAS the MicroSludge™ System 50 has approximate capital and O&M costs of $\$1.7\times10^6$-$2\times10^6$ and $68-119/dry ton treated, respectively. Electrical, chemical, and maintenance demands were considered in the O&M costs and were reasoned for the processing of WAS to a range of 4-7% total solids. Electricity and chemicals were assumed to be purchased at $0.07/kWh and $0.46/kg, respectively. The former was listed as the largest O&M cost contributor with power consumptions of 500-1,000 kWh/ton dry solids. Paradigm Environmental Technologies, Inc. was the reported vendor.

Objectives for ENZ hydrolysis included organic material degradation for dewaterability enhancement, odour reduction, and in some cases, AD ameliorations. Development status lies primarily in the meat industry where fats and oils breakdown was deemed promising. Studies were found, as they were in this literature review, revolving around COD in biosolids digesters. Some research was also listed as having shown significant increases in cake percent solids from conventional dewatering units. Limited cost information was listed. The approximate capital cost was stated as $68/kg of enzyme solution with 2.2 kg needed for 1-5 tons of sludge and 4.4 kg needed for 6-25 tons. The noted vendor was Eco-Cure, Inc.

Thermal hydrolysis can be conducted by the patented CAMBI process. Biosolids reductions and biogas production improvements are its major objectives. This process is deemed innovative and was first incorporated at a full-scale facility in 2002 in Scotland. Further installations have been made across Europe, Australia, and Japan. CAMBI involves the dewatering (15-20% solids) of the sludge prior to hydrolysis by high

temperatures (160°C) and pressures (690 kPa). An approximate 65% solids reduction is achieved and pathogen reduction is high. Odours are however, an important downfall. When compared to the similar Zimpro Wet Air Oxidation process, it was found to result in more biogas. The approximate capital and O&M costs were $\$6\times10^6$ and \$360/dry ton treated, respectively. The O&M costs include WWTP operation, biosolids disposal, labour, overhead, depreciation, and interest. All costs are based on the 19,000 m^3/d Hamar WWTP in Norway. The listed vendor was RDP Technologies, Inc.

Finally, the review evaluated the innovative conditioning and thickening technologies. As adapted from 'Fig. 2.1' and 'Fig. 4.1', Fig. 2.18 shows the state of development, applicability, potential benefits, and positive/negative comparative criteria with respect to established technologies. Applicability is industry wide for all but the CAMBI process where usefulness seems to be reserved to larger plants. Operational and maintenance savings alongside sludge volume reductions have been named as incorporation benefits. The comparative criteria show both positive and negative impacts for each technology.

Process	Evaluation Criteria: Development	Applicability	Potential Benefits	Beneficial Use	Impact on Other Processes	Complexity	Air Emissions	Energy	Footprint	Environmental
Chemical Cell Destruction (MicroSludge™)	D	I	V,O	N/A	⊖	▼	⊖	▼	▲	⊖
Ultrasonic Cell Destruction	D	I	V,O	N/A	⊖	▼	⊖	▼	▲	⊖
Thermal Hydrolysis (CAMBI Process)	D	L	C,O,V	N/A	▲	▼	▼	▲	⊖	⊖

Statement of Development
B = Bench scale
D = Full-scale demonstrations in North America
I = Full-scale industrial applications, with demonstrations or pilots for municipal sewage sludge
O = Full-scale operations overseas
N = Full-scale operations in North America
P = Pilot

Applicability
F = Few plants
I = Industrywide
L = Primarily large plants
S = Primarily small plants

Comparative Criteria
▲ Positive feature
⊖ Neutral or mixed
▼ Negative feature

Potential Benefits
A = Produces Class A biosolids
C = Capital savings
O = Operational/maintenance savings
F = Produces high-nutrient fertilizer
M = Minimizes odors
R = Provides beneficial use (nonagricultural)
V = Sludge volume reduction

Figure 2.18 Qualitative innovative technologies evaluation (adapted: [167])

Sludge handling and disposal is explained further in Chapter 3. Biosolids and their classifications by the US EPA will be addressed here. The goal of this brief

discussion is to establish the necessary treatment requirements and the potential financial benefit of SPT incorporation if more desirable biosolids designations can be obtained.

A few disposal and reuse pathways exist for the biosolids produced in a WWTP. Landfilling, incineration, and land application are predominant as shown in Fig. 2.19 (as adapted from 'Fig. 1.1' of the review). Where land application is preferred (based on availability, accessibility, costs, and ability to meet federal regulations), biosolids can be sold as soil, dried pellets, liquid or compost.

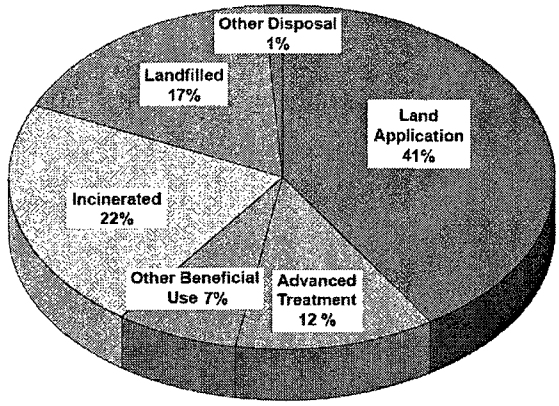


Figure 2.19 WW solids management in the US in 1999 (adapted: [167])

The US EPA created the 40-CFR Part 503 Rule for biosolids categorization and thus, Class A, B or EQ (exceptional quality) requirements. These requirements are based on the presence and quantity of pathogenic organisms in the stabilized sludge. Another concept used in the classification of biosolids is vector attraction reduction. It relates to the biosolids potential for spreading infectious disease agents by vectors such as flies, birds, and rodents [182].

Class B biosolids contain low allowable bacteria levels and require less stringent treatment. This class still requires that pathogen levels are below those that could cause public and environmental health concerns. Some restrictions on public and animal contact apply to Class B. Heating, composting or digestion (or alkaline stabilization) are required as part of the treatment train Class B designation of biosolids. As these biosolids will be applied to agricultural lands, some further environmental stabilization (i.e., natural attenuation) is permitted in place of in-situ care as long as it rapidly becomes free of pathogens [182].

Class A biosolids contain finite bacteria levels that cannot be detected. The same treatment train as that used for Class B designation is employed. Certain technologies can also be applied to pelletize these biosolids. No environmental stabilization is permitted. Heavy metals concentration requirements are identical for both classes [182].

Exceptional quality biosolids have the same pathogen reduction targets as for Class A but metals concentrations targets are lower [182].

The potential value of typical anaerobically digested biosolids to be applied to soils after dewatering is shown in Table 2.20 (as adapted from [165]). Values incorporate the need for 12.4-24.7 ton biosolids/hectare.

Table 2.20 Land application values per acre based on nutrients

Nutrient	kg/hectare applied	Value/hectare ($)
Nitrogen	168.5	74
Phosphorous	168.5	74
Potassium	11.0	3
Copper	7.9	35
Zinc	11.0	31
Sulfur	22.5	25
Lime	2,471.0	69
Spreading	–	37
Total value[1]		347

[1]Organic matter value is in addition to the total value

Exceptional quality biosolids can be applied to public parks, plant nurseries, roadsides, golf course, lawns, and home gardens provided contaminant concentration levels are met. These products have sold in bulk for up to $190/ton with sufficiently desirable nitrogen levels. The WWTP in Tampa, Florida markets 10-15% of their biosolids and sells them at $85-120/dry ton. It is clear that if SPT incorporation ameliorates designation achievement then biosolids can be "reused" and costs be reduced. It was found that sludge handling and disposal costs range from 20-60% of overall plant costs [13, 162, 163, 165]. This reflects the opinion of numerous authors who stated that the global potential of SPT incorporation lies where WWTPs have especially difficult to treat sludges and/or high sludge handling and disposal costs [13].

2.7.2 Full-Scale SPT Facilities Summary

Incorporation of SPT at full-scale facilities has primarily been successful. Though inadequate cost information was provided, all studies stated concluding remarks in favour of incorporation. Of the studies evaluated, CH processes achieved the most overall benefits in terms of sludge solubilisation, AD solids reductions, and biogas improvements. Ultrasound and OZ technologies were not shown to provide especially high hydrolysis levels but still reported significant AD improvements. These improvements were minimal in the case of LC.

The most significant results in comparison to LSR studies were the important positive dewaterability impacts and viscosity effects. In almost all cases dewaterability was enhanced by 20 and up to 80%. Though most LSR studies state improvements by CST tests (some state negative results), upgrading these results to full-scale dewatering units was not proven. These full-scale results suggest that dewaterability is in fact strongly and positively affected. Digestion was primarily improved by the higher feed solids concentration enabled by sludge viscosity improvements. Finally, dewatered cake solids were produced in 20-50% lower daily quantities. With the incentives to optimize WWTPs and "reuse" biosolids through various pathways, these reductions certainly promote SPT incorporation.

Sludge pretreatments were however noted as typically being incapable of providing continuous feed or treating substantial WAS loads. Thus, such important results may not necessarily be reproducible for larger facilities as current SPT technologies limit unit size and treatment capacities. A look at SPT equipment theory and current technologies is provided in Chapter 3 and results in the conclusion that perhaps achieving required E_{spec} levels for solubilisation and subsequent digestion improvements may not in fact be reasonable.

2.8 QUALITATIVE EVALUATION

Remarks on process complexity, operation, drawbacks, and benefits are useful to the designer as they provide an outlook as to what to expect from SPT incorporation. A

handful of SPT review papers is available. In this section an attempt was thus made to gather all potential qualitative observations and list them only where sufficient information (many studies in agreement) was found. A note on whether or not contradictory information was found in the literature review was made and is addressed by footnotes of Tables 2.21-23. The SPTs that were considered in PretrAD to evaluate the efficacy of SPTs are included in this analysis. Low (L), medium (M), and high (H) evaluations were made relative to all SPTs. That is to say, although pathogen reduction could be high for a certain process, it may not be as high as for another SPT and would be annotated "M". Four score columns are shown. The first three makeup the results from three SPT reviews performed by Marjoleine et al. (1998), Müller (2001, 2003), and Pérez-Elvira et al. (2006) [11, 21, 50, 52]. The fourth column shows the score given from the review conducted by this thesis with consideration for the assessments given in the reviews.

Odour and pathogen reduction are jointly considered in Table 2.21. Their results were found to be identical when separate and were joined for simplicity. No link is being proposed between these two observations. The table should be read, for example, as SBM having a low overall score for both odour generation and pathogen reduction.

Table 2.21 Qualitative results summary: odour and pathogen reduction

	Odour Generation or Pathogen Reduction			
	[11]	[21]	[50]	Thesis & Overall
SBM	L		L	L
HPH	L		L	L
ULT	L		L	L
CH	H	H	H	H[1]
MWH				H
CM		L	M	L[2]
OZ			M	M
TC		H		H

[1]Odorous compounds generation during digestion could be relatively lower when digestion of pretreated WAS is used in place of untreated WAS

[2]Insignificant CM odour remarks were found

Dewaterability results are listed in Table 2.22 and energy input results are listed in Table 2.23. Again, all specific SPT results have been made relative to all other SPTs.

Table 2.22 Qualitative results summary: dewaterability

	Dewaterability			
	[11]	[21]	[50]	Thesis & Overall
SBM	M		L	L
HPH	M		L	L
ULT	M		L	L[1]
CH	H		M	H
MWH				H
CM	M		M	M[2]
OZ	M		L	M[3]
TC				H

[1]ULT was typically found to insignificantly, if not negatively affect, dewaterability

[2]Dewaterability results varied between M and H

[3]Full-scale OZ studies showed good dewaterability improvements

Table 2.23 Qualitative results summary: energy input

	Energy Input			
	[11]	[21]	[50]	Thesis & Overall
SBM	M	M	M	M
HPH		L	L	M
ULT		H	H	H
CH	H	H	H	H
MWH				M
CM	L	M	H	M[1]
OZ	H	H	M	M
TC	H	H		H

[1]Overall score for CM is based on more than chemicals cost as shown by 'L' score in [11]

A comparison of SPT technologies as adapted from two of the above mentioned review papers [11, 21] is given in Table 2.24. The authors conducted an extensive review of SPT processes and those which have been reviewed in this thesis are included in Table 2.24. It is clear that performing a review which attempts to compare SPTs is not easily done with respect to specifying probable treatment. The study by Marjoleine et al. (1998) presented highest observed improvements (shown by the second value in the % solids reduction column) and potential treatment costs (shown by the right-most column). Sludge characteristics ranges in their study varied from 2-8% DS and 0.83-1.16% DS for PS and WAS, respectively. The study by Pérez-Elvira et al. (2006) chose average improvement ranges for average energy inputs. This study's results are given in columns 1-5. The first column lists sCOD as a function of the control values observed. The result

is for example, a sCOD concentration that is 15 (SBM) or 18-20 (HPH) times higher than the control concentration, respectively. Influence of SPTs on pathogen reduction and dewatering were also given. It is important to note that the cost evaluation was based on operation costs with 1 kWh = $0.083 and under the assumption that total costs equal operation costs in addition to capital investment (listed as ~2 times operation costs). These costs (right-most column) were established in 1998 and were converted from Euros to US dollars for this thesis. A correction for inflation was not applied.

Table 2.24 Comparison of sludge pretreatment technologies

SPT	sCOD (# x Control)	Solids Redu. [11],[21] (%)	Biogas Prod. (% Impr.)	Pathogen Redu.	Dewatering Influence	Cost ($/ton DS)
SBM	15	40-60, 90	10	No	High	455-2,750
HPH	18-20	23-64, 85	Up to 300	Low	High	46-161
ULT	6	40-70, 100	10-60	Low	High	9,163
CH	10-20	60-80, 30	Up to 400	Total	Very High	209
CM	–	–	–	–	High	–
OZ	5	36	8	–	High	–
TC	–	–, 15-60	–	–	–	–

It is clear that average results span large ranges and are not stated as ensuing from specific scenarios, whether they are unique or common. Specific costs were also not incorporated in the reviews and have not been found in other works. There is a lack of economic comparison among these processes. An economic analysis and model of available SPT processes tying results to their specified conditions would be a valuable tool for designers and operators in the WW treatment field.

Additional observations from the literature review conducted for this work have been gathered and are included in Table 2.25 [significantly adapted from the study by Marjoleine et al. (1998)].

Table 2.25 Primary benefits and drawbacks to SPTs retained for further evaluation

	Benefits	Drawbacks
SBM	High efficiency, simple design, scalable	Energy intensive, clogging, erosion
HPH	High efficiency, known MicroSludge™ process, low energy	Energy intensive, clogging, erosion
ULT	Complete WAS solubilisation, moderate heat recovery	Energy intensive, erosion
CH	Known CAMBI and MicroSludge™ processes, complete pathogen reduction, dewaterability improvements, heat recovery	Energy intensive, odour problems, fouling
MWH	High efficiency, low to average energy demands, complete pathogen reduction, high heat recovery	Complexity, odour problems, scalability
CM	Known MicroSludge™ process, potential dewaterability improvements, potential pathogen reduction	Chemical costs, corrosion, HCL neutralisation, odour
OZ	High efficiency, FS results, dewaterability improvements, pathogen reduction	Potential heavy metals solubilisation, potential solids mineralization
TC	Simple design, FS results, phosphate generation	Corrosion, odour, HCL neutralisation, energy intensive

CHAPTER 3

Prior Treatment/Post SPT Impacts and SPT Equipment

3.0 PRIOR TREATMENT IMPACTS

Conventional WWTPs using MTAD consist of a preliminary treatment phase in which bulky solids (e.g., solid wastes, plastics, branches, and rocks), both inorganic and organic, are removed by bar racks and grit chambers. After preliminary treatment, the WW continues to flow to the primary sedimentation (primary clarifier or PC) unit. Solids are permitted to settle and the clarified effluent flows to the biotreatment (BT) unit.

Aerobic biotreatment occurs rapidly by the addition of excess oxygen for a chosen SRT (1-7 d). This step's clarified effluent is directed to the secondary sedimentation (secondary clarifier or SC) unit. It functions in the same manner as PC. Its underflow (WAS) however, is split and typically the larger fraction is recycled to the BT unit to maintain a high solids concentration in the mixed liquor (MLTSS or MLVSS). The BT and SC units make up the secondary treatment phase. The clarified effluent is disinfected in a fourth treatment phase (explained below).

The portion of underflow from the secondary clarifier which is not recycled is diverted to the thickening unit (TH). In the third phase (sludge treatment), TH can treat either or both the WAS and the PS underflow. With or without commingled thickening, both sludges enter the digester. An HRT of 13-30 d is maintained in the anaerobic digester to achieve solids reductions, pathogen diminutions, and methane generation.

Anaerobic digestion is the key to the methane generation and follows the well-known pathway of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. As mentioned earlier, the hydrolysis stage is deemed to be the rate-limiting step. The limiting nature of this step is reduced by SPT incorporation. Thus, if SPT were to be incorporated, it would necessarily be to treat the WAS stream entering the digester. Mesophilic AD is more widely used and requires lower amounts of energy while providing higher stability. Thermophilic AD however, could be considered where thermal

SPTs are used as the heat energy input associated with them can be recovered to a higher extent to sustain the elevated digestion temperature.

Following the MTAD unit, the biosolids are handled by a dewatering (DE) unit. Solids drying will also typically occur and a final solids concentration of 40-60% is attained. Supernatants from TH, MTAD, and DE units are recycled back to the PC and/or the BT unit. A fourth phase known as advanced treatment includes nitrogen and phosphorous removal alongside disinfection prior to the treated WW entering a neighbouring water body. Fig. 3.1 shows the treatment train for a conventional WWTP

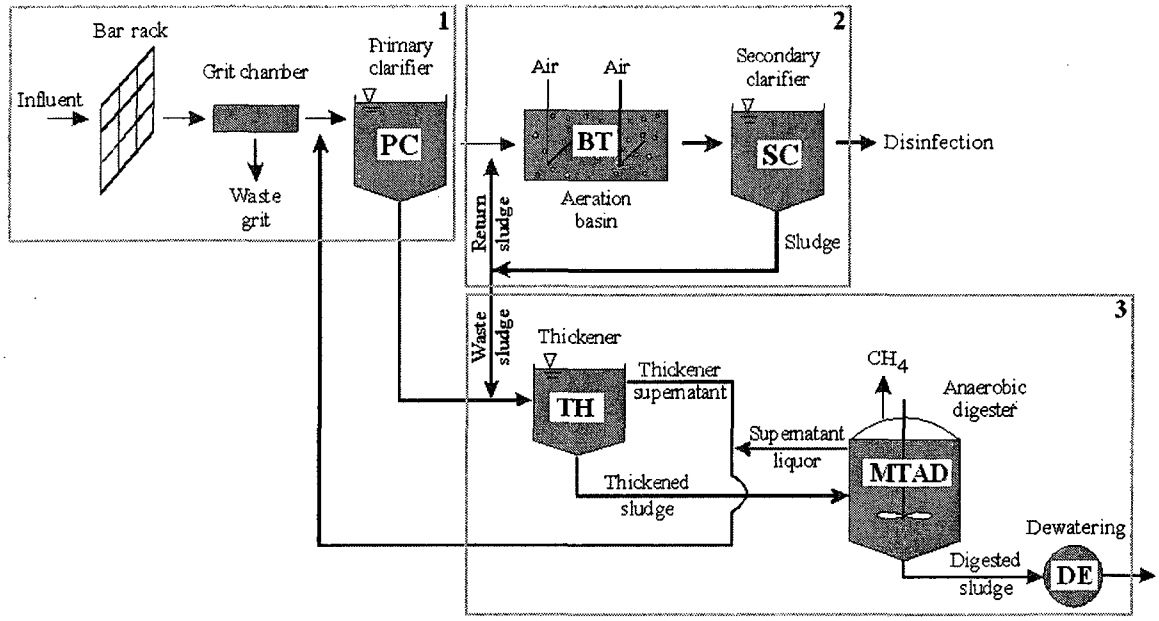


Figure 3.1 Conventional WWTP with MTAD. Numbers 1, 2, and 3 in the upper right corners of the three delineated portions refer to primary, secondary, and sludge treatments, respectively

A few major SPT impacts on various treatment processes were listed in Chapter 2; all are explained below. It has been largely observed that the effect of SPT hydrolysis on PS provides no real improvement in AD as the PS is already easily degraded. Primary sludge may still be thickened prior to AD but if SPT incorporation is considered, it should not likely be commingled with WAS at the SPT unit. The SRT of the BT unit which, produces the WAS, has a significant impact on further WAS biodegradability. Certainly, if an older sludge age is used and therefore WAS has been degraded to a greater extent, the SPT unit provides more substantial initial AD improvements with

regards to the rates of degradation and biogas production. Improved overall solids reductions for an unchanged HRT would thus be observed. As expected it was also observed that SPT efficiency is improved with more concentrated sludges. That is to say, if the WAS can feasibly be thickened to 5-7% instead of the typical 2-4%, SPT energy demands will be reduced.

3.1 BASIC PRETREATMENT EQUIPMENT THEORY

Literature and industry contacts provided the data on energy requirements and efficiencies for the SPT equipment and chemical costs for CM SPT. Heat and mass transfer balances were completed alongside basic accounting calculations to fully assess the economic viability of incorporating any of the SPT processes. This work was done in the following chapters using a conventional WWTP spreadsheet model.

All SPT processes evaluated require additional appurtenances such as chemical feed systems, heat exchangers, grinding mills, as well as the necessary pumps and piping. Materials selection for the design of any unit demands that many factors be considered. Those factors include availability, mechanical properties, strength-to-weight ratios, physical properties, electrical properties, corrosion properties, and cost [159]. The purpose of this section is to provide a physical and visual understanding of each SPT technology.

3.1.1 Mechanical Processes

3.1.1.1 Stirred Ball Mill

Steel, ceramic or glass grinding beads can be used in SBMs where agitator discs, in a cylindrical chamber, create rotational movement that disrupts cell membranes by shear and pressure stresses. A horizontal and a vertical industrial SBM (photographs are not to scale) are shown in Fig. 3.2.

The three above mentioned grinding beads that were listed by authors in the literature review are shown in Fig. 3.3.

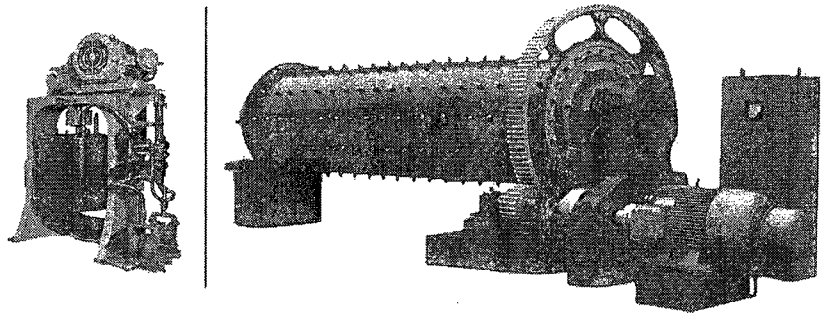


Figure 3.2 Industrial SBMs (adapted: [190, 191])

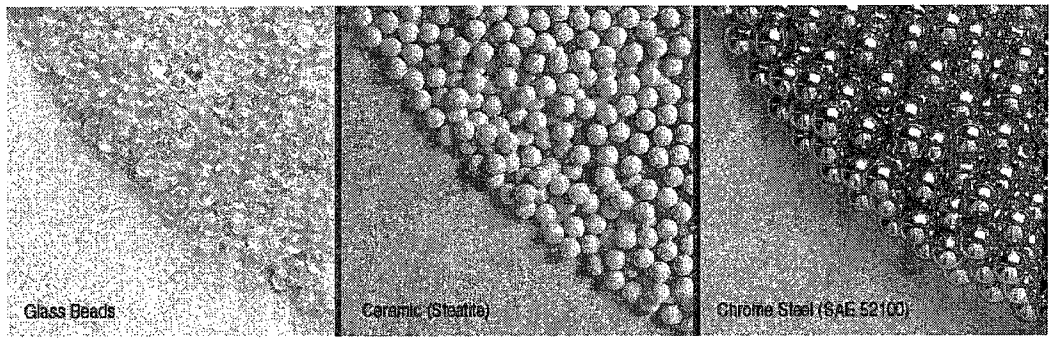


Figure 3.3 Glass, ceramic, and steel grinding beads (adapted: [191])

Drawbacks to this SPT process include clogging and erosion in the chamber as well as friction losses [11, 21]. Variables such as agitator speed, feed rate, bead diameter, solids concentration in the feed, and pretreatment contact time affect the efficacy of SBMs [176]. Sludge exposure to milling can be improved with a high feed rate and up to 10 passes through the mill [176]. The size of a mill can vary from 1 to 1,000 L and the mill can have a power capacity of up to 320 kW [176]. These values will likely increase as industrial unit technologies evolve.

Insufficient information was found to adequately assess the efficiency of power input for hydrolysis by SBMs. The efficiency in the energy input demand, if this information is available, can however be incorporated into PretrAD by increasing the E_{spec} setting.

As a full-scale design including capital costs that vary by region and chosen manufacturer is not the objective of this study, additional and highly variable information will not be gathered in regards to industrial capacities. Evaluating energy inputs and

outputs associated with incorporating SPT along with ancillary operational costs such as sludge dewatering and disposal into a WWTP is the primary objective of the work.

3.1.1.2 High Pressure Homogenizer

High pressure homogenizers work by compressing sludge with pressures up to 90 MPa and subsequently directing the sludge through a homogenising valve [11, 21]. The surrounding pressure decreases and as a result, the sludge's velocity increases significantly [11, 21]. The cell membranes in the sludge are disrupted by shear, turbulence, and cavitation stresses as they collide against an impaction ring [11, 21]. One resource showed HPH models having throughputs of 0.1-50 m^3/h and pressures of 10 to 150 MPa. Their power consumption was stated as ranging from 5.5 – 315 kW [192].

A lab-scale HPH schematic of its operation is shown in Fig. 3.4. Again, and for all upcoming SPT unit and process depiction figures, images are not to scale.

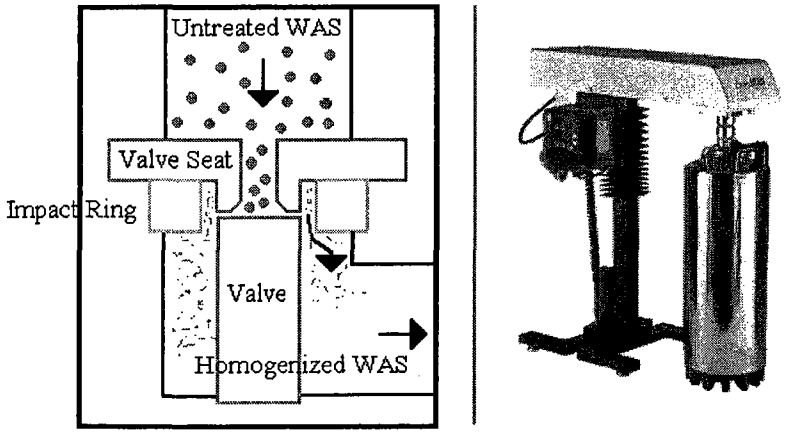


Figure 3.4 HPH effect sketch and lab-scale HPH photo (adapted: [193])

Drawbacks to this SPT process include minimal pathogen reduction (as compared to thermal SPTs), clogging, and erosion in the pump and valve [11]. Though some HPHs are not designed with an impaction ring, those that have one are more effective. The efficiency of any HPH depends on the pressure, temperature, the number of passes, and the flow rate, as well as the valve and impaction ring designs [170]. Cell disruption occurs at a rate which is approximately proportional to the turbulent velocity cubed $[(m/s)^3]$ of the fluid passing through the homogenizer [170]. The turbulent velocity is itself proportional to the applied pressure and it is clear that an increase in pressure

improves cell disruption for each pass [170]. An increase in pressure will reduce the required number of passes as cell disruption will be improved. High pressure homogenizers capable of 69 MPa can disrupt cells on the first, second, and third pass up to 40, 60, and 85%, respectively [170]. Continuous HPHs can generally handle up to 4,500 L/h with cell concentrations of 10-17% w/v [170]. Coupling a heat exchanger to the outlet port is essential as a substantial amount of heat is generated [170]. The average temperature increase could not be found in the literature.

Insufficient information was found to adequately assess the efficiency of power input for hydrolysis by HPHs. As for SBM, the efficiency can however, be incorporated by altering the E_{spec} value set by the user in PretrAD. This holds for all mechanical SPTs and MWH.

3.1.1.3 Ultrasound

Ultrasonic treatment is said to not only improve methane generation but also reduce required HRT in the digester [21]. Ultrasound frequency and E_{spec} are the main factors affecting pCOD solubilisation and biogas production. Low frequencies (<100 kHz) are thought to promote mechanical and physical degradation while high frequencies promote sonochemical effects [11]. For ultrasonic SPT, TAD conditions are said to enhance the rate of biogas and methane production compared to MAD and TAD should therefore enhance the rate of organic matter removal [11]. The sound waves of the ultrasonicator propagate through the sludge and cause high and low pressure cycles (~20,000 cycles/s) [196]. The low pressure cycle leads to the creation of high intensity vacuum bubbles during the attainment of liquid vapour pressure. The bubbles implode during the high pressure cycle creating localized high speed liquid phase "jets". These jets provide additional hydrolysis through collisions with neighbouring particles. A significant advantage to ULT is the low number of moving parts which reduces wear and down-time. In its design, oscillation amplitudes (1-200 μm) and pressures (0-3.4 MPa) can be varied to extremes and thus provide low to high extents of hydrolysis. Under constant operational parameters sonication results remain consistent and scale-up is quantifiable.

Industrial ultrasonic homogenizers, when clustered to meet throughput demands, have capacities of 0.2-32 m^3/h. These capacities applied to 4×16 kW ultrasonicators [195].

A lab-scale and two industrial-scale ultrasonic homogenizers are shown in Fig. 3.5. The first industrial scale photograph (center image) depicts a cluster of seven sonotrodes and the second (right most) shows a single 16 kW unit.

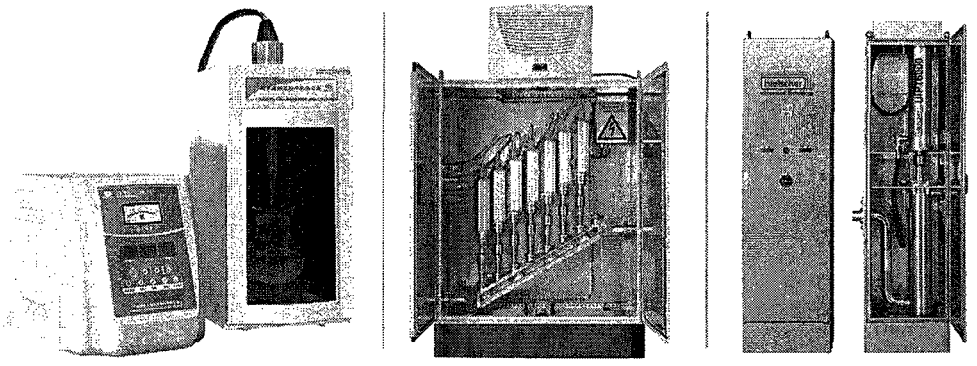


Figure 3.5 Lab and industrial scale ultrasonic homogenizers (adapted: [194, 195])

3.1.2 Thermal Processes

3.1.2.1 Conventional Heating

Temperatures required for thermal SPT typically range from 60-180°C [3]. They are induced by either heat exchangers or steam injection [3]. Biogas production improvements, enhanced dewaterability, and complete pathogen reduction promote the incorporation of thermal SPTs. Sludge disposal costs and improved sludge stabilization are generally observed [4]. A vertical and a horizontal autoclave are shown in Fig. 3.6. The sample volume is added to the autoclave which is then sealed. The pressure and temperature of the vessel can be manipulated. Since time must pass before the treatment temperature is reached, the sample is also subjected to lower temperatures.

Heat exchangers used in CH are limited by the heat transfer rate of the receiving WW [4, 14]. This rate is determined by the WW's thermal conductivity, density, viscosity, and specific heat [176, 173]. During CH the surface of the material is subjected to the heat and heating to the depth of the material is time-consuming [173].

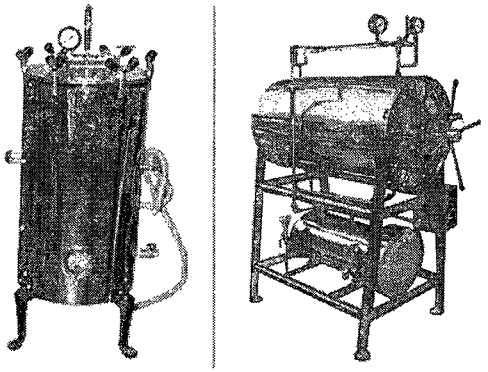


Figure 3.6 Vertical and horizontal autoclaves (adapted: [195]).

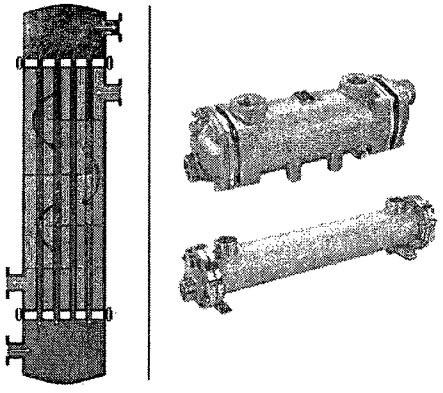


Figure 3.7 Vertical and horizontal heat exchangers (adapted: [197, 198]).

Steam boilers can also be used in place of heat exchangers. Industrial systems with capacities up to 4,000 kg steam/h at working pressures of 0.1-2 MPa are available. These systems have 85-95% efficiencies. Horizontal steam boilers are shown in Fig. 3.8.

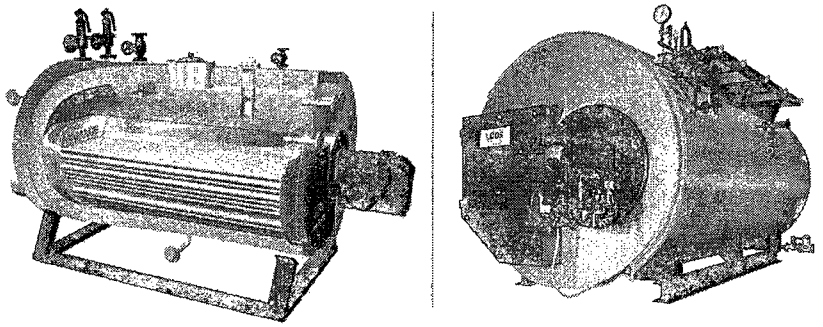


Figure 3.8 Horizontal steam boilers (adapted: [199, 200]).

Energy is lost in the heating process and the efficiency can be manipulated in PretrAD by varying the specific heat constant and heat recovery application efficiency. Heating time and required heating area are higher than for MWH [173].

3.1.2.2. Microwave Heating

Microwave irradiation has been studied as an alternative to CH. Microwave heating can be up to 50% more energy efficient than CH methods [173]. Microwave units also experience less fouling because their surfaces are not brought to the same high temperatures as the surfaces in CH [173]. Warming or cooling the unit as in CH is not required and energy is conserved because microwaves can be instantly activated or deactivated [173]. A lab-scale MARS 5 microwave unit and an industrial scale conveyor-type microwave system are shown in Fig. 3.9.

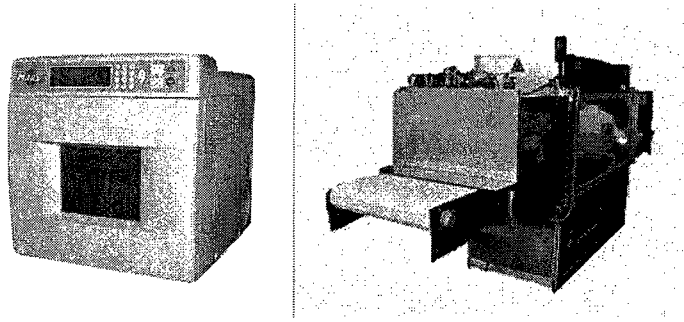


Figure 3.9 Lab and industrial scale microwave units (adapted: [201, 202])

Perry's Chemical Engineer's Handbook (1997) states that heating by microwaves has an approximate 50% conversion of "at-the-wall" (power obtained from the utility line) power to microwaves. A manufacturer of industrial microwave systems, I.M.S., stated that units which operate at a frequency of 915 MHz have a conversion efficiency of 85% [173]. Once the electricity is converted to microwaves, up to 95% of the energy is transferred into the material as heat [173]. For units operating at 2,450 MHz, overall efficiency, including at-the-wall conversion and useful heat transfer, ranges between 55-70% [173]. In 1980, MWH costs were about $2,500/kW, $500/kW, and $0.06/h for vacuum tubes (travelling wave tubes, klystrons, gyrotrons, and magnetrons), microwave energy applicators, and vacuum tube replacement costs, respectively [173] Magnetrons available for industrial purposes can provide from 1-30 kW for frequencies of 2,450 MHz and up to 100 kW for frequencies of 915 MHz [173]. They can be scaled up from 50 kg/h throughput to multiples of 1,000 kg/h.

3.1.3 Chemical Processes

3.1.3.1 Alkaline

Substantial solubilisation of WAS at ambient temperatures can be achieved [18] with alkaline SPT. The aim of this SPT is to raise and maintain an elevated pH (10-12) for a chosen contact time (0.15-24 h). As the pH has been increased and additional solids have been added, a major drawback to chemical processes includes chemical requirements (typically HCl) to reduce the pH to 6-8 for AD and the added sludge handling costs based on increased amounts of solids. With adequate mixing, chemical dispersion is improved and contact between the alkali and the sludge is enhanced. This promotes an increase in the rate of hydrolysis in the SPT unit.

Insufficient information on the experimental apparatus used for CM SPT was found. It is well known however, that chemical mixing typically occurs in a batch reactor consisting of a corrosion resistant material and an agitator. One such study used a 1 L batch reactor with a magnetic stirrer and maintained contact (WAS and NaOH) under anoxic conditions for 24 h [18]. An in-line flash mixer and a chemical agitator are shown in Fig. 3.10. The principle difference is that no mechanical agitation requiring energy input is needed in the flash mixer. The forward flow collides with a plate, the chemical diffusion ports, and a static mixing device to create a mixed flow regime powered only by the hydraulic pumping force already being employed. Other advantages to this mixer are the touted low head loss, its ability to treat highly turbid waters, and high diffusion efficiency [203].

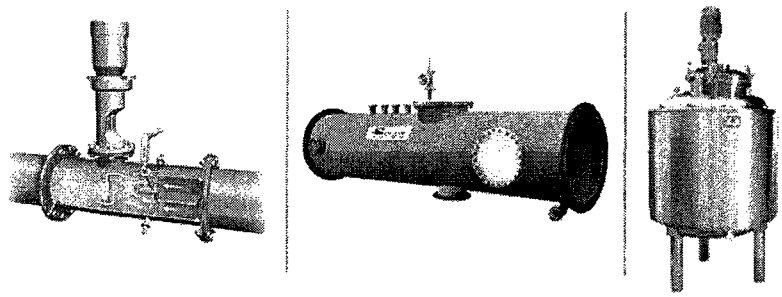


Figure 3.10 In-line flash mixer schematic and photograph and a chemical agitator (adapted: [203, 204, 205])

3.1.3.2 Ozone

Ozonation is a well-established water disinfection technique. Ozone is a volatile reagent that will quickly dissociate and in doing so, react with unsaturated bonds in organic matter in the sludge and generate radicals that oxidize organic matter [173]. As with most other SPTs, particle sizes are decreased and particulate matter is solubilised as cell membranes are lysed. It was observed, however, that the more easily oxidized and already soluble substances also interact with O_3 and delay particulate matter solubilisation. Mineralization of the desirable organic matter by CO_2 formation was also observed at higher O_3 doses.

Ozone dosages were commonly prepared by an ozone generator (ozonator) and applied in a bubble column. Though O_3 can be generated by different means (e.g., with pure O_2, air, or application of UV), an industrial ozonator was found to have a production capacity of 6.25 kg O_3/h at a cost of $1.20/kg and an energy demand of 10-20 kWh/kg O_3 produced. Past demands of 40-100 kWh/kg O_3 with an additional 5×10^{-3}-10×10^{-3} kWh/kg O_3 for mixing were common [157, 208]. The reduction in energy requirements listed above promotes the potential scalability of O_3 processes for conventional WWTPs.

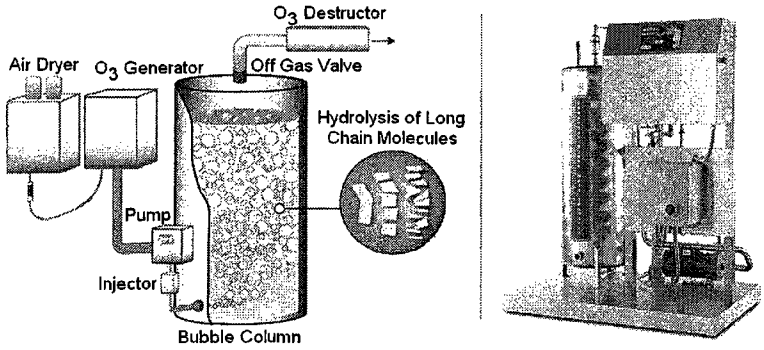


Figure 3.11 Ozone effect diagram and industrial ozone generator (adapted: [206, 207])

3.1.4 Biological Processes

3.1.4.1 Enzyme

As shown in the literature review, some enzymatic processes have been observed to improve hydrolysis and thus, AD. At this time however, there is insufficient information

with regards to obtaining average treatment conditions and required hydrolysis equipment. The full-scale potential and setup could not be ascertained.

3.1.5 Combined Processes

Combining certain SPT processes will likely yield benefits from each process and improved results with respect to sludge solubilisation, biogas production, and biosolids handling. However, each process will consume energy and together they may exceed the energy gains. A showcase of one such patented treatment is presented below. This process consists of chemical and mechanical SPTs. A TC combination, on the other hand, can more easily be understood as a combination of the thermal and alkaline SPTs.

A patented combined process called MicroSludge™ has been demonstrated in 2004 and 2005 in Canada and the US, respectively, but neither full-scale demonstration was in operation as of 2006 [167]. The process first chemically hydrolyzes thickened WAS (TWAS) from the secondary clarifier in a central unit using NaOH. A retention time of 1 h is maintained to lyse the cell membranes and lower the sludge viscosity. High pressure homogenization at 83 MPa is then employed to further disintegrate the sludge as it flows at a rate of 300 m/s through the homogenizing valve to impinge on an impaction ring within 2 μs. As a result of the treatment a 25°C increase in temperature is observed and this waste heat can be recovered. Pretreated sludge is then combined with PS and transferred to the anaerobic digester. The simplified process schematic is shown in Fig. 3.12 [83].

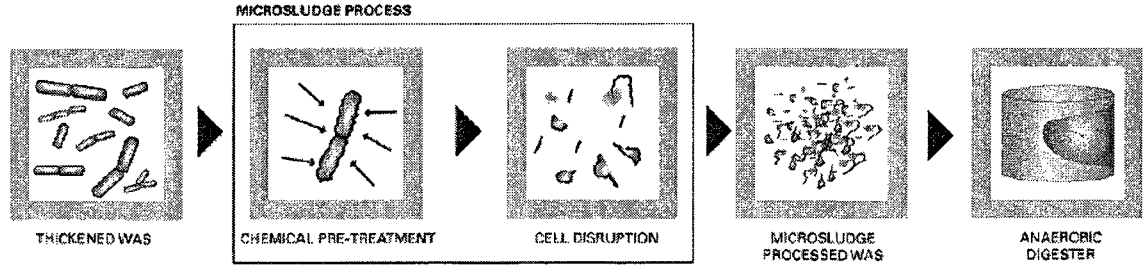


Figure 3.12 Simplified process schematic for the MicroSludge process (adapted: [83])

The additional unit requirements based on combined SPT use are outlined in Fig. 3.13. They are specific to MicroSludge™ but it provides a glance at appurtenance incorporation requirements and complexity.

Hydrolysis of the TWAS (5-6% solids content) at the L.A. County Sanitation Districts' Joint Water Pollution Control Plant achieved a 100% improvement in the sCOD concentration. Enhanced solubilisation and viscosity improvements led to a VS reduction of 51% (compared to 28% for the control) in the MAD unit for a 19 d HRT. This represents an 80% increase in VS reduction and was stated as being significantly lower than the 200% increase observed at the Chilliwack WWTP, in BC, Canada. An increase (31%) in CH_4 production as assessed by BMP tests was commensurate with a reduction in biosolids to be disposed (35% less). Dewaterability was not improved (or worsened) and the increase in soluble heavy metals was insignificant.

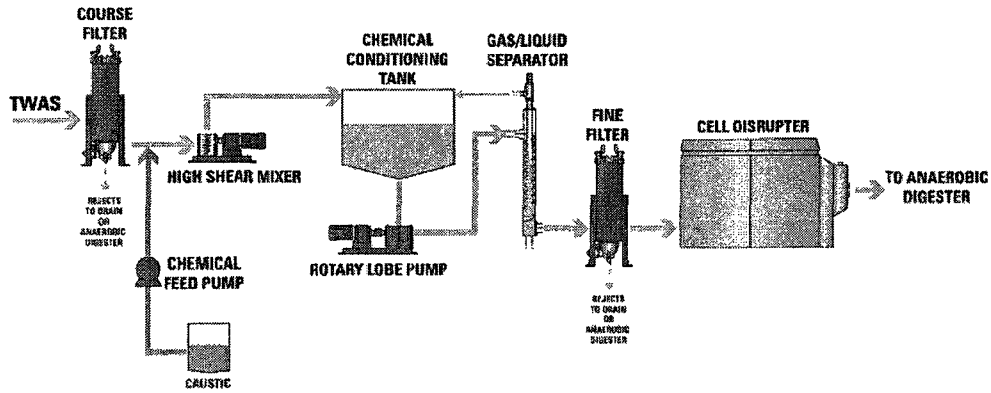


Figure 3.13 MicroSludge™ process trail (adapated: [83])

The vendor, Paradigm Environmental Technologies, Inc., located in Vancouver, BC, provided the US EPA with approximate capital and O&M costs in 2006 of $1.7-2 million and $68-199/dry ton of activated sludge, respectively. These costs reflect a unit which can process 190 m^3 TWAS/d. Installation costs are not included in the approximations and it is also stated that scaling-up lowers the daily sludge processing cost. The O&M cost approximation includes electricity, chemicals, and maintenance for WAS processing having a total solids content range of 4-7%. It should be noted that the assumed costs of electricity and chemicals were $0.07/kWh and $0.46/kg, respectively. Power consumption lies in the range of 500-1,000 kWh/ton dry solids.

3.2 POST SPT IMPACTS AND DEMANDS

Sludge pretreatment influences on subsequent AD results have already been described and summarized in Chapter 2. They consist of biosolids reductions, biogas improvements, potential dewatering improvements (though insufficient data have been found), improved biosolids classifications for land application, and all of the associated energy and financial gains. The additional SPT demands (typically, in terms of added costs) based on current industrial electricity prices, chemical costs, sludge handling costs, and energy conversion potentials are considered here.

Most authors have observed that SPT can lower the required anaerobic digester volume and/or the HRT. Insufficient information has been found to correlate quantitative SPT hydrolysis results to specific AD HRT reductions (in terms of days gained) and MTAD volumes. Certainly, this qualitative observation does imply that a lower digestion capacity would be needed for the construction of a new WWTP and would thus translate to further financial gains and improved ability to treat influent WWs. Financial gains and treatment capacity would also be gained through shorter HRT demands at an existing facility.

3.2.1 Historical Electricity Prices

The historical price of electricity in North America was researched to ascertain a trend that could be used for different runs of the spreadsheet model. The trends observed will enable the user to not only determine if SPT is economically viable based on electricity prices and delivery rates at the date of running PretrAD but also predict viability up to a specified future date. It must be noted however, that price predictions based on historical trends that are dependent on numerous political, economical, and geographical variables can only serve as a rough guide. PretrAD will thus be capable of accepting current, user-input prices at their respective WWTP, regardless of historical electricity prices. At the date of usage, a more accurate estimate of future prices will presumably be available to the user and can also be input. Official energy statistics for the US are conducted by the Energy Information Administration [210]. Industrial electricity prices from the year 1960 to 2006 are shown in Fig. 3.14 [210]. They have been adapted from their 2006 Annual

Energy Review, publicly available as of June 2007 [210] The price of electricity could be made 'real' (reflective of changes in purchasing power of the US dollar) by dividing 'nominal' price (reflective of buying power in the year of the transaction) with the gross domestic product implicit price deflator available in 'Table D.1' of the review [210] 'Nominal' prices are considered to better compare with the electricity prices found for the EU.

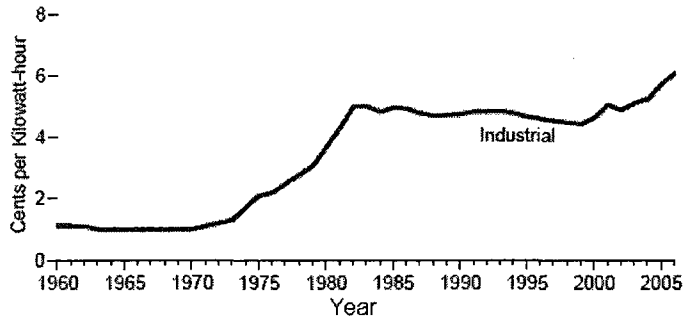


Figure 3.14 Cents per kWh charged to industrial concerns between the years 1960-2006 (adapted: EIA Annual Energy Review, 2007)

Electricity prices for the EU were collected from publicly available data on energy compiled by Eurostat (2007). The historical trend in electricity prices for the industrial sector for the years 1996-2006 is shown in Fig. 3.15. Since the prices are averaged among 15 EU countries, Fig. 3.16 is also included to better reflect the significant variation in prices between countries such as the United Kingdom (7.99 Eurocents/kWh in 2006) and France (5.33 Eurocents/kWh in 2006) [211].

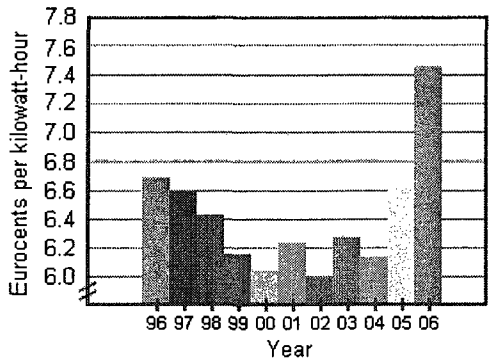


Figure 3.15 Averaged Eurocents per kWh charged to industrial concerns between the years 1996-2006 (adapted: Eurostat energy tables, 2007)

Electricity price variations for Canada could not be found. Runs of the model with varying electricity prices will be conducted using typical US prices. For simplicity and to

minimize permutation variables, no other country's electricity prices will be considered in the assessment of SPT viability.

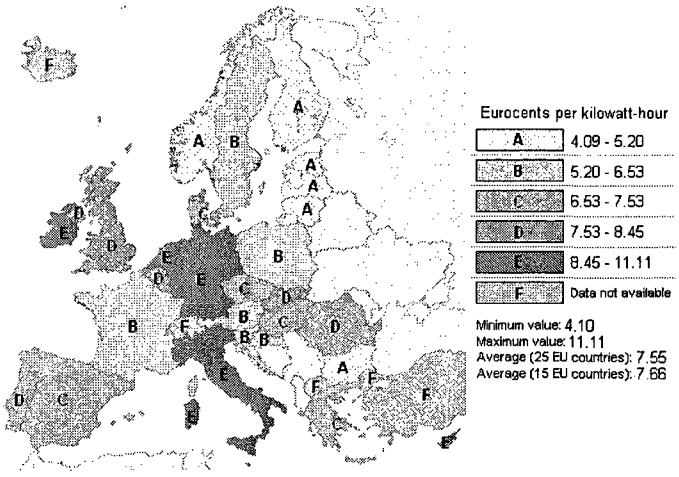


Figure 3.16 Averaged Eurocents per kWh charged to industrial concerns for individual EU countries in 2006 (adapted: Eurostat Energy Tables, 2007)

3.2.2 Chemical Costs

Operation and maintenance costs will increase with chemical usage. Uses of chemicals include alkaline or acid hydrolysis SPT, necessary pH modifications following chemical and other SPT processes and agents used for sludge dewatering. The acetogenesis stage, where acids are produced, is regulated by the organics loading. Improved hydrolysis will thus require more alkalinity to balance the system pH as the additional carbohydrates are consumed. Chemical use results in additional sludge production and can result in increased equipment corrosion. Prices for NaOH, sodium carbonate (Na_2CO_3), KOH, calcium oxide (CaO), and calcium hydroxide [$Ca(OH)_2$] are considered herein. It is important to note that although list prices may not vary significantly by region, the actual purchase price of industrial chemicals regularly varies due to contract discounts, purchasing history, current market conditions, and bulk purchasing. Various runs of PretrAD will be performed using found prices and PretrAD will be capable of accepting user-input chemical prices.

List prices in for NaOH, Na_2CO_3, KOH, CaO, and $Ca(OH)_2$ between 2005 and 2007 are shown in Tables 3.1-4. Purity, unit cost, packaging, package cost, and an approximate discount cost are included. An approximate discount cost based on bulk

purchasing and contract details was assumed at 15%. The list prices for caustic soda (NaOH) and caustic potash (KOH) from reference [174] include a $20 hazardous materials charge as well as a $10 packaging cost to meet US Department of Transportation regulations. List prices for NaOH, KOH from reference [175] as well as all the list prices for quick lime (CaO), hydrated lime [$Ca(OH)_2$], soda ash (Na_2CO_3), do not note these charges.

Table 3.1 List prices for caustic soda

Chemical and Form	Purity %	Unit Cost ($/kg)	Packaging	Package Cost ($)	Discount Cost ($)
NaOH beads[1]	99.12	2.82	22.7 kg bag	94.00	79.90
NaOH flakes[1]	90.00	2.93	24.9 kg bag	103.15	87.68
NaOH liquid[2a]	N/A	0.31	907.2 kg	282.50	240.13
NaOH liquid[2a]	N/A	0.33	907.2 kg	291.44	247.72
NaOH liquid[2a]	N/A	0.35	907.2 kg	325.00	276.25

1 –reference [174]

2 –reference [175]

a –updated 2007 prices, otherwise 2006 prices are listed

Table 3.2 List prices for soda ash

Chemical and Form	Purity %	Unit Cost ($/kg)	Packaging	Package Cost ($)	Discount Cost ($)
Na_2CO_3[1]	N/A	1.32	22.7 kg bag	30.00	25.50
Na_2CO_3 dense[2a]	N/A	0.15[b]	1,016.1 kg	150.00	127.50

1 –reference [174]

2 –reference [175]

a –updated 2007 prices, otherwise 2006 prices are listed

b –the unit cost was not found but calculated using the packaging and package cost

Table 3.3 List prices for caustic potash

Chemical and Form	Purity %	Unit Cost ($/kg)	Packaging	Package Cost ($)	Discount Cost ($)
KOH flakes[1]	90.00	3.35	24.9 kg bag	135.60	115.26
KOH flakes[2]	90.00	0.97[b]	181.4 kg drum	44.00	37.40
KOH liquid[2]	45.00	0.33[b]	45.4 kg tank	14.63	12.44

1 –reference [174]

2 –reference [175]

b –the unit cost was not found but calculated using the packaging and package cost

Table 3.4 List prices for quicklime and hydrated lime

Chemical and Form	Purity %	Unit Cost ($/kg)	Packaging	Package Cost ($)	Discount Cost ($)
CaO pebble[2]	N/A	0.07[b]	907.2 kg	61.00	51.85
CaO pebble[2]	N/A	0.07[b]	1,016.1 kg	70.00	59.50
$Ca(OH)_2$ hydrated[2]	N/A	0.07[b]	1,016.1 kg	69.50	59.08

2 –reference [175]

b –the unit cost was not found but calculated using the packaging and package cost

3.2.3 Sludge Handling Costs

Sludge pretreatment processes are capable of contributing to the overall stabilisation and dewatering of sludge and thus sludge handling costs will be affected. Gains might be made if the treated biosolids can be used for land application. Disposal fees include tipping and permits. Tipping fees vary monthly and geographically. Disposal costs include labour and transportation. Transportation costs include distance travelled, fuel consumption, and depreciation. Fuel prices vary significantly on a daily basis. Due to the large variation in yearly average prices in the regions that were briefly researched and the significance of numerous factors affecting those prices, no trends were established for fuel prices.

PretrAD runs were conducted for different scenarios which were specific to Eastern Ontario, where prices were easily obtainable. PretrAD will be capable of accepting user-input variables for sludge handling under current conditions. A cost comparison with the incorporation of a SPT can then be quickly made by altering the percent solids content and flow of biosolids as a result of the chosen process. The variables that the user is capable of inputting are illustrated in Fig. 3.17. Those values which were used are outlined in Chapter 5. Only landfilling was considered for ultimate sludge disposal in the runs by varying related landfill costs. Although a few values were found for the evaluation of incineration and land application, more detailed information would be needed to establish realistic costs. For instance, available incineration data showed only that a substantial energy input, of unknown range, would be required but that the input was recoverable by 33-50% through the use of heat exchangers. It was also found that incineration costs decrease with higher percent feed solids concentration. For 5

to 25% solids, the energy input decreases from 65,000 to 7,000 kJ/kg VS [164]. For land application, Class A biosolids were found to be sold at prices of $40-100/ton or $120-200/ton including delivery [163, 164, 165].

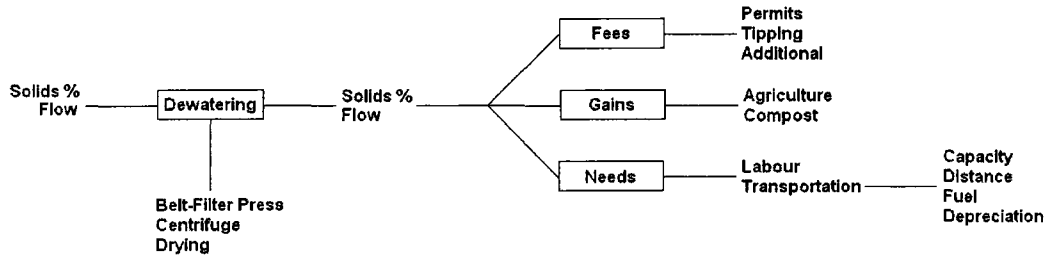


Figure 3.17 User-inputted variables prior to SPT

3.2.4 Energy Conversion

Methane generation is the key to AD and SPT incorporation potential. If CH_4 generation can be improved, gains are made as the CH_4 is directed to different energy recovery pathways. Those pathways that were considered in PretrAD are shown in Fig. 3.18. The CH_4, which is a fraction (50-80%) of the produced biogas can be flared (at a cost), returned to any portion of the WWTP in the form of heat energy or electricity, or it can be sold to the electrical grid (at a gain).

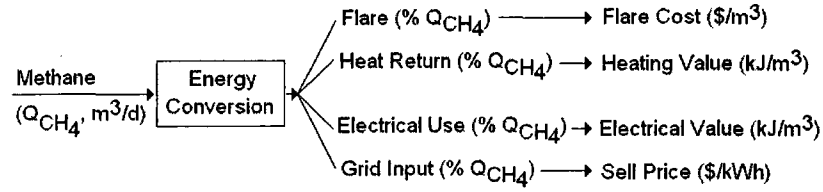


Figure 3.18 Energy conversion pathways available in the constructed model

The user can direct the CH_4 produced to one or more of the pathways. Flare cost and grid sell price could not be found with sufficient consistency to establish average values. Heating and electrical methane conversion values were found [160, 161]. With an initial energy value of 34,093 kJ/m^3 CH_4, 70-90% of the methane can be converted to heat or electricity. Conversion to electrical energy again reduces the overall energy value to a low 30-45% of its initial potential energy. The heating and electrical values were thus considered to be 75% (25,575 kJ/m^3) and 35% (11,935 kJ/m^3) of the initial value, respectively. Efficiencies have thus been included in the conversion values within PretrAD.

CHAPTER 4

Model, Functionality, Equations, and Validation

4.0 MODEL CONCEPTION AND PURPOSE

A large interest in SPTs as a means to improve MTAD and subsequent treatment steps is evident in literature. Most of the studies are lab-scale and many of those studies are not comparable. All of the available SPT parameters and results were compiled and are listed in Chapter 2. A model was needed to concretely assess SPT potential in terms of energy costs and biogas improvements. More specifically, a model, capable of handling various raw WW feed characteristics and treatment settings, was needed for an efficient and comprehensive comparison of all SPTs and possible WWTP schemes. Other advantages to creating a model consist of the generation of tabulated and graphical result reports, the ease of changing run parameters and outputs, and the potential market value of the only WWTP model that considers SPT technologies.

To serve as a reminder, the terminology used throughout this thesis to represent WWTP runs with and without SPT will again be described. Runs without SPT are labelled 'control'. Incorporation runs (with SPT) are labelled 'SPT'. This was done to clearly define the control costs from the SPT (i.e., incorporation scheme) costs.

4.1 FUNCTIONALITY AND BRIEF WALKTHROUGH

The model was created using Microsoft Excel and is thus composed of a Workbook containing various Worksheets. These worksheets and the built-in commands are explained in Sections 4.1.1-7. Print-screens of PretrAD are shown in Figs 4.1-4 and in some cases the nomenclature used does not entirely match that of the finalized nomenclature used in this thesis. A guide to the abbreviations for the few cases of initial nomenclature is provided in Appendix C.

A user may install the file to the directory of their choice. Endless copies of the file can be made, thus providing the user with infinite multiples of the 4 runs that are defaults in PretrAD. Users select the run which they want to operate and either input their

own settings or import the default literature values provided. The Excel Visual Basic interface shows a conventional WWTP where the user can input their data. The user may however choose to work in the basic Excel spreadsheets specific to each run. At any point, the PretrAD Output worksheet, which is continually updated, can be accessed for a 10 page report consisting of important tabulated data and pre-made figures. A concise 1 page report listing a single user-chosen run may also be viewed. All data are easily printed.

4.1.1 Welcome Form and Run Selection

Users are greeted by a sign-in welcome form that functions when macros are enabled. Within this form the user can enter a username and/or select a run. The selection of a run must be completed before the form can be closed. The purpose for the mandatory run selection is to enable the subsequent Excel Visual Basic 'Forms' to load and save data in and from the appropriate Run Condition worksheets. A Run Condition worksheet exists for each of the 4 runs.

4.1.2 Worksheet: WWTP Interface

A WWTP layout was selected for the user interface. It shows a conventional and common layout scheme for WWTPs. Also shown are the important flows and solids concentrations that are updated continuously as the user progresses through PretrAD (if macros are enabled).

The first sheet was named 'WWTP Interface'. It can be used only by users who have enabled Excel to handle macros. It functions in the same way as the following 4 Run Condition sheets. It permits users to enter their RF characteristics, subsequent treatment settings, and energy and cost information. The additional benefits to working directly from the WWTP Interface are both functional and aesthetic. The coded interface is simplistic and demonstrative. Users can also easily load or import values located on the Default Values sheet or in any of the Run Condition sheets. Values entered in the WWTP Interface sheet are copied into the user selected Run Condition sheet and are therefore saved when the Workbook is saved. A print screen of the WWTP Interface is shown in Fig. 4.1. All WWTP units are shown in grey. Values shaded in yellow are the stream characteristics flowing into and out of each unit. The flows, COD, BOD_5 and solids are shown until the SC unit, after which only the flows and solids are listed. The SPT unit is

shown in blue and is not employed for control runs (from which this print screen was created).

The bottom of the figure reveals primary commands available to the user. Data from any run can be accessed and showcased in the interface using the 'Run Selection' command. The second command enables the user to hide or show the worksheets for runs that are not currently being employed. Data can be loaded from the currently selected (active) run, from the Default Values worksheet or imported from any of the three unselected (passive) runs. The WWTP Interface may be cleared of values (this does not affect the Run Condition data) and the Output worksheet can be quickly accessed via the final command button.

4.1.3 Worksheets: Run Condition 1,2,3,4

The second, third, fourth, and fifth sheets were named 'Run Condition 1', 'Run Condition 2', 'Run Condition 3', and 'Run Condition 4', respectively. The user can choose to work from any of these sheets. Information entered on any of these sheets is saved when the Workbook is saved. Checks and balances are provided to the right of the workable section. These are also hardcoded in the WWTP Interface sheet and benefit the user by highlighting correct, incorrect, or impossible to handle user defined values (UDVs). A user who has not enabled macros must manually copy and paste information from other sheets to perform the hardcoded load or import function. A print screen of the Run Condition 1 worksheet is shown in Fig. 4.2. All runs have identical worksheets. At the top right of the worksheet is a command that enables the user to "simplify" the worksheet by hiding the checks and balances section (shown to the right of the vertical dotted line).

The workable section can be printed as a mass balance report for all units and the Output need not be used. Important comparative table and graphs are however, only provided in the output. By default, the data from all units print onto a single page and the entire input and output section (left of the vertical dotted line) prints onto 8 separate pages.

Run Condition sheets serve two purposes. They were provided to serve as a bare-bones interface for users who do not enable macros and they also serve as a record and report for UDVs entered using the WWTP Interface.

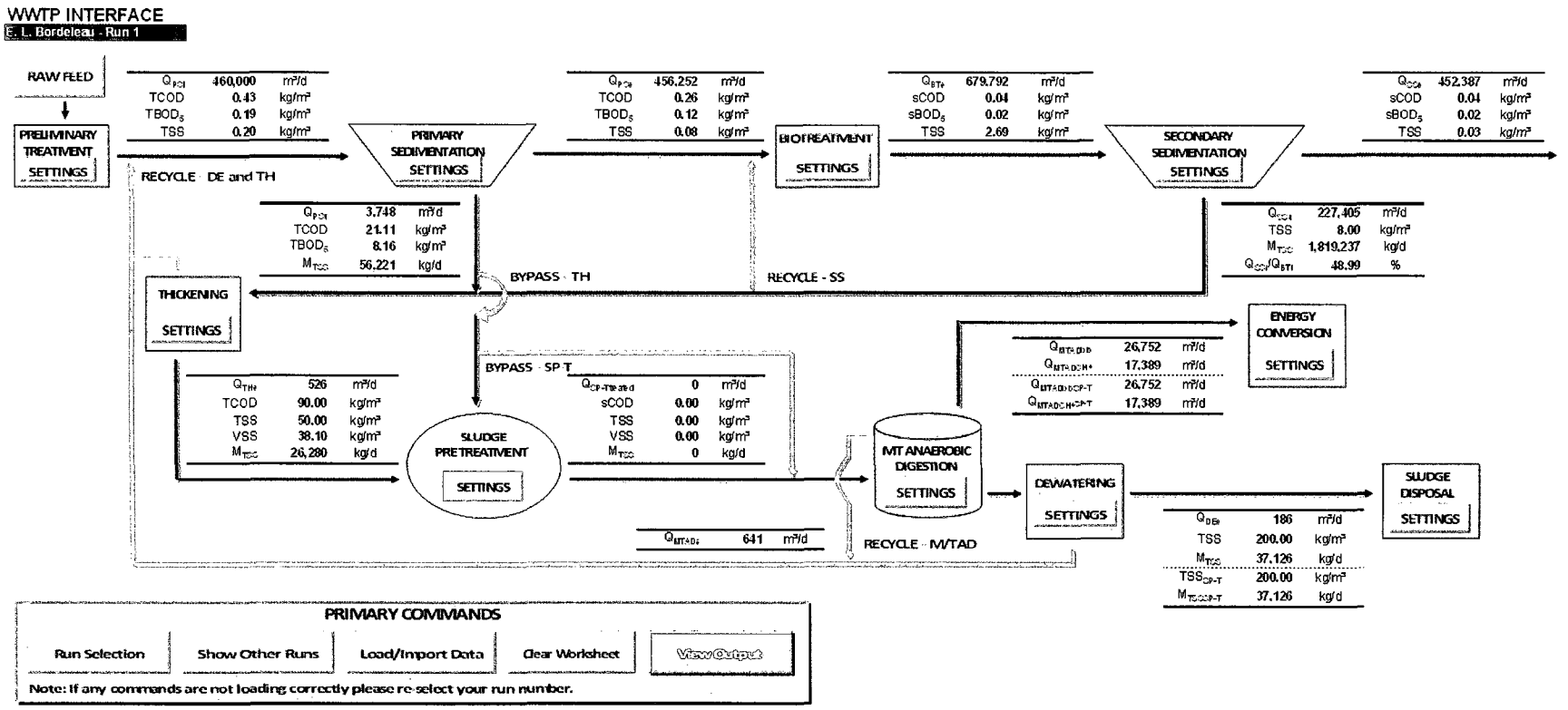


Figure 4.1 Print screen of the WWTP Interface worksheet

BACKUP USER INFO

E. L. Bordeleau - Run 1

Hide Checks & Balances

'USER INPUT CELLS ARE SHADED LIGHT GREEN

DISCLAIMER

1. This worksheet serves both as a bare-bones version of the "WWTPInterface" worksheet and as a backup for information entered on that worksheet.
2. Most users should only alter data that has not been protected and that is shaded light green.
3. Advanced users may modify data by unprotecting the workbook (password: "wastewater").
4. ***Any modifications (including 'Page Setup') may lead to functionality or output errors.***

RAW FEED

INFLUENT		Units
Inhabitant Equivs.	1,000,000	IE
Q_{RFI}	460,000	m³/d
TCOD	0.43	kg/m³
$TBOD_5$	0.19	kg/m³
TSS	0.21	kg/m³
VSS	0.16	kg/m³
TS	0.72	kg/m³
TVS	0.36	kg/m³
Feed Temp., T_{IRF}	15	°C

PRELIMINARY TREATMENT

INFLUENT		Units
Q_{RF}	460,000	m³/d
Q_{PTI}	460,000	m³/d
SETTINGS		**Units**
TSS Reduction	3.00	%
EFFLUENT		**Units**
Q_{PTe}	460,000	m³/d
TCOD	0.43	kg/m³
$TBOD_5$	0.19	kg/m³
TSS	0.20	kg/m³

PRIMARY SEDIMENTATION

INFLUENT		Units
Q_{PTeff}	460,000	m³/d
Q_{THPC}	3,339	m³/d
Q_{DEPC}	4,088	m³/d
Q_{MTADP}	641	m³/d
Q_{PCI}	460,000	m³/d
TCOD	0.43	kg/m³
$TBOD_5$	0.19	kg/m³
TSS	0.20	kg/m³
VSS	0.16	kg/m³
M_{TSS}	93,702	kg/d

SETTINGS		Units
TCOD Removal	40.00	%
$TBOD_5$ Removal	35.00	%
TSS Removal	60.00	%
Dedicate Flow TH	0.00	% Q
Dedicate Flow SP T	0.00	% Q
Underflow TSS Conc.	15.00	kg/m³
TBOD:TCOD After PC	55.00	kg/100 kg
TCOD:TSS After PC	110.00	kg/100 kg
Specific Gravity	1.02	

EFFLUENT		Units
O_{PCe}	456,252	m³/d
TCOD	0.26	kg/m³
$TBOD_5$	0.12	kg/m³
TSS	0.08	kg/m³
VSS	0.06	kg/m³
M_{TSS}	37,175	kg/d
UNDERFLOW		**Units**
Q_{PCu}	3,748	m³/d
TCOD	21.11	kg/m³
$TBOD_5$	8.16	kg/m³
TSS	15.00	kg/m³
VSS	11.43	kg/m³
M_{TSS}	56,221	kg/d
Solids Content	1.47	%
DEDICATED FLOW		**Units**
Q_{PCTH}	0	m³/d
Q_{PCSPT}	0	m³/d
Q_{PCMTAD}	3,748	m³/d

FLOW NOMENCLATURE

Flows - "Qab" or "Qabc"	a - Process Step	b - Stream or Direction
Example - Q_{PTI}	Preliminary Treatment	Influent
Example - Q_{THPC}	THickening	Recycles to Primary Sedimentation
Example - Q_{PCSPT}	Primary Sedimentation	Directed to Sludge Pre-Treatment
Example - $Q_{MTADPCSPT}$	M/T Anaerobic Digestion	Underflow with SP-T (c - with SP-T)

*Overall WWTP Influent and Effluent flows must balance	**Flow In**	**Flow Out**	**Negl. Recycle**
*Overall WWTP Flow Check: **Flow Respected**	**460,000**	**452,573**	**7,427**

*Overal WWTP Influent and Effluent mass must balance	**Mass In**	**Mass Out**	**Negl. Recycle**
*Overall WWTP Mass Check: **Mass Respected**	**99,632**	**90,869**	**8,763**

(SI or US Units)	M_{TSSI}	M_{TSSe}	$M_{TSSc,d,r,t}$	% Change
Primary Sedimentation	93,702	93,397	305	**0.33**
Biotreatment	1,825,494	1,831,425	5,930	**0.32**
Secondary Sedimentation	1,831,425	1,831,425	0	**BALANCED**
Thickening	30,918	30,918	0	**BALANCED**
Sludge Pre-Treatment	26,280	26,280	0	**BALANCED**
M/T Anaerobic Digestion	82,501	41,251	41,251	**50.00**
Dewatering	41,251	41,251	0	**BALANCED**

*M_{TSSc} = created, M_{TSSd} = destroyed, M_{TSSr} = retained, M_{TSSs} = solubilized

*SP-T and M/TAD % Changes should match user defined removals
*% Change Check: **MTSS Balanced**

*Influent, Supernatant, and Effluent flows must balance
*Flow Balance Check: **Flow Respected**

*Total bypass flows and MTAD flow must equal Q_{PCI}
*Underflow Flow Check: **Flow Respected**

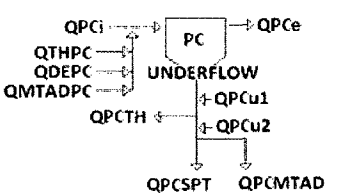


Figure 4.2 Print screen of the Run Condition 1 worksheet

The user may progress through PretrAD solely within the Run Condition worksheet and can easily copy and paste values from other runs or from the Default Values worksheet.

4.1.4 Worksheet: Default Values

The sixth sheet was named 'Default Values'. These values were gathered from literature sources. These values are provided along with a column for referenced sources in Appendix A. They were provided to reference UDVs and to promote quick and simple run generations from low to high values. With or without macros, the user can easily load 'LOW', 'AVERAGE', 'HIGH', and 'USER' values into the work section. The term 'USER' refers to user defined default values and was included to allow for minor to major variations of the LOW-HIGH default values. Some equations were also provided to determine the suitability and range of UDVs for PC settling efficiencies, PC sludge production, specific gravity, and MTAD heat flow coefficients.

Whether users have macros enabled or not, they can easily alternate between the four default value types (i.e., LOW, AVERAGE, HIGH, and USER). Since this worksheet is similar in design to the Run Condition worksheets it can be used to provide a report identical to the Run Condition worksheets. The Output worksheet however, is not linked to default values; it is linked to values entered into the Run Condition worksheets. To vary the output in accordance with default values, those values must be copied and pasted in any of the Run Condition worksheets.

A print screen of the Default Values worksheet is shown in Fig. 4.3. Both the workable section (left of vertical dotted line) and the default values section (right of vertical dotted line) are shown. When values are loaded into the Run Condition worksheets, values from the working section (shaded in light blue) are those that are copied when the load or import functions are used. The user alters the working section by altering the cells that, in this case (Fig. 4.3), are shown as 'LOW' and 'USER' after the fifth and sixth numbered information points in the Input and Selection section. The fifth numbered point refers to RF settings and as such the header for the first set of default values has conditional formatting applied to the 'LOW' cell. It is encased by a border and shaded light blue to identify that its values are being accessed by the working section.

The same principle applies to the treatment settings as selected by the sixth numbered point. Below these numbered points the LOW-HIGH and USER values are listed. Those shaded in green are UDVs and those that aren't were taken from literature. Equations 1-4 of Fig. 4.3 are secondary checks to ensure that UDVs and the subsequent outputs match with known literature ranges. They are explained in Appendix A.

No default values were specified for the energy and cost considerations as almost all of these UDVs are highly specific or they are to be assigned as user desired values.

4.1.5 Worksheet: Output – All Runs

An output consisting of comparative data for all 4 runs is provided. On the left a working section is provided with access to energy and cost considerations for each step shown. The data presented in this region are for only 1 run. Users can select the run for which they desire to have a more concise, 1 page output. The print screen of the single page printout that is also available on the Output worksheet is shown in Fig. 4.4. The run (currently Run 1) that is showcased by values for SPT, MTAD, DE, SD, and EC can be changed. Control and SPT results are given and since the print screens are all based on the control run, no SPT results are listed. The user can also easily update energy values previously entered when working in the WWTP Interface or in the Run Condition worksheets by selecting any of the 'Energy Editor' commands (macros must be enabled).

The Output is continually updated as the user progresses through PretrAD and can be viewed at any time. To the right of the workable section are the comparative tables and graphs for an improved 10 page visual report that highlights a chosen run and also compares all runs. Users who have macros enabled can choose to compare any runs (e.g., 1, 2, 3, 4 or 1, 2, 4 or 2, 3). The results are separated by WWTP units [SPT, MTAD, DE, sludge disposal (SD), and energy conversion (EC)]. Among the figures of interest are TSS/M_{TSS} evolutions (solids quantities throughout the WWTP) and cost and gain comparisons for each unit.

DEFAULT VALUES

Treatment & Energy Settings

'DEFAULT VALUES CELLS ARE SHADED LIGHT BLUE

DISCLAIMER

1. This worksheet serves both as a bare-bones version of the "WWTPInterface" worksheet and as a backup for information entered on that worksheet.
2. Most users should only alter data that has not been protected and that is shaded light green.
3. Advanced users may modify data by unprotecting the workbook (password: "wastewater").
4. ***Any modifications (including 'Page Setup') may lead to functionality or output errors.***

RAW FEED

INFLUENT		Units
Inhabitant Equivs.	1,000,000	IE
Q_{PF}	750,000	m³/d
TCOD	0.25	kg/m³
$TBOD_5$	0.11	kg/m³
TSS	0.12	kg/m³
VSS	0.10	kg/m³
TS	0.39	kg/m³
TVS	0.21	kg/m³
Feed Temp., T_{PF}	10	°C

PRELIMINARY TREATMENT

INFLUENT		Units
Q_{PF}	750,000	m³/d
Q_{PTI}	750,000	m³/d
SETTINGS		Units
TSS Reduction	3.00	%
EFFLUENT		Units
Q_{PTe}	750,000	m³/d
TCOD	0.25	kg/m³
$TBOD_5$	0.11	kg/m³
TSS	0.12	kg/m³

PRIMARY SEDIMENTATION

INFLUENT		Units
Q_{PTeff}	750,000	m³/d
Q_{THPS}	1,931	m³/d
Q_{DEPS}	3,704	m³/d
Q_{MT+DPS}	576	m³/d
Q_{PSI}	750,000	m³/d
TCOD	0.25	kg/m³
$TBOD_5$	0.11	kg/m³
TSS	0.12	kg/m³
VSS	0.09	kg/m³
M_{TSS}	87,300	kg/d
SETTINGS		Units
TCOD Removal	40.00	%
$TBOD_5$ Removal	38.00	%
TSS Removal	60.00	%
Dedicate Flow TH	0.00	% Q
Dedicate Flow SP-T	0.00	% Q
Underflow TSS Conc.	15.00	kg/m³
TBOD:TCOD After PS	50.00	kg/100kg
TCOD:TSS After PS	170.00	kg/100kg
Specific Gravity	1.02	

EFFLUENT		Units
Q_{PSe}	746,508	m³/d
TCOD	0.15	kg/m³
$TBOD_5$	0.07	kg/m³
TSS	0.05	kg/m³
VSS	0.04	kg/m³
M_{TSS}	34,757	kg/d
UNDERFLOW		Units
Q_{PSd}	3,492	m³/d
TCOD	21.48	kg/m³
$TBOD_5$	8.98	kg/m³
TSS	15.00	kg/m³
VSS	11.88	kg/m³
M_{TSS}	52,380	kg/d
Solids Content	1.47	%
DEDICATED FLOW		Units
Q_{PSTH}	0	m³/d
Q_{PSSP-T}	0	m³/d
Q_{PSMT+D}	3,492	m³/d

INPUT AND SELECTION 'USER INPUT CELLS ARE SHADED LIGHT GREEN

1. Default values for all user defined values are found below in their respective sections.
2. Equations are also provided to better predict typical values based on other user defined values.
3. This worksheet enables the user to quickly alternate between low, average, high, and user defaults.
4. All users can input their own default values in the cells that are shaded light green.
5. *Selected Raw Feed strength values in the light blue cells are:* LOW
6. *Treatment settings from Preliminary Treatment onward are:* USER

	LOW	AVERAGE	HIGH	USER	Units
Inhabitant Equivs.	1,000,000	1,000,000	1,000,000	1,000,000	IE
Q_{PF}/IE	0.75	0.46	0.24	0.46	m³/IE·d
TCOD	0.25	0.43	0.80	0.43	kg/m³
$TBOD_5$	0.11	0.19	0.35	0.19	kg/m³
TSS	0.12	0.21	0.40	0.21	kg/m³
VSS	0.10	0.16	0.32	0.16	kg/m³
TS	0.39	0.72	1.23	0.72	kg/m³
TVS	0.21	0.36	0.66	0.36	kg/m³
Feed Temp.	10	15	20	15	°C

	LOW	AVERAGE	HIGH	USER	Units
TSS Reduction	2.00	4.00	6.00	3.00	%

EQUATION 1 & 2 - $TBOD_5$ and TSS Settling Efficiencies (Influent Concentrations: 0.1-0.3 kg/m³)

Detention Time, T_d	3.00	h
$TBOD_5$ Settling Eff.	38.46	%
TSS Settling Eff.	60.61	%

$$TBOD\ Settling\ Eff. = \frac{T(h)}{0.018(h) + 0.02 \cdot T(h)}$$

$$TSS\ Settling\ Eff. = \frac{T(h)}{0.0075(h) + 0.014 \cdot T(h)}$$

EQUATION 3 - Primary Sludge Production

PS Solids Prod.	50,012	kg/d

$$PS\ Prod. = Q \quad TSS \quad \frac{T(h)}{0.006767(h) + 0.0152 \cdot T(h)}$$

EQUATION 4 - Specific Gravity Selection

Specific Gravity, S_g	1.01	

$$S = 1 + 0.005 \cdot TS\ (\%\ Total\ Solids)$$

	LOW	AVERAGE	HIGH	USER	Units
TCOD Removal	20.00	30.00	40.00	40.00	%
$TBOD_5$ Removal	20.00	30.00	40.00	38.00	%
TSS Removal	40.00	55.00	70.00	60.00	%
Dedicate Flow TH	0.00	0.00	100.00	0.00	% Q
Dedicate Flow SP-T	0.00	0.00	100.00	0.00	% Q
Underflow TSS Conc.	20.00	40.00	80.00	15.00	kg/m³
TBOD:TCOD After PS	40.00	55.00	70.00	50.00	kg/100 kg
TCOD:TSS After PS	160.00	185.00	210.00	170.00	kg/100 kg
Specific Gravity	1.01	1.03	1.05	1.02	

Figure 4.3 Print screen of the Default Values worksheet

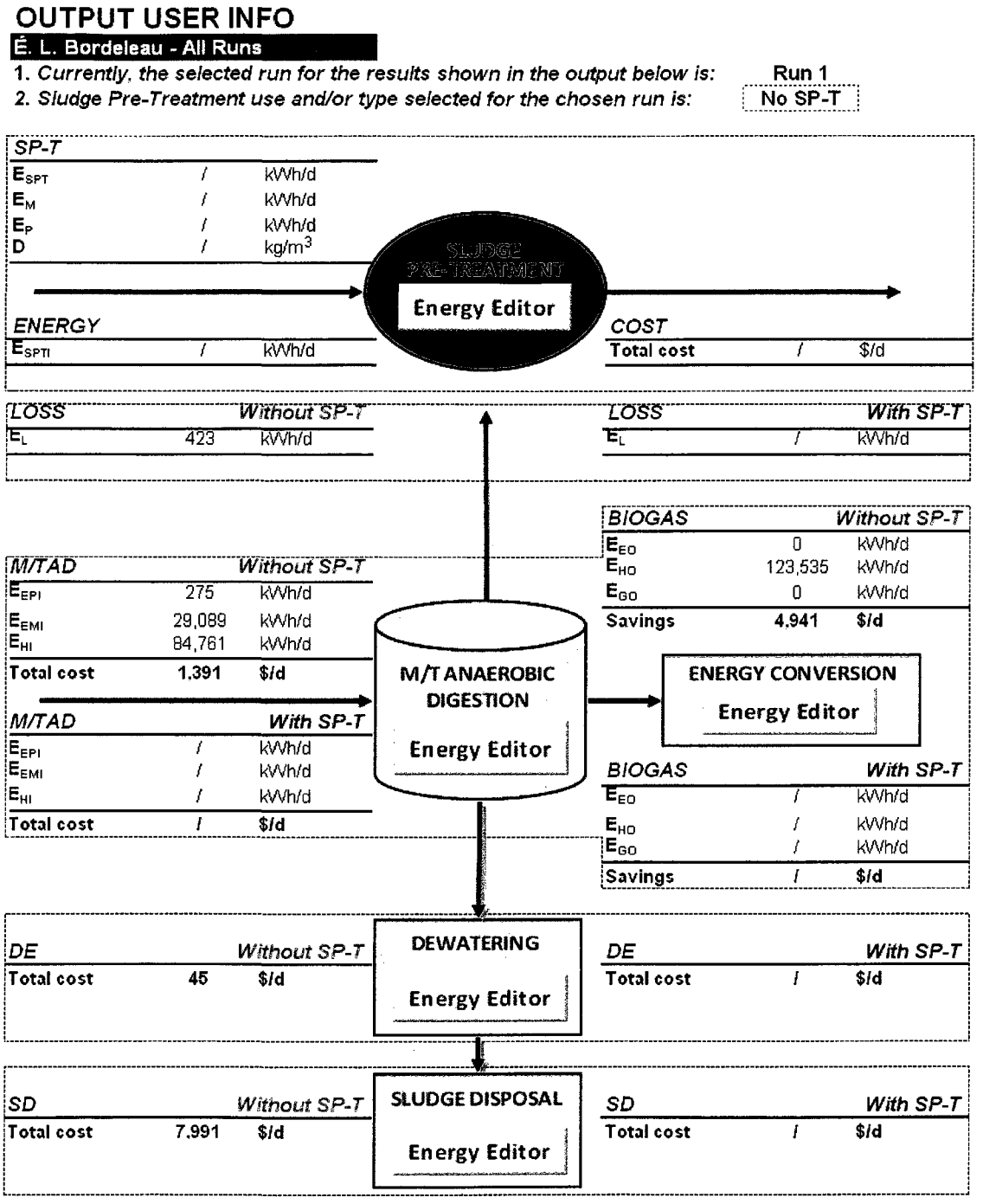


Figure 4.4 Print screen of the one page report from the Output worksheet

4.1.6 WWTP Functions

Forms for each unit in the treatment train can be accessed by selecting the 'SETTINGS' button for each unit.

Raw feed characteristics and treatment settings for all other steps can be altered within these forms. Typical treatment settings include settling efficiencies, COD, BOD_5, and TSS removals, effluent concentrations, recycling decisions, and treatment efficiencies.

An 'Energy Editor' button was provided to access important considerations for thickening (TH), SPT, MTAD, DE, SD, and EC within the WWTP Interface. This button can also be found on the Output worksheet.

4.1.7 Energy and Cost Functions

Forms for energy and cost considerations can be accessed by selecting the 'Energy Editor' button found on the 'SETTINGS' form for each unit. They can also be accessed in the output sheet by selecting the 'Energy Editor' button for each unit.

These forms have been created to assess the energy and cost demands and gains for TH, SPT, MTAD, DE, SD, and EC. Energy and cost considerations for TH and SPT are found within the same form. All other WWTP process units have their own form with regards to energy and cost considerations.

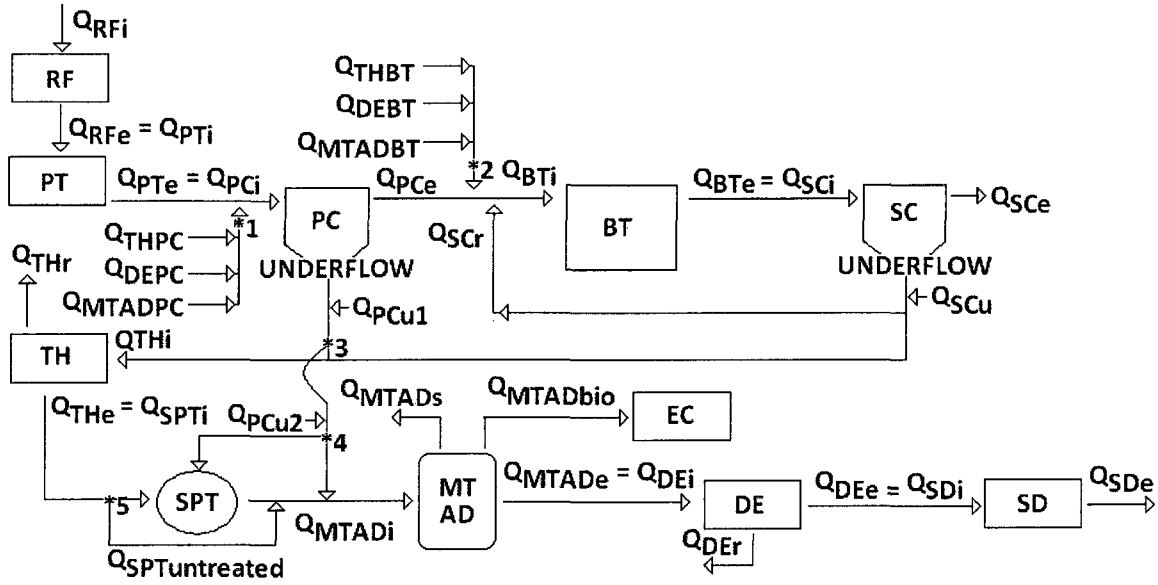
Users can alter electrical demands such as pumping, mixing, and treatment power use. Heating requirements and recoveries can also be varied. Biogas dedication (to a specific use/energy conversion pathway) and subsequent cost or gain can also be determined.

4.2 TREATMENT EQUATIONS

This section details the equations and the average UDVs employed to generate the typical WWTP output. Low and high flow WWTP outputs were also generated using the same equations. The change in UDVs and in results can be found in Chapter 5.

A graphical model overview is provided in Fig. 4.5. The streams for the entire WWTP are shown. Recycle streams may be conceptually added (i.e., solids and flows are not subsequently added to the directed inputs). The possible paths indicated by the *1 and *2 denoted guidelines below the figure. The recycle streams were neglected to avoid circular references in Excel, these flows are conceptually directed to either the PC or the

biotreatment (BT) unit. It will be shown in Section 4.4, when validity is assessed by comparison to the Plan-It STOAT model, that neglecting recycle flows that are relatively negligible (not including SC_r) does not significantly alter unit or overall influent and effluent flows and solids concentrations. The *3 and *4 flow paths enable the bypassing of PC underflow from the TH and SPT units, respectively. Flow path *5 simply depicts that not all TWAS is necessarily treated in the SPT unit. Effluent flows clearly become influent flows to the immediate downstream units.



*1 - Q_{THr}, Q_{DEr}, and Q_{MTADs} can be directed to PC or MTAD
*2 - Q_{THr}, Q_{DEr}, and Q_{MTADs} can be directed to PC or MTAD
*3 - Q_{PCu1} can be split and directed to or bypass TH
*4 - Q_{PCu2} can be split and directed to or bypass SPT
*5 - Q_{SPTi} can be split to treat a fraction or all of the influent

Figure 4.5 Complete WWTP flow schematic

Some sections show equations in SI and US units. This was necessary for the conversion or use of UDV and literature-obtained coefficients.

The user alters the settings shaded in green. Values may also be loaded from the Default Values worksheet. All UDVs shown in Sections 4.2.1-9 are for the 'Average' default values as shown in Appendix A with the reference source.

4.2.1 Raw Feed

Calculations and UDVs, are shown in Table 4.1. No equations are used in the specification of RF UDVs.

Table 4.1 Raw feed settings

SETTINGS	Units	UDV
Inhabitant Equivalents	IE	1,000,000
Q_{RF}	m^3/d	460,000
TCOD	kg/m^3	0.43
$TBOD_5$	kg/m^3	0.19
TSS	kg/m^3	0.21
VSS	kg/m^3	0.16
TS	kg/m^3	0.72
TVS	kg/m^3	0.36
Feed Temperature, $T°_{RFi}$	°C	15

4.2.2 Preliminary Treatment

Calculations and UDVs for preliminary treatment are shown in Table 4.2 and in the equations below.

Table 4.2 Preliminary treatment settings

SETTINGS	Unit	UDV
TSS Reduction	%	3.00

One equation is used at this time. The TSS reduction setting is applied to the RF influent to obtain the PT effluent TSS concentration.

$$TSS_e = TSS_i \cdot \left(\frac{100 - P_r}{100} \right) \qquad 4.1$$

4.2.3 Primary Sedimentation

Calculations and UDVs for PC are shown in Table 4.3 and in the equations below.

Equations for influent to clarified effluent are the same for COD, BOD_5, and TSS. The variable X is used to represent all three concentrations in Eq 4.2. Percent removal is represented by P_r.

Table 4.3 Primary sedimentation settings

SETTINGS	Units	UDV
TCOD Removal	%	40.0
$TBOD_5$ Removal	%	35.0
TSS Removal	%	60.0
Dedicate Underflow to TH	% Q_{PCu1}	0.0
Dedicate Underflow to SPT	% Q_{PCu2}	0.0
Underflow TSS Concentration	kg/m^3	15.0
TBOD:TCOD After PC	kg/100 kg	55.0
TCOD:TSS After PC	kg/100 kg	110.0
Specific Gravity		1.02

$$X_e = X_i \cdot \left(\frac{100 - P_r}{100}\right) \tag{4.2}$$

Equations for COD and BOD_5 in the underflow are the same.

$$X_u = \frac{X_i \cdot Q_i \cdot \left(\frac{P_r}{100}\right)}{Q_u} \tag{4.3}$$

Underflow TSS concentration is set by the user. The effluent and underflow VSS concentrations are obtained using the ratios shown below.

$$VSS_e = VSS_i \cdot \left(\frac{TSS_e}{TSS_i}\right) \tag{4.4}$$

$$VSS_u = VSS_i \cdot \left(\frac{TSS_u}{TSS_i}\right) \tag{4.5}$$

Underflow solids M_{TSS} are calculated using PC influent values and percent TSS removal.

$$M_{TSSu} = TSS_i \cdot Q_i \cdot \left(\frac{P_r}{100}\right) \tag{4.6}$$

Flow balances are shown in Fig. 4.6. In the equations below, P_d represents the UDV for percent dedicated flow. These dedicated flows are user defined at downstream units. For example, the supernatant flow of the TH unit is recycled to either the PC or BT unit. As such, in both Figs. 4.6 and 4.7, dedicated flows are listed. If the portion of

overall flow from the TH is directed (dedicated) to the PC unit, the flow is labelled Q_{THPC} as per the given Flow Nomenclature Legend. To simplify PretrAD and avoid any circular references and subsequent need for iterations, recycle flows (not including SC_r) and concentrations were neglected. The recycle flows (not including SC_r) and solids concentrations in them are negligible compared to Q_{PCi} and Q_{BTi} and are thus rightfully ignored. As described earlier, the dedication of flows is purely conceptual. Further explanations concerning PretrAD validation are given in Section 4.4.

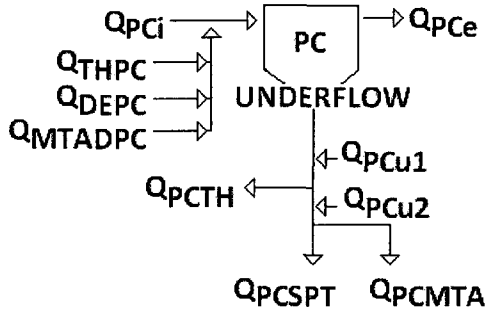


Figure 4.6 Primary sedimentation flow schematic

$$Q_{PCi} = Q_{PCe} = Q_{PCu1} \tag{4.7}$$

$$Q_{PCu1} = Q_{PCTH} + Q_{PCSPT} + Q_{PCMTAD} = MTSS_u / TSS_u \tag{4.8}$$

$$Q_{PCu2} = Q_{PCu1} = Q_{PCTH} \tag{4.9}$$

$$Q_{PCTH} = Q_{PCu1} \cdot \left(\frac{P_d}{100}\right) \tag{4.10}$$

$$Q_{PSSP-T} = Q_{PSu2} \cdot \left(\frac{P_d}{100}\right) \tag{4.11}$$

$$Q_{PCMTAD} = Q_{PCu2} = Q_{PCSPT} \tag{4.12}$$

Ratios for TBOD:TCOD and TCOD:TSS following PC are UDVs and apply to BOD_5, TCOD, and TSS concentrations at the TH, SPT, MTAD, DE, and SD steps. At each of those steps the TSS concentrations in the influents and effluents are known and/or set by the user and thus the BOD_5 and COD concentrations can be obtained. Concentarions of any of these constituents are a function of all of the incoming streams. The subscript 'j' represents the specific incoming stream.

$$COD_{step} = \sum\left(\frac{TSS_j \cdot Q_j \cdot TCOD:TSS}{Q_{step}}\right) \quad 4.13$$

$$BOD_{step} = \sum\left(\frac{TSS_j \cdot Q_j \cdot (TBOD:TCOD \cdot TCOD:TSS}{Q_{step}}\right) \quad 4.14$$

Percent underflow solids is computed in SI and US units as shown below. This approach to showing SI (Eq #a) and US (Eq #b) unit equations is used throughout Sections 4.2.1-9.

$$\%_{undsolids} = \left(\frac{M_{TSSu}\frac{\text{kg}}{\text{d}}}{Q_{PCu}\frac{m^3}{d}}\right)\cdot\left(\frac{\text{L}}{1.0\ kg}\right)\cdot\left(\frac{1}{S_g}\right)\cdot\left(\frac{1\ m^3}{1000\ L}\right)\cdot(100) \quad 4.15a$$

$$\%_{undsolids} = \left(\frac{M_{TSSu}\frac{lb}{d}}{Q_{PCu}\frac{gal}{d}}\right)\cdot\left(\frac{gal}{8.345\ lb}\right)\cdot\left(\frac{1}{S_g}\right)\cdot(100) \quad 4.15b$$

4.2.4 Biotreatment

Calculations and UDVs are shown in Table 4.4 and in the equations below.

Table 4.4 Biotreatment settings

SETTINGS	Units	UDV
TCOD Treatment Efficiency	%	85.0
$TBOD_5$ Treatment Efficiency	%	85.0
Biomass Net Yield, Y_{net}	kg TSS/kg BOD_5	0.90
Volume, V_{BT}	m^3	80,000
SRT	d	5

Influent TBOD is composed of soluble and particulate fractions. During BT the influent particulate BOD, pBOD, is partially converted into sBOD. Clarified BT effluent concentrations of sCOD and sBOD are reported but TCOD and TBOD are not reported in PretrAD for SC effluent because they are not pertinent to the analysis of SPT incorporation. Secondary sedimentation clarified effluent TSS is reported. All removals are computed using the UDVs for treatment efficiencies.

$$X_e = X_i \cdot \left(\frac{100 - P_r}{100} \right) \quad 4.16$$

The effluent TSS concentration (also MLTSS from the BT basin) is calculated as shown below. To again maintain a simplified model and avoid circular references, recycle flows and concentrations within them were set by UDVs. The dedicated flows and solids concentrations are negligible when compared to PC_e and SC_r and can thus be neglected without substantial modifications in the treatment equations. The dedicated flows can however, be included in the effluent.

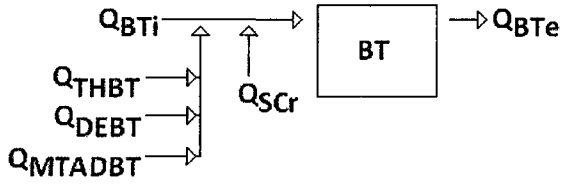


Figure 4.7 Biotreatment flow schematic

$$Q_{BTi} = Q_{PCe} \quad 4.17$$

$$Q_{BTe} = Q_{BTi} + Q_{SCr} \quad 4.18$$

The food to microorganism (F:M) ratio is calculated to verify if the settings the user has entered provide an F:M ratio that falls within the typical range of 0.2-0.6 g BOD_5/d·g MLVSS [160].

$$MLTSS = TSS_e = \frac{Q_{BTi} \cdot (TBOD_{5i} - sBOD_{5e}) \cdot Y_{net} \cdot \theta_X}{V_{BT}} \quad 4.19$$

$$MLVSS = VSS_i \cdot \left(\frac{TSS_e}{TSS_i} \right) \quad 4.20$$

$$F:M = \left(\frac{Q_{BTi} \cdot TBOD_{5i}}{V_{BT} \cdot MLVSS} \right) \quad 4.21$$

4.2.5 Secondary Sedimentation

Calculations and UDVs are as shown in Table 4.5 and in the equations below.

The effluent TSS concentration is determined using the UDV for P_r.

$$TSS_e = TSS_i \cdot \left(\frac{100 - P_r}{100}\right) \quad 4.22$$

Table 4.5 Secondary sedimentation settings

SETTINGS	UDV	Units
TSS Settling Efficiency	%	99.0
Underflow TSS Concentration	kg/m^3	8.0
TCOD:TSS After SC	kg/100 kg	180.0

Effluent and underflow M_{TSS} are defined as shown below. The subscript 'j' is used to represent either stream.

$$M_{TSSj} = TSS_j \cdot Q_{SCj} \quad 4.23$$

Soluble concentrations of COD and BOD_5 are not changed from the influent to the clarified effluent stream.

$$X_i = X_e \quad 4.24$$

Underflow TSS concentration is a UDV and enables the determination of the sludge volume index (SVI). It was computed in SI and US units as shown in Eqs 4.25a-b.

$$\text{SVI} = \frac{1000 \text{ mL/L} \times 1000 \text{ mg/g}}{\text{TSS}_u \text{ kg/m}^3 / 1000} = \frac{10^3}{\text{TSS}_u} (\text{mg/L}) \quad 4.25a$$

$$\text{SVI} = \frac{10^6}{TSS_u} \cdot \frac{\text{lb/gal}}{8.34x10^{-6} \text{ mg/L}} \quad 4.26b$$

Underflow TCOD concentration is determined using the UDV as follows.

$$TCOD_u = \frac{TSS_u \cdot TCOD:TSS}{100} \quad 4.27$$

Flows for the SC unit are labelled and balanced as shown in Fig. 4.8.

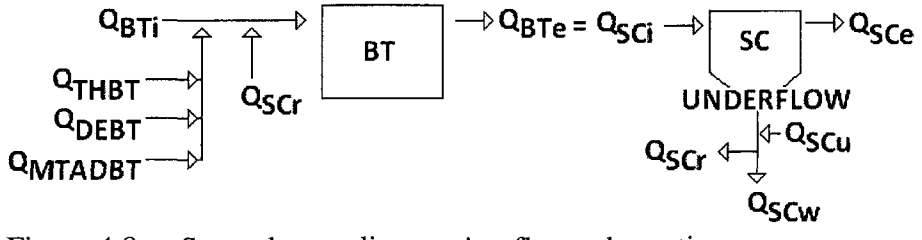


Figure 4.8 Secondary sedimentation flow schematic

Eqs 4.28-34 were used to solve the flows and include the UDVs for V_{BT} and the recycle ratio Q_{SCr}/Q_{BTi}.

$$Q_{SCi} = Q_{SCe} + Q_{SCu} \quad 4.28$$

$$Q_{SCe} = Q_{BTe} - Q_{SCu} \quad 4.29$$

$$Q_{SCu} = Q_{SCr} + Q_{SCw} = Q_{SCi} - Q_{SCe} \quad 4.30$$

$$Q_{SCw} = \left(\frac{V_{BT} \cdot (TSS_i / \theta_x) - (Q_{BTi} \cdot sBOD_{5i})}{(TSS_u - TSS_e)} \right) \quad 4.31$$

$$\frac{Q_{SCr}}{Q_{BTi}} = \frac{(1 - \theta_d / \theta_x)}{(TSS_u / TSS_{BTe} - 1)} \cdot 100\% \quad 4.32$$

$$\theta_d = V_{BT} / Q_{BTi} \quad 4.33$$

$$Q_{SCr} = Q_{BTi} \cdot \left(\frac{Q_{SCr} / Q_{BTi}}{100} \right) \quad 4.34$$

4.2.6 Thickening

Calculations and UDVs for TH are shown in Table 4.6 and in the equations below. The Recycle type refers to the directing of the recycle stream to either the primary clarifier (PC), the biotreatment unit (BT) or for NO recycle to occur.

Table 4.6 Thickening settings

SETTINGS	UDV	Units
TSS Capture Efficiency	%	85.0
Underflow TSS Concentration	kg/m^3	50.0
Chemical Dosage	kg/kg TSS	0.0040
Recycle? Type: PC/BT/NO		PC
pCOD	% $TCOD_e$	70.0

The concentration of TSS in the underflow stream is a function of the influent TSS concentration and the UDV for percent capture of influent solids, P_c.

$$TSS_u = TSS_i \cdot \left(\frac{100 - P_c}{100} \right) \quad 4.35$$

$$M_{TSSu} = TSS_u \cdot Q_{THu} \quad 4.36$$

The underflow is dictated by the UDVs for effluent TSS concentration and TSS capture efficiency. Once it is found, the recycle flow can be determined. The TH and SPT streams balance as shown in Fig. 4.9 and Section 4.1.7.

$$Q_{THr} = Q_{THPC} \text{ or } Q_{THBT} \quad 4.37$$

$$Q_{THr} = Q_{THi} - Q_{THu} \quad 4.38$$

$$Q_{THu} = \frac{Q_{THi} \cdot TSS_i \cdot (P_c/100)}{TSS_e} \quad 4.39$$

Solids content in the underflow is determined in SI and US units using the TSS concentration and the density of water, ρ_w.

$$\text{Solids Content}(\%) = \frac{TSS\ (\text{kg/m}^3)}{\rho_w\ (1000\ \text{kg/m}^3)} x\ 100\% \quad 4.40a$$

$$\text{Solids Content}(\%) = \frac{TSS\ (lb/gal)}{\rho_w\ (8.34\ gal/lb)} x\ 100\% \quad 4.40b$$

The TH recycle and underflow COD and $TBOD_5$ concentrations are not reported in PretrAD but can be determined for each step as explained in the Primary Sedimentation section. Influent TCOD and $TBOD_5$ concentrations are reported for each unit process throughout PretrAD. The TH recycle concentrations of TCOD, $TBOD_5$ are assumed to be the same as in the influent. The TH recycle TSS concentration is computed as shown below.

$$M_{TSSr} = M_{TSSi} - M_{TSSu} \quad 4.41$$

$$M_{TSSi} = TSS_i \cdot Q_{THi} \quad 4.42$$

$$TSS_r = \frac{M_{TSSr}}{Q_r} \quad 4.43$$

The UDV for pCOD is used in the SPT section. The chemical dose value used to improve sludge thickening is considered in Section 4.3.

4.2.7 Sludge Pretreatment

Calculations and UDVs for SPT are as shown in Table 4.7 and in the equations below. When SPT is not in use the cells shown remain empty.

The legend needed for the user to enter the appropriate SPT Type is shown in Table 4.8 and is provided alongside the settings on the Run Condition and Default Values worksheets. The user enters the SPT type in the green UDV cell.

Table 4.7 Sludge pretreatment settings

SETTINGS	Units	UDV
SPT Type		***Type***
Percent Flow Treated	%	100.0
pCOD Solubilisation	%	60.0
TSS Solubilisation	%	20.0
VSS Solubilisation	%	20.0

Table 4.8 Sludge pretreatment settings

SPT Use	*Type*
Ultrasound	ULT
High Pressure Homogenizer	HPH
Stirred Ball Mill	SBM
Conventional Heating	CH
Microwave Heating	MWH
Chemical	CM
Ozone	OZ
Thermochemical	TC

The UDV for pCOD Solubilisation was set at a favourable 60%. The SPT hydrolysis ranges established in Chapter 2 mostly peak at 45%. Some outlier pCOD solubilisation values found in the literature were higher than 80%. The ranges were established to demonstrate the most feasible full-scale results. A 60% value was chosen to conduct PretrAD cost and energy use scenario results primarily under ideal conditions. As described in Chapter 5, favourable (Low) SPT energy demands were the first to be evaluated. If practical (SPT scenario costs lower than control costs) scenarios could not be found during the initial evaluations, scenarios using less-favourable treatment

parameters would be unnecessary. The UDV for SPT Type enables the user to pursue further settings based on energy and costs of that SPT. The option to treat a percent of the influent flow to the SPT unit was given. A UDV that is lower than 100% can be set to improve AD while controlling SPT energy requirements.

Solubilisation of pCOD alters the fraction of influent TCOD (pCOD and sCOD). The variable P_s represents the percent solubilisation.

$$sCOD_e = TCOD_i - TCOD_i \cdot \left(\frac{pCOD\ \%}{100}\right) \cdot \left(1 + \frac{pCOD\ solu.\ \%}{100}\right) \qquad 4.44$$

The concentrations of TSS and VSS in the SPT effluent stream are a function of the influent concentrations and the UDVs for percent capture at the TH unit.

$$X_e = X_i \cdot \left(\frac{100 - P_c}{100}\right) \qquad 4.45$$

$$M_{TSSe} = TSS_e \cdot Q_{SPTe} \qquad 4.46$$

The flows balance as shown in Fig. 4.9 below. As mentioned earlier, the PC underflow can bypass the TH and/or the SPT unit. These streams are listed as per the flow nomenclature legend [e.g., Q_{PC}(from PC)$_{TH}$(towards TH)]. If the entire PC underflow stream were directed to the TH unit than both streams Q_{PCSPT} and Q_{PCMTAD} would be null. The Q_{THe} flow of course consists of Q_{PCTH} and Q_{SCw}. The percent flow treated, P_f in the SPT unit is set by the user.

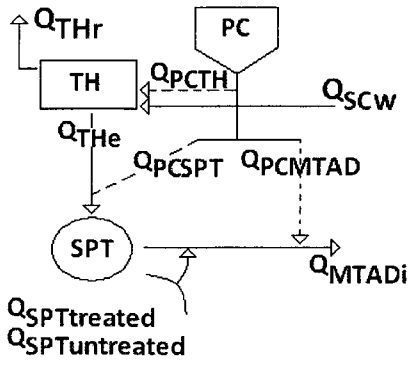


Figure 4.9 SPT flow schematic

$$Q_{SPTi} = Q_{SPTe} = Q_{SPTtreated} + Q_{SPTuntreated} \qquad 4.47$$

$$Q_{SPTtreated} = Q_{SPTi} \cdot \left(\frac{P_f}{100}\right) \quad 4.48$$

TSS concentration in the portion of underflow from the thickener that was not sent to SPT is unchanged and it is used to determine the M_{TSS} of the non-SPT treated underflow if it exists.

$$M_{TSSe} = TSS_i \cdot Q_{SPTuntreated} \quad 4.49$$

4.2.8 Mesophilic/Thermophilic Anaerobic Digestion

Calculations and UDVs are as shown in Table 4.9 and in the equations below. Removal improvements for TSS and sCOD are left blank when SPT use is not considered.

The concentration of TSS in the sludge stream from the MTAD unit is a function of the influent TSS concentration and the UDV for percent TSS removal in the MTAD unit. The calculations are performed for both treated and untreated SPT influents.

$$TSS_u = TSS_i \cdot \left(\frac{100 - P_r}{100}\right) \quad 4.50$$

$$M_{TSSu} = TSS_u \cdot Q_{MTADu} \quad 4.51$$

For the MTAD unit flows are named and balanced as shown in Fig. 4.10 and by Eqs 4.52-55 and Eq 4.64. The Recycle type refers to the directing of the recycle stream to either the primary clarifier (PC), the biotreatment unit (BT) or for NO recycle to occur.

Table 4.9 Mesophilic/thermophilic anaerobic digestion settings

SETTINGS	Units	UDV
TSS Removal Efficiency	%	50.0
TSS Removal Impr.	%	10.0
sCOD Removal Efficiency	%	50.0
sCOD Removal Impr.	%	10.0
CH_4 Content	%	65.0
Supernatant Flow	% Q_{MTADi}	15.0
Recycle? PC/BT/NO		PC
Biomass Yield, Y_{net}	kg VSS/kg COD	0.04
Volume, V_{MTAD}	m^3	50,000
Digester Temperature	°C	35
HRT	d	20

The MTAD subscript 'bio' refers to biogas. The flow $Q_{MTADbio}$ is that of the biogas stream which is input to the EC step.

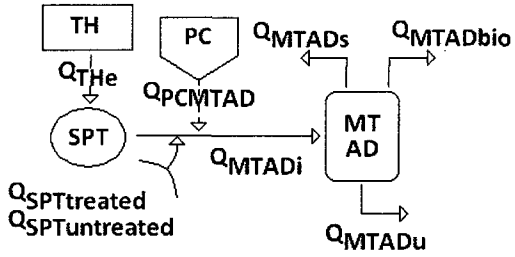


Figure 4.10 Mesophilic/thermophilic anaerobic digestion flow schematic

$$Q_{MTADi} = Q_{THe} + Q_{PCMTAD} = Q_{MTADu} + Q_{MTADs} \quad 4.52$$

$$Q_{THe} = Q_{SPTtreated} + Q_{SPTuntreated} \quad 4.53$$

The MTAD supernatant flow and it return flow path are UDVs. Once the supernatant flow is determined using the percent flow, the MTAD sludge underflow is found.

$$Q_{MTADs} = Q_{MTADPC} + Q_{MTADBT} = Q_{MTADi} \cdot \left(\frac{P_f}{100} \right) \quad 4.54$$

$$Q_{MTADu} \approx Q_{MTADi} \quad 4.55$$

The theoretical biogas flow is found as shown in Fig. 4.11 and by Eqs 4.56-64.

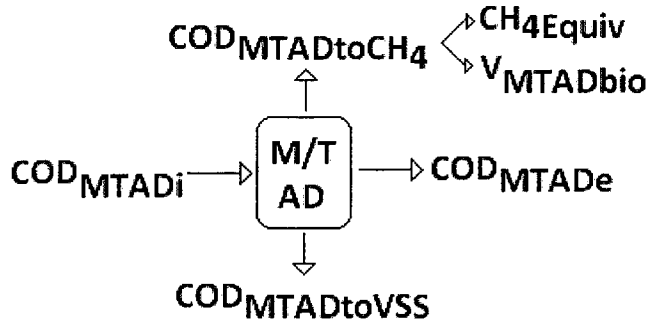


Figure 4.11 Biogas production based on COD removal schematic

$$COD_{MTADi} = Q_{MTADi} \cdot TCOD_i \qquad 4.56$$

$$COD_{MTADe} = COD_{MTADi} \cdot \left(\frac{100 - P_r}{100}\right) \qquad 4.57$$

$$COD_{MTADtoVSS} = 1.42 \cdot Y_{net} \cdot COD_{MTADi} \cdot \left(\frac{P_r}{100}\right) \qquad 4.58$$

$$COD_{MTADtoCH4} = COD_{MTADi} - COD_{MTADe} - COD_{MTADtoVSS} \qquad 4.59$$

The volume of biogas occupied by 1 mole at a given digester temperature can be determined from the ideal gas law. This volume was pre-calculated for all anaerobic digester treatment temperatures (35, 55°C or 95, 131°F) and in both SI and US units.

$$V_{MTADbio} = \frac{n \cdot R \cdot T}{P} \qquad 4.60$$

At MAD and TAD temperatures, $V_{MTADbio}$ will have different values and these are shown below, respectively.

$$V_{MTADbio} = 0.02529,\ 0.02693\ \text{m}^3/\text{mol} \qquad 4.61a$$

$$V_{MTADbio} = 6.68,\ 7.11\ \text{gal/mol} \qquad 4.61b$$

$$CH_{4\,Equiv} = \frac{V_{MTADbio}}{0.064}\ (\text{m}^3\ CH_4/\text{kg COD}) \qquad 4.62a$$

$$CH_{4\,Equiv} = \frac{V_{MTADbio}}{0.1411}\ (\text{gal}\ CH_4/\text{lb COD}) \qquad 4.62b$$

$$Q_{MTADCH4} = CH_{4\,Equiv} \cdot COD_{MTADtoCH4} \qquad 4.63$$

$$Q_{MTADbio} = Q_{MTADCH4} \cdot \left(\frac{100}{CH_4 \ Content \ \%} \right) \quad 4.64$$

The UDVs for digester volume and HRT are not used at this time.

4.2.9 Dewatering

Calculations and UDVs are as shown in Table 4.10 and in the equations below. The Recycle type refers to the directing of the recycle stream to either the primary clarifier (PC), the biotreatment unit (BT) or for NO recycle to occur.

Table 4.10 Dewatering Settings

SETTINGS	Units	UDV
TSS Capture Efficiency	%	90.0
Solids Content	%	20.0
Recycle? Type: PC/BT/NO		PC
Polymer Dosage	kg/kg TSS	0.0050

The TSS concentration in the cake stream from dewatered sludge (SD influent) is determined with the UDV for TSS capture efficiency.

$$M_{TSSsludge} = M_{TSSi} \cdot \left(\frac{P_c}{100} \right) \quad 4.65$$

$$TSS_{sludge} = \frac{M_{TSSsludge}}{Q_{DEsludge}} \quad 4.66$$

Once the sludge flow from the DE unit is determined using the UDV for percent capture and solids content, the recycle flow or overflow from the dewatering unit is found.

$$Q_{DEsludge} = \frac{MTSS_i \cdot P_c}{Solids \ Content \cdot 1000} \quad 4.67$$

$$Q_{DEr} = Q_{DEi} - Q_{DEsludge} \quad 4.68$$

Mass of solids in the recycle is found by the following balance. The recycle TSS concentration can then be found.

$$M_{TSSr} = M_{TSSi} - M_{TSSsludge} \quad 4.69$$

$$TSS_r = \frac{M_{TSSr}}{Q_{DEr}} \quad 4.70$$

Polymer concentration used to dewater the sludge is used in Section 4.3.

4.3 ENERGY AND COST EQUATIONS

4.3.1 Sludge Pretreatment General Parameters

Calculations and general UDVs for all SPTs are shown in Table 4.11a and in the equations below. Effluent temperature from the SPT process, $T°_{el}$ depends on the SPT in use. The specific SPT effluent temperatures are given in Table 5.3, Chapter 5.

Table 4.11a Sludge pretreatment general treatment settings

SETTINGS	Units	UDV
TEMPERATURES		
Influent Temperature, $T°_{il}$	°C	15
Effluent Temperature, $T°_{el}$	°C	25
BATCH		
Treatment Time	h/batch	0.25
Setup/Down Time	h/batch	0.08
Daily Batches	batch/d	72
Total Batch Volume	m^3/batch	7.3
ENERGY COST		
Electricity Price	$/kWh	0.04
THICKENING PARAMETERS		
Coagulant Change (±)	%	0.00
Chemical Price	$/kg	0.00
Power Supplied	kJ/kg TSS	0.00

Daily batches and total batch volume are determined for energy and cost assessment and basic design values, respectively.

$$\text{Daily Batches} = \frac{24}{\text{Treatment Time} + \text{Setup/Down Time}} \quad 4.71$$

$$\text{Total Batch Volume} = \frac{Q_{SPTtreated}}{\text{Daily Batches}} \quad 4.72$$

Daily costs with and without SPT incorporation for thickened sludge are calculated as follows. The UDV for electricity price is represented by EP.

$$\text{Daily Cost}_{\text{without SPT}} = Power \cdot EP + M_{TSSTHi} \cdot Dose \cdot \text{Price} \quad 4.73$$

$$\text{Daily Cost}_{\text{with SPT}} =$$

$$Power \cdot EP + M_{TSSTHi} \cdot Dose \cdot (100 + Change)/100 \cdot \text{Price} \quad 4.74$$

Pumping and mixing settings available to the user for the SPT unit are shown in Tables 4.11b and 4.11c, respectively.

Table 4.11b Sludge pretreatment pumping settings

SETTINGS	Units	UDV
PUMPING - USER DATA		
Fluid Density	kg/m^3	1,000
Differential Head, H_d	m	25.0
Efficiency	%	60.0
PUMPING - SUPPLIER DATA		
Capacity	m^3/d	0.00
Power	kW	0.00
Energy Consumption	kWh/d	0.00
Batch Cost	$/batch	0.00
Daily Cost	$/d	0.00

Energy consumption for pumping can be determined with or without known supplier data. Pumping energy incorporating user and supplier data is calculated as shown in Eqs 4.5-6. Daily costs are the product of daily energy use (kWh/d) and the UDV for electricity price ($/kWh). Batch costs are found by dividing daily costs with daily batches.

$$\text{Pumping}_{\text{UD}} = \frac{g \cdot Q_{SPTtreated} \cdot \rho \cdot H_d}{3600 \cdot 1000 \cdot (P_e/100)} \quad 4.75$$

$$\text{Pumping}_{\text{SD}} = Power \cdot \text{Setup/Down Time} \cdot Daily\ Batches \quad 4.76$$

$$\text{Daily Cost} = Energy \cdot EP \quad 4.77$$

$$\text{Batch Cost} = \frac{Daily\ Cost}{Daily\ Batches} \quad 4.78$$

Energy consumption for mixing, as with pumping, can be determined with or without known supplier data. Mixing energy with user data for impeller and paddle type mixers and supplier data is calculated as shown in Eqs 4.79-81.

Table 4.11c Sludge pretreatment mixing settings

SETTINGS	Units	UDV
MIXING - USER DATA		
Fluid Density	kg/m^3	1,000
Impeller		
Revolutions	rps	6.0
Impeller Diameter	m	0.50
Impeller Power Number		2.00
Paddle Mixer		
Cross-Sect. Paddle Area	m^2	0.00
Paddle Tip Speed	m/s	0.00
Perpendicular Drag Coefficient		0.00
MIXING - SUPPLIER DATA		
Power	kW	0.00

$$\text{Mixing}_{\text{UDimp}} = \frac{N_P \cdot \rho \cdot n^3 \cdot D_{imp}{}^5 \cdot (Treatment\ time \cdot Daily\ batches)}{1000} \quad 4.79$$

$$\text{Mixing}_{\text{UDpad}} = \frac{C_D \cdot A \cdot \rho \cdot (v_p \cdot 0.7)^3 \cdot (Treatment\ time \cdot Daily\ batches)}{2 \cdot 1000} \quad 4.80$$

$$\text{Mixing}_{\text{SD}} = Power \cdot (Treatment\ time \cdot Daily\ batches) \quad 4.81$$

4.3.2 Sludge Pretreatment Specific Parameters

Calculations and UDVs for each SPT are shown in the tables below where each table is followed by supplementary equations as necessary. Cells shaded light green are calculated based on UDVs. Insufficient data were available for SGH, ENZ, and LYS SPTs.

Few full-scale SPT technologies exist and thus, design equations were constructed for ULT, HPH, SBM, and MWH SPTs. Equations for CH, CM, OZ, and TC were not provided as design equations for these full-scale technologies are readily available in the literature and from suppliers. The goal here was to provide an approximation of the full-

scale SPT unit requirements based on power, throughput, torque, and/or pressure requirements to achieve the UDVs for percent flow treated (at the SPT unit) and percent solublisations. An example is given in the following paragraph.

Authors have concluded that between 4,000-20,000 kJ/kg TSS are needed to sufficiently solubilize sludge for optimal AD and biogas production. The user enters the desired E_{spec} and maximum power, pressure, or torque and speed per SPT unit. In this way, design values can be found for different runs. Since the user selects the quantity of WAS to be treated and given that a minimal E_{spec} input must be set, the resultant design data can help dictate feasibility of an SPT. For instance, the largest ULT sonotrode found consisted of 4 sonotrodes of 16 kW. For the permutations conducted in this study, 64 kW would be insufficient, thus making incorporation at those settings not feasible.

The specific SPT settings for all processes included in PretrAD are shown in Tables 4.12-18.

Table 4.12 Sludge pretreatment specific settings: ULT

SETTINGS	Units	UDV
Specific Energy	kJ/kg TSS	8,500
DESIGN		
Power	kW/ULT	0.00
Total Operating Time	h/d	0.00
A - Power Needed	kW	0.00
B - Capacity Needed	m^3/h·ULT	0.00

Total operating time is found by multiplying the treatment time with the number of batches per day. Two design values were provided for ULT: the total required power and capacity based on E_{spec} and the single unit power. They are related by the equations below to achieve the required E_{spec}.

$$\text{Total Operating Time} = Treatment\ time \cdot Daily\ batches \qquad 4.82$$

$$\text{Power Needed} = \frac{E_{spec} \cdot Q_{SPTtreated} \cdot TSS_{SPTi}}{t_{TotalOper.} \cdot 3600} \qquad 4.83$$

$$\text{Capacity Needed} = \frac{Power \cdot 3600}{E_{spec} \cdot TSS_{SPTi}} \qquad 4.84$$

Energy supplied, E_{sup}, is the product of the M_{TSS} to be treated by SPT and the E_{spec}. It is easily found in either kJ/d or kWh/d. Daily and batch costs are found as shown earlier. Equation 4.85 is used throughout Section 4.3.2 for every SPT excluding CM, OZ, and TC.

$$E_{sup} = E_{spec} \cdot Q_{SPTtreated} \cdot TSS_{SPTi} \qquad 4.85$$

Table 4.13 Sludge pretreatment specific settings: HPH

SETTINGS	Units	UDV
Specific Energy	kJ/kg TSS	8,500
DESIGN		
Pressure	MPa/HPH	0.00
Total Operating Time	h/d	0.00
A - Pressure Needed	MPa	0.00

Assuming the treated flow is composed primarily of water and thus the correlation of 1 MPa to 1 J/m^3 holds, Eq 4.86 shows the overall design pressure required to deliver the UDV for E_{spec}.

$$\text{Pressure Needed} = \frac{E_{spec} \cdot TSS_{SPTi}}{1000} \qquad 4.86$$

Table 4.14 Sludge pretreatment specific settings: SBM

SETTINGS	Units	UDV
Specific Energy	kJ/kg TSS	8,500
DESIGN		
Torque, τ	N·m/SBM	0.00
Agitator Speed, n	rpm	0.00
Total Operating Time	h/d	0.00
A - M_{TSS} Needed	kg/d	0.00
B - τ·N Needed	N·m/min	0.00

Two design values were provided for SBM: The maximum M_{TSS} capacity and the required torque-speed product based on E_{spec}, torque, and agitator speed. They are related by the equations below to achieve the required E_{spec}.

$$M_{TSS}\ \text{Capacity} = \frac{2 \cdot \pi \cdot \tau \cdot n \cdot 60 \cdot 24}{1000 \cdot E_{spec}} \qquad 4.87$$

$$\tau \cdot n \text{ Needed} = \frac{E_{spec} \cdot Q_{SPTtreated} \cdot TSS_{SPTi}}{2 \cdot \pi \cdot 1000 \cdot 60 \cdot 24} \quad 4.88$$

Table 4.15 shows the SPT settings for the CH process. The selected heat transfer coefficient, sludge density, and heat loss were gathered from well-established literature values as described in Appendix A.

Table 4.15 Sludge pretreatment specific settings: CH

SETTINGS	Units	UDV
Heat Transfer Coefficient	kJ/kg·°C	4.20
Sludge Density	kg TSS/m^3	1,100
Heat Loss	%	4.0

Heat requirements and losses were used to determine the E_{spec} input and E_{sup}. The UDV for percentage heat loss is represented by P_{HL}.

$$E_{HN1} = \frac{Q_{SPTtreated} \cdot \rho \cdot C_p \cdot (T_{e1} - T_{i1})}{3600} \quad 4.89$$

$$E_{HL1} = E_{HN1} \cdot \left(\frac{P_{HL}}{100}\right) \quad 4.90$$

Total heat input is the sum of heat requirements and losses. This value is found on a basis of kg TSS treated using Eq 4.91.

$$E_{spec} = \frac{(E_{HN1} + E_{HL1}) \cdot 3600}{Q_{SPTtreated} \cdot TSS_{SPTi}} \quad 4.91$$

Table 4.16 Sludge pretreatment specific settings: MWH

SETTINGS	Units	UDV
Specific Energy	kJ/kg TSS	8,500
DESIGN		
Microwave Power	kW/MWH	0.00
Total Operating Time	h/d	0.00
A - Power Needed	kW	0.00
B - Capacity Needed	m^3/h·MWH	0.00

Two design values were provided for MWH: the total required power and capacity based on E_{spec} and single unit power. They are related by the equations below to achieve the required E_{spec}. Solving for each is identical to Eqs 4.87 and 4.88.

Batch cost and daily cost were obtained using Eqs 4.92 and 4.93.

Table 4.17 Sludge pretreatment specific settings: CM

SETTINGS	Units	UDV
NaOH or KOH Concentration	kg/m^3	2.5
Price	$/kg	2.0

$$\text{Batch cost} = [Dose] \cdot Price \cdot Batch\ volume \quad (4.92)$$

$$\text{Daily cost} = Batch\ cost \cdot Daily\ batches \quad (4.93)$$

Table 4.18 Sludge pretreatment specific settings: OZ

SETTINGS	Units	UDV
O_3 Concentration	kg/m^3	5.0
Energy Supplied	kWh/kg O_3	12.5

First the O_3 production cost is determined and subsequently the batch cost and daily costs can be found. Both costs are found as shown in Eqs 4.94 and 4.95.

$$O_3 \text{ production cost} = E_{sup} \cdot EP \quad (4.94)$$

$$\text{Batch cost} = [Dose] \cdot O_3 \text{ prod. cost} \cdot \text{Batch volume} \quad (4.95)$$

Results for TC are equivalent to the total energy and cost demands for CH+CM.

4.3.3 Mesophilic/Thermophilic Anaerobic Digestion

Calculations and UDVs for MTAD are shown in Tables 4.19a and 4.19b and in the equations below. Pumping, mixing, and temperature settings required for MTAD are listed in Table 4.19a. The settings required for anaerobic digester design are listed in Table 4.19b. The design results are utilized in the heat losses calculations.

Dry solids content is easily determined using Eq 4.96 for both solids having undergone or not undergone SPT. Equation 4.96 approximates the density of the incoming solids to that of water at 1,000 kg/m^3.

$$\text{Dry Solids Content } (\%) = \frac{TSS_{MTADi}}{10} \quad (4.96)$$

The sludge volume determination according to the various UDVs (as shown in Table 4.19a) for a pancake anaerobic digester design is found using Eq 4.97.

$$\text{Sludge Volume} = \pi \cdot \left[\left(\frac{D_i}{2} \right)^2 \cdot (H_e + H_i) + \left(\frac{H_{bg}}{3} \right) \right] \qquad 4.97$$

Table 4.19a Operational requirements for MTAD settings

SETTINGS	Units	UDV
Pumping – Consumption, E_{EPI}	kJ/kg TSS	12.00
Stirring – Consumption, E_{EPI}	kJ/kg TSS·d	20.00
Heat Transfer Coefficient, C_p	kJ/kg·°C	4.2
Sludge Density	kg TSS/m^3	1,000
Heat Recovered Application Efficiency	%	80.0
TEMPERATURES		
Influent Temperature, $T°_{i2}$	°C	15
Ambient Air Temperature	°C	18
Surface Material Temperature	°C	30

Table 4.19b Heating requirements for MTAD settings

SETTINGS	Units	UDV
HEAT FLOW COEFFICIENTS		
Floating Cover, C_{pfc}	kJ/m^2·d·°C	108
Ambient Air, C_{pamb}	kJ/m^2·d·°C	80
Surface Material, C_{psur}	kJ/m^2·d·°C	82
DIGESTER DESIGN - Cylinder		
Inner Diameter, D_i	m	25.0
Height Exposed, H_e	m	4.0
Height Insulated, H_i	m	6.0
Height Below Ground, H_{bg}	m	2.0

Energy use and costs are determined with SPT and without SPT. Differences are observed where flows and solids are affected by SPT incorporation. Equations in the previous section were distinguished by 'a' and 'b' for SI and US units. Instead, equations are now annotated with 'i' or 'ii' or 'iii' or 'iv' to represent a sequence of equations needed to find the total value of a parameter. For example, heat losses occur through the underground, above ground, and cover portions of the anaerobic digester. Total heat loss would be found by adding equation 'i', 'ii', and 'iii' for all losses. With SPT incorporation, equation numbering simply proceeds as in Equations 4.98i and 4.98ii. It is

clear that when SPT is used, only Eqs 4.98ii-iii would be used to compute the electrical total shown in Eq 4.99.

$$\text{Pumping, } E_{EPI} = \frac{M_{TSSMTADi} \cdot E_{specEPI}}{3600} \qquad 4.98i$$

$$\text{Pumping, } E_{EPI} = \frac{M_{TSSMTADi}\ with\ SPT \cdot E_{specEPI}}{3600} \qquad 4.98ii$$

$$\text{Mixing, } E_{EMI} = \frac{Sludge\ Volume \cdot E_{specEMI} \cdot \rho}{3600} \qquad 4.98iii$$

$$\text{Electrical Total, } E_{EI} = E_{EPI} + E_{EMI} \qquad 4.99$$

Anaerobic digester design and flow and energy balances are depicted in Figs. 4.12 and 4.13, respectively. They were used to evaluate total heating input and recovery according to needs and losses based on the UDVs for a cylindrical anaerobic digester design.

Figure 4.12 Anaerobic digester design schematic

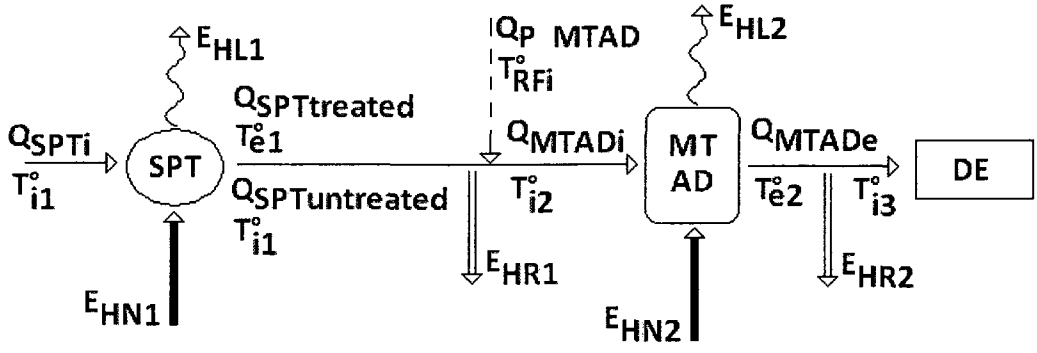


Figure 4.13 Flow and heating energy balance for the SPT unit to the DE unit

Heating energy needs are solved using Eqs 4.100a-101.

$$\text{Heating Energy, } E_{HN2} = \frac{Q_{MTADi} \cdot \rho \cdot C_p \cdot (T_{e2} - T_{i2})}{3600} \qquad 4.100i$$

Heating Energy for $SPT_{treated}$, $E_{HN2SPTtr}$ =

$$\frac{Q_{SPTtreated} \cdot \rho \cdot C_p \cdot (T_{e2} - T_{i2})}{3600} \quad 4.100ii$$

Heating Energy for $SPT_{untreated}$, $E_{HN2SPTuntreated} =$

$$\frac{Q_{SPTuntreated} \cdot \rho \cdot C_p \cdot (T_{e2} - T_{i1})}{3600} \quad 4.100iii$$

Heating Energy for PC to $MTAD_i$, $E_{HN2MTADi} =$

$$\frac{Q_{PCMTAD} \cdot \rho \cdot C_p \cdot (T_{e2} - T_{iRF})}{3600} \quad 4.100iv$$

Total Heating Energy, $E_{HN2} = E_{HN2SPTtreated} + E_{HN2SPTuntreated} + E_{HN2MTADi}$ 4.101

Heating losses are solved using Eqs 4.102i-103.

Heating loss by cover, $E_{HL2fc} = \frac{C_{pfc} \cdot \pi \cdot \left(\frac{D_i}{2}\right)^2 \cdot (T_{e2} - T_{amb})}{3600}$ 4.102i

Heating loss by height exposed, $E_{HL2he} =$

$$\frac{\pi D_i H_e C_{pamb} (T_{e2} - T_{amb})}{3600} \quad 4.102ii$$

Heating loss by height insulated, $E_{HL2hi} =$

$$\frac{\pi \cdot D_i \cdot H_i \cdot C_{psur} \cdot (T_{e2} - T_{sur})}{3600} \quad 4.102iii$$

Total Heating Loss, $E_{HL2} = E_{HL2fc} + E_{HL2he} + E_{HL2hi}$ 4.103

Finally, the total heat energy input is solved using Eqs 4.104.

Total Heating Input, $E_{EHI2} = E_{EHN2} + E_{EHL2}$ 4.104

Using the UDV for percentage heat recovered application efficiency, P_{hrae}, the amount of heat that can be recovered and subsequently used is shown in Eq 4.105.

Heating Recovered, $E_{HR2} = \frac{Q_{MTADi} \cdot \rho \cdot C_p \cdot (T_{i3} - T_{e2}) \cdot \left(\frac{P_{hrae}}{100}\right)}{3600}$ 4.105

When SPT is considered an additional recovery of heat energy is available and labelled as E_{HR1}.

$$\text{Heating Recovered, } E_{HR1} = \frac{Q_{SPTi} \cdot \rho \cdot C_p \cdot (T_{i2} - T_{i1}) \cdot \left(\frac{P_{hrae}}{100}\right)}{3600} \qquad 4.106$$

Daily and batch costs are found as shown in Eqs 4.107 and 4.108, respectively.

$$\text{Daily Cost} = (E_{EI} + E_{HI2} + E_{HR2}) \cdot EP \qquad 4.107$$

$$\text{Batch Cost} = \frac{Daily\ Cost}{Daily\ Batches} \qquad 4.108$$

4.3.4 Dewatering

Calculations and UDVs for DE are as shown in Table 4.20 and in the equations below.

Table 4.20 Dewatering settings

SETTINGS	Units	UDV
Influent Temperature	°C	15
Power Supplied	kJ/kg TSS	0.00
Price of Polymer	$/kg	0.00

Daily costs are determined for cases where SPTs are and are not considered. The difference in daily costs is caused by the solids concentration employed.

$$\text{Daily cost} = TSS_{DEi} \cdot \left(\frac{Power \cdot EP}{3600} + Price \cdot [Dose]\right) \qquad 4.109i$$

$$\text{Daily cost} = TSS_{DEi}\ with\ SPT \cdot \left(\frac{Power \cdot EP}{3600} + Price \cdot [Dose]\right) \qquad 4.109ii$$

4.3.5 Sludge Disposal

Calculations and UDVs for SD are shown in Tables 4.21a, 4.21b, and in the equations below. The SD settings that apply to all biosolids use pathways (e.g., landfilling, incineration) are listed in Table 4.21a. The SD settings that apply to the specific disposal methods are listed in Table 4.21b.

Pumping energy demands for SD are found as they were for the SPT and MTAD steps. Similarly, the daily cost calculation for drying is again used and it is now combined with Eqs 4.98i and 4.98ii to determine daily incineration costs. The user specifies whether the sludge cakes are landfilled, incinerated, or reused in land applications.

The determination of energy supplied for drying the sludge is as shown below. Differences are found with the underflow solids content percentage of the MTAD step as a result of SPT use.

Table 4.21a General sludge disposal settings

SETTINGS	Units	UDV
PUMPING		
Power Supplied	kJ/kg TSS	12.00
DRYING		
Dried Solids Content	%	60.0
LABOUR		
Salary	$/h·Lbr	20.00
Hours Worked	h/d	12.0
Labourers Required	Lbr	4.0

Table 4.21b Specific sludge disposal settings

SETTINGS	Units	UDV
TRANSPORTATION		
Fuel Cost	$/L	1.00
Consumption	L/km	0.35
Disposal Distance	km/Load	160.0
Sludge Cake Density	kg/m^3	1,200
Truck Capacity	m^3/Load	15.0
LANDFILLING		
Tipping Fee	$/ton	30.00
INCINERATION		
Power Supplied	kJ/kg TSS	0.00
LAND APPLICATION		
Sell Price	$/ton	0.00

E_{sup} =

$$\frac{\left[Q_{DEi}\cdot\left(\frac{MTADu_{Solids\%}}{DEe_{Solids\%}}-\frac{MTADu_{Solids\%}}{SDe_{Solids\%}}\right)\right]\cdot 1000\cdot(3650+144))}{3600} \qquad 4.110i$$

E_{sup} with SPT =

$$\frac{\left[Q_{DEi}\cdot\left(\frac{MTADu_{Solids\%SPT}}{DEe_{Solids\%}}-\frac{MTADu_{Solids\%SPT}}{SDe_{Solids\%}}\right)\right]\cdot 1000\cdot(3650+144))}{3600} \quad 4.110ii$$

Labour costs are the same with or without SPT and apply to all biosolids use pathways.

$$\text{Labour cost} = \text{Salary}\cdot\text{Hours Worked}\cdot\text{Labourers Required} \quad 4.111$$

Transportation costs apply to landfilling, incineration, and land application. Differences between control and SPT SD costs are found because the influent SD solids are reduced when SPT is incorporated. For example, total landfilling cost as shown in PretrAD is the sum of the fuel and tipping costs with and without SPT.

Landfilling fuel cost =

$$\text{Fuel cost}\cdot\text{consumption}\cdot\text{distance}\cdot\left(\frac{M_{TSSDEe}}{\text{Cake Density}\cdot\text{Truck Capacity}}\right) \quad 4.112i$$

Landfilling fuel cost with SPT =

$$\text{Fuel cost}\cdot\text{consumption}\cdot\text{distance}\cdot\left(\frac{M_{TSSDEe}\ with\ SPT}{\text{Cake Density}\cdot\text{Truck Capacity}}\right) \quad 4.112ii$$

Landfilling tipping cost = Tipping fee$\cdot M_{TSSDEe}$ 4.112iii

Landfilling tipping cost with SPT = Tipping fee$\cdot M_{TSSDEe}$ with SPT 4.112iv

Total landfilling cost = Fuel cost + Tipping cost 4.113

Agriculture use gains are calculated with and without SPT use. As mentioned in Chapter 2, the precise potential for SPTs to subsequently enable the achievement of Class EQ, A or B biosolids for land application could not be determined. It is likely however, that substantial gains can be made at the SD unit with enhanced pathogen reduction and the redirected of previously landfilled biosolids.

Daily gain = Sell price$\cdot M_{TSSDEe}$ 4.114i

Daily gain with SPT = *Sell price*$\cdot M_{TSSDEe}$ *with SPT* 4.114ii

4.3.6 Energy Conversion

Calculations and UDVs are shown in Table 4.22 and in the equations below. The selection of the UDVs employed was explained in Chapter 3.

The user can split and direct the methane flow to different uses. Costs and gains are calculated for methane that is flared, returned as heat, used as electricity, and input into the electrical grid. Calculations are performed with and without SPT. Differences are observed because the methane flow is greater when SPT is considered.

$$\text{Flare cost} = \textit{Flare price} \cdot Q_{ECi} \cdot \left(\frac{Q_{ECCH4Flare}}{100} \right) \qquad 4.115i$$

$$\text{Flare cost with SPT} = \textit{Flare price} \cdot Q_{ECiSPT} \cdot \left(\frac{Q_{ECCH4Flare}}{100} \right) \qquad 4.115ii$$

Daily costs for heat return and electrical use are found using Eq 4.77. Heat gain with and without SPT can be found using Eqs 4.116i-ii.

Table 4.22 Energy conversion settings

SETTINGS	Units	UDV
CH_4 Heating Value[1]	kJ/m^3	25,575
CH_4 Electricity Value[1]	kJ/m^3	11,935
Q_{ECCH4} Flare	% Q_{ECCH4i}	0.00
Q_{ECCH4} Heat Return	% Q_{ECCH4i}	100.00
Q_{ECCH4} Electrical Use	% Q_{ECCH4i}	0.00
Q_{ECCH4} Grid Input	% Q_{ECCH4i}	0.00
Flare Cost	$\$/m^3$	0.00
Grid Sell Price	\$/kWh	0.00

[1]UDVs contain efficiency factors as discussed in Section 3.2.4, Chapter 3

$$\text{Heat gain} = \frac{CH_4 \textit{ Heating Value} \cdot Q_{ECi} \cdot \left(\frac{Q_{ECCH4HeatReturn}}{100} \right)}{3600} \qquad 4.116i$$

Heat gain with SPT =

$$\frac{CH_4 \textit{ Heating Value} \cdot Q_{ECiSPT} \cdot \left(\frac{Q_{ECCH4HeatReturn}}{100} \right)}{3600} \qquad 4.116ii$$

Electricity gain with and without SPT can be found using Eqs 4.117i-ii.

$$\text{Electricity gain} = \frac{CH_4 \textit{ Electricity Value} \cdot Q_{ECi} \cdot \left(\frac{Q_{ECCH4ElectricalUse}}{100} \right)}{3600} \qquad 4.117i$$

Electricity gain with SPT =

$$\frac{CH_4\ Electricity\ Value \cdot Q_{ECiSPT} \cdot \left(\frac{Q_{ECCH4ElectricalUse}}{100}\right)}{3600} \qquad 4.117ii$$

Grid gain with and without SPT can be found using Eqs 4.118i-ii.

$$\text{Grid gain} = \frac{CH_4\ Electricity\ Value \cdot Q_{ECi} \cdot \left(\frac{Q_{ECCH4GridInput}}{100}\right)}{3600} \qquad 4.118i$$

Grid gain with SPT =

$$\frac{CH_4\ Electricity\ Value \cdot Q_{ECiSPT} \cdot \left(\frac{Q_{ECCH4GridInput}}{100}\right)}{3600} \qquad 4.118ii$$

Daily cost reduction for grid input with and without SPT uses Eq 4.77 but the EP is replaced by the UDV for grid sell price, GSP.

$$\text{Daily Grid Cost Reduction} = Energy \cdot GSP \qquad 4.119$$

4.4 CONTROL WWTP AND PLAN-IT STOAT

The spreadsheet model validity in terms of treatment variable selection, results, and fixed plant characteristics was assessed by comparison to results obtained using Plan-It STOAT [209].

Although some aspects of Plan-It STOAT (referred to as Plan-It from this point forward) resemble the spreadsheet model, design values for vessel sizes (which are not generally necessary in the spreadsheet model and are therefore not included) had to be ascertained for Plan-It. They were calculated using well-known treatment unit design equations that are shown in Appendix B. This work was performed by Kévin Rochelet. Kévin assisted in PretrAD design, Output worksheet creation, and the PretrAD versus Plan-It validation. He attended the University of Ottawa during a 4 month exchange from l'école nationale supérieurs d'ingénieurs de Limoges of the University of Limoges, France. The UDVs that were used to test agreement between PretrAD and Plan-It are those for the control 'Average' RF and treatment default values. Mesophilic AD was selected for validation. The RF and treatment default values are both listed in this chapter (green shaded table cells) and in Appendix A. PretrAD's output values for average

conditions (as well as low and high conditions) are stored electronically and can be accessed as described in Appendix C.

There are 3 UDVs that were changed from the 'Average' default values in order to conduct the PretrAD to Plan-It comparison. The first is the PT 'TSS Reduction' setting. It was changed to 0% from 3%. Plan-It does not allow TSS reduction in PT; therefore this makes the models equivalent in behaviour. The second is the SC 'TCOD:TSS After SC' setting in PretrAD. It was set at 210 kg/kg instead of 180 kg/kg. This was done to compensate for another parameter within Plan-It's SC COD underflow calculation sequence which is a different approach from that taken in the PretrAD. The Plan-It value is based on fixed WAS settleability dictating the fraction of TCOD that is directed to the clarified effluent and that which is directed to the underflow of the SC unit. PretrAD is primarily based on mass balances and functions with UDVs that have been observed within acceptable ranges in the literature (see Appendix A). The usage of the 210 kg/kg reflects the settleability fractions that are default and were unchanged within Plan-It. The third is that the DE 'TSS Capture Efficiency' setting was set at 95% instead of 90%. This was deemed acceptable as the vessel sizing process (as shown in Appendix B) also relies on typical default ranges. The higher Plan-It DE flow values and thus, effluent M_{TSS} value were correlated to higher throughput efficiencies and a different recycle to sludge effluent ratio scheme. The change to 95% increased PretrAD's DE_e flow to compensate for the unchanged Plan-It calculation sequence that dictates DE recycle and sludge effluent flows and solids concentrations. An acceptable difference (<10%) between WWTP effluent solids was found.

Once correlations were made and both average RF characteristics and treatment settings were input, the two outputs were compared. An explanation of treatment models selected for each unit is given in Appendix B.

The Plan-It interface is shown in Fig. 4.14. The plant layout is on the right (shaded in light yellow). The left-hand menu (in Fig. 4.14), where the user inputs variables, has the PC unit showcased. The main inputs are dimensions, operations, and parameters (shaded green). Similar menus apply to each unit in the WW treatment operation.

The flow report generated from Plan-It is shown in Fig. 4.15. The report gives unit flowrates, mass loadings, and concentrations. Those of interest are COD, BOD, TSS, and VSS. Again, the various design equations and parameters that were needed in addition to the PretrAD inputs (Appendix A) and results (Appendix C) required for the comparison are listed in Appendix B.

The influent, underflow, and effluent of the PC unit are listed in Table 4.23. The RF and PT steps are not shown as the values do not vary in either output and thus, no significant differences between outputs were found.

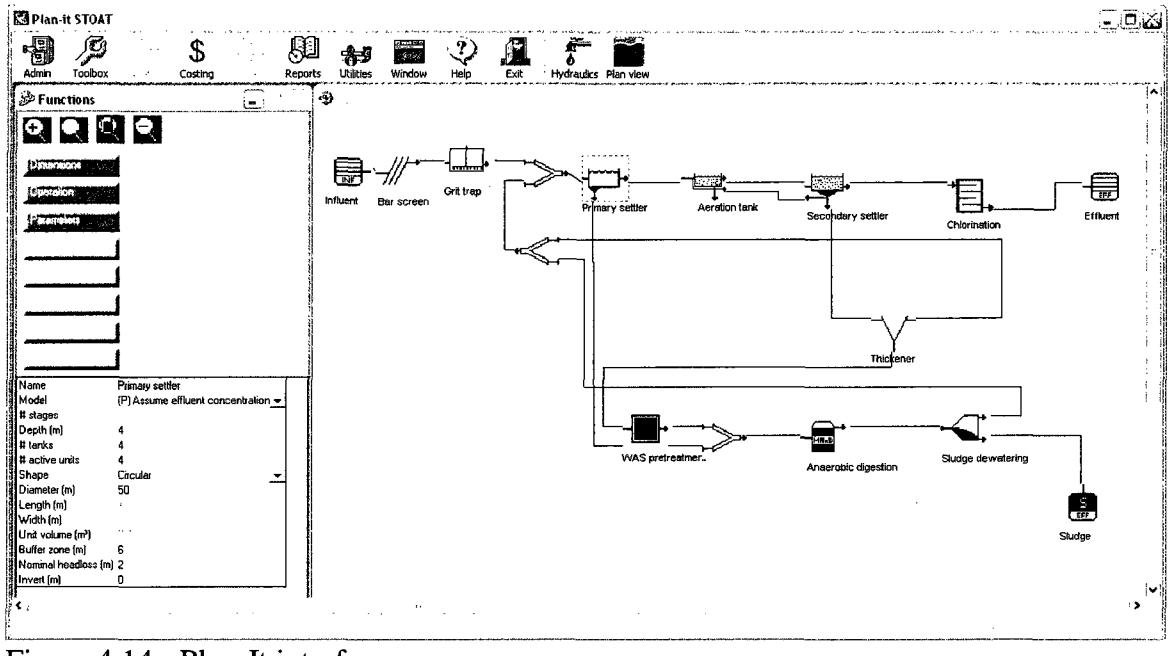


Figure 4.14 Plan-It interface

Figure 4.15 Plan-It mass balance report

Table 4.23 Primary sedimentation streams comparison (PretrAD vs Plan-It)

	PC_i		PC_u		PC_e	
	PretrAD	Plan-It	PretrAD	Plan-It	PretrAD	Plan-It
Q (m^3/d)	460,000	460,800	3,864	4,080	456,136	456,720
TCOD (kg/m^3)	0.43	0.44	28.15	32.20	0.19	0.19
$TBOD_5$ (kg/m^3)	0.19	0.19	11.31	13.50	0.10	0.08
TSS (kg/m^3)	0.21	0.21	15.00	15.00	0.08	0.09
VSS (kg/m^3)	0.16	0.16	11.43	11.30	0.06	0.07
M_{TSS} (kg/d)	96,600	96,768	57,960	61,200	38,315	41,105

The influent and effluent of the BT unit are listed in Table 4.24. From this point forward, unit influents will not be shown since they are equal to the preceding unit's effluent. A negligible difference between the models' solids loadings now occurs (as a result of recycle which was neglected in the spreadsheet model) and carries forward to all the treatment units. Also, PretrAD does not track TCOD and $TBOD_5$ following the BT unit. Instead, sCOD and $sBOD_5$ are considered but only in PretrAD's BT and SC effluents. As shown in Table 4.3, the sCOD and $sBOD_5$ values do not differ greatly between the two outputs. Both models have similar MLTSS values and TSS/VSS ratios.

Table 4.24 Biotreatment streams comparison (PretrAD vs Plan-It)

	BT_i		BT_e	
	PretrAD	Plan-It	PretrAD	Plan-It
Q (m^3/d)	456,136	456,720	693,388	693,600
TCOD (kg/m^3)	0.19	0.19	0.03[a]	0.03[a]
$TBOD_5$ (kg/m^3)	0.10	0.08	0.02[b]	0.02[b]
TSS (kg/m^3)	0.08	0.09	3.47	3.60
VSS (kg/m^3)	0.06	0.07	2.61	2.68
M_{TSS} (kg/d)	38,315	41,105	2,406,056	2,496,960

[a,b]These model outputs are for the clarified BT_e sCOD and $sBOD_5$, respectively

The recycle, influent, and effluent of the SC unit are listed in Table 4.25. Insignificant differences are found by comparing flows and only small differences are found by comparing TSS values.

Table 4.25 Secondary sedimentation streams comparison (PretrAD vs Plan-It)

	SC_r		SC_w		SC_e	
	PretrAD	Plan-It	PretrAD	Plan-It	PretrAD	Plan-It
Q (m^3/d)	237,252	237,600	1,544	1,320	454,592	453,600
TCOD (kg/m^3)	22.00	22.10				
TSS (kg/m^3)	10.00	10.40	10.00	10.40	0.03	0.03
VSS (kg/m^3)	8.00	7.71	8.00	7.71	0.02	0.02
M_{TSS} (kg/d)	2.37×10^6	2.47×10^6	15,440	13,728	13,638	13,608

The recycle and effluent of the TH unit are listed in Table 4.26. From this point forward excluding SPT, TCOD and $TBOD_5$ were no longer considered in PretrAD as it, in most cases (i.e., at each treatment step), no longer considers these values and/or does not output them to the user. No major differences are found at the TH unit.

The influent and underflow to the MAD unit and the recycle of the DE unit are listed in Table 4.27. The supernatant flow was comparable for both models and is not shown. The DE unit sludge effluent is given in Table 4.28. No major differences are found at the MAD treatment step.

Table 4.26 Thickening streams comparison (PretrAD vs Plan-It)

	TH_r		TH_e	
	PretrAD	Plan-It	PretrAD	Plan-It
Q (m^3/d)	1,251	1,061	293	259
TSS (kg/m^3)	0.62	0.65	50.00	50.00
M_{TSS} (kg/d)	772	689	14,669	12,960

Table 4.27 Mesophilic AD and DE streams comparison (PretrAD vs Plan-It)

	MAD_i		MAD_u		DE_r	
	PretrAD	Plan-It	PretrAD	Plan-It	PretrAD	Plan-It
Q (m^3/d)	4,157	4,320	4,157	4,320	3,968	3,912
sCOD (kg/m^3)	15.00	15.00				
TSS (kg/m^3)	17.47	17.10	9.61	10.70	0.50	0.56
M_{TSS} (kg/d)	72,629	73,872	39,946	46,224	1,997	2,190

Finally, the global M_{TSS} balance is given in Table 4.28. Showcased are the RF_i, SC_e, and DE_e streams. Both models intake and output approximately the same daily solids amounts. Discrepancies listed above are mainly due to the Plan-It BT unit coefficients for biomass growth/decay, the default and unchanged settleability factors, and the different SC and DE calculation approaches. Another source of discrepancy between models is the recycle streams that are neglected in PretrAD and not neglected in Plan-It. The extent of discrepancy between daily effluent solids at the DE unit is 9.7%. It should be noted that a further reduction in this discrepancy could be obtained by changes

to the BT coefficients which involve some complex manipulation. Since treatment and costs are primarily based on solids reductions and energy requirements based on solids loadings, PretrAD's output was deemed valid.

Table 4.28 Global M_{TSS} balance (PretrAD vs Plan-It) Results

	RF_i		**SC_e**		**DE_e**	
	PretrAD	Plan-It	PretrAD	Plan-It	PretrAD	Plan-It
M_{TSS} (kg/d)	96,600	96,768	13,638	13,608	37,948	42,000

CHAPTER 5

Results and Discussion

5.0 RUN VARIABLES AND PERMUTATIONS

Over 320 sets of runs were conducted to assess the energy demands and financial feasibility of SPT incorporation. The variables used (and their permutations) to perform these runs are described here to provide quick reference to the run labelling system used and the parameters responsible for the results described in Sections 5.1-4.

The low to high strength RF characteristics that were used in PretrAD are shown in Table 5.1. These values are identical to those shown with all default values in Appendix A. The flow and wastewater characteristics were arbitrarily selected for a population of 10^6 based on typical North American values for WWTPs handling domestic and industrial wastewaters [160].

Table 5.1 Raw feed variations

	Units	Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Q_{RFi}	m^3/d	750,000	460,000	240,000
TCOD	kg/m^3	0.25	0.43	0.80
$TBOD_5$	kg/m^3	0.11	0.19	0.35
TSS	kg/m^3	0.12	0.21	0.40
VSS	kg/m^3	0.10	0.16	0.32
TS	kg/m^3	0.39	0.72	1.23
TVS	kg/m^3	0.21	0.36	0.66
Feed Temp.	°C	15	15	15

Daily peak flow was estimated using Fig. 5.1 and the inhabitant equivalents value of 1×10^6 IE. A peaking factor of 1.7 was applied to the average daily flow and 782,000 m^3/d was obtained.

The peak flowrate can also be obtained more precisely. The average daily flow can be broken down into three components; domestic, commercial, and infiltration contributions. The US EPA regards these flow rate contributions to be 270,000, 40,000,

and 150,000 m^3/d for a population of 1×10^6 IE, respectively. The peak daily flow can therefore be determined as shown below. A final peak flow of 750,000 m^3/d was chosen and deemed to be sufficiently representative.

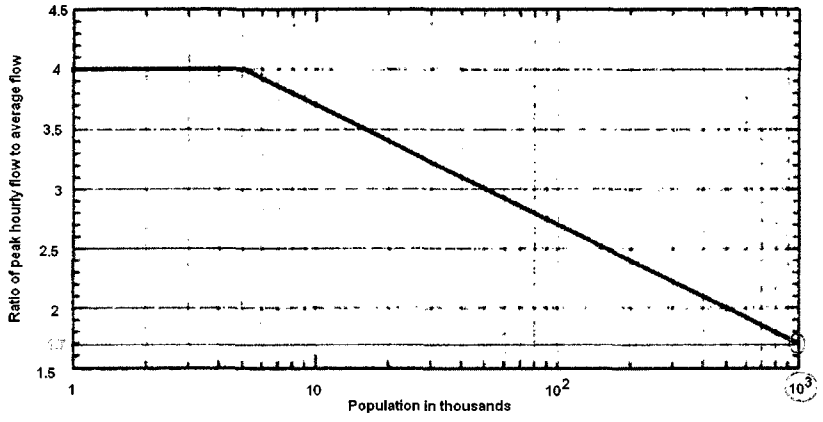


Figure 5.1 Peaking factor curve: ratio of peak hourly to average daily flow (adapted: 'Figure 3-13' Metcalf and Eddy, 4th ed., 2003).

$$\text{Peak Flow} = (270{,}000 \times 1.7 + 40{,}000 \times 1.5 + 150{,}000)\ m^3/d = 669{,}000\ m^3/d$$

The low daily flowrate value is given in literature alongside the average flowrate [160]. A flow regime breakdown is explained in Section 5.1.4. Diurnal flowrate and quality variations during a day were not considered because detention times in the anaerobic digester are considerably longer than one day and diurnal daily variations have insignificant influence on the behaviour of MTAD.

Benefits or costs of incorporation of SPTs into the control plant scenario were now systematically investigated based on information presented in earlier chapters pertaining to energy demands of SPTs and their improvements of MTAD, DE, and SD. Since the costs and operations of all processes except for MTAD, DE, and SD in the WWTP do not change as a result of STP they are not included in the cost analyses.

Each SPT was incorporated into the control plant. The energy input/output characteristics of each SPT along with their effects on other unit processes such as DE are not definitive in many respects. A range of operating conditions and performance

characteristics was thus evaluated to determine the scenarios where an overall benefit is realized from SPT use.

The initial runs were made incorporating each SPT at 'Low' energy demands (E_{spec}, from Table 5.3 below) determined for the SPT type. Furthermore, heat recovery potential at the MTAD step and sludge hauling distance at the SD step were varied in these initial runs. In the MTAD step, the heat transfer coefficient and heat recovery application efficiencies were varied from normal heat recoveries (NHR: 4.2 kJ/kg·°C and 80%) to low heat recoveries (LHR: 5.0 kJ/kg·°C and 60%). The heat transfer coefficient would not in fact vary from 4.2 to 5.0 kJ/kg·°C but the change permits a variation of heating efficiency that PretrAD has not enabled elsewhere. In the SD step, the disposal distance increased from a normal sludge transport distance (NSD: 160 km/Load) to a doubled sludge transport distance (320 km/Load). The values of these parameters are summarized in Table 5.2.

Table 5.2 MTAD and SD specific permutation variations

		Units	**NHR**	**LHR**
MTAD	Heat Transfer Coefficient	kJ/kg·°C	4.20	5.00
	Heat Recovery Application Eff.	%	80	60
		Units	**NSD**	**DSD**
SD	Disposal Distance	km/Load	160	320

The general breakdown of Runs 1-4 and Runs 1a-2b is given below. Following this, a more detailed run labelling system is presented for simple referencing of all variables responsible for specific results discussed in Sections 5.1-4.

Runs 1-4 are MAD or TAD based and SPT WWTP scenarios with the following MTAD and SD permutations: Run 1 (NHR-NSD), Run 2 (NHR-DSD), Run 3 (LHR-NSD), Run 4 (LHR-DSD). These runs were also conducted with Low SPT energy demand variables (in Table 5.3). Runs 1-4 were also conducted for low to high strength RF variables (Table 5.1).

Runs 1a-b and 2a-b are MAD or TAD based and SPT WWTP scenarios conducted with the following MTAD and SD permutations: Runs 1a-b have NHR-NSD values and Runs 2a-b have LHR-DSD values. The 'a' and 'b' designations of these runs refer to use of the following SPT variables: Runs 1a and 2a (Medium = Med SPT energy demands) and Runs 1b and 2b (High SPT energy demands). Runs 1a,b-2a,b were conducted for average strength RF variables from Table 5.1.

The SPT variables altered for the general breakdown of Runs 1-4, 1a-b, and 2a-b are listed in Table 5.3.

Table 5.3 Variables specific to each SPT

	Permutation Variable	**Units**	**Runs 1 – 4**	**Runs 1a, 2a**	**Runs 1b, 2b**
	E_{spec} designation[1]		**Low**	**Med**	**High**
ULT/SBM/HPH	E_{spec}	kJ/kg TSS	8,500	10,625	12,750
	$T°_{el}$	°C	25	25	25
CH	Heat Transfer Coeff.	kJ/kg·°C	4.20	5.00	5.00
	Sludge Density	kg/m^3	1,100	1,100	1,100
	Heat Loss	%	4.00	8.00	8.00
	$T°_{el}$	°C	80	100	120
MWH	E_{spec}	kJ/kg TSS	8,500	10,625	12,750
	$T°_{el}$	°C	60	75	90
CM	[NaOH] or [KOH]	kg/m^3	2.50	3.13	3.75
	Price	$/kg	2.00	2.50	3.00
	$T°_{el}$	°C	20	20	20
OZ	$[O_3]$ Dose	kg/m^3	5.00	6.25	7.50
	E_{prod}	kWh/kg O_3	12.50	15.63	18.75
	$T°_{el}$	°C	20	20	20
TC	**CH + CM or MWH + CM variables apply**				

[1]Different E_{spec} values result in changes in other variable such as $T°_{el}$.

The visual representation of all runs is given in Fig. 5.2. It is clear that if control scenarios are evaluated, 0% SPT energy demands and 0% solubilisations were input. When SPT scenarios were evaluated, Low, Med, and High SPT energy demands and the percentage solubilisations shown in Chapter 4, Table 4.7 were input. Control and SPT scenarios were evaluated first with low to high RF strength characteristics for Runs 1-4

and Runs 1a-2b and second with only average RF strength characteristics and Runs 1a-2b. The results from the first evaluation showed that fewer permutations of the MTAD and SD variables were needed and that average flow and RF strength characteristics were sufficiently representative of costs incurred at all flow regimes (where more realistic typical flow and WW strength variations from low to high were considered).

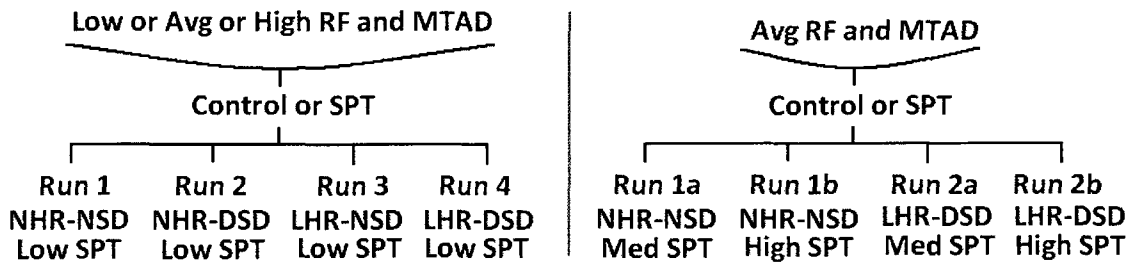


Figure 5.2 Graphical representation of the general run breakdown

The detailed run labelling system is shown in Fig. 5.3

Examples: Run 2 $RM(H_1\text{-}D_2\text{-Low})_L$ Run 2b $RT(H_2\text{-}D_2\text{-High})_A$

Legend:
R (run), M (MAD) or T (TAD)
H_1 (NHR = 4.2 kJ/kg°C and 80%) or H_2 (LHR = 5.0 kJ/kg°C and 60%)
D_1 (NSD = 160 km/Load) or D_2 (DSD = 320 km/Load)
Low, Med or High (SPT energy demand)
Subscripts: L, A or P (low, average or peak flow RF variables)

Figure 5.3 Detailed run labelling system used throughout Chapter 5

5.1 RESULTS AND DISCUSSION

This section details the results obtained from running the numerous permutations of treatment operations outlined in Section 5.0. These permutations were conducted to assess the overall impact of SPT incorporation. After a number of observations for the various flow regimes with various treatment options, it was established that results from runs under the average flow regime were reflective of SPT energy demand increases or decreases for the other flow regimes. Therefore only average RF characteristics were used following Section 5.1.4. An observations and highlights summary is provided in

Section 5.2. This is followed by the PretrAD outputs using low to high RF characteristics and their impacts on unit, WWTP, and net costs.

All discussions will use the terms control (without SPT) and SPT scenarios as described in Section 4.4 of Chapter 4. The other 2 terms that will be commonly used are 'practical' and 'impractical'. The first (practical) refers to cost scenarios that warrant SPT incorporation. That is to say, if the net daily or annual costs of SPT incorporation are lower than or closely resemble control costs under identical conditions, then that situation is deemed practical. The second (impractical) refers to cost scenarios where SPT incorporation would not be preferred because net daily or annual costs of SPT incorporation are not sufficiently higher than control costs under identical conditions. As such, practical and impractical results reflect cost effective and cost burden (SPT incorporation cannot be recovered by potential cost gains) scenarios.

Energy inputs (translated to costs) and energy gains from CH_4 conversion (also translated to costs) have been kept separate. Results will typically represent costs per treatment unit (heat recoveries are included), WWTP costs (excluding cost gains from CH_4 conversion), and net costs. Net costs were found when the cost gains (i.e., CH_4 conversion to energy) were subtracted from WWTP

5.1.1 Control and SPT WWTP with Low Strength RF

Treatment costs are based on current energy prices (UDV of $0.04/kWh) and operational energy requirements. Highly variable capital costs were not considered. The SPTs included are listed in Table 5.3.

Separate evaluation of MTAD and SD variables was deemed necessary to establish the extent at which each variable impacts daily operation costs. This approach, however, required that an initial evaluation of a set of 4 runs be conducted for the all possible permutations of NHR-NSD, NHR-DSD, LHR-NSD, and LHR-DSD. As mentioned above, control and SPT scenarios alongside MAD and TAD were evaluated. A total of 8 runs were thus needed for each SPT and for the control scenario to establish the cost breakdown per treatment unit and per AD type. Since only a few variables were

altered at once, increases or decreases in costs compared to the control cost rankings were found to be fairly similar. Therefore not all results are shown graphically. The goal here is to establish whether practical and impractical scenarios exist for each SPT.

An analysis of the SPT, MTAD, WWTP, and net daily costs for low strength RF characteristics will now be made. The results of this analysis will provide the basis for the relative rankings of each SPT (compared to the control scenario) reported throughout Sections 5.1.1-3.

The results in Fig. 5.4 are for $RM(H_1\text{-}D_1\text{-}Low)_P$. The SPTs ULT, SBM, and HPH are handled together in all cost evaluations because their SPT energy demands are sufficiently similar (i.e., they were found in literature to have analogous working ranges and could meet the same subsequent improvements at nearly the same E_{spec} values). No control cost exists (no column is shown in the figure) for the SPT unit as it is not in use during the control scenario. From Runs 1 to 4 SPT costs remained constant as SPT energy demands were not varied.

The SPTs CH, MWH, and OZ are observed to have the three lowest costs. ULT/SBM/HPH as well as CM processes follow and closely match MWH costs for the SPT unit. Costs for the MTAD unit during SPT scenarios were lower than control costs for $RM(H_1\text{-}D_1\text{-}Low)_P$. This fact is solely due to heat recovery and thus, the $T°_{el}$ as shown in Table 5.3 dictates the extent to which costs are reduced by SPT incorporation. Net costs are lower than WWTP costs as a result of energy recoveries attained by CH_4 conversion to heat (as set by UDVs for EC). The relative rankings for each SPT as shown by the WWTP costs and net costs columns are identical. This was observed because the percent solubilisations achieved as a result of SPT hydrolysis were kept the same for all SPTs. As shown in Chapter 2 in Tables 2.1-2.18, SPT working ranges for pCOD solubilisation and AD improvement ranges were fairly similar. The goal here was to establish net costs for each SPT based on the same amount of pCOD solubilisation and thus commensurate improvements in MTAD, DE and SD. It should be noted that there is no direct setting for PretrAD's SPT unit that prescribes biogas production improvement.

Instead, all biogas production improvements are a result of enhanced $MTAD_i$ sCOD availability.

Additional energy input costs specific to each SPT varied from $1,000 to 4,000/d based on energy demands to achieve the same desired level of subsequent treatment improvements. Costs for the MTAD unit with SPT were found to be similar or lower (as much as $950/d) than control MTAD costs is shown by WWTP costs (CH_4 conversion energy gains are excluded). High CH treatment temperatures lead to significant heat recoveries and WWTP costs were actually reduced. Net daily costs were reduced by $250-2,000/d for all but TC(CH) and TC(MWH) SPTs.

Results for the DE and SD units are not shown because DE costs were comparatively very small and SD is not heavily affected by sludge transport distance. The most significant SD variable is actually the desired dried solids content due to the energy demand for drying the DE cake. A change in SD variables for this entire evaluation was not made because regardless of the cost impacts of specific variables, all results are still heavily reliant on the RF characteristics and WWTP treatment settings.

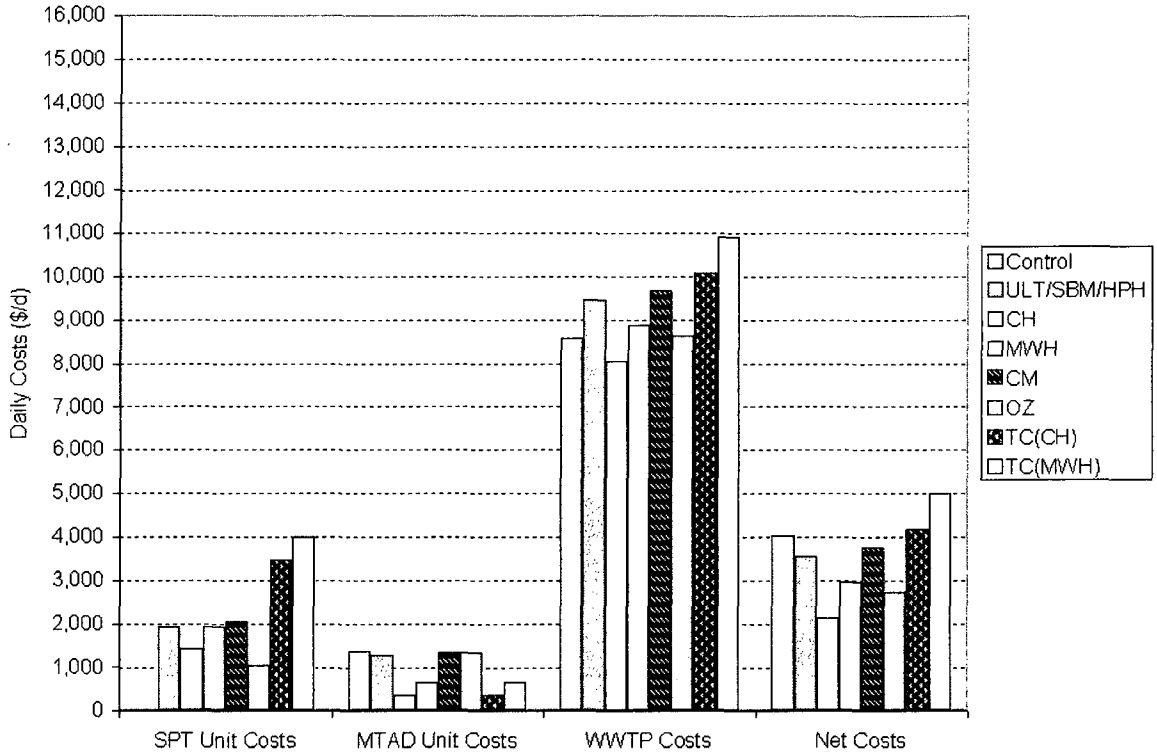


Figure 5.4 Lowest daily costs found [$RM(H_1\text{-}D_1\text{-}Low)_P$]

The lowest daily costs have been found for the evaluation of Runs 1-4. A comparison of the lowest [Run 1: $RM(H_1\text{-}D_1\text{-}Low)_P$] to highest [Run 4: $RT(H_2\text{-}D_2\text{-}Low)_P$] net costs per influent flowrate will now be made. This comparison effectively provides a range of net daily costs to be expected.

The results of the comparison are given in Fig. 5.5. The stacked columns represent the lowest to the highest net costs for control and SPT scenarios. For example, the lowest net control cost is $\$0.005/m^3$ RF_i for $RM(H_1\text{-}D_1\text{-}Low)_P$. The second lowest net control cost is $\$0.006/m^3$ RF_i for $RT(H_1\text{-}D_1\text{-}Low)_P$ (shown by the yellow bar on top of the blue bar for the control). Net control costs were similar to or surpassed by CM, TC(CH) and TC(MWH) scenarios, respectively. Though PretrAD does not directly compute TC(MWH) costs, the SPT demands for both MWH and CM were added to obtain the combined SPT unit cost along with the new WWTP and net costs.

Net control and SPT costs per peak (low strength) flowrates ranged from \$0.005-0.009/m^3 RF_i and \$0.0031-0.0098/m^3 RF_i, respectively. Again, these net costs reflect the sum of all unit costs and/or gains for the SPT, MTAD, DE, SD, and EC units. The control scenario has no SPT cost. The relative rankings for each SPT scenario compared to the control scenario are shown in Fig. 5.5.

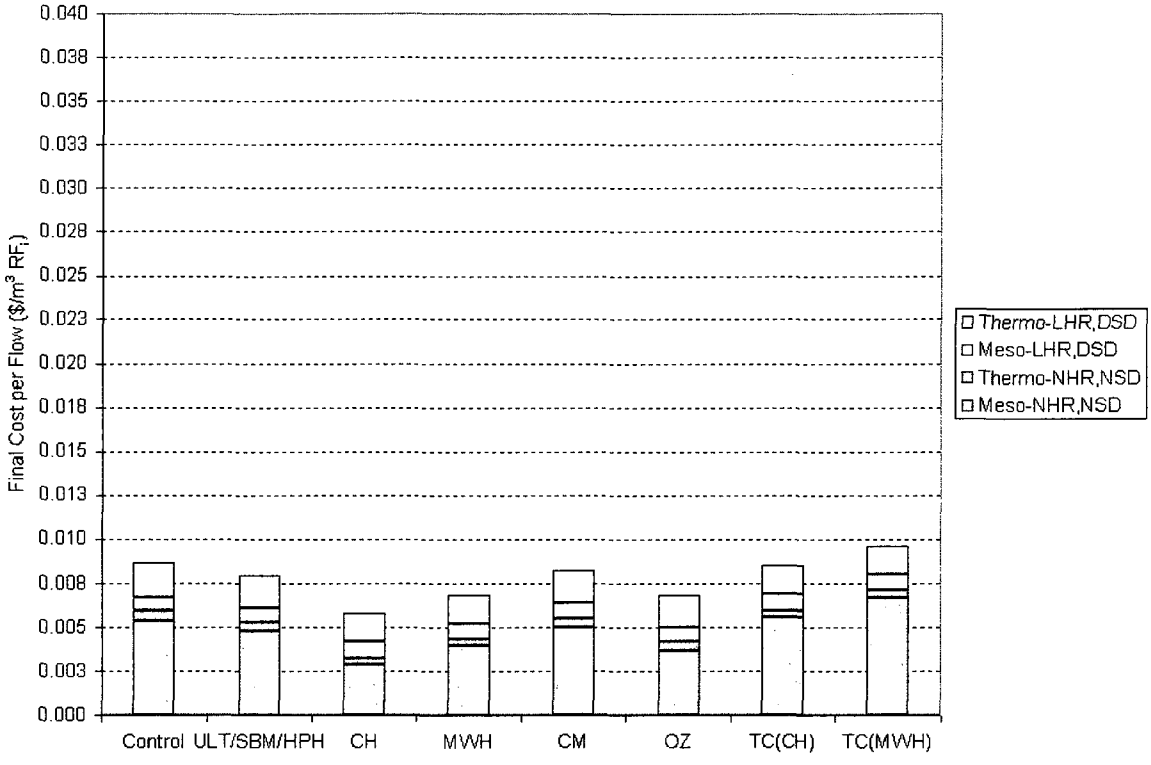


Figure 5.5 Net costs per peak flowrate for $RM(H_1\text{-}D_1\text{-}Low)_P$, $RT(H_1\text{-}D_1\text{-}Low)_P$, $RM(H_2\text{-}D_2\text{-}Low)_P$, and $RT(H_2\text{-}D_2\text{-}Low)_P$

5.1.2 Control and SPT WWTP with Average Strength RF

The lowest daily costs have been found for the evaluation of Runs 1-4 when average strength RF is an input condition. A comparison of the lowest [Run 1: $RM(H_1\text{-}D_1\text{-}Low)_A$] to highest [Run 4: $RT(H_2\text{-}D_2\text{-}Low)_A$] net costs per influent flowrate was again made and the results are shown in Fig. 5.6. This comparison effectively provides a range of net daily costs to be expected for average strength RF characteristics. No other average flow (average strength) results are shown as the relative rankings remain unchanged from

those in Figs. 5.5 and 5.6 and the amounts of the costs per influent flowrate lie in between peak and low flow scenarios.

Net control and SPT costs per average (average strength) flowrates ranged from \$0.010-0.016/m^3 RF_i and \$0.005-0.0018/m^3 RF_i, respectively. Again, the relative ranking shown in Fig. 5.6 does not vary from that in Fig. 5.5 but the separations are amplified by increased solids loadings in the average compared to the peak flow influents.

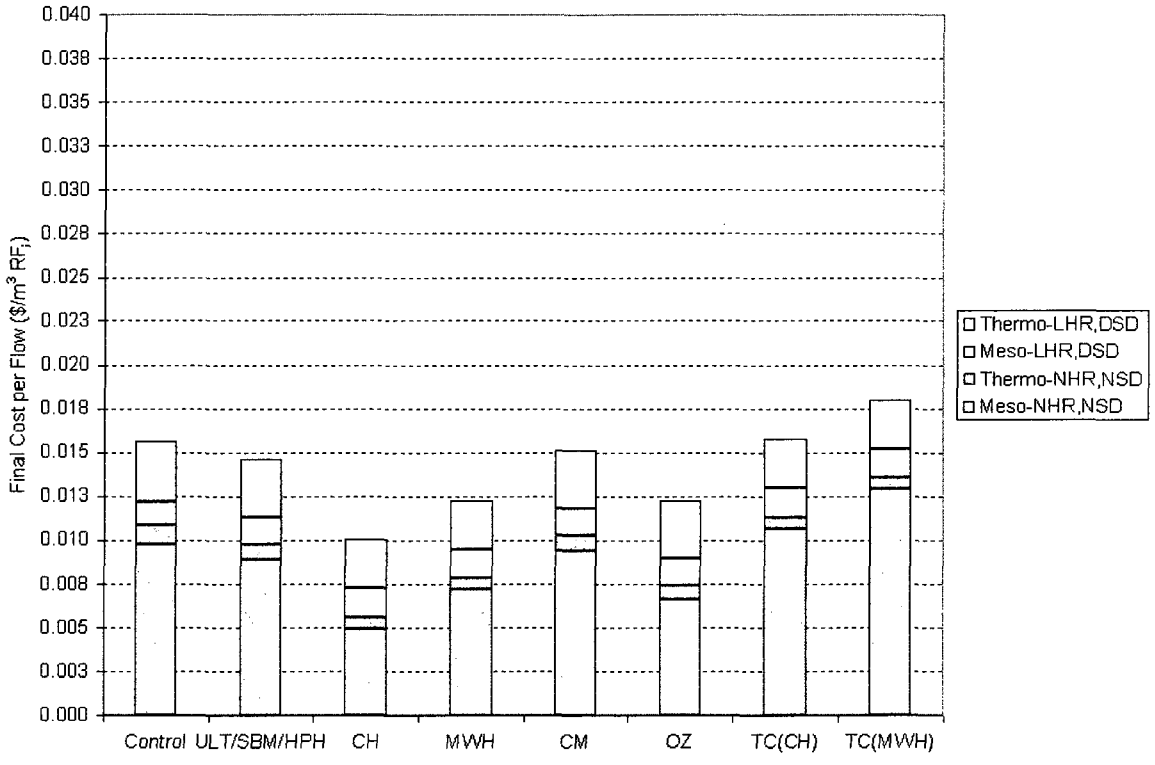


Figure 5.6 Net costs per average flowrate for $RM(H_1\text{-}D_1\text{-}Low)_A$, $RT(H_1\text{-}D_1\text{-}Low)_A$, $RM(H_2\text{-}D_2\text{-}Low)_A$, and $RT(H_2\text{-}D_2\text{-}Low)_A$

5.1.3 Control and SPT WWTP with High Strength RF

High strength RF characteristics (which occur at low flows) necessarily result in the highest unit and net daily costs and gains found. Since the costs are primarily based on solids loadings, the increase in solids entering the WWTP upwardly affects operating costs.

The highest daily costs [RT(H_2-D_2-Low)$_L$] occurred for the high strength-low flow and they are shown in Fig. 5.7. No control cost exists (no column is shown in the figure) for the SPT unit as it is not in use.

Specific SPT costs varied from $1,300/d to $5,600/d based on energy demands of each SPT to achieve the same desired level of subsequent treatment improvements. Mesophilic/thermophilic AD costs were reduced by as much as $1,400/d. Increased WWTP costs occur for all but CH SPT incorporation. Net SPT costs were reduced by $100-2,700/d compared to the control results for all but TC(CH) and TC(MWH) SPTs.

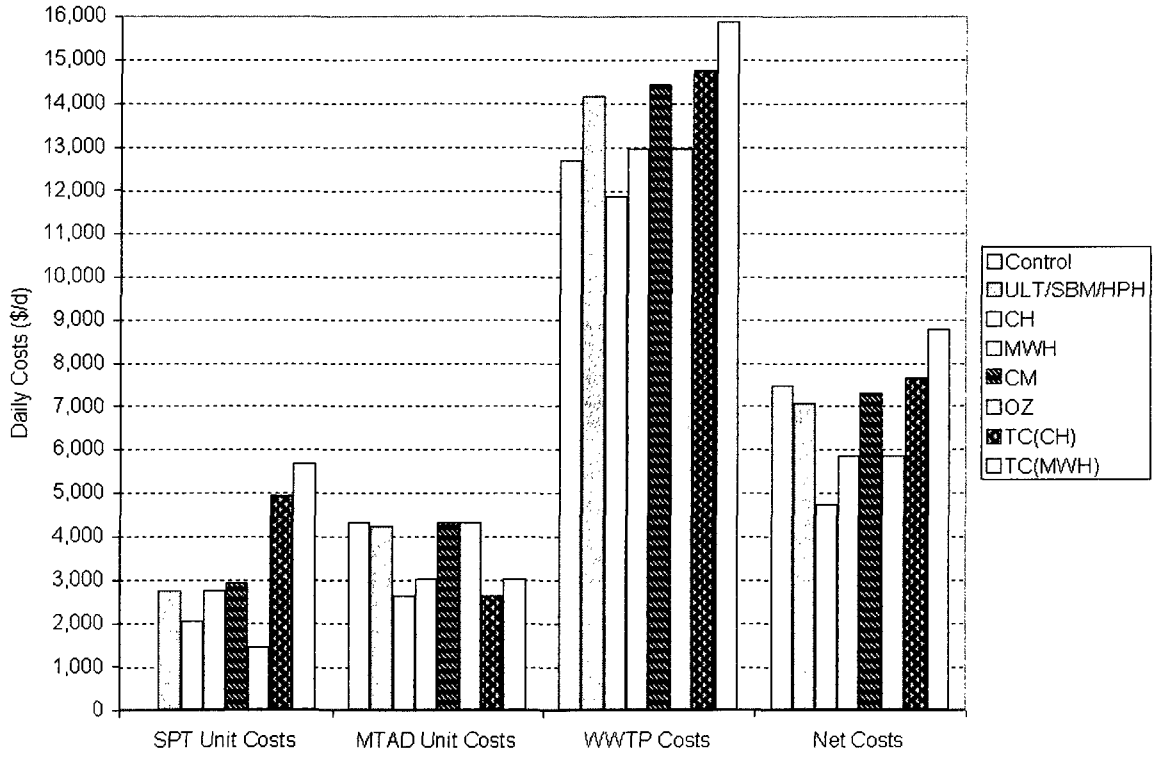


Figure 5.7 Highest daily costs found [RT(H_2-D_2-Low)$_L$]

The lowest daily costs have been found for the evaluation of Runs 1-4. A comparison of the lowest [Run 1: RM(H_1-D_1-Low)$_L$] to highest [Run 4: RT(H_2-D_2-Low)$_L$] net costs per influent flowrate is given by the results in Fig. 5.8. Net control costs were of course, similar to or surpassed by CM, TC(CH), and TC(MWH) scenarios, respectively. This figure highlights the significant amplification of costs due to solids loading under

low flow (high strength) conditions compared to peak flow (low strength) conditions shown in Fig. 5.5. Not only are the costs elevated for all runs but the difference in costs for any run is greater.

Net control and SPT costs per low (high strength) flowrates ranged from \$0.020-0.032/m^3 RF_i and \$0.01-0.0037/m^3 RF_i, respectively.

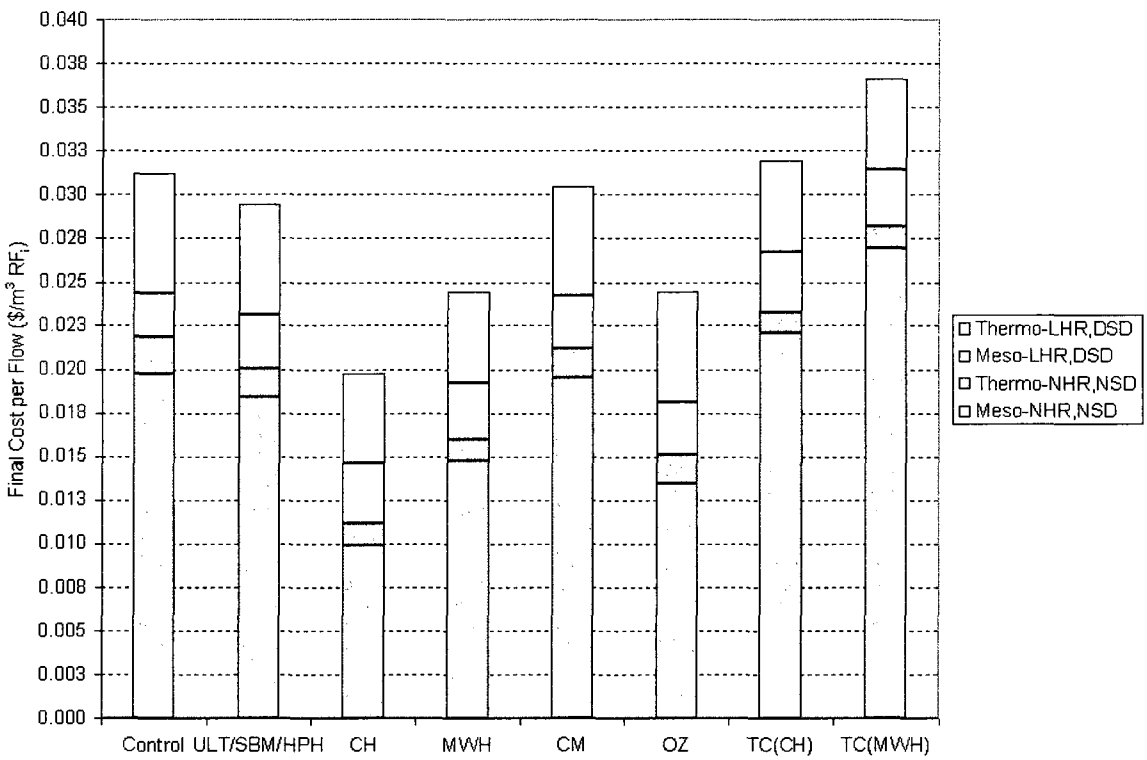


Figure 5.8 Net costs per low flowrate (high strength) for $RM(H_1\text{-}D_1\text{-}Low)_L$, $RT(H_1\text{-}D_1\text{-}Low)_L$, $RM(H_2\text{-}D_2\text{-}Low)_L$, and $RT(H_2\text{-}D_2\text{-}Low)_L$

To review the increase in costs based primarily on MAD or TAD, Fig. 5.9 was created. Though only $RM(H_1\text{-}D_1\text{-}Low)_P$, $RT(H_2\text{-}D_2\text{-}Low)_L$ are shown, TAD costs were always higher than MAD costs. It is important to note that the MAD and TAD costs are for peak (low strength), and low (high strength) influent flowrates, respectively. Thus, TAD costs can be but are not always as significantly different from MAD costs as shown in this figure. It was observed that net costs range from \$0.020-0.037/m^3 RF_i [$RT(H_2\text{-}D_2\text{-}Low)_L$] at their highest and from \$0.03-0.07/m^3 RF_i at their lowest [$RM(H_1\text{-}D_1\text{-}Low)_P$].

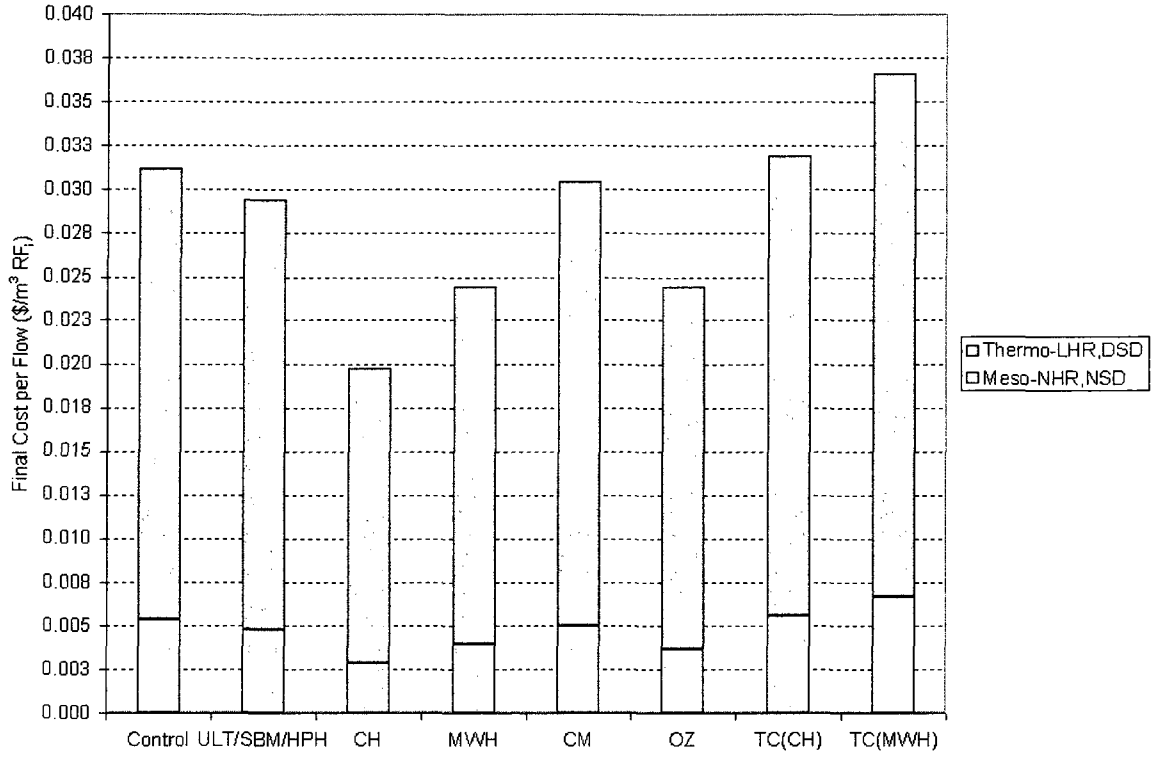


Figure 5.9 Lowest [$RM(H_1\text{-}D_1\text{-}Low)_P$] versus highest [$RT(H_2\text{-}D_2\text{-}Low)_L$] net daily costs per influent flowrates

It was now deemed important to establish net annual costs under various flow regimes in order to differentiate between permanent daily conditions (as costs reflect a day of operation under identical conditions) and the always fluctuating flow conditions experienced by WWTPs.

5.1.4 Flow Regime Determinations

Prior to establishing possible flow regimes, net costs per flow (peak, average, and low) were obtained for control and SPT scenarios. All costs per flow and how they increase from $RM(H_1\text{-}D_1\text{-}Low)_P$ to $RM(H_1\text{-}D_1\text{-}Low)_A$ and finally to $RM(H_1\text{-}D_1\text{-}Low)_L$ are shown in Fig. 5.10. For all flow conditions the relative rankings for each SPT compared to control costs do not change. During peak, average, and low flow occurrences, net costs range from \$0.003-0.007, 0.005-0.013, and 0.010-0.028/m^3 RF_i, respectively.

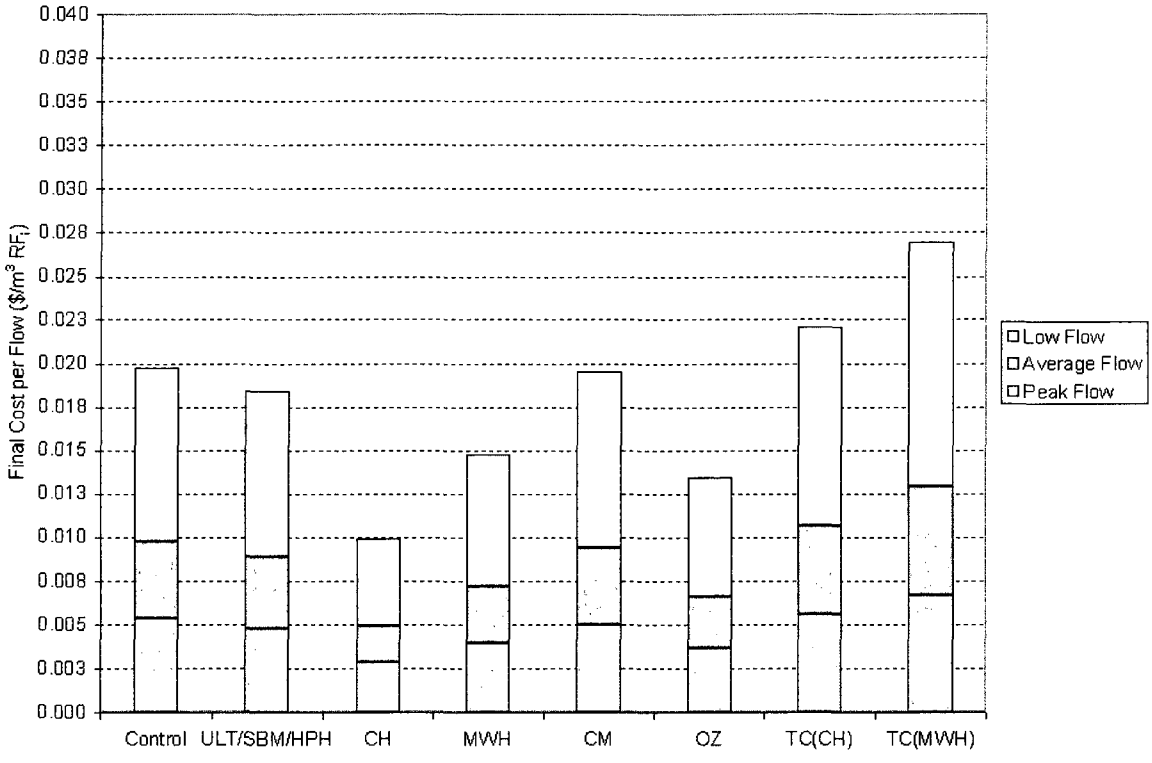


Figure 5.10 Net costs for $RM(H_1\text{-}D_1\text{-}Low)_P$, $RM(H_1\text{-}D_1\text{-}Low)_A$, and $RM(H_1\text{-}D_1\text{-}Low)_L$

Now the effects of changing heat recovery variables and sludge hauling distance on costs were examined. For all flow conditions and TAD the relative rankings for SPT costs compared to the control costs are the same as those shown for MAD in Fig. 5.11; thus the figure for TAD was not shown. The raw data and both MAD and TAD figures that were created can be found in the electronic Appendix C. During peak, average, and low flows, net costs for $RT(H_1\text{-}D_1\text{-}Low)_P$, $RT(H_1\text{-}D_1\text{-}Low)_A$, and $RT(H_1\text{-}D_1\text{-}Low)_L$ range from \$0.003-0.008, 0.005-0.014, and 0.011-0.030/m^3 RF_i, respectively. Net costs on an influent flowrate basis are only slightly affected when TAD is used in place of MAD.

The relative rankings that have been observed in Fig. 5.10 are again observed in Fig. 5.11. This figure outlines the net costs per flow for $RM(H_2\text{-}D_2\text{-}Low)_P$, $RM(H_2\text{-}D_2\text{-}Low)_A$, and $RM(H_2\text{-}D_2\text{-}Low)_L$. During peak, average, and low flows, net costs range from \$0.004-0.008, 0.008-0.015, and 0.015-0.032/m^3 RF_i, respectively.

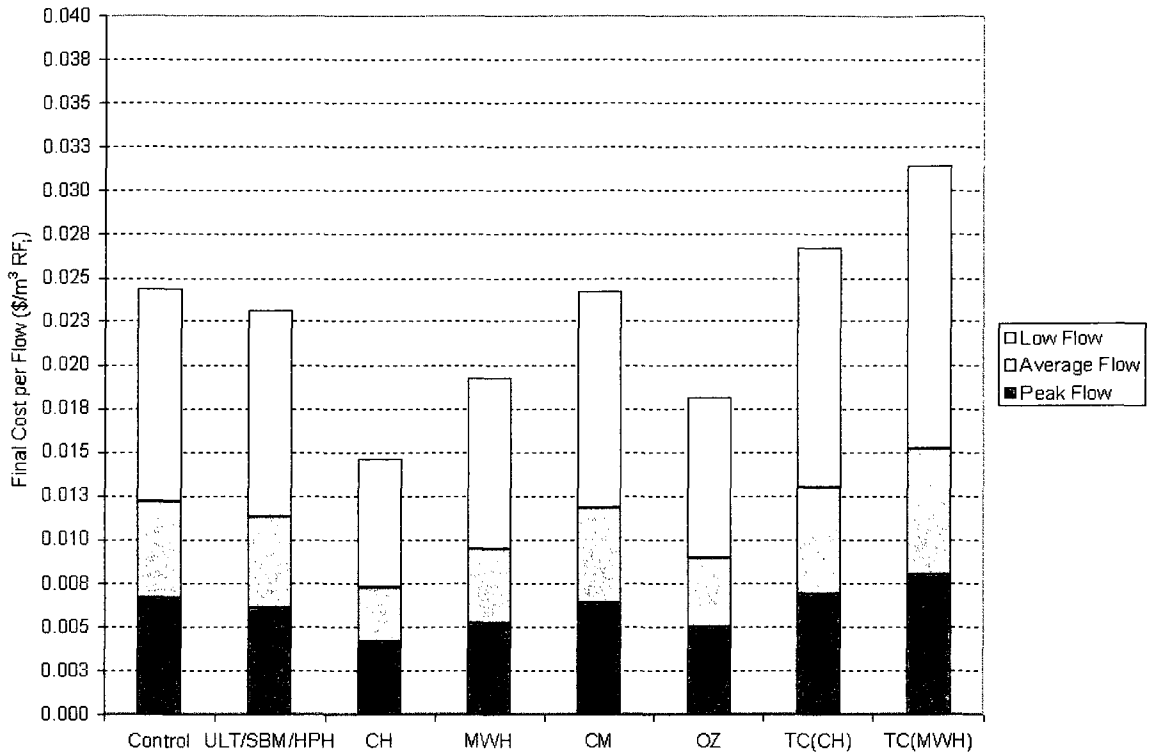


Figure 5.11 Net costs for $RM(H_2\text{-}D_2\text{-}Low)_P$, $RM(H_2\text{-}D_2\text{-}Low)_A$, and $RM(H_2\text{-}D_2\text{-}Low)_L$

For all flow conditions and TAD the relative rankings for SPT costs compared to the control costs are unchanged from the MAD rankings shown in Fig. 5.11. During peak, average, and low flows, net costs for $RT(H_2\text{-}D_2\text{-}Low)_P$, $RT(H_2\text{-}D_2\text{-}Low)_A$, and $RT(H_2\text{-}D_2\text{-}Low)_L$ range from \$0.006-0.010, 0.010-0.018, and 0.020-0.037/m^3 RF_i, respectively. The figure for TAD was thus not shown. Net costs on an influent flow basis are more significantly affected when TAD is used in place of MAD. This magnification of costs is due almost solely to low values of heat recovery variables.

Flow regimes were now considered since WWTPs do not experience constant yearly influents of identical characteristics (strength) and magnitudes (flowrates). As explained in the literature, WWTPs receiving combined sewer flows experience on average high flow (low strength) conditions over 10% of the time due to system infiltration as a result of precipitation. Minimum daily flowrates range from 30-70% of the yearly flows experienced by WWTPs [160]. Thus, by fixing the high flow condition

at 10% of the time and varying the low flow from 30-70% of the time with average flow comprising the remainder of the time, an overall average flow occurrence was obtained and ratios for low/average regimes were created. Daily costs could now be estimated for the year. The days/year values as a function of the low/average ratios for each flow condition are outlined in Table 5.4. All columns sum to 365 days.

Table 5.4 Days per year for each flow condition and the respective ratio

FLOWS / Days (d)					
PEAK	36.5	36.5	36.5	36.5	36.5
AVERAGE	219	182.5	146	109.5	73
LOW	109.5	146	182.5	219	255.5
Low/Average Ratio	0.5	0.8	1.25	2	3.5

The yearly net costs based on all flow occurrence regime ratios were calculated for control and each SPT. The control and SPT results shown in Fig. 5.12 are from RM(H_1-D_1-Low). The subscript defining flow selection is not shown because flow conditions comprised of the flow ratios in Table 5.4 were used. A slight increase in costs from a primarily average flow regime to a primarily low flow regime is observed for control and SPT scenarios. This same increase (but at higher initial costs) is observed with RT(H_1-D_1-Low). Both MAD and TAD (the figure for TAD is not shown) exhibited a 5-15% difference in net yearly costs based on an all peak, all average or all low flow regime. A net yearly cost variation of 2.5-3.5% for low/average flow occurrence ratios of 0.5-3.5 was found and a less than 5% difference for yearly cost in an all average regime versus varied flow regimes was also observed. Thus, average flow results were deemed to be sufficiently representative of any results for different flow regimes. From this point forward, only average RF variables would be used in the SPT energy demand increase permutations (Runs 1a-2b) in Section 5.1.5.

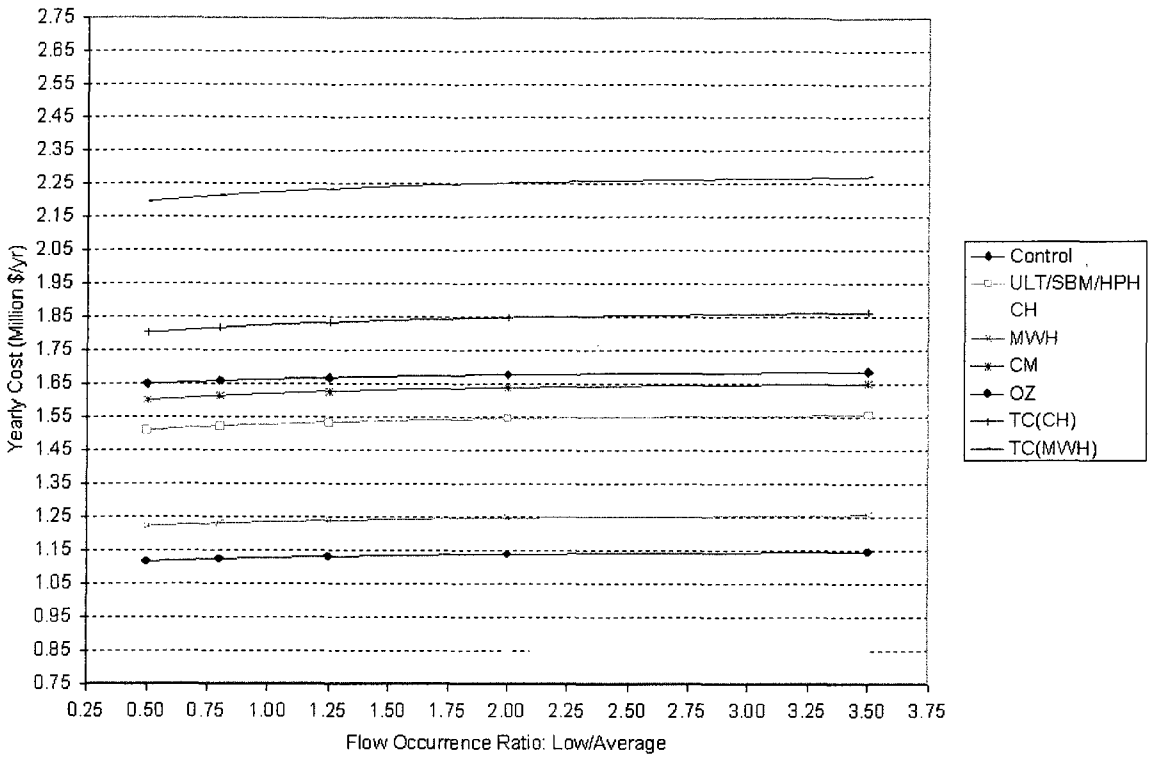


Figure 5.12 Net yearly costs increases for various flow occurrence ratios from evaluations of control and SPT RM(H_1-D_1-Low)

5.1.5 Average Strength RF and Increased SPT Energy Demands

In the section above, results for net yearly costs under average RF scenarios were found to be sufficiently representative of all regime flows evaluated. Energy demand increases for the SPT units were now evaluated under only average RF characteristics. All SPTs at Low, Med, and High energy demands (see Table 5.3) were compared to control costs. At Low energy demand, all SPTs other than TC(CH) and TC(MWH), were found to have a net energy gain once incorporated into the WWTP. Practical situations were found and will be addressed in the Observations and Highlights Summary (Section 5.2).

The first set of Runs 1-4 evaluated the incorporation of SPT at low (labelled Low) energy demand for SPT (results are shown in Fig. 5.6). Now reasonable increases in SPT energy demands (25-50% based on literature ranges shown in the summary tables of Chapter 2) were considered. Many treatment parameters within the plant could also be varied as conditions are seldom constant, but only heat recoveries and sludge disposal

distances were again considered along with SPT energy input. It should be noted that the Low energy demand variables for each SPT were selected to represent a slightly lower than average energy input to achieve the UDVs for hydrolysis (pCOD solubilisation). In this analysis the percent solubilisations were not changed for any runs; they may be difficult to achieve with only energy demands set at the 'Low' value. Similarly, with 'High' SPT energy demands, increased percent solubilisations may in fact be realised with further treatment benefits.

The following evaluation (Figs. 5.13-14) compares net daily costs for the lowest and highest net cost scenarios (Runs 1 and 4) observed earlier. Both figures also show the newly determined net daily costs for Runs 1a, 1b, 2a, and 2b. An assessment of practicality and impracticality can now be made on a basis of increased (Med and High) SPT energy demands. Although both figures have the control results linked by a line, no relationship exists between the values indicated by the points. The line is meant to serve as a visual reference guide for a simplified practical and impractical costs evaluation. Points above this line reflect net costs that are higher than control costs and the scenarios that provided these results are thus, impractical.

The results shown in Fig. 5.13 are for $RM(H_1\text{-}D_1\text{-}Low)_A$ (Run 1) and $RM(H_2\text{-}D_2\text{-}Low)_A$ (Run 4). The newly determined net daily costs are for $RM(H_1\text{-}D_1\text{-}Med)_A$, $RM(H_1\text{-}D_1\text{-}High)_A$, $RM(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_2\text{-}D_2\text{-}High)_A$, respectively. From Section 5.1.1-3 with Low SPT energy demands (Runs 1 and 4), net energy gains were obtained for all but TC(CH) and TC(MWH).

For $RM(H_1\text{-}D_1\text{-}Med)_A$ and $RM(H_1\text{-}D_1\text{-}High)_A$ ULT/SBM/HPH, CM, TC(CH), and TC(MWH) scenarios yielded impractical results. Ozone incorporation was found to have slightly impractical (scenario costs > control costs) results for $RM(H_2\text{-}D_2\text{-}Med)_A$ and $RM(H_2\text{-}D_2\text{-}High)_A$. The CH and MWH SPTs were not found to have impractical results with MAD for any of the energy input scenarios examined.

The same comparison of Low to High SPT energy demands as was conducted in Fig. 5.13 is shown in Fig. 5.14 for TAD. Runs 1 and 4 (lowest and highest net cost

scenarios observed earlier) are the results of $RT(H_1\text{-}D_1\text{-}Low)_A$ and $RT(H_2\text{-}D_2\text{-}Low)_A$. The TAD Runs 1a $RT(H_1\text{-}D_1\text{-}Med)_A$, 1b $RT(H_1\text{-}D_1\text{-}High)_A$, 2a $RT(H_2\text{-}D_2\text{-}Med)_A$ and 2b $RT(H_2\text{-}D_2\text{-}High)_A$ are shown.

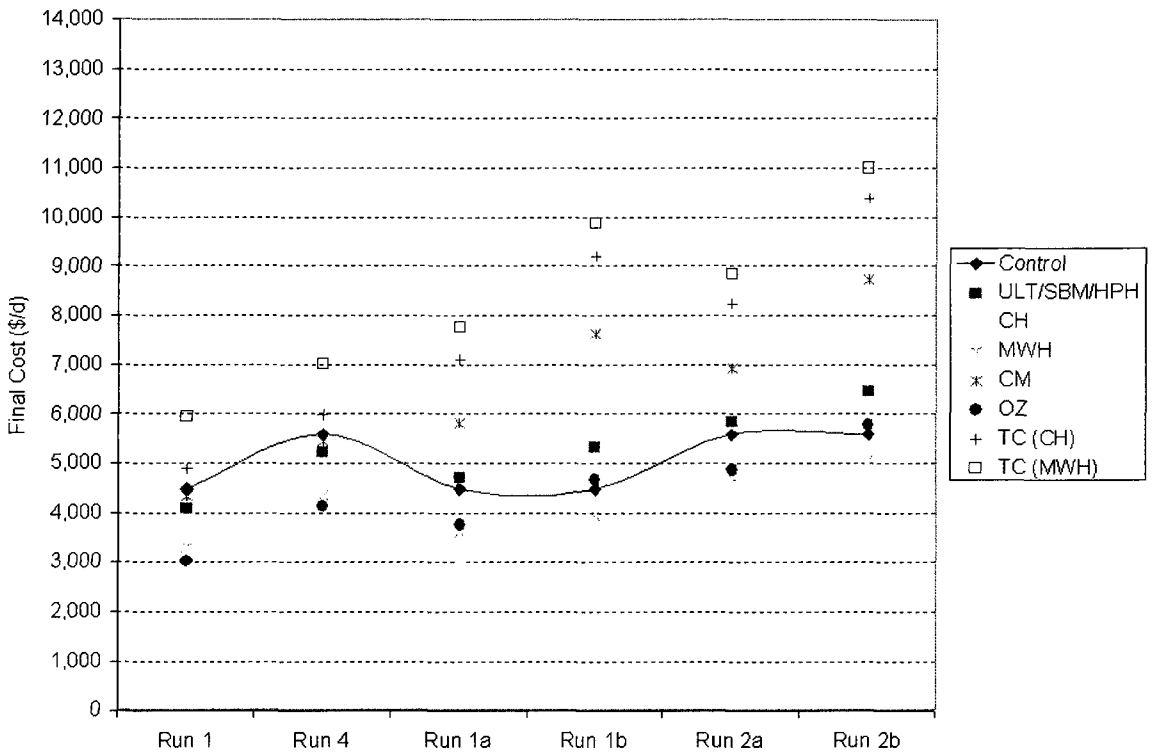


Figure 5.13 Net costs for Run 1 $RM(H_1\text{-}D_1\text{-}Low)_A$ and Run 4 $RM(H_2\text{-}D_2\text{-}Low)_A$ as well as Run 1a $RM(H_1\text{-}D_1\text{-}Med)_A$, Run 1b $RM(H_1\text{-}D_1\text{-}High)_A$, Run 2a $RM(H_2\text{-}D_2\text{-}Med)_A$, and Run 2b $RM(H_2\text{-}D_2\text{-}High)_A$

The relative rankings in Fig. 5.14 are similar to those in Fig. 5.13 but since TAD requires additional energy input, control costs are higher and TC(CH) had practical results. The ULT/SBM/HPH and OZ SPTs are practical (or almost practical) with Med SPT energy demands for all runs. Net daily costs were not impractical for CH and MWH with TAD.

Scenario costs with SPT have been dutifully compared to control costs using identical parameters. A thorough comparison of control and SPT scenario costs with MAD is now presented.

The results in Fig. 5.15 outline cost differentials for control and SPT MAD scenarios. The columns are shown in sets of 2 for the comparisons of Run 1 with 4, Run 1a with 2a, and Run 1b with 2b. In other words, the columns are stacked in sets for the following comparisons: $RM(H_1\text{-}D_1\text{-}Low)_A$ with $RM(H_2\text{-}D_2\text{-}Low)_A$, $RM(H_1\text{-}D_1\text{-}Med)_A$ with $RM(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_1\text{-}D_1\text{-}High)_A$ with $RM(H_2\text{-}D_2\text{-}High)_A$.

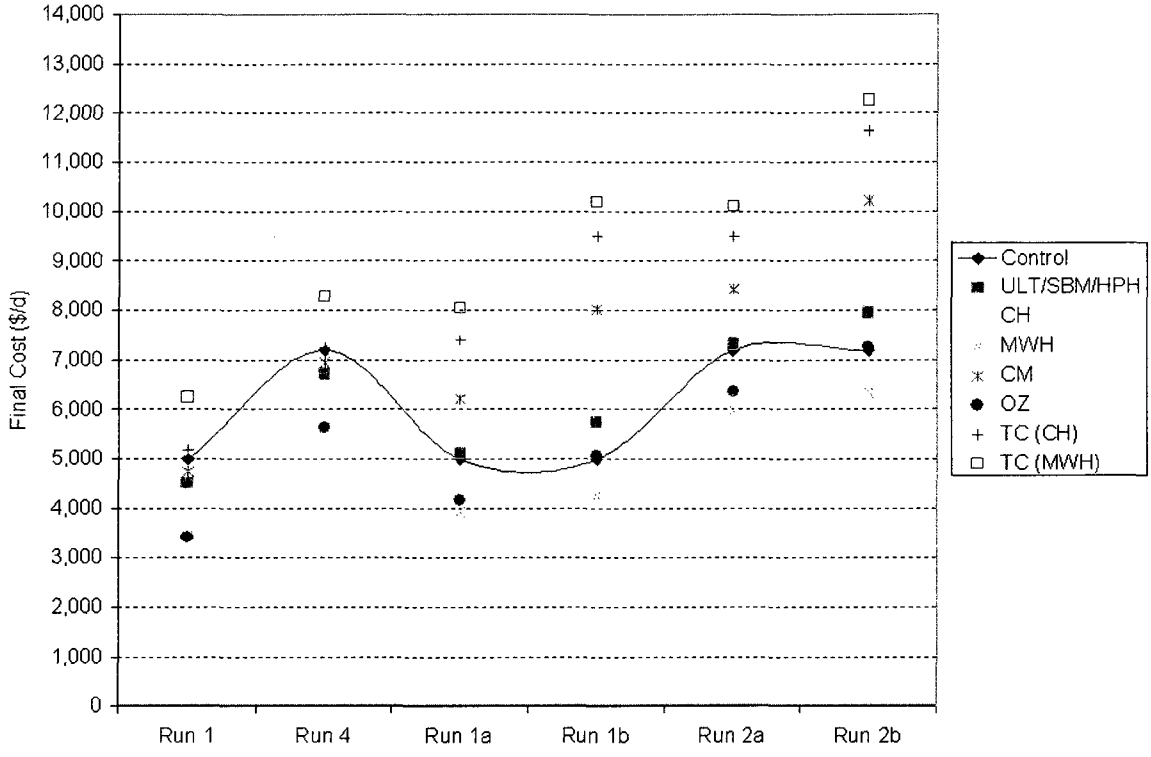


Figure 5.14 Net costs for Run 1 $RT(H_1\text{-}D_1\text{-}Low)_A$ and Run 4 $RT(H_2\text{-}D_2\text{-}Low)_A$ as well as Run 1a $RT(H_1\text{-}D_1\text{-}Med)_A$, Run 1b $RT(H_1\text{-}D_1\text{-}High)_A$, Run 2a $RT(H_2\text{-}D_2\text{-}Med)_A$, and Run 2b $RT(H_2\text{-}D_2\text{-}High)_A$

The control cost columns do not have values for Runs 1a-2b as these involve SPT energy demand increases that are only reflected in SPT scenarios. It is interesting to note that net costs per flow for $RM(H_2\text{-}D_2\text{-}Low)_A$ with ULT/SBM/HPH, CH, and MWH resemble or surpass those of $RM(H_1\text{-}D_1\text{-}High)_A$. The reason this trend does not apply to all SPTs is based on temperatures of the effluent from the SPT. A sufficiently higher than ambient (+ 7°C) SPT effluent temperature provides a higher reduction in heat energy to

be supplied for MTAD. This additional heat recovery lowers the impact of SPT energy demand increases compared to the impact of MTAD and SD variables.

Impractical scenarios are found for ULT/SBM/HPH, CM, TC(CH) and TC(MWH) for $RM(H_1\text{-}D_1\text{-}Med)_A$ or $RM(H_2\text{-}D_2\text{-}Med)_A$. Additional impractical situations are found for the preceding list and OZ with $RM(H_1\text{-}D_1\text{-}High)_A$ or $RM(H_2\text{-}D_2\text{-}High)_A$. No impractical situation is found for CH or MWH. Under MAD, CH and MWH offer the only SPT scenarios that were always shown to be more cost effective than control.

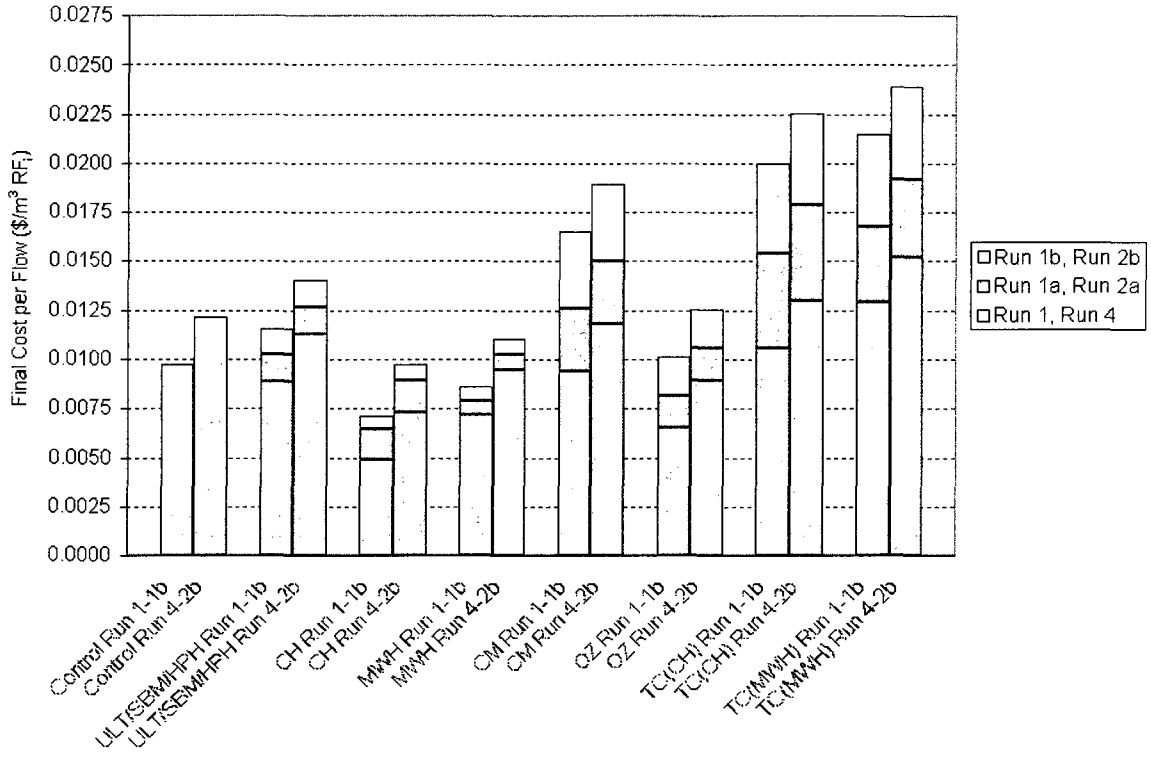


Figure 5.15 Net costs per average influent flowrate for the comparisons of Run 1 $RM(H_1\text{-}D_1\text{-}Low)_A$ with Run 4 $RM(H_2\text{-}D_2\text{-}Low)_A$, Run 1a $RM(H_1\text{-}D_1\text{-}Med)_A$ Run 2a with $RM(H_2\text{-}D_2\text{-}Med)_A$, and Run 1b $RM(H_1\text{-}D_1\text{-}High)_A$ with Run 2b $RM(H_2\text{-}D_2\text{-}High)_A$

As noted above, SPT energy demand increases are not always more important than MTAD and SD variables. Specifically in the case of TAD (figure not shown) where energy costs are amplified, an additional SPT (OZ) is added to the list of processes where energy demand increases are relatively unimportant compared to MTAD and SD

variables. All SPTs (except for CH) provided both practical and impractical scenarios as shown in Fig. 5.15. When TAD was used however, not all CH scenarios were deemed practical as compared to $RT(H_1\text{-}D_1\text{-}Low)_A$.

When evaluating treatment costs based on operational energy requirements it is clear that TAD in control cost scenarios will be costlier than MAD. This was observed under all flow conditions. Since operational fluctuations exist and treatment parameters cannot be consistently maintained, heat recovery and energy demands were varied. Again, with low heat recoveries and higher energy demands, control and SPT scenarios for TAD were more costly. It was thought however, that if preferable MTAD heat recoveries (lower heat losses and higher application efficiencies, Table 5.2) could be maintained at higher rates of recurrence for TAD WWTPs, some SPT TAD scenarios would be preferred over SPT MAD scenarios. That is to say, if heat recoveries fluctuate more frequently during SPT scenarios and as a result lead to higher occurrences of increased daily costs, SPT scenarios with MAD might not be as cost effective. This is especially the case in regards to thermal SPTs where the energy demand translates to a significant heat input prior to AD that would be used at the anaerobic digester in every case. A cost occurrence evaluation was performed and is shown in Figs. 5.21 and 5.22.

An evaluation of control and SPT MAD compared to SPT TAD scenarios is now presented. Sludge pretreatment scenarios with either MAD or TAD can be compared to control scenarios with either MAD or TAD. Practicality or impracticality can be assigned on the basis of AD type and treatment parameters that result in low or high costs.

In a similar manner to Fig. 5.15, the results that are shown in Fig. 5.16 outline cost differentials for control and SPT MAD and TAD scenarios. The columns are shown in sets of 2 for the comparisons of Run 1 with 4, Run 1a with 2a, and Run 1b with 2b. In other words, the columns are stacked in sets for the following comparisons: $RM(H_1\text{-}D_1\text{-}Low)_A$ with $RT(H_2\text{-}D_2\text{-}Low)_A$, $RM(H_1\text{-}D_1\text{-}Med)_A$ with $RT(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_1\text{-}D_1\text{-}High)_A$ with $RT(H_2\text{-}D_2\text{-}High)_A$.

The MAD results are identical to those shown in Fig. 5.15. The cost amplifications based on AD temperatures are shown in Fig. 5.16.

A reversed situation is depicted in Fig. 5.17. Now, the highest cost, control and SPT MAD scenarios, are compared to the lowest cost, control and SPT TAD scenarios. In other words, the columns are stacked in sets for the following comparisons: RM(H_2-D_2-Low)$_A$ with RT(H_1-D_1-Low)$_A$, RM(H_2-D_2-Med)$_A$ with RT(H_1-D_1-Med)$_A$, and RM(H_2-D_2-High)$_A$ with RT(H_1-D_1-High)$_A$.

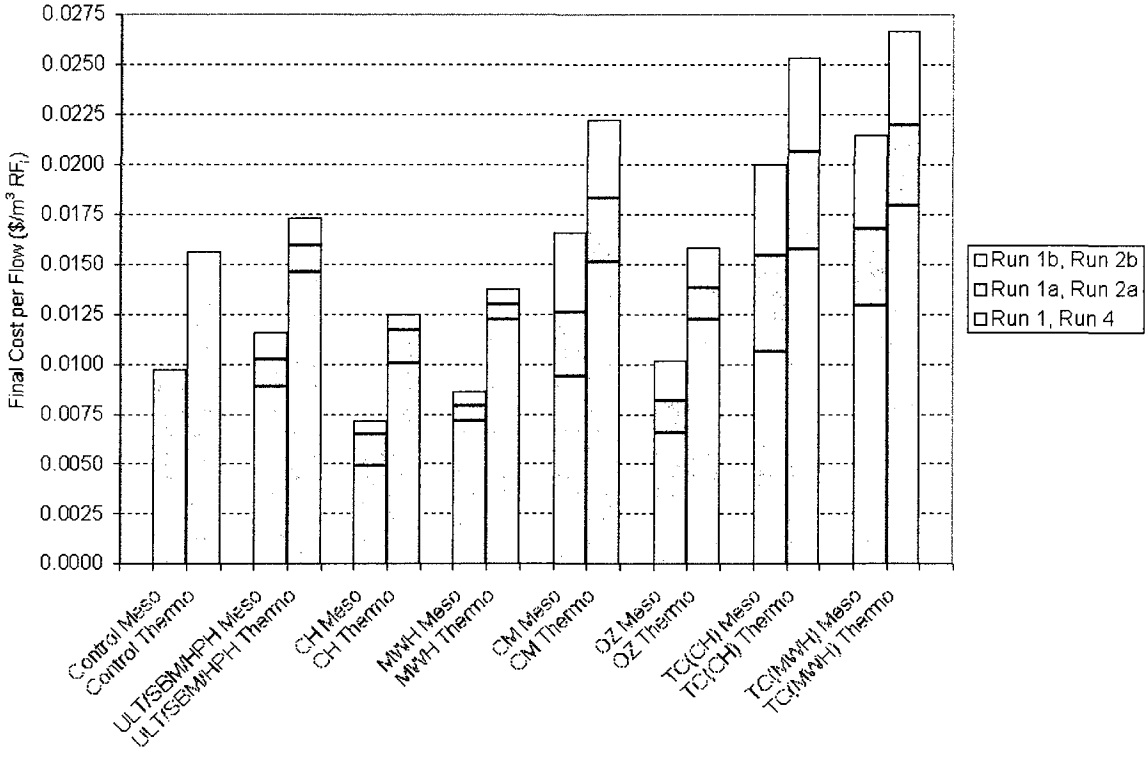


Figure 5.16 Net costs per average influent flowrate for the comparisons of Run 1 RM(H_1-D_1-Low)$_A$ with Run 4 RT(H_2-D_2-Low)$_A$, Run 1a RM(H_1-D_1-Med)$_A$ with Run 2a RT(H_2-D_2-Med)$_A$, and Run 1b RM(H_1-D_1-High)$_A$ with Run 2b RT(H_2-D_2-High)$_A$

As is easily seen, net costs for control and SPT TAD scenarios are always less than those for control and SPT MAD scenarios. No matter the SPT energy demand, TAD scenarios can be more practical than MAD scenarios if preferable heat recoveries occur and sludge transport distances exist.

As done in Sections 5.1.1 and 5.1.3, the SPT and MTAD unit costs will again be evaluated along with WWTP (excluding energy gains) and net (including energy gains) costs. In Fig. 5.18 columns are now stacked to show the lowest found costs [Run 1 $RM(H_1\text{-}D_1\text{-Low})_A$] and the highest found costs [Run 2b $RM(H_2\text{-}D_2\text{-High})_A$] for control and SPT scenarios with MAD. This provides the likely low to high cost ranges for daily operations.

Figure 5.18 should be read as per this example: the ULT/SBM/HPH columns are stacked to compare the lowest to the highest cost MAD scenarios for these SPTs. As such, $RM(H_1\text{-}D_1\text{-Low})_A$ is stacked below $RM(H_2\text{-}D_2\text{-High})_A$ and net daily costs for ULT/SBM/HPH range from $2,500-3,800/d. A range of net daily operational costs is thus established for control and SPT scenarios with MAD. The control scenario shows no columns at the SPT unit because it is not in use. As previously stated, average RF characteristics on a yearly basis were sufficiently representative of all yearly flow regimes.

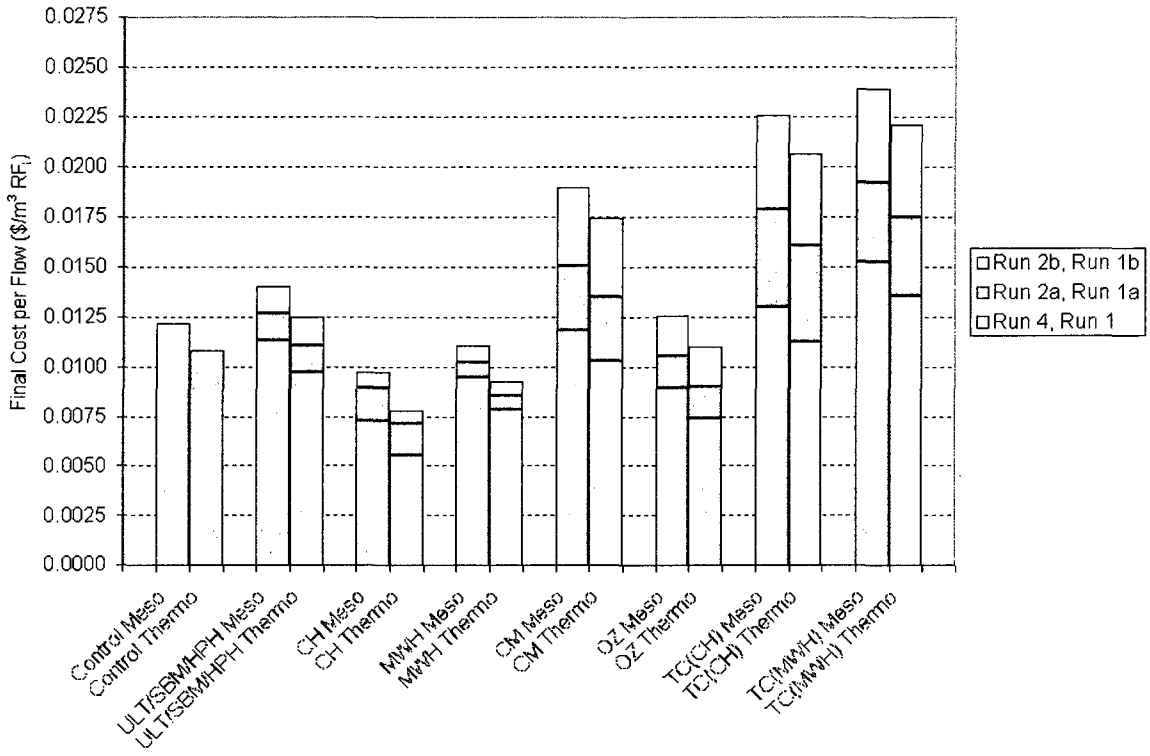


Figure 5.17 Net costs per average influent flowrate for the comparisons of Run 4 $RM(H_2\text{-}D_2\text{-Low})_A$ with Run 1 $RT(H_1\text{-}D_1\text{-Low})_A$, Run 2a $RM(H_2\text{-}D_2\text{-Med})_A$ with Run 1a $RT(H_1\text{-}D_1\text{-Med})_A$, and Run 2b $RM(H_2\text{-}D_2\text{-High})_A$ with Run 1b $RT(H_1\text{-}D_1\text{-High})_A$

Unit costs for SPT ranged from \$1,300-5,100/d and \$3,000-9,800/d for $RM(H_1\text{-}D_1\text{-Low})_A$ and $RM(H_2\text{-}D_2\text{-High})_A$, respectively. Costs at the MTAD unit were reduced by as much as \$1,900/d. Increased WWTP costs are shown under all SPT scenarios for run $RM(H_2\text{-}D_2\text{-High})_A$. Net costs were reduced by \$100-2,000/d for all but TC(CH) and TC(MWH) SPTs with $RM(H_1\text{-}D_1\text{-Low})_A$. For $RM(H_2\text{-}D_2\text{-High})_A$, net costs were only reduced by SPT scenarios incorporating CH or MWH. All other SPT scenarios showed an increase in net costs ranging from \$200-5,500/d.

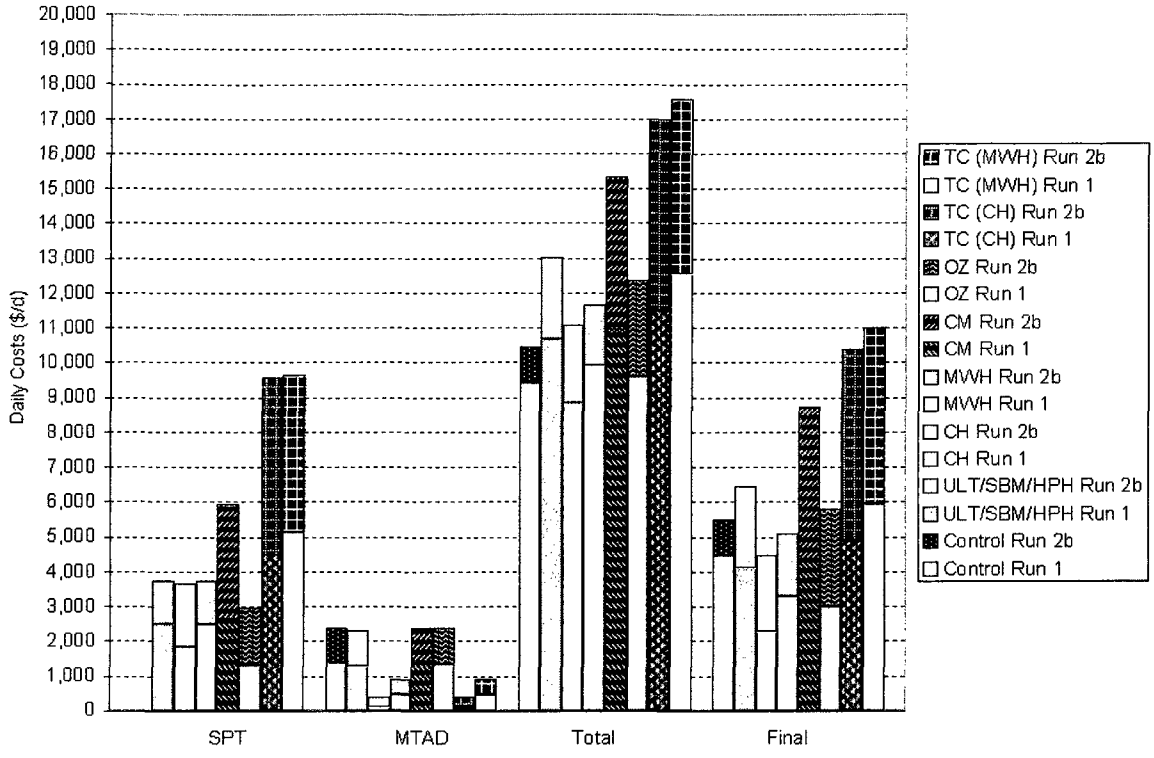


Figure 5.18 Lowest and highest net daily cost ranges for control and SPT scenarios with Run 1 RM(H_1-D_1-Low)$_A$ stacked below Run 2b RM(H_2-D_2-High)$_A$

The same evaluation as that made for MAD scenarios shown in Fig. 5.18 is given for TAD by the results in Fig. 5.19. For each SPT the result for RT(H_1-D_1-Low)$_A$ is stacked below RT(H_2-D_2-High)$_A$. A range of net daily operational costs is thus established for control and SPT scenarios with TAD.

Units costs for SPT ranged from \$1,300-5,100/d and \$3,000-9,800/d for RM(H_1-D_1-Low)$_A$ and RM(H_2-D_2-High)$_A$, respectively. SPT costs do not increase without SPT energy demand changes. Costs at the MTAD unit were reduced by as much as \$1,900/d. Increased WWTP costs are shown under all SPT scenarios for run RM(H_2-D_2-High)$_A$. The relative rankings with TAD are the same as for MAD but the actual costs are amplified. As shown in Fig. 5.18 however, control costs for RM(H_2-D_2-High)$_A$ were less than those of ULT/SBM/HPH, CM, TC(CH), and TC(MWH) SPTs for RM(H_1-D_1-Low)$_A$. In Fig. 5.19, control costs for RT(H_2-D_2-High)$_A$ are higher than all SPT costs for RT(H_1-D_1-Low)$_A$. If low cost treatment parameters (as shown in Tables 5.2-3) were more

easily maintained as a result of SPT incorporation in a TAD WWTP, a scenario exists where all SPTs but TC(MWH) are practical. Net costs were reduced by \$100-2,400/d for all but TC(CH) and TC(MWH) SPTs with $RT(H_1\text{-}D_1\text{-Low})_A$. For $RT(H_2\text{-}D_2\text{-High})_A$, net costs were only reduced by SPT scenarios incorporating CH or MWH. All other SPT scenarios showed an increase in net costs ranging from \$100-5,100/d.

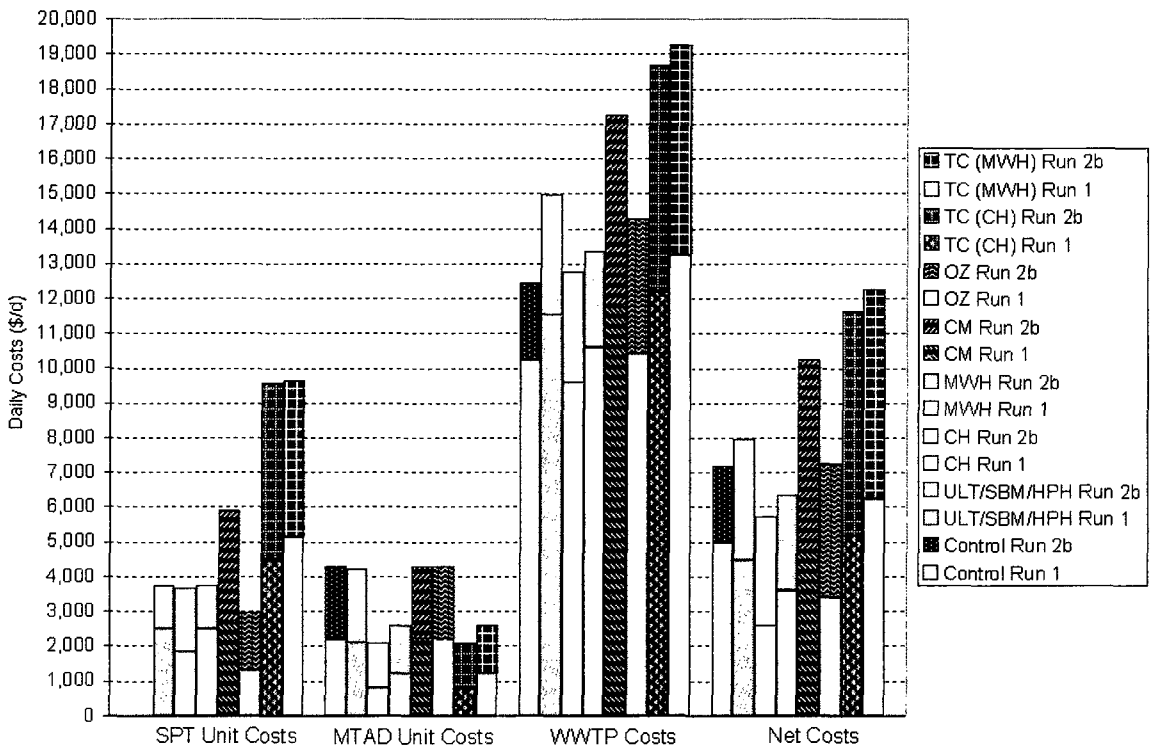


Figure 5.19 Lowest and highest net daily cost ranges for control and SPT scenarios with Run 1 $RT(H_1\text{-}D_1\text{-Low})_A$ stacked below Run 2b $RT(H_2\text{-}D_2\text{-High})_A$

Control and SPT scenarios have been compared using identical run parameters and different run parameters for both MAD and TAD. Low to high net costs ranges were established based on normal heat recoveries, a normal sludge hauling distance, and Low SPT energy demands compared to low heat recoveries, a doubled sludge distance, and High SPT energy demands. These low to high net costs ranges were established for both MAD and TAD.

Low to high net costs per influent flowrate ranges will now be used to make a MAD versus TAD comparison. The results are shown in Fig. 5.20. The relative rankings

are of course identical to those of the net daily costs shown in Figs. 5.18-19. What is now found is the net daily costs based on the comparison of low cost parameters to high cost parameters with MAD and TAD. In other words, the columns are stacked in sets for the following comparisons: $RM(H_1\text{-}D_1\text{-}Low)_A$ with $RT(H_1\text{-}D_1\text{-}Low)_A$ stacked below the $RM(H_2\text{-}D_2\text{-}High)_A$ with $RT(H_2\text{-}D_2\text{-}High)_A$.

Ranges of net daily operational costs per influent flow are thus established for control and SPT scenarios with MAD. They are \$0.0097-0.0121, 0.0089-0.014, 0.0049-0.0097, 0.0072-0.0111, 0.0094-0.0019, 0.0066-0.0126, 0.0106-0.0226, 0.0129-0.00239/m^3 RF_i for control, ULT/SBM/HPH, CH, MWH, CM, OZ, TC(CH), and TC(MWH), respectively.

The ranges for TAD are shown in Fig. 5.20 and are not listed here. With TAD the CH and MWH SPTs have net energy gains even with a High SPT energy demand. Based on a Low SPT energy demand (Table 5.3), ULT/SBM/HPH and OZ also have net energy gains with TAD. Again, these results heavily rely on energy use and heat recoveries from SPT effluent.

A cost occurrence regime was created for MAD and TAD scenarios. The cost occurrence regime was established from 0:1 (lowest:highest) to 1:0. That is to say, at a cost occurrence ratio of 0.25:0.75, the lowest costs and highest costs scenarios have yearly rates of recurrence of 25 and 75%, respectively. The percentage yearly rate of recurrence dictates the number of days in a year where low or high costs scenarios occur.

The cost occurrence regime evaluations are shown in Figs. 5.21 and 5.22. Not all SPTs are shown in these figures because they do not all traverse from practical to break-even or impractical situations. Only those SPTs that reach or lose practicality based on cost occurrence regimes are depicted. The relative rankings depicted between control MAD and TAD scenarios are in fact representative of those of all SPTs, including those that are not shown.

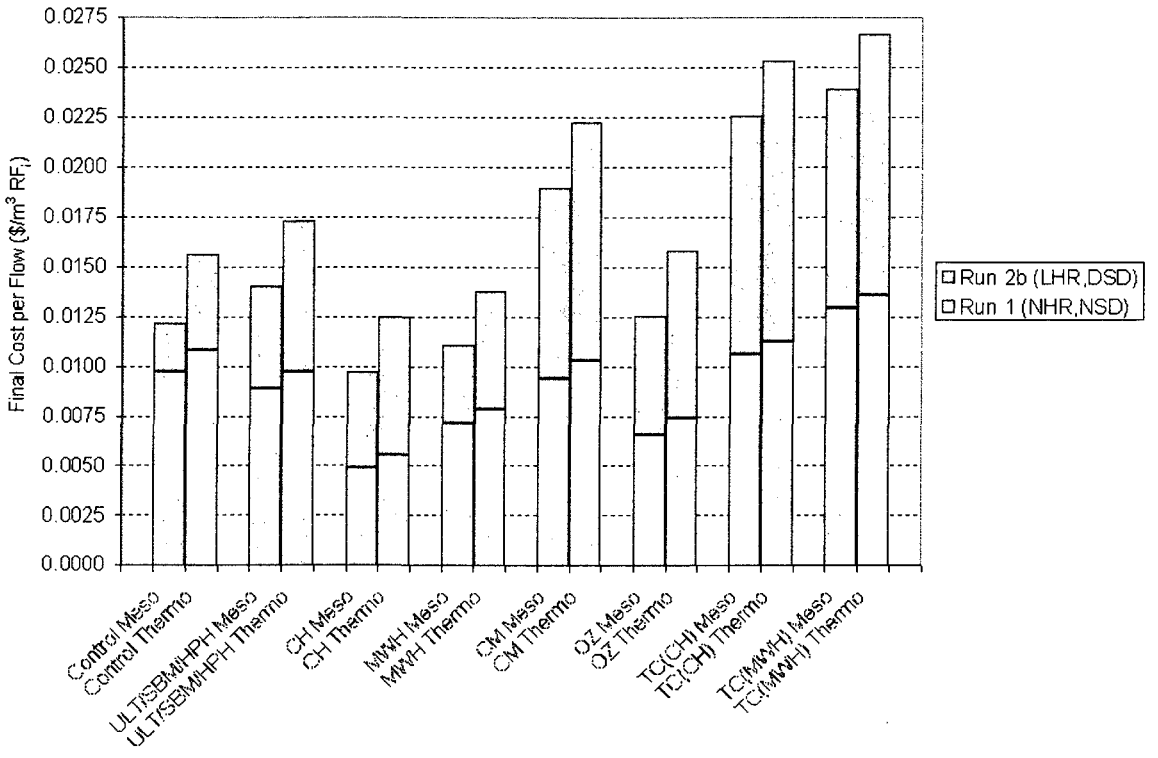


Figure 5.20 Net costs ranges per influent flowrate for Run 1 $RM(H_1\text{-}D_1\text{-}Low)_A$ with Run 1 $RT(H_1\text{-}D_1\text{-}Low)_A$ stacked below the Run 2b $RM(H_2\text{-}D_2\text{-}High)_A$ with Run 2b $RT(H_2\text{-}D_2\text{-}High)_A$

In Fig. 5.21, control and SPT scenario results (for Runs 1 and 4) are for the lowest yearly costs found for $RM(H_1\text{-}D_1\text{-}Low)_A$ or $RT(H_1\text{-}D_1\text{-}Low)_A$ to the highest yearly costs found for $RM(H_2\text{-}D_2\text{-}Low)_A$ or $RT(H_2\text{-}D_2\text{-}Low)_A$.

The TC(MWH) SPT has not been shown to be practical on a daily basis in any of the results seen thus far. It is interesting to note that with MAD and at a cost occurrence ratio of 0:1 for yearly results TC(MWH) becomes more cost effective (practical) than control TAD WWTPs. In the case of a cost occurrence ratio that favours low costs (1:0), ULT/SBM/HPH with TAD is shown to be just as practical as control scenarios with MAD. Both SPT TAD WWTPs with MWH or OZ were just as practical as control WWTPs using MAD. That is to say, if TAD were to provide additional qualitative (pathogen reduction, bulking and foaming reduction) and quantitative benefits (Class A stabilization for land applications), it would be preferred over the same cost MAD

scenario. However, numerous other factors would need to be minimal, such as, additional labour and treatment issues associated with SPT incorporation.

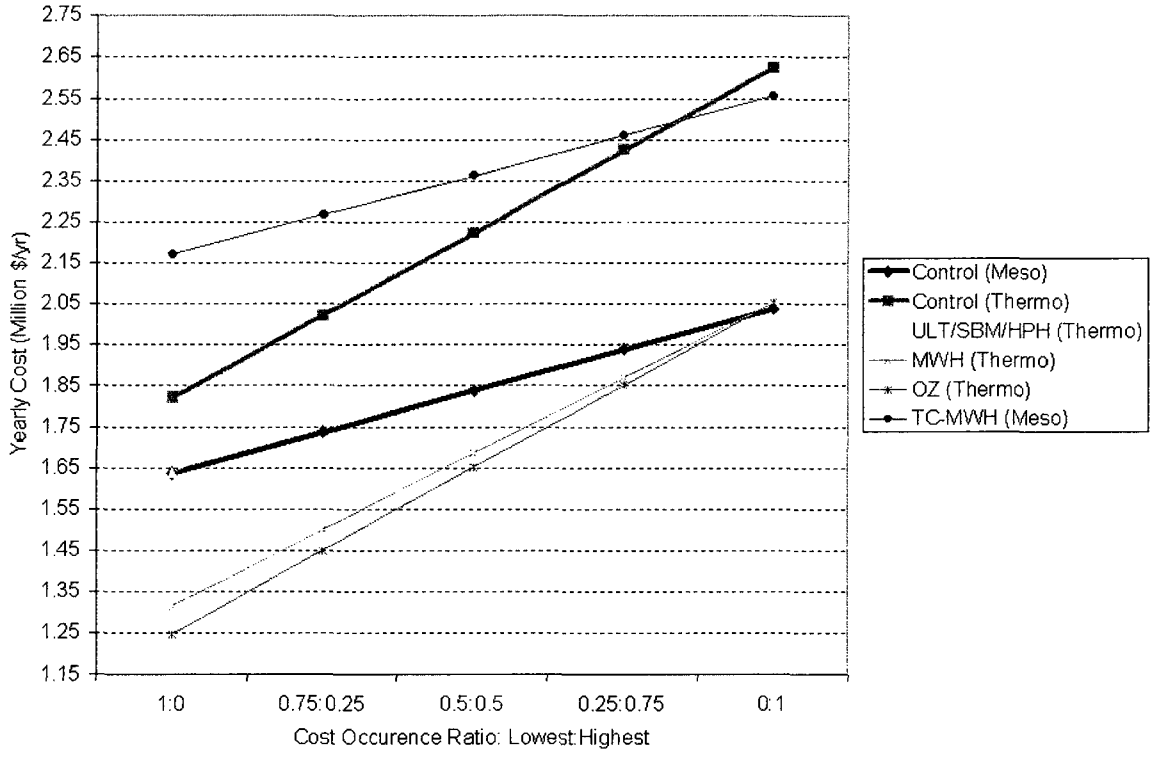


Figure 5.21 Yearly cost increases as a function of the cost occurrence ratio for the lowest yearly costs for $RM(H_1\text{-}D_1\text{-}Low)_A$ or $RT(H_1\text{-}D_1\text{-}Low)_A$ to the highest yearly costs for $RM(H_2\text{-}D_2\text{-}Low)_A$ or $RT(H_2\text{-}D_2\text{-}Low)_A$

In Fig. 5.22, control and SPT scenario results (for Runs 1b and 2b) are for the lowest yearly costs found for $RM(H_1\text{-}D_1\text{-}High)_A$ or $RT(H_1\text{-}D_1\text{-}High)_A$ to the highest yearly costs found for $RM(H_2\text{-}D_2\text{-}High)_A$ or $RT(H_2\text{-}D_2\text{-}High)_A$.

The ULT/SBM/HPH with MAD scenarios become practical in comparison to the control TAD scenario as the cost occurrence ratio moves past 0.75:0.25 (<0.75:>0.25). The MWH with TAD scenario was only practical or as practical as the control MAD scenario when the cost occurrence ratio was 1:0 and 0.75:0.25, respectively. Finally, an impractical scenario for CH with TAD was found when compared to the control MAD scenario at a cost occurrence ratio of 0:1. Thus, if high cost treatment parameters are

highly recurrent in the CH with TAD incorporation scenario the control MAD scenario would actually be preferred.

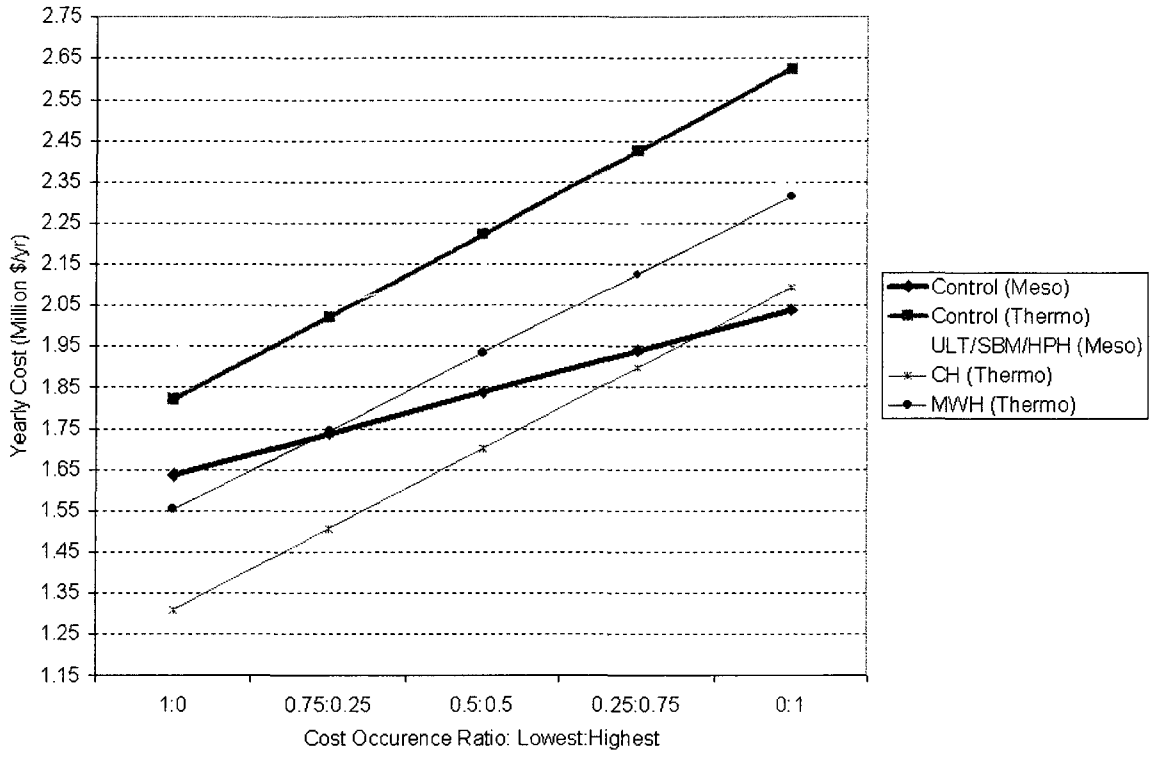


Figure 5.22 Yearly cost increases as a function of the cost occurrence ratio for the lowest yearly costs for $RM(H_1\text{-}D_1\text{-High})_A$ or $RT(H_1\text{-}D_1\text{-High})_A$ to the highest yearly costs for $RM(H_2\text{-}D_2\text{-High})_A$ or $RT(H_2\text{-}D_2\text{-High})_A$

5.2 OBSERVATIONS AND HIGHLIGHTS SUMMARY

A summary of results (e.g., costs, regimes, and practical scenarios) is given here. They are categorized as they were dissected in Section 5.0. In each category relevant figures and significant rankings along with the reasons they occur are listed. A final optimal conditions list can be found in Section 5.3 where a single preferred SPT is prescribed.

5.2.1 Low Strength RF (Runs 1-4)

Figure 5.4: Lowest daily costs found $[RM(H_1\text{-}D_1\text{-Low})_P]$.

Observations:

- CH and OZ have lowest SPT costs
- ULT/SBM/HPH, MWH, and CM have similar SPT costs
- MTAD costs always reduced by SPT incorporation
- TC(CH) and TC(MWH) have higher net costs than control runs

Reasoning: Heat recoveries, effluent SPT temperatures, and SPT energy requirements.

Figure 5.5: Net costs per peak flowrate for $RM(H_1\text{-}D_1\text{-}Low)_P$, $RT(H_1\text{-}D_1\text{-}Low)_P$, $RM(H_2\text{-}D_2\text{-}Low)_P$, and $RT(H_2\text{-}D_2\text{-}Low)_P$.

Observations:

- Control costs are higher than or similar to all SPTs except TC(MWH)
- Control costs range from \$0.0054-0.0074/m^3 RF_i

Overall Highlight:

- All SPTs but TC(MWH) show practical scenarios

5.2.2 Average Strength RF (Runs 1-4)

Figure 5.6: Net costs per average flowrate for $RM(H_1\text{-}D_1\text{-}Low)_A$, $RT(H_1\text{-}D_1\text{-}Low)_A$, $RM(H_2\text{-}D_2\text{-}Low)_A$, and $RT(H_2\text{-}D_2\text{-}Low)_A$.

Observations:

- Identical relative rankings to those in Fig. 5.5
- Control costs range from \$0.0097-0.0132/m^3 RF_i
- Lowest cost (CH, Run 1, \$0.0020/m^3 RF_i higher than low strength cost)
- Highest cost (TC(MWH), Run 4, + \$0.0073/m^3 RF_i from low strength)

Reasoning: Amplified costs for higher strength flow, costs based on solids loadings and heat recoveries. Since treatment parameters used were identical between SPTs, the overall relative rankings are identical to those in Fig. 5.5.

Overall Highlights:

- All SPTs but TC(CH) during Run 4 and TC(MWH) during Runs 1-4 show practical scenarios

5.2.3 High Strength RF (Runs 1-4)

Figure 5.7: Highest daily costs found [$RT(H_2\text{-}D_2\text{-}Low)_L$].

Observations:

- CH and OZ have the lowest costs
- MWH has similar to control costs whilst CM has slightly higher costs
- TC(CH) and TC(MWH) have the highest costs
- MTAD costs are lower for all SPTs
- ULT/SBM/HPH, CM, and OZ show the least reductions in MTAD costs

Reasoning: Low effluent SPT temperatures provide low heat recoveries.

Figure 5.8: Net costs per low flowrate for $RM(H_1\text{-}D_1\text{-}Low)_L$, $RT(H_1\text{-}D_1\text{-}Low)_L$, $RM(H_2\text{-}D_2\text{-}Low)_L$, and $RT(H_2\text{-}D_2\text{-}Low)_L$.

Observations:

- Amplified separations for relative rankings as compared to peak or average flowrates
- Lowest cost (CH, Run 1, + $\$0.0070/m^3$ RF_i from low strength costs)
- Highest cost (TC(MWH), Run 4, + $\$0.0239/m^3$ RF_i from low strength costs)
- Control costs range from $\$0.0198\text{-}0.0266/m^3$ RF_i

Reasoning: High strength RF increases solids loading and most energy demands are solids based

Figure 5.9: Lowest [$RM(H_1\text{-}D_1\text{-}Low)_P$] versus highest [$RT(H_2\text{-}D_2\text{-}Low)_L$] net daily costs per influent flowrates.

Observations:

- Lowest costs (MAD, Run 1) range from $\$0.0029\text{-}0.0067/m^3$ RF_i

- Highest costs (TAD, Run 4) range from \$0.0198-0.0366/m^3 RF_i

Overall Highlights:

- All SPTs but TC(CH) during Run 4 and TC(MWH) during Runs 1-4 show practical scenarios

5.2.4 Flow Regimes (Runs 1-4)

Figure 5.10: Net costs for $RM(H_1\text{-}D_1\text{-}Low)_P$, $RM(H_1\text{-}D_1\text{-}Low)_A$, and $RM(H_1\text{-}D_1\text{-}Low)_L$.

Observations:

Costs below are listed as lowest (CH) to highest (TC(MWH)) for all flows

- Peak: \$0.0029-0.0067/m^3 RF_i (increase for TAD is 13.8-6.9%)
- Average: \$0.0049-0.0129/m^3 RF_i (increase for TAD is 14.3-6.4%)
- Low: \$0.0099-0.0270/m^3 RF_i (increase for TAD is 13.1-4.4%)

Reasoning: Different percent increases occur with different flows as a result of solids loadings and influent MTAD flow variations.

Figure 5.11: Net costs for $RM(H_2\text{-}D_2\text{-}Low)_P$, $RM(H_2\text{-}D_2\text{-}Low)_A$, and $RM(H_2\text{-}D_2\text{-}Low)_L$.

Observations:

Costs below are listed as lowest (CH) to highest [TC(MWH)] for all flows

- Peak: \$0.0042-0.0080/m^3 RF_i (increase for TAD is 38.0-12.0%)
- Average: \$0.0073-0.0152/m^3 RF_i (increase for TAD is 38.4-18.4%)
- Low: \$0.0146-0.0314/m^3 RF_i (increase for TAD is 36.6-16.6%)

Reasoning: Different percent increases are seen with different flows as a result of solids loadings and influent MTAD flow variations. Percent increases are significantly higher as low heat recoveries have greater influence on the heat intensive TAD process.

Figure 5.12: Net yearly costs increases for various flow occurrence ratios from evaluations of control and SPT $RM(H_1\text{-}D_1\text{-}Low)_A$.

Observations:

- 5-15% difference in net yearly costs based on all peak, all average or all low regimes
- Maximum 5% difference in net yearly costs based on an all average flow regime as compared to all flow regime ratios evaluated.
- 2.3-3.5% increase in costs for MAD, Run 1 from ratios 0.5-3.5, respectively
- 1.8-3.3% increase in costs for TAD, Run 1 from ratios 0.5-3.5, respectively
- 1.7-3.0% increase in costs for MAD, Run 4 from ratios 0.5-3.5, respectively
- 1.6-2.5% increase in costs for MAD, Run 4 from ratios 0.5-3.5, respectively

Reasoning: Peak flows (low strength due to infiltration dilution) represent reduced solids loadings and result in the lowest costs as overall results are primarily based on energy demands for influent solids. As average flows make up a significant portion of all regimes evaluated, average flows on a yearly basis would necessarily be fairly representative of flow regime costs.

Overall Highlights:

- Overall costs do not increase for TAD by fixed factors when flow regimes are altered
- With NHR,NSD, low flow shows lowest cost increase when switching to TAD
- With LHR,DSD, low flow and peak flow shows lowest cost increase for CH and TC(MWH), respectively when switching to TAD
- Results based on average flow scenarios are sufficiently representative of results from all regime flow evaluations

5.2.5 Increased SPT Energy Demands (Runs 1-4 and 1a-2b)

Figure 5.13: Net costs for $RM(H_1\text{-}D_1\text{-}Low)_A$ and $RM(H_2\text{-}D_2\text{-}Low)_A$ as well as $RM(H_1\text{-}D_1\text{-}Med)_A$, $RM(H_1\text{-}D_1\text{-}High)_A$, $RM(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_2\text{-}D_2\text{-}High)_A$.

Observations:

- Runs 1-4: All SPTs but TC(CH) and TC(MWH) are practical

- Runs 1a and 2a: CH, MWH, and OZ are practical
- Runs 1b and 2b: CH and MWH are practical, OZ is close to practical

Reasoning: The relative rankings are maintained for TAD conditions. See reasoning for Fig. 5.14 below.

Figure 5.14: Net costs for $RT(H_1\text{-}D_1\text{-}Low)_A$ and $RT(H_2\text{-}D_2\text{-}Low)_A$ as well as $RT(H_1\text{-}D_1\text{-}Med)_A$, $RT(H_1\text{-}D_1\text{-}High)_A$, $RT(H_2\text{-}D_2\text{-}Med)_A$, and $RT(H_2\text{-}D_2\text{-}High)_A$.

Observations:

- Runs 1-4: All SPTs but TC(MWH) are practical
- Runs 1a and 2a: CH, MWH, and OZ are practical, ULT/SBM/HPH is close to practical
- Runs 1b and 2b: CH and MWH are practical, OZ is close to practical

Reasoning: Though OZ does not elevate SPT effluent temperature to the same extent as ULT/SBM/HPH, its energy demands translated into costs are lower.

Figure 5.15: Net costs per average influent flowrate for the comparisons of $RM(H_1\text{-}D_1\text{-}Low)_A$ with $RM(H_2\text{-}D_2\text{-}Low)_A$, $RM(H_1\text{-}D_1\text{-}Med)_A$ with $RM(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_1\text{-}D_1\text{-}High)_A$ with $RM(H_2\text{-}D_2\text{-}High)_A$.

Observations:

- Costs below are listed as lowest (CH) to highest (TC(MWH))
- Runs 1-4: \$0.0049-0.0152/m^3 RF_i (increase for TAD is 13.2-18.1%)
- Runs 1a-2a: \$0.0065-0.0192/m^3 RF_i (increase for TAD is 9.9-14.6%)
- Runs 1b-2b: \$0.00715-0.0239/m^3 RF_i (increase for TAD is 9.1-11.7%)
- OZ approaches practicality in scenarios regardless of SPT energy demand increases
- CH and MWH are always practical

Reasoning: Based on potential heat recoveries for thermal SPTs CH and MWH are practical under identical treatment schemes as the control scenarios.

Figure 5.16: Net costs per average influent flowrate for the comparisons of $RM(H_1\text{-}D_1\text{-}Low)_A$ with $RT(H_2\text{-}D_2\text{-}Low)_A$, $RM(H_1\text{-}D_1\text{-}Med)_A$ with $RT(H_2\text{-}D_2\text{-}Med)_A$, and $RM(H_1\text{-}D_1\text{-}High)_A$ with $RT(H_2\text{-}D_2\text{-}High)_A$.

Observations:

- MAD (Runs 1-1b) as compared to TAD (Runs 4-2b)
- Low SPT energy demands: all costs for MAD lower than with TAD
- Med SPT energy demands: all costs for MAD lower than with TAD
- High SPT energy demands: ULT/SBM/HPH, CH, MWH, and OZ lower than with TAD

Reasoning: Thermophilic AD energy demand is more significant than SPT energy demand increases.

Figure 5.17: Net costs per average influent flowrate for the comparisons of $RM(H_2\text{-}D_2\text{-}Low)_A$ with $RT(H_1\text{-}D_1\text{-}Low)_A$, $RM(H_2\text{-}D_2\text{-}Med)_A$ with $RT(H_1\text{-}D_1\text{-}Med)_A$, and $RM(H_2\text{-}D_2\text{-}High)_A$ with $RT(H_1\text{-}D_1\text{-}High)_A$.

Observations:

- TAD (Runs 1-1b) as compared to MAD (Runs 4-2b)
- Low SPT energy demands: all costs for TAD are lower than with MAD
- Med SPT energy demands: ULT/SBM/HPH, CH, and MWH costs for TAD are lower than with MAD
- High SPT energy demands: MWH MAD costs are lower than with TAD

Reasoning: Conventional heating with Low or Med SPT energy demands shows better results with TAD than with MAD. Microwave heating with High SPT energy demands shows better results with TAD than with MAD. The increase to High SPT energy demand for CH demands an energy intensive sludge temperature elevation that surpasses the High SPT energy demand for MWH.

Figure 5.18: Lowest and highest net daily cost ranges for control and SPT scenarios with $RM(H_1\text{-}D_1\text{-Low})_A$ stacked below $RM(H_2\text{-}D_2\text{-High})_A$.

Observations:

- Run 1: ULT/SBM/HPH, CH, MWH, OZ have lower than control costs (OZ is close)
- Run 2b: Only CH and MWH have lower than control costs
- TC(CH) and TC(MWH) have the highest costs for both runs
- MTAD costs are lower for all SPTs
- ULT/SBM/HPH, CM, and OZ show the least reductions in MTAD costs

Reasoning: Low effluent SPT temperatures provide low heat recoveries.

Figure 5.19: Lowest and highest net daily cost ranges for control and SPT scenarios with $RT(H_1\text{-}D_1\text{-Low})_A$ stacked below $RT(H_2\text{-}D_2\text{-High})_A$.

Observations:

- Run 1: ULT/SBM/HPH, CH, MWH, OZ have lower than control costs (OZ is close)
- Run 2b: Only CH and MWH have lower than control costs
- TC(CH) and TC(MWH) have the highest costs for both runs
- MTAD costs are lower for all SPTs
- ULT/SBM/HPH, CM, and OZ show the least reductions in MTAD costs

Reasoning: Same relative rankings as for MAD because the sole change is the energy increase for maintaining the higher TAD temperature.

Figure 5.20: Net costs ranges per influent flowrate for $RM(H_1\text{-}D_1\text{-Low})_A$ with $RT(H_1\text{-}D_1\text{-Low})_A$ stacked below the $RM(H_2\text{-}D_2\text{-High})_A$ with $RT(H_2\text{-}D_2\text{-High})_A$.

Observations:

- Lowest costs (MAD, Run 1) range from 0.0049-0.0129 $\$/m^3$ RF_i
- Highest costs (MAD, Run 2b) range from 0.0097-0.0239 $\$/m^3$ RF_i

- Lowest costs (TAD, Run 1) range from 0.0055-0.0136 $/m^3$ RF_i
- Highest costs (TAD, Run 2b) range from 0.0125-0.0267 $/m^3$ RF_i

Figure 5.21: Yearly cost increases as a function of the cost occurrence ratio for the lowest yearly costs for $RM(H_1\text{-}D_1\text{-}Low)_A$ or $RT(H_1\text{-}D_1\text{-}Low)_A$ to the highest yearly costs for $RM(H_2\text{-}D_2\text{-}Low)_A$ or $RT(H_2\text{-}D_2\text{-}Low)_A$.

Observations:

- Runs 1-4 used as lowest:highest in cost occurrence ratio
- Ratio (1:0): ULT/SBM/HPH with TAD is as practical as control (MAD)
- Ratio (0:1): TC(MWH) with MAD is practical compared to control (TAD). MWH and OZ with TAD are practical as compared to control (MAD)

Figure 5.22: Yearly cost increases as a function of the cost occurrence ratio for the lowest yearly costs for $RM(H_1\text{-}D_1\text{-}High)_A$ or $RT(H_1\text{-}D_1\text{-}High)_A$ to the highest yearly costs for $RM(H_2\text{-}D_2\text{-}High)_A$ or $RT(H_2\text{-}D_2\text{-}High)_A$.

Observations:

- Runs 1b-2b used as lowest:highest in cost occurrence ratio
- Ratio (0.75:0.25): MWH with TAD is impractical as compared to control MAD. ULT/SBM/HPH with MAD is practical as compared to control (TAD)
- Ratio (0:1): CH with TAD is impractical as compared to control (MAD)

Reasoning: Impractical thermal SPT scenarios were found when comparing energy intensive (Runs 1b, 2b with TAD) to low cost parameters with MAD. If preferred conditions could not be maintained with thermal SPT incorporation in a TAD WWTP, a control scenario with MAD would be preferred.

Overall Highlights:

- When MAD and TAD are more thoroughly evaluated at different SPT energy demand levels, impractical scenarios were found for all SPTs (except CH and MWH). Thermal

SPTs (CH and MWH) will not result in impractical scenarios (due to energy recoveries) compared to control scenarios using identical run conditions. PretrAD could be adapted to lower energy recoveries with SPT incorporation compared to a control scenario if the user has made such an observation.

5.3 IMPACTS OF WWTP OUTPUTS AND VARIABLES

The results of various treatment parameters have been established. Final remarks on observations, relative rankings, and overall highlights for each series of significant figures were given. It was mentioned that solids loadings and heat recoveries were the most important cost affecting variables evaluated. The following tables and discussion outline only the PretrAD output values that subsequently affect unit costs and how they were altered based on the various treatment parameters (Section 5.0) used in Section 5.1. This evaluation demonstrates the solids loadings changes that resulted in the net costs differences for the control and SPT RM(H_1-D_1-Low). The subscript defining flow selection is not shown because all 3 flow conditions were used. The SPT scenario is that for CH incorporation.

The influent and effluent flows, TSS concentrations, and solids loadings under low, average, and high strength RFs are shown in Table 5.5. Beginning with the first two rows, higher influent flows to the plant result in higher BT influents and effluents. Total suspended solids concentrations are also affected directly by lower flows (decreased dilution). As the solids loading values are a function of TSS and Q, no explanation for the change based on flows is required. Though incoming flow conditions vary, certain parameters must be maintained to ensure proper treatment. The volume of the BT reactor (V_{BT}) was altered to achieve the preferred F:M ratio. This was done under the assumption that existing reactor capacity was available as the WWTP would likely be capable of adjusting online and offline reactors to compensate for low to peak RF flows. It was used in conjunction with the underflow TSS concentration at the SC unit to also monitor the SVI. As given in Chapter 4 and in Appendix A, both the F:M and the SVI are ideally maintained in the ranges of 0.2-0.6 g BOD_5/d·g ML_{VSS} and 50-150 mL/g, respectively.

The SVI, which relies on the underflow TSS concentration, was allowed to vary in order to obtain similar F:M ratios for all RF strengths. As such, the underflow TSS concentration was altered. The low, average, and high strength flow values for TSS_u were 7, 8, and 9 kg/m^3, respectively. Costs are not considered at this point and are not taken into consideration until the TH unit.

Table 5.5 Important PretrAD outputs for the BT unit

		Low Strength (Peak Flow)	**Average Strength (Average Flow)**	**High Strength (Low Flow)**
Q	BT_i	746,502	456,252	263,275
(m^3/d)	BT_e	1,095,777	679,792	343,959
TSS	Influent	0.05	0.08	0.16
(kg/m^3)	Effluent	2.27	2.69	2.94
M_{TSS}	Influent	51,019	55,389	53,382
(kg/d)	Effluent	2,485,717	1,831,424	1,010,275
F:M (g BOD_5/d·g MLVSS)		0.48	0.51	0.48
Volume, V_{BT} (m^3)		90,000	80,000	70,000

As mentioned above the important variables at the SC unit are the SVI and underflow TSS concentration. Considering influent RF strengths, flows and solids loadings results for peak to low flows are to be expected for influent, recycle, and effluent flows and TSS concentrations at the SC unit (Table 5.6).

The most significant flow and solids loadings output by PretrAD have been shown above for the BT and SC units. For the costs analysis, units following SPT are of interest. The MTAD unit outputs are shown in Table 5.7. The higher recycle and effluent SC flows that are output during low strength RF occurrences to maintain treatment result in the lowest MTAD influent flows. This flow is the sum of SPT (treated and untreated flows) and the underflow from the PC unit. These are not shown as the trend is the same (low strength feeds have lower flows following the BT unit). Evidently, more of the daily load is collected and maintained in the BT+SC units. The high effluent TSS concentration following the TH unit is passed to the SPT unit. Effluent SPT flow however, is relatively low compared to the PC unit underflow and the TSS concentration

is diluted upon entering the digester. As the SPT reductions (percentage based) apply wholly to a stream, the SPT decreases in both M_{TSS} values is lower for peak flows.

Table 5.6 Important PretrAD outputs for the SC unit

		Low Strength (Peak Flow)	**Average Strength (Average Flow)**	**High Strength (Low Flow)**
Q (m^3/d)	SC_i	1,095,777	679,792	343,959
	SC_r	349,269	223,540	107,684
	SC_e	743,083	452,387	232,465
TSS (kg/m^3)	Influent	2.27	2.69	2.94
	Recycle	7.00	8.00	9.00
	Effluent	0.02	0.03	0.03
M_{TSS} (kg/d)	Influent	2,485,717	1,831,424	1,010,275
	Recycle	2,444,885	1,788,319	969,154
	Effluent	16,856	12,188	6,828
SVI (mL/g)		143	125	111
Underflow [TSS] (kg/m^3)		7.00	8.00	9.00

Chapter 4 describes all PretrAD output equations and cost calculations. The most important costs as shown in PretrAD by the breakdown of MTAD demands are heating need (E_{HN2}) and heat recovered (E_{HR2}). Both values are a result of direct multiplication by Q_{MTADi} and as such, MTAD unit costs are lowest for peak flow scenarios. Those control costs were found to be \$1,372/d (SPT \$363/d), \$1,391/d (SPT \$90/d), and \$1,393/d (SPT \$-50/d) for peak, average, and low flows, respectively.

Table 5.7 Important PretrAD outputs for the MTAD unit

		Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Q (m^3/d)	$MTAD_i$	3,900	4,274	4,308
	$MTAD_e$	3,900	4,274	4,308
TSS (kg/m^3)	Influent	18.66	19.30	19.74
	Effluent	9.33	9.65	9.87
Control M_{TSS} (kg/d)	Influent	72,759	82,501	85,021
	Effluent	36,380	42,251	42,510
SPT M_{TSSi} (% Decrease)		5.60	6.37	6.86
SPT M_{TSSe} (% Decrease)		15.04	15.74	16.17
Heat Transfer Coeff. (kJ/kg·°C)		4.2 (NHR) 5.0 (LHR)	4.2 (NHR) 5.0 (LHR)	4.2 (NHR) 5.0 (LHR)
Heat Recovery Appl. Eff. (%)		80% (NHR) 60% (LHR)	80% (NHR) 60% (LHR)	80% (NHR) 60% (LHR)

Decreases of 5.6-6.86% and 15.04-16.17% are observed at the influent and the effluent (underflow) MTAD unit streams, respectively. PretrAD outputs for the DE unit are shown in Table 5.8. Results show the same flow and TSS concentration trends that are observed in Table 5.7. It is interesting to note the lowered effect on DE solids decrease for high strength RF scenarios. Cost variables (i.e., Polymer Dosage, Price of Polymer, Power Supplied) are listed below the SPT scenario percent decreases to demonstrate why the DE unit costs were not substantial. Control costs were found to be \$39/d (SPT \$33/d), \$44/d (SPT \$35/d), and \$46/d (SPT \$38/d), for peak, average, and low flows, respectively. The decrease in DE unit costs due to SPT incorporation ranges from 15.4-20.5%. The DE unit was on average responsible for 0.43-0.46% of WWTP costs for all flows, respectively.

Table 5.8 Important PretrAD outputs for the DE unit

		Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Q (m^3/d)	DE_i	3,900	4,274	4,308
	DE_r	3,736	4,088	4,116
	DE_e	164	186	191
TSS (kg/m^3)	Influent	9.33	9.65	9.87
	Recycle	0.97	1.01	1.03
	Effluent	200	200	200
Control M_{TSS} (kg/d)	Influent	36,380	42,251	42,510
	Recycle	3,638	4,125	4,215
	Effluent	32,742	37,126	38,259
SPT M_{TSSr} (% Decrease)		15.04	15.73	15.44
SPT M_{TSSe} (% Decrease)		15.04	15.74	16.17
Polymer Dosage (kg/kg TSS)		0.005	0.005	0.005
Price of Polymer ($/kg)		0.070	0.070	0.070
Power Supplied (kJ/kg TSS)		68	68	68

Two tables were constructed for the SD unit output. The first, Table 5.9, depicts influent flow as well as solids loading for control and SPT scenarios. The sludge transport distance was among the modified parameters and is shown among two more significant but unchanged variables. The dried solids content, which was deemed to be an important constant, was not changed. The tipping fee (a highly variable parameter) was set at a low value of $30/ton. This parameter could have been modified for a more significant SD influence on unit and WWTP costs.

Since tipping fee has more influence on total SD unit costs than does the distance travelled for disposal, Table 5.10 was created to provide an impact breakdown for the two above mentioned variables (dried solids content and tipping fee). If the tipping fee were doubled, the control and SPT WWTP costs would be $8,138/d (SPT $7,059/d), $9,099/d (SPT $7,819/d), and $9,348/d (SPT $7,992/d), for peak, average, and low flows, respectively. When disposal distance and tipping fees are varied independently under average flow characteristics, the impact of disposal travel distance remains less than 10% of the landfilling cost. The percent total decrease (as shown by the final row in Table 5.10) improves by only 1.26% for peak to low flow conditions.

Table 5.9 Important PretrAD outputs for the SD unit

		Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Q (m^3/d)	SD_i	164	186	191
Control	(kg/d)	32,742	37,126	38,259
M_{TSSi}	(ton/d)	33	37	38
SPT M_{TSSi} (% Decrease)		15.04	15.74	16.17
Disposal Distance (km/Load)		160 (NSD) 320 (DSD)	160 (NSD) 320 (DSD)	160 (NSD) 320 (DSD)
Dried Solids Content (%)		60	60	60
Tipping Fee ($/ton)		30	30	30

Table 5.10 Cost breakdown for the SD unit

		Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Control ($/d)	Drying	5,112	5,796	5,973
	Labour	960	960	960
	Landfilling	1,084	1,229	1,267
	Total ($/d)	7,156	7,985	8,200
SPT ($/d)	Drying	4,343	4,884	5,007
	Labour	960	960	960
	Landfilling	921	1,035	1,062
	Total (% Decr.)	13.02	13.85	14.28

Energy gains translated to costs were found to be $4,554/d (SPT $5,907/d), $4,941/d (SPT $6,593/d), and $4,901/d (SPT $6,674/d), for peak, average, and low flows, respectively. The SPT biogas production percentage increase relates directly to the financial gain. Biogas production was permitted to rely solely on influent sCOD and since PretrAD regards this value as a function of the TSS following the TH unit, lower gains are made when peak flows are experienced.

Table 5.11 Important PretrAD outputs for the EC unit

		Low Strength (Peak Flow)	Average Strength (Average Flow)	High Strength (Low Flow)
Control Q_{ECi} (m^3/d)	Biogas	24,658	26,752	26,531
	CH_4	16,027	17,389	17,245
SPT Q_{ECi} (% Incr.)		29.71	33.42	36.20
CH_4 Heating Value (kJ/m^3)		25,575	25,575	25,575

5.4 OPTIMAL CONDITIONS

The optimal conditions for which practical scenarios were found for all SPTs are listed in Tables 5.12-14. It is important to note that these are highly dependent on the numerous treatment parameters that were unchanged as well as those that were. Endless permutations could be performed to determine the infinite combinations of practical and impractical SPT incorporation results. Raw feed strengths, treatment parameters, and obtainable treatment levels vary widely among WWTPs, however, and the simple establishment of practical and impractical situations warrants site specific evaluation of SPT incorporation. Daily costs differences between control and SPT scenarios for some SPTs approached break-even (costs slightly higher than control cost) situations. The cost differences were of course magnified when put on a yearly basis and the incorporation of these SPTs (CM and OZ) was subsequently deemed impractical.

Practicality and impracticality as compared to control costs with identical treatment parameters is shown in Table 5.12. The SPTs found most often in the practical column suggests that they are the preferable processes.

Practicality and impracticality as compared to specific control costs with different treatment parameters are shown in Tables 5.13-14. The results provided in these tables were given graphically in Figs. 5.21-22. All unmentioned SPTs are either always impractical or always practical. Tables 5.13-14 should be read as in the following example: ULT/SBM/HPH scenarios with TAD were made practical as compared to

control scenarios with MAD when a cost occurrence ratio favouring 100% lowest costs (treatment parameters that provided the lowest costs) is observed. That is to say, incorporating ULT/SBM/HPH into a WWTP using TAD would be deemed feasible and more cost effective than simply maintaining a WWTP with MAD.

Table 5.12 Practical and impractical results for all SPTs with MAD and TAD

	Practical	**Impractical**
Run 1 and 4	ULT/SBM/HPH, CH, MWH, CM, OZ	TC(CH), TC(MWH)
Run 1a and 2a	CH, MWH, OZ	ULT/SBM/HPH, CM, TC(CH), TC(MWH)
Run 1b and 2b	CH, MWH	ULT/SBM/HPH, CM, OZ, TC(CH), TC(MWH)

The interesting results are the TC(MWH) made practical (Table 5.13) and the MWH and CH made impractical (Table 5.14).

Table 5.13 Practical and impractical results for specific SPTs with Runs 1 and 4

	Practical	**Impractical**
Cost occurrence ratio (1:0)	ULT/SBM/HPH with TAD as compared to control MAD	
Cost occurrence ratio (0:1)	TC(MWH) with MAD as compared to control TAD MWH and OZ with TAD as compared to control MAD	

Table 5.14 Practical and impractical results for specific SPTs with Runs 1b and 2b

	Practical	**Impractical**
Cost occurrence ratio (0.75:0.25)	ULT/SBM/HPH with MAD as compared to control TAD	MWH with TAD as compared to control MAD
Cost occurrence ratio (0:1)		CH with TAD as compared to control MAD

CHAPTER 6

Overview, Conclusions, and Recommendations

6.0 SUMMARY

Mechanical, chemical, thermal, biological, and thermochemical SPT technologies have been extensively studied at the laboratory scale and have been incorporated into a handful of documented full-scale WWTPs in recent years. Their potential to improve AD by influencing solids removals, biogas productions, and retention times alongside numerous other fairly unquantifiable parameters has been established in literature. The question remained whether the significant SPT energy demand (when translated to costs) would exceed the financial and possible environmental/political benefits (e.g., attenuation criteria).

A comprehensive evaluation of available and sufficiently comparable data for all SPTs was performed to compile their energy demand and performance improvements. An adaptable multi-variable spreadsheet model of a WWTP (referred to as PretrAD) was created where incorporation of any SPT and thus, their feasibilities, could be ascertained. Sludge pretreatment affects not only AD but also other solids treatment and disposal operations. Once comparable SPT data were linked to potential subsequent treatment improvements at the MTAD, DE, SD, and EC units, control (WWTP without SPT) and SPT (WWTP with SPT incorporation) costs could be compared.

PretrAD's output (based on well established mass balances and energy equations) was compared with that of Plan-It STOAT under similar treatment parameters and conditions. No major differences could be found in daily influent and effluent solids to the unit processes of concern. It was shown that some discrepancies (<10%) take place where Plan-It's complex BT parameters and its iterative capacity displace more or fewer

solids within the WWTP by not neglecting certain recycle streams. However the discrepancies are relatively minor.

Confidence in PretrAD was also established by the global MTSS balance which had almost identical daily solids loading rates (±1-9%). Though it is evident that the Plan-It STOAT software considers additional variances in solids within the WWTP, a cost and energy evaluation with and without SPT is not influenced by these variances. Since PretrAD's primary purpose is to serve as an SPT incorporation tool and uses solids in most cost evaluations, sufficient similarities were found to validate the use of this simpler WWTP management model.

Control and SPT scenarios were initially run with varied RF strengths (peak, average, and low flows), heat recovery alterations (normal and low), and sludge disposal distance changes (normal and double) for both MAD and TAD. In these initial runs SPT energy demand were set at the lower values of the ranges reported for each SPT technology. This portion of the evaluation resulted in the observation that heat recoveries and solids loadings were responsible for the most important cost fluctuations at each treatment step. This happens because costs are directly calculated from energy demands based on current electricity prices and these demands rely on the above-mentioned parameters. All SPTs were deemed practical [except for TC(CH) and TC(MWH)] in these scenarios. Costs for scenarios using MAD were in all cases lower than those for scenarios using TAD with identical treatment parameters.

Cost outputs are on a daily and/or batch treatment basis. To establish yearly costs in terms of the three common RF flows (low, average, and peak), typical ratios of these flows were created for annual flow regimes. It was shown that an all average regime accurately reflected costs within 5% for all ratios. As such, only average flows were considered for the next portion of the PretrAD evaluation.

The third portion of runs consisted of reasonable (according to literature treatment ranges) SPT energy demand increases of 25-50%. The goal was to now establish impractical situations for all SPTs. The energy demand increase was used to observe the

change in SPT practicality by maintaining that, at times, important SPT energy demands may be required to maintain treatment improvements in downstream processes. Some formerly practical SPTs were found to be impractical with a 25% increase in SPT energy consumption and most were deemed impractical with a 50% increase in energy consumption.

Thermal SPTs, which instil heat energy that would otherwise need to be supplied at the anaerobic digester, promote heat recoveries that always outweighed their incorporation costs. They were deemed practical in all cases that involved comparison to control scenarios with identical parameters. When comparing high cost SPT scenarios (parameters evaluated that resulted in higher costs) with CH or MWH to low cost control scenarios (parameters evaluated that resulted in lower costs), impractical situations were found for both SPTs. This observation along with the low cost MAD versus high cost TAD and low cost TAD versus high cost MAD findings showed that in those instances, where minor variations in treatment parameters resulted in significant cost increases, SPT incorporation for any of the technologies was not practical.

The CH and MWH SPTs could be incorporated successfully under the conditions evaluated herein. It is quite possible that other SPT specific costs would be encountered and would render their use impractical. It is also possible that other important costs were not evaluated for other treatment units and that these would again outweigh the additional SPT energy demands. Site-specific evaluations are extremely vital and with the fact that practical and impractical situations were found for a number of conditions, the potential for thermal SPT incorporation exists. The OZ SPT was another low cost process that under many scenarios was found to be practical. Once again, it is possible that full-scale ozone production and application costs outweigh the potential benefits. Regardless, prescribing a preferred SPT should depend on all available scenarios and CH incorporation ranks first. Not surprisingly, CH SPT under the trade name CAMBI was the most prevalent incorporation process at WWTPs across the globe.

6.1 LIST OF CONCLUSIONS

A bulleted summary of findings and results is presented here under 8 points. The first lists average ranges representative of all SPT summary tables. The second lists each SPT and its 2 most important qualitative benefits and drawbacks. The third lists those SPTs that were included in PretrAD and have been evaluated in full-scale WWTPs. The fourth and fifth points list practical SPT scenarios found for all runs. If an SPT is not listed it has been deemed impractical. In this list, practicality is assigned for the SPT scenario as compared to the control scenario using identical parameters. The sixth and seventh points show impractical SPT scenarios for all runs under different cost occurrence ratios. Finally, the eighth point lists several of the more influential PretrAD parameters.

1. Average (for all SPTs) WW compositions, SPT solubilisations, and AD treatment ranges following SPT use:

- TCOD: 16-43, TS: 13-39, VS: 10-33, TSS: 10-31, and VSS: 7-25 (g/L)
- pCOD: 13-42, TSS: 13-43, and VSS: 12-39 (%)
- TCOD: 24-55, TS: 22-46, VS: 23-54 (% reduction) and biogas production improvement: 9-43%

2. All SPTs and the 2 most important qualitative benefits and drawbacks:

- SBM benefits: unit efficiency and scalability

  drawbacks: energy intensive and unit erosion
- HPH benefits: unit efficiency and energy use

  drawbacks: unit clogging and erosion
- ULT benefits: WAS solubilisation and heat generation for recovery

  drawbacks: energy intensive and unit erosion
- CH benefits: dewaterability improvement and pathogen reduction

  drawbacks: energy intensive and odour generation

- MWH benefits: dewaterability improvement and pathogen reduction

  drawbacks: scalability and complexity

- CM benefits: potential dewaterability improvement and pathogen reduction

  drawbacks: chemical costs and odour generation

- OZ benefits: unit efficiency and pathogen reduction

  drawbacks: heavy metals solubilisation and mineralization

- TC benefits: dewaterability improvement and pathogen reduction

  drawbacks: energy intensive and unit corrosion

3. Full-scale SPTs (location, IE or m^3/d) and if given, trade names and vendors:

   - SBM (Germany, 17,000 IE), HPH (Germany, 35,000 IE), ULT (Singapore, 310,000 m^3/d), OZ (Japan, 1,000,000 IE)
   - ULT, unknown, EIMCO® Water Technologies
   - CH, CAMBI, RDP Technologies, Inc
   - HPH + CM, MicroSludge™, Paradigm Environmental Technologies, Inc

4. Practical MTAD scenarios with Low, Average, and Peak RF flows (Runs 1-4):

   - $RM,T(H_{1,2}\text{-}D_{1,2}\text{-}100)_{L,A,P}$: ULT/SBM/HPH, CH, MWH, CM, OZ

5. Practical MTAD scenarios with SPT energy input increases (Runs 1a to 2b):

   - $RM,T(H_{1,2}\text{-}D_{1,2}\text{-}125)_A$: CH, MWH, OZ
   - $RM,T(H_{1,2}\text{-}D_{1,2}\text{-}150)_A$: CH, MWH

6. Impractical MTAD scenarios with cost occurrence variations (Runs 1-4):

   - Cost occurrence ratio (0:1): MWH and OZ with $RT(H_2\text{-}D_2\text{-}100)_A$ compared to control $RM(H_2\text{-}D_2\text{-}100)_A$

7. Impractical MTAD scenarios with cost occurrence variations (Runs 1a to 2b):

- Cost occurrence ratio (0.75:0.25): MWH with 75% annual occurrence of $RT(H_1\text{-}D_1\text{-}150)_A$ and 25% $RT(H_2\text{-}D_2\text{-}150)_A$ compared to 75% annual occurrence of control $RM(H_1\text{-}D_1\text{-}150)_A$ and 25% $RM(H_2\text{-}D_2\text{-}150)_A$
- Cost occurrence ratio (0:1): CH with $RT(H_2\text{-}D_2\text{-}100)_A$ compared to control $RM(H_2\text{-}D_2\text{-}100)_A$

8. Impact of several influential PretrAD parameters:
   - Cost evaluations are most affected by influent solids concentrations, SPT effluent temperatures, and AD treatment temperatures
   - Average flows based on the North American default value ranges gathered from the literature sufficiently represent all flow regime evaluations
   - Cost gains from heat recoveries at the SPT and MTAD units are crucial for practical SPT scenarios to be obtained
   - Tipping fee and dried solids content variables at the SD unit are more important than the hauling distance variable
   - Thermophilic AD energy demands are more significant than SPT energy demand increases and thus, thermal SPTs are less costly with TAD than MAD

6.2 RECOMMENDATIONS FOR FUTURE WORK

Many interesting unit evaluations can be easily assessed with PretrAD. Additions to the PretrAD inputs and outputs could involve:

- Solids loading rates
- Nitrogen and phosphorous removals
- Alkalinity observations
- Oxygen requirements
- Unit full-scale design equations

- SPT full-scale design equations
- Green house gas emissions analysis and output

Similarly, additions could be made to the 'Run Condition" and 'Default Values' worksheets that include:

- Y_{net} subroutine determination based on UDVs
- Additional default values equations for UDVs and model outputs
- Additional default values for model outputs (shown and not shown)
- Additional UDV checks and balances
- SPT batch cost concept could be applied to other treatment units

One change was found that could be made to the way PretrAD handles the UDV for MTAD sCOD reduction and reduction improvement:

- Currently, the reduction and improvement directs that fraction of sCOD to the effluent stream and a portion of the remainder is directed to biogas conversion. The effluent reduction could be partitioned to specific sCOD streams as depicted in Figure 4.11 of Chapter 4.

CHAPTER 7

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Appendix A

Default Values

A.0 RAW FEED STRENGTH AND FLOW

Values provided to the user for RF strength according to North American ranges are shown in Table A.1.

Table A.1 Raw feed strength and flow default values

	Units	LOW	AVERAGE	HIGH	REF.
Inhabitant Equivs.	IE	1,000,000	1,000,000	1,000,000	
Q_{RFi}/IE	m^3/IE·d	0.75	0.46	0.24	[160]
TCOD	kg/m^3	0.25	0.43	0.80	[160]
$TBOD_5$	kg/m^3	0.11	0.19	0.35	[160]
TSS	kg/m^3	0.12	0.21	0.40	[160]
VSS	kg/m^3	0.10	0.16	0.32	[160]
TS	kg/m^3	0.39	0.72	1.23	[160]
TVS	kg/m^3	0.21	0.36	0.66	[160]
Feed Temp.	°C	10	15	20	

A.1 PRELIMINARY TREATMENT

The single default value provided for PT is shown in Table A.2.

Table A.2 Preliminary treatment default value

	Units	LOW	AVERAGE	HIGH	REF.
TSS Reduction	%	2.00	4.00	6.00	[160]

A.2 PRIMARY SEDIMENTATION

The default values provided for PC are shown in Table A.3.

Table A.3 Primary sedimentation default values

	Units	LOW	AVERAGE	HIGH	REF.
TCOD Removal	%	20.00	30.00	40.00	[160]
$TBOD_5$ Removal	%	20.00	30.00	40.00	[160]
TSS Removal	%	40.00	55.00	70.00	[160]
Dedicate Flow TH	% Q_{PCu1}	0.00	0.00	100.00	
Dedicate Flow SPT	% Q_{PCu2}	0.00	0.00	100.00	
Underflow TSS Conc.	kg/m^3	20.00	40.00	80.00	[158]
TBOD:TCOD After PC	kg/100 kg	40.00	55.00	70.00	[158]
TCOD:TSS After PC	kg/100 kg	160.00	185.00	210.00	[158]
Specific Gravity, S_g		1.01	1.03	1.05	[160]

A.3 BIOTREATMENT

The default values provided for BT input settings are shown in Table A.4a.

Table A.4a Biotreatment default values for input settings

	Units	LOW	AVERAGE	HIGH	REF.
TCOD Treatment Eff.	%	60.00	70.00	95.00	[158]
$TBOD_5$ Treatment Eff.	%	60.00	70.00	95.00	[158]
Biomass Yield, Y_{net}	kg TSS/ kg BOD_5	0.80	0.95	1.30	[160]
Volume, V_{BT}	m^3	70,000	70,000	70,000	
SRT	D	1	4	7	[160]

Default values are provided to the user for the results that will be obtained at the BT unit. They serve as a guide to ensure UDVs are appropriate as they should provide within-range result values. These default values for results obtained from BT are shown in Table A.4b.

Table A.4b Biotreatment default values for results obtained

	Units	LOW	AVERAGE	HIGH	REF.
TSS (MLSS)	kg/m^3	2	6	15	[160]
F:M Ratio	g BOD_5/ d·g MLVSS	0.2	0.4	0.6	[160]

A.4 SECONDARY SEDIMENTATION

The default values provided for SC input settings are shown in Table A.5a.

Table A.5a Secondary sedimentation default values for input settings

	Units	LOW	AVERAGE	HIGH	REF.
TSS Settling Eff.	%	95.00	97.00	99.00	[158]
Underflow TSS Conc.	kg/m^3	5.00	10.00	15.00	[158]
TCOD:TSS After SC	kg/100 kg	140.00	180.00	220.00	[158]

Default values are provided to the user for the results that will be obtained at the SC unit. They serve as a guide to ensure UDVs are appropriate as they should provide within-range result values. These default values for results obtained from SC are shown in Table A.5b.

Table A.5b Secondary sedimentation default values for results obtained

	Units	LOW	AVERAGE	HIGH	REF.
Q_{SCr}/Q_{BTi}	%	25.00	50.00	150.00	[160]
Sludge Volume Index	mL/g	50	125	150	[160]

A.5 THICKENING

The default values provided for TH input settings are shown in Table A.6a.

Default values are provided to the user for the results that will be obtained at the TH unit. They serve as a guide to ensure UDVs are appropriate as they should provide within-range result values. These default values for results obtained from TH are shown in Table A.6b.

Table A.6a Thickening default values for input settings

	Units	LOW	AVERAGE	HIGH	REF.
TSS Capture Eff.	%	80.00	85.00	95.00	[160]
Effluent TSS Conc.	kg/m^3	20.00	50.00	90.00	[158]
Chemical Dosage	kg/kg TSS	0.0020	0.0040	0.0060	[160]
Recycle? PC/BT/NO	PC/BT/NO	PC	PC	PC	
pCOD	% $TCOD_e$	60.00	70.00	80.00	[158]

Table A.6b Thickening default values for results obtained

	Units	LOW	AVERAGE	HIGH	REF.
Solids Content	%	2	5	9	[160]

A.6 SLUDGE PRETREATMENT

The default values provided for SPT are shown in Table A.7. References are not provided as these values were compiled from the ranges observed in the literature review summary tables of Chapter 2.

Table A.7 Sludge pretreatment default values

	Units	LOW	AVERAGE	HIGH
Percent Flow Treated	%	100.00	100.00	100.00
pCOD Solubilisation	%	20.00	40.00	60.00
TSS Solubilisation	%	10.00	20.00	30.00
VSS Solubilisation	%	10.00	20.00	30.00
Biogas Increase	%	20.00	40.00	60.00

A.7 MESOPHILIC/THERMOPHILIC AD

The default values provided for MTAD are shown in Table A.8.

Table A.8 Mesophilic/Thermophilic AD default values

	Units	LOW	AVERAGE	HIGH	REF.
TSS Removal Eff.	%	40.00	60.00	80.00	[160]
TSS Removal Impr.		5.00	10.00	20.00	
sCOD Removal Eff.	%	40.00	60.00	85.00	[160]
sCOD Removal Impr.		5.00	10.00	20.00	
CH_4 Content	%	40.00	65.00	75.00	[158]
Supernatant Flow	% Q_{MTADi}	10.00	15.00	20.00	[158]
Recycle? PC/BT/NO	PC/BT/NO	PC	PC	PC	
Biomass Yield, Y_{net}	kg VSS/ kg COD	0.02	0.04	0.06	[160]
Volume, V_{MTAD}	m^3	80,000	80,000	80,000	
Digester Temp.	°C	35	35	55	
SRT	d	15	25	40	[160]

A.8 DEWATERING

The default values provided for DE are shown in Table A.9.

Table A.9 Dewatering default values

	Units	LOW	AVERAGE	HIGH	REF.
TSS Capture Eff.	%	85.00	90.00	95.00	[160]
Solids Content	% Q_{DEi}	15.00	20.00	25.00	[160]
Recycle? PC/BT/NO	PC/BT/NO	PC	PC	PC	
Polymer Dosage	kg/kg TSS	0.0020	0.0050	0.0070	[159]

A.9 TREATMENT AND RESULTS EQUATIONS

Some equations were provided in the Default Values section to enable quick estimation of appropriate treatment settings and results. The user defines the variables shown in the equations that are not pre-determined by PretrAD. Equations A.1 and A.2 are valid only for $TBOD_5$ and TSS influent ranges of 0.1-0.3 kg/m³ (8.4×10^{-4}-2.5×10^{-3} lb/gal) ([161]).

$$\text{TBOD}_5 \text{ Settling Eff} = \frac{T_d \text{ (h)}}{0.018 \text{ (h)} + 0.02 \cdot T_d \text{ (h)}} \quad \text{A.1}$$

$$\text{TSS Settling Eff} = \frac{T_d \text{ (h)}}{0.0075 \text{ (h)} + 0.014 \cdot T_d \text{ (h)}} \quad \text{A.2}$$

Equations A.3-5 represent the PS production, specific gravity, and daily biogas production estimation. Using Eq A.5 to estimate biogas production renders the same result with and without SPT use because VS is employed and is unchanged during SPT ([161]). A literature value of 0.94 m^3/kg VS destroyed for VS_d was used ([161]).

$$\text{PS Production} = Q_{PTi} \cdot TSS_{PTi} \frac{T_d \text{ (h)}}{0.006767 \text{ (h)} + 0.0152 \cdot T_d \text{ (h)}} \quad \text{A.3}$$

$$\text{Specific Gravity,} S_g = 1 + 0.005 \cdot TS \text{ (\% Total Solids)} \quad \text{A.4}$$

$$Q_{MTADbio} = Q_{MTADbioSPT} = 0.94 \cdot VS_{MTADi} \cdot Q_{MTADi} \cdot \left(\frac{VS_d}{100}\right) (m^3/d) \quad \text{A.5}$$

Equation A.6 was computed in both SI and US units and is used for heat flow coefficient determinations ([160, 161]).

$$\text{Heat Flow Coefficient} = \frac{C_i}{\text{Material Thickness (m or in)}} \quad \text{A.6}$$

Where:

C_i is the heat flow coefficient for different materials, kJ·m/m^2·d·°C or Btu·in/ft^2·d·°F

C_i = 30.15 (SI), 60.00 (US), uninsulated concrete

C_i = 70.34 (SI), 134.40 (US), uninsulated steel

C_i = 3.42 (SI), 6.60 (US), mineral wool insulation

C_i = 55.27 (SI), 108.00 (US), brick

C_i = 2.01 (SI), 4.08 (US), air space

C_i = 246.18 (SI), 480.00 (US), surface material (e.g., earth)

Appendix B

Plan-It STOAT Design

B.0 PURPOSE OF DESIGN

Plan-It STOAT was used as described in Chapter 4 to validate PretrAD's solids handling and flow regimes. If PretrAD were to sufficiently represent the results obtained using Plan-It, it would be deemed valid. The financial analysis, which is based on solids and energy demands, would thus also be valid. This was in fact the case and the sections below describe the design performed primarily by Kévin Rochelet that was necessary for the PretrAD versus Plan-It comparison.

PretrAD does not, in most cases, account for WWTP design. Where various unit sizes are needed, PretrAD does consider them. Though Plan-It performs similarly to PretrAD with regards to a direct mass balance design, some additional unit design was needed. For all sections listed below, the unit design was conducted to obtain values that were within known North American sizing and operating ranges and to obtain similar effluent results with Plan-It as those that were observed with PretrAD. Calculated design values will not be given as they reflect specific RF and treatment conditions (that were purposely varied for different runs) within both Plan-It and PretrAD. What is shown are the equations required to perform the design.

B.1 PRIMARY SEDIMENTATION

Minor design requirements for the Bar Screen and Grit Trap steps of Plan-It were performed. These are not provided as they do not pertain to the "paralleling" of PretrAD and Plan-It influents and effluents.

Required 'dimensions', 'operation', and 'parameters' are listed as they appear in Plan-It and reflect the data input of the left-hand menu as seen in Figure 4.14 of Chapter 4. The variables needed for input in Plan-It are listed for the PC unit in Table B.1. Effluent TSS and percent sludge solids were set to obtain effluents observed in PretrAD.

All items listed in Tables B.1-5 represent required Plan-It design variables. As mentioned above, they are not given as they reflect specific RF and treatment conditions that were purposely varied for PretrAD results given in Chapter 5. The methodology by which they were obtained is given.

Table B.1 Dimensions, operation, and parameters for Plan-It design of the PC unit

Dimensions	Operation	Parameters
Model (Assume Effluent Conc.)	Sludge Solids (%)	Effluent Solids (mg/L)
Depth (m)		
# of Units		
Shape (circular)		
Diameter (m)		
Unit Volume (m^3)		

With an assumed average overflow rate (OR, within the 30-50 m^3/m^2d range [160]) and a chosen no. of units, the area (A) can be found with Eq B.1. By setting the height (H, within the 3-5 m range [161]) the unit diameter and volume can then be found with Eqs B.2-3. Finally, Eq B.4 computes the unit detention time and with it, TSS and $TBOD_5$ settling efficiencies can be estimated using Eqs A.1-A.2 of Appendix A.

$$A = \frac{Q_{unit}}{OR} = \frac{\mathrm{m}^3}{d\left(\mathrm{m}^3/\mathrm{m}^2 \cdot \mathrm{d}\right)} = \mathrm{m}^2 \qquad \text{B.1}$$

$$D = \sqrt{\frac{A \cdot (4)}{\pi}} = \sqrt{\mathrm{m}^2} = \mathrm{m} \qquad \text{B.2}$$

$$V = \frac{H \cdot \pi \cdot D^2}{4} = \mathrm{m} \cdot \mathrm{m}^2 = \mathrm{m}^3 \qquad \text{B.3}$$

$$t = \frac{24 \cdot V}{Q_{unit}} = \frac{\left(h/d\right) \cdot \mathrm{m}^3}{\left(\mathrm{m}^3/\mathrm{d}\right)} = h \qquad \text{B.4}$$

B.2 BIOTREATMENT

Required dimensions and parameters are given in Table B.2 for BT. Plan-It provides default parameters and they were not altered.

Table B.2 Dimensions, operation, and parameters for Plan-It design of the BT unit

Dimensions	Operation	Parameters
Model (SRT Equation)	Aerobic SRT (d)	SRT Method (BOD)
# of Units	MLSS (mg/L)	Yield Method (User-defined Net Yield)
Shape (rectangular)		Heterotroph and Autotroph growth rates
Length (m)		Temperature Coefficients
Width (m)		Half-Saturation Coefficients
Depth (m)		Heterotroph and Autotroph Yields
Unit Volume (m^3)		

The total volume (V_{Total}) was obtained using PretrAD's effluent values which in turn depend on the SC underflow, recycle stream flowrates, and SS concentrations. The V_{Total} was calculated as shown by Eqs 4.19-21 in Chapter 4. The criteria were aerobic digestion SRT (1-7 d), MLSS concentration, and user-defined net yield. The MLSS concentration is in turn a function of the approximate 50-150% Q_{SCr}/Q_{BTi} relationship [160]. Insufficient data could be obtained from the literature for BT dimensioning (i.e., length, L, width, W, and height, H). Because population size and RF characteristics resembled those of the city of Ottawa, ON, Canada, the design was instead approximated by the design which currently exists for the Robert O. Pickard Environmental Center (ROPEC) which is the central WWTP for Ottawa. Again, it is important to note that these values served the sole purpose of obtaining similar effluents based on influent conditions and were deemed correct based on established design and operating ranges.

$$V = \frac{V_{Total}}{\#\ \text{of Units}} = \text{m}^3 \qquad \text{B.5}$$

$$L = \frac{V_{Total}}{(H \cdot W)} = \frac{\text{m}^3}{(\text{m} \cdot \text{m})} = \text{m} \qquad \text{B.6}$$

B.3 SECONDARY SEDIMENTATION

Required dimensions, operation, and parameters are shown in Table B.3. For the operation of the SC unit, the Q_{SCr} (RAS as given in Plan-It) flow was set using PretrAD's effluent value. Settleability factors for TCOD were not altered.

Table B.3 Dimensions, operation, and process for Plan-It design of the SC unit

Dimensions	Operation	Process
Model (Solids Loading Rate, SLR)	RAS Flow (m^3/h)	SLR ($kg/m^2 \cdot d$)
Depth (m)	Sludge Wastage Flow (m^3/h)	
# of Units	Effluent TSS (m^3/h)	
Shape (circular)		
Diameter (m)		
Unit Volume (m^3)		

At this stage, since Plan-It uses an iterative approach to determine influent and effluent values for both BT and SC (due to WAS recycle), the OR was varied to obtain similar flows (influent, effluent, underflow, and recycle). Varying the OR changed the unit sizing until comparable flows were found. Based on the estimated OR (within the 16-40 m^3/m^2d range [161]) and a selected # of units, the area could be calculated by rearranging Eq B.1. Unit diameter, volume, and depth (within range of 3.6-4.6 m [161]) could then be found using Eqs B.2, B.5, and B.3, respectively.

B.4 THICKENING

Required dimensions and operation are shown in Table B.4 for TH. For the operation of the TH unit, the loading rate, percent underflow TSS, and solids recovery were set using the PretrAD inputs.

Using PretrAD's influent TSS concentration and common WAS density (ρ, 1,000-1,200 kg/m^3 [160]), the influent solids concentration (within a range of 0.5-1.5 % [160]) was computed with Eq B.7. A solids loading rate was then assumed (within a range of 20-80 $kg/ m^2 \cdot d$ [160]) to compute the unit area, diameter (maximum 20 m [160]), and depth (3.6-4.6 m [161]). The sizing method is the same as that for the PC unit.

Table B.4 Dimensions and operation for Plan-It design of the TH unit

Dimensions	Operation
Model (WRc)	Underflow TSS (%)
# of Units	Solids Recovery (%)
Shape (circular)	
Diameter (m)	
Depth (m)	
Unit Volume (m^3)	

$$\%\ solids = \frac{TSS}{\rho} \times 100\% = \frac{kg/m^3}{kg/m^3} \times 100\% = \% \qquad \text{B.7}$$

B.5 MESOPHILIC/THERMOPHILIC AD

Required dimensions and operation are shown in Table B.5 for MTAD. For the operation of the MTAD unit, the loading rate, percent underflow TSS, and solids recovery were set using the PretrAD inputs. Knowing the VSS/TSS ratio within PretrAD, both the VSS and sCOD removals could be set. Again, as insufficient anaerobic digester design values were found, diameter and depth were approximated using ROPEC sizes. The unit volume can then be found with Eq B.3. The number of units can subsequently be set to meet volumetric criteria (0.07-0.11 or 0.11-0.17 m^3/IE for low rate and high rate AD, respectively [159]). The Eqs B.8 and B.5 are used for this computation.

Table B.5 Dimensions and operation for Plan-It design of the MTAD unit

Dimensions	Operation
Model (Hydraulic Loading)	Hydraulic Retention Time (d)
# of Units	VSS Removal (%)
Shape (circular)	sCOD Removal (%)
Diameter (m)	Digester temperature (°C)
Depth (m)	
Unit Volume (m^3)	

$$V_{Total} = Volume\ criteria \cdot IE = \left(m^3/IE\right) \cdot IE = m^3 \qquad \text{B.8}$$

Appendix C

Model Permutations and Raw Data

C.0 MODEL PERMUTATION FILES

Over 320 runs were conducted for various plant designs and varied RF settings or SPT treatment values and type of SPT to establish the WWTP operating costs without SPT (control costs) and with SPT (SPT costs) shown in Chapter 5.

The PretrAD outputs were saved for each set of 4 runs under control and SPT scenarios for both MAD and TAD. The Windows XP file folder arrangement for the electronic Appendix C where all permutations can be found is shown in Figure C.1. It is given to provide a visual nomenclature for the labelling of the 8 files found in each folder. The first word defines the focus of the run (e.g., Control or CH). The first parentheses of the first 2 files outlines that they were created for the second evaluation using Runs 1a-2b. The second parentheses of the first two files contain M or T and A (M = MAD, T = TAD, and A = Average). The following 6 files do not have the '(a,b)' notation as they were created for the first evaluation using Runs 1-4. All files are labelled with the heat recovery and disposal distance parameters that were set at normal/low (N,L) and normal/double (N,D), respectively.

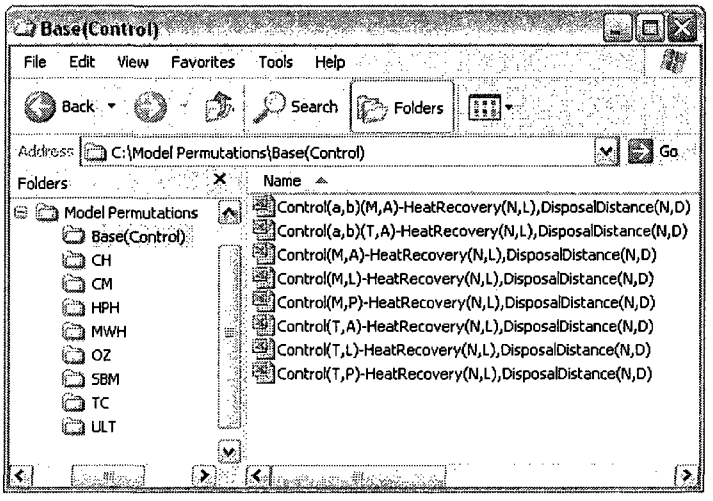

Figure C.1 Print screen of model permutations as found in the electronic Appendix C

C.1 RAW DATA COLLECTION AND GRAPHS

The PretrAD-outputted data was collected in 2 Microsoft Excel files. The first 'Data,Graphs-Runs1-4' presents the data and created graphs using results from Runs 1 to 4. The second file 'Data,Graphs-Runs1a-2b' presents the data and created graphs using results from Runs 1a to 2b. They are located inside the folder named 'Raw Data and Graphs' and can be found alongside the 'Model Permutations' folder in the electronic Appendix C. The runs were conducted prior to the finalization of the nomenclature that was used in this thesis. The following abbreviations were used in PretrAD: PS (primary sedimentation and primary sludge), SS (secondary sedimentation and secondary sludge), SP-T (sludge pretreatment), and M/TAD (mesophilic or thermophilic anaerobic digestion). All other nomenclature used in PretrAD is identical to that of this thesis.