Investigation of Potato Starch and Sonicated Return Activated Sludge as Alternative Carbon Sources for Biological Nitrogen Removal

by

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Declaration

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Abstract

High nitrogen discharge from the municipal wastewater is a major concern for the South Australian Government, primarily due to negative impacts on the marine environment. Therefore, under the South Australian Environmental Improvement Program, (SA EIP), all metropolitan wastewater treatment plants have been reconfigured to achieve enhanced nitrogen removal. Secondary treatment (denitrification process) at the metropolitan wastewater treatment plants must be optimised to meet the discharge guideline of 10 mg/L total nitrogen. However, secondary treatment at some plants is carbon limited (low C/N ratio), and external carbon supplementation is required to meet this discharge guideline.

Molasses provides the current external carbon source at two plants. It is relatively inexpensive, but other carbon sources, particularly industrial waste streams, may be more attractive, due to the potentially lower material cost, as it is practically free, and environmentally friendly. Potato starch and sonicated return activated sludge (RAS) were considered.

In this study, the bioavailability of the soluble carbon in potato starch and ultrasound treated RAS were assessed. The associated objective was to investigate the potential of both carbon sources as an external carbon donor for the denitrification zone of wastewater treatment plants to economically improve biological nitrogen removal. The economic analysis was performed using mainly United States dollars and the fixed capital investments and total capital costs were converted to Australian dollars. This was due to the United States dollars currency quotes obtained for the materials and unit operations required.

SCOD from the three sources was quantified and preliminary results were presented. Molasses provided the highest SCOD release of 1.1285×10^6 mg-SCOD/L, sonicated RAS produced 5.6 to 68.4 times the SCOD release of the untreated RAS (35.6 mg-SCOD/L) depending on the ultrasound intensity and treatment time, while the highest soluble carbon release obtained using potato starch was 809 mg-SCOD/L (using 20.9 g/100 mL potato starch concentration).

Based on the experimental SCOD results, batch denitrification tests using the proposed carbon sources were carried out. The nitrogen removal efficiency at low dose (12.48 mg-SCOD/L) using molasses, potato starch and sonicated RAS were 77.54%, 57.24%, and 72.76% respectively, whilst at high dose (124.80 mg-SCOD/L) were 94.04%, 66.32%, and 92.10% correspondingly. In similar order of the proposed carbon sources, the nitrate removal rates for the first phase denitrification with low dose were 1.44, 1.16, and 1.18 mg-NO_3^-/h respectively, whilst the nitrate removal rate of the first phase denitrification with high dose improved to 2.01, 1.26, and 1.96 mg-NO_3^-/h correspondingly.

From the denitrification test results, molasses proved to be the optimal carbon source in terms of nitrate removal. However sonicated RAS possesses similar denitrification performance and may be a suitable alternative.

An economic analysis for sonicated RAS Option 2 confirmed it as the most viable substitute. The time to recover the initial investment (payback period) is approximately 6.5 years and the breakeven point is approximately 8 years.

Both denitrification tests and economic analyses demonstrate that sonicated RAS may be a viable and attractive substitute for the molasses.

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I would like to dedicate this thesis to my parents, Dr. Tjahjono Koentjoro, MPH, PhD and Dr. Lina Koerniawati, MPH.

I hope that the results of my thesis would satisfy the expectations of the people associated and provide a significant contribution to the society.

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Refereed Publications from this Thesis

Refereed International Journals

G. Kuncoro, Y. Ngothai, D. Sweeney, B. O'Neill, U. Kaeding, Investigation of potato starch and sonicated RAS as alternative carbon sources for biological nitrogen removal, International Journal of Environment and Waste Management (IJEWM), accepted for publication in Volume xxx, 2009.

Refereed Australasian Conference

G. Kuncoro, Y. Ngothai, D. Sweeney, B. O'Neill, U. Kaeding, Investigation of potato starch and sonicated RAS as alternative carbon sources for biological nitrogen removal, Proceedings: Chemeca 2006 34th Australasian Chemical Engineering Conference, D. Patterson & B. Young, Eds., The Institution of Engineers, Auckland, New Zealand, 17 – 20 September 2006, Environmental: Biological Treatment Processes II, Paper 248. (ISBN: 0-86869-110-0).

Nomenclature

A	area (m^2)
Alm	log mean area (m^2)
A_{st}	Area of steel (cu.in)
b	width of member in tank (in)
d	wall thickness (in)
cp	specific heat capacity (J/g.K)
d	tank diameter (m)
D	tank diameter (in, ft; see referred equation information)
E	Denitrification Efficiency
f_r	ring tension (lb/in^3)
G	gravitational acceleration (m/s^2)
h	tank depth (ft)
H	head of pump (m)
I	current (A)
I_E	actual vessel volume (m^3)
K	thermal conductivity (W/m.K)
L	length of conveyor (m)
m	mass flow rate (kg/s)
m	modular ratio
$[NO_x^- - N]$	nitrate concentration
p_{st}	tension of steel in the wall of the tank (lb/in^2)
P	power requirement (kW)
P	maximum pressure at bottom wall (kg/m^2)
pH	acidity of medium
q	heat; heat loss (W)
r_i	radius (m)
R^2	Correlation coefficient
R_1	resistance (K/W)
t	time (minutes; for carbon dosing test and denitrification analysis)
t	time (seconds; for power output and insulator thickness)

t	mixing time (h, for jet mixers)
t	wall thickness (in)
T_i, maximum assumed	inside temperature (^{o}C)
T_0	ambient temperature (^{o}C)
T	temperature (^{o}C)
T	tension (kg)
V	voltage (V)
V	volume (m^3)
W	Branson Sonicator power output (W/ml)
W_s	mechanical energy (J/kg)
X	retention time (s)
X	*V5* Sonix power output (W/ml)
Y	concentration of SCOD released (mg-SCOD/L)

Subscripts

f	final
i	initial, inside
1	propylene layer
2	polystyrene layer

Greek

ΔQ	energy (J)
ΔT	temperature difference (^{o}C or K)
$\sum V$	total delivered flow to jet mixers (m^3/h)
η	fractional efficiency
η_e	motor efficiency
ρ	density (kg/m^3)

Abbreviations

AU$	Australian dollars
C/N	carbon to nitrate ratio
COD	chemical oxygen demand
GBP	Great Britain Pounds

GF/C	glass fibre filter
HDPE	high density polyethylene
kWh	kilowatt hour
MLR	mix liquor return
PE	primary effluent
RAS	return activated sludge
SCOD	soluble chemical oxygen demand
SG	Specific Gravity
TEFC	totally enclosed fan cooled
US$	United States dollars
WWTP	Wastewater Treatment Plant

1 INTRODUCTION

Significant health and environmental issues arise as consequences of high nitrogen discharges in wastewaters. The high nitrogen discharge, a consequence of the intensive use of nitrogenous fertiliser and addition of industrial effluent, produces a high level of nitrate-nitrogen in groundwater. This causes infant methaemoglobinemia in small children and formation of carcinogenic nitrosoamines (Mohseni-Bandpi and Elliot, 1998). A further significant impact from excessive nitrogen discharge is the eutrophication of aquatic systems (Boaventura and Rodrigues, 1997). In the Adelaide's coastal environment, seagrass loss, algal blooms and mangrove loss have been attributed to excessive nutrient release (i.e., nitrogen) from wastewater plants (Bayard, 1992). Therefore, under the South Australian Government's Environmental Improvement Program (EIP), all metropolitan wastewater treatment plants have been reconfigured to provide enhanced nutrient removal and meet a total nitrogen discharge limit less than 10 mg/L N (Sweeney, 2005[a]). To achieve this limit, the biological nutrient (nitrogen) removal process (secondary treatment) at all United Water's wastewater treatment plants (WWTPs) must be optimised. Glenelg WWTP was chosen for the study case.

Normal secondary treatment now includes of nitrification and denitrification processes as part of the conventional activated sludge treatment process. However, low carbon/nitrogen (C/N) ratios in the wastewater limit the efficiency of the denitrification process resulting in excessive nitrogen discharge levels. The process is carbon constrained and a higher carbon/nitrogen ratio is required (Sweeney, 2005[a]). Clearly, the carbon/nitrogen ratio may be increased by external carbon dosing.

Currently, the external carbon source for the process is molasses, and it results in improved nitrogen removal. Molasses is an effective and cheap carbon source (Miranda et al., 1996), but cost reductions may be achieved by the use of other carbon sources. The first alternative carbon source proposed by United Water is potato starch. However, there is no conclusive evidence to demonstrate that the soluble carbon provided by the starch is as bio-available as that produced by molasses (Ford, 2005). Hence, further investigation is required to resolve this issue. A preliminary study performed by United

Water showed that only 40% of the potato starch is soluble at room temperature and the remaining starch settles quickly in the solution, potentially leading to major operating concerns such as pipe-work blockage and excessive build-up in tanks (Ford, 2005). Clearly, potato starch cannot be considered as a carbon source, unless a method for increasing its solubility is developed and validated.

The second proposed carbon source is ultrasonically disrupted return activated sludge (RAS). The application of ultrasound in sewage sludge treatment and in anaerobic digestion has become routine in the past few years. Ultrasound treatment is a well established method for releasing soluble organic cell compounds into the aqueous phase (Groonroos et. al., 2005). The released carbon provides an accessible food source for growth of the denitrifying organisms. Consequently, the bio-available carbon for denitrification in the return activated sludge (RAS) is expected to increase. Should this occur, then dosing with an external carbon source may be avoided. Obviously, an economic comparison of this process and external carbon dosing is required. As a result, this investigation into the effectiveness of ultrasonic treatment as a cell disruption mechanism to increase the available carbon in the sludge, including determination of capital and operating cost estimates were undertaken. Furthermore, the flow rate of the return activated sludge may require adjustment to provide sufficient available carbon. This change may impact on the overall sludge age and mass balance for the process and consequences must be investigated and resolved.

Significance of the project

To overcome problems associated with inadequate carbon in the wastewater stream, the research objective of this study is to reduce costs and increase the carbon content in the wastewater using either carbon source to achieve improved biological nitrogen removal. The level of bio-available carbon will be quantified as Chemical Oxygen Demand (COD). COD is a widely applied measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by use of a strong chemical oxidant. It can be correlated to BOD (Biological Oxygen Demand) and organic matter measure, such as DOC (Dissolved Organic Carbon) (Greenberg et al., 1992).

The materials and methods used in the conduct of this research are explained in Chapter 3.

2 LITERATURE REVIEW

In this chapter, conventional biological waste treatment was reviewed to provide an understanding particularly denitrification. As mentioned in Chapter 1, carbon availability is critical for efficient denitrification process. It provides a basic substrate for growth. Hence, widely used sources of external carbon for denitrification was also reviewed. A promising approach for improving carbon availability is the use of ultrasonic treatment. The effects of ultrasonic treatment will also be reviewed to provide insights and understandings of the process and its application.

2.1 Wastewater Treatment Overview

Conventional wastewater treatment plants normally combine physical, biological and chemical treatment processes to guarantee effective treatment of raw wastewater from domestic and industrial sources prior to release of reclaimed water to the environment. A schematic of a typical water treatment plant for municipal wastewater is provided in Figure 2-1.

NOTE: This figure is included on page 3 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2-1 Wastewater treatment process flow diagram (Reproduced from Tchobanoglous et al., 2003)

2.2 Biological Treatment

Biological treatment for nitrogen removal involves two major stages, in the initial stage ammonia (organic N) is converted to nitrite then to nitrate (nitrification). The second stage involves nitrate conversion to nitrogen (denitrification). The nitrification process can be represented by the following reaction scheme (Tchobanoglous et al., 2003):

$$2NH_3 + 3O_2 \xrightarrow{\textit{Nitrosomonas}} 2NO_2^- + 2H^+ + 2H_2O \tag{2-1}$$

$$2NO_2^- + O_2 \xrightarrow{\textit{Nitrobacter}} 2NO_3^- \tag{2-2}$$

The overall oxidation reaction may be summarised as:

$$NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O \tag{2-3}$$

The simplified stages in the sequence of reactions for denitrification

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\ (g) \rightarrow N_2O\ (g) \rightarrow N_2\ (g) \tag{2-4}$$

Figure 2-2 illustrates two common plant configurations for nitrification/denitrification (Tchobanoglous et al., 2003). The configuration of the denitrification process at Glenelg WWTP (Wastewater Treatment Plant) follows the pre-anoxic denitrification scheme.

NOTE: This figure is included on page 4 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2-2 Types of nitrification/denitrification process: (a) preanoxic denitrification and (b) postanoxic denitrification (Reproduced from Tchobanoglous et al., 2000)

Nitrification is performed by autotrophic micro-organisms, whereas denitrification is performed by heterotrophic micro-organisms, which require a carbon source (Tchobanoglous et al., 2003). It is crucial to provide sufficient carbon in the sludge for the second step, as the carbon source can be the limiting nutrient. Even if sufficient carbon is available, Isaacs and Henze (1995) found that low denitrification rate may result in low levels of denitrification for a given plant size with consequent high nitrite and nitrate discharge. They also reported that the rate of denitrification is strongly affected by the nature of the carbon source. A more easily degradable carbon source produces a higher rate of denitrification.

2.3 Carbon Sources

The use of an external carbon source was found to increase the denitrification efficiency (Her and Huang, 1995). Denitrification efficiency (E) can expressed as the percentage of total nitrogen removed from the wastewater system (Her and Huang, 1995)

$$E = \left(1 - \frac{\left[NO_{\mathrm{x}}^{-} - N \right]_f}{\left[NO_{\mathrm{x}}^{-} - N \right]_i} \right) \mathrm{x}100\% \qquad \textbf{2-5}$$

where $[NO_{X}^{-} - N] = [NO_{2}^{-}-N] + [NO_{3}^{-}-N]$, subscript “$f$” for final and subscript “i” for initial. In this project, $[NO_{X}^{-} - N]$ refers to nitrate concentration.

The most abundant carbon source is organic matter in the wastewater. Additional carbon sources that have been widely used for denitrification of wastewater are methanol, acetic acid, and glucose (Cervantes et al., 2001). Other sources that have also been used include ethanol (Constantin and Fick, 1997) and molasses (Boaventura and Rodrigues, 1997).

Methanol is the most widely used supplementary carbon source in denitrification processes. As well, the methanol residual is readily removed by aeration (McCarty et al., 1969, cited in Her and Huang, 1995). These researchers found that complete denitrification is achieved at a lower C/N ratio when compared to acetic acid or glucose. However, methanol is extremely toxic to humans and micro-organisms, and strict safety standards for application are required. Methanol toxicity at high concentration was confirmed by Her and Huang (1995). Methanol inhibited the denitrification process at high C/N (>15 g-C/g-NO_3^-). Methanol is an expensive carbon source (Aravinthan et al., 2001), Peng (2007) noted that pure methanol is now more expensive compared to ethanol.

Another common carbon source for denitrification is acetic acid. Acetic acid produces high denitrification efficiency, but the minimum required C/N ratio is higher than that required for methanol (Her and Huang, 1995). These researchers also observed that at high C/N ratio (~ 25 g-C/g-NO_3^-) acetic acid did not inhibit the denitrification reactions. However, acetic acid is more expensive compared to molasses.

Glucose is another widely used carbon source for denitrification. Her and Huang (1995) determined that glucose showed similar behaviour to that of acetic acid. It required a slightly higher C/N ratio to achieve the same denitrification efficiency. Table 2-1 compares the minimum C/N ratio necessary for nearly complete denitrification for methanol, acetic acid and glucose.

Table 2-1 Minimum C/N ratio for nearly complete denitrification

Carbon Source	Minimum C/N ratio for nearly complete denitrification					Reference
	g-C/ g-NO_3–N	g-C/ g-NO_2–N	Tank size, L	Residence time, h	Efficiency	
Methanol	0.9 ~ 10.0	0.6 ~ 10.0	4.5	12	93 – 100%	Her and Huang, 1995
Methanol			2.7	12	85.3 ± 2%	Quan et al., 2005
Acetic Acid	1.9	1.3	4.5	12	97 – 99%	Her and Huang, 1995
Glucose	2.0	1.6	4.5	12	98 – 100%	Her and Huang, 1995
Hydrolysed Molasses	4.3 ~ 5.8		2.7	12	91.6 ± 1.6%	Quan et al., 2005

Ethanol and acetic acid efficiencies were compared in an experiment conducted by Constantin and Fick (1997). The results demonstrated that ethanol provides far more favourable growth of micro-organisms compared to methanol. Ethanol allows the formation of $NADH_2$, an enzyme that produces ATP which is required to provide energy for cellular functions, therefore providing a new energy source for the micro-organisms leading to higher overall denitrification rates. Figure 2-3 (Ghose an Badra, 1985, cited in Constantine and Fick, 1997) presents the reaction sequence for the formation of $NADH_2$ from ethanol. However, from an industrial point of view, low concentrations of micro-organisms and high denitrification rates are preferred. Acetic acid delivered improved denitrification for the same biomass quantity.

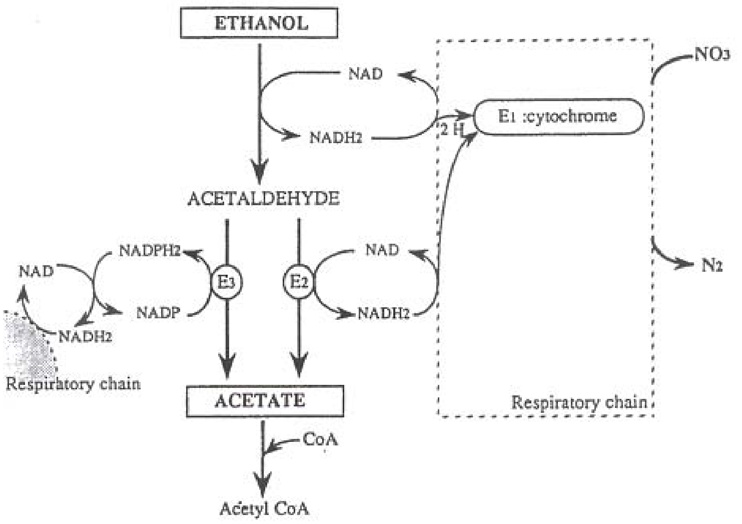

Figure 2-3 Scheme of ethanol and acetic acid evolution in the bacteria metabolism during denitrification process. (E_1): alcohol-cytochrome reductase; (E_2): coenzyme-independent aldehyde dehydrogenase; (E_3): NAPD-dependent aldehyde dehydrogenase (Reproduced from Constantine and Fick, 1997)

Therefore, in relation to the biomass amount, acetic acid proved to deliver a higher specific denitrification rate (i.e. nitrate consumption rate divided by the biomass concentration (Constantin and Fick, 1997)). This high specific denitrification rate was explained by the fact that acetic acid is a readily digestible carbon, and that ethanol must first be converted into acetate. Hence, denitrification was carried out more efficiently using acetic acid as the carbon source.

Molasses has also been studied as an external carbon source for denitrification (Boaventura and Rodrigues, 1997). Molasses is a by-product from sugar production. It contains approximately 48% – 50% sugar content (Quan et al., 2005). However, the remaining polysaccharides, the major component of molasses, have very long carbon chains that need to be hydrolysed to simpler sugars such as sucrose, glucose to allow rapid digestion by denitrifying bacteria (Najafpour and Shan, 2003). To overcome this problem, Quan et al. (2005) attempted to increase the effectiveness of molasses as a carbon source by resorting to thermohydrolyzation under acidic conditions. Their results confirmed that hydrolysed molasses achieved 91.6±1.6% nitrogen removal with a denitrification rate ranging from 4.2 mg [NO_3^-–N] g $VSS^{-1}.h^{-1}$. This was higher than the rate achieved by using methanol (85.3±2.0%). Table 2-2 shows a comparison of denitrification rates using acetic acid, ethanol, methanol and hydrolysed molasses.

Table 2-2 Denitrification Rate

Carbon Source	Denitrification Rate	Reference
Acetic Acid	10 – 81 mM NO_3.g $biomass^{-1}$. h^{-1}	Constantin and Fick, 1997
Ethanol	6 - 63 mM NO_3. g $biomass^{-1}$. h^{-1}	Constantin and Fick, 1997
Hydrolysed Molasses	4.2 mg NO_3.g $VSS^{-1}.h^{-1}$	Quan et al., 2005
Methanol	1.0 mg NO_3. g $VSS^{-1}.h^{-1}$	Quan et al., 2005
Methanol	1.3 mg NO_3. g $VSS^{-1}.h^{-1}$	Louzeiro et al., 2003

An alternative carbon source for denitrification suggested by United Water is potato starch (Sweeney, 2005^a). Potato starch is a non toxic material and is a cheap readily available carbon source. It is easily obtained from potato factory waste. The starch has been found to have high carbon content: 21% amylose and 79% amylopectin (Van Beynum and Roels, 1985). Figure 2-4 shows the chemical structure of amylose and amylopectin (Ullmann, 2001). Amylose is a linear polymer containing up to 6000 glucose units, whereas amylopectin is a branched polymer consisting of amylose chains.

Although this starch has high carbon content, preliminary study carried out by United Water indicated only 40% of the potato starch is soluble at room temperature. This implies a substantial fraction is insoluble and leads to major operating concern such as pipework blockages and build-up in tanks if directly dosed. Therefore, an investigation of potential methods for improving the solubility of starch is crucial. Furthermore, there is little information available about the amount of soluble carbon (soluble COD) in the starch. Hence, investigation to determine the amount of soluble carbon in the potato starch needs to be performed.

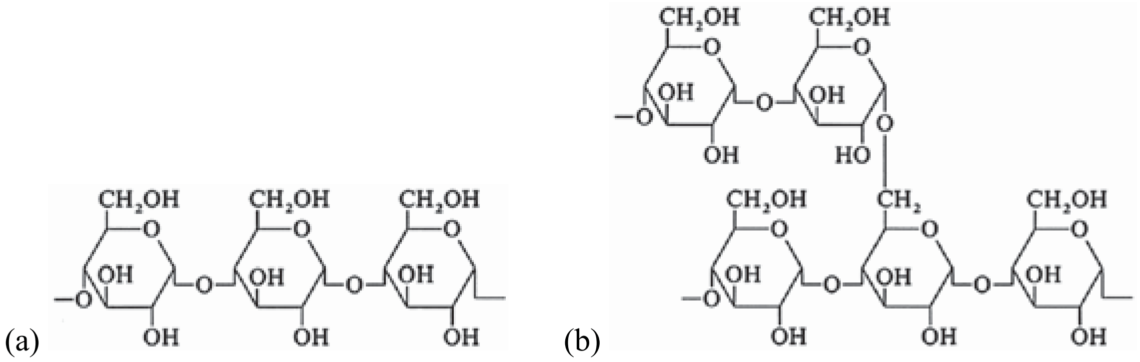

Figure 2-4 Chemical structure of: (a) linear amylose; (b) amylopectin (Reproduced from Ullmann, 2001)

Despite the use of a diverse range of carbon sources, Bernet et al. (1996) noted that the nature of a carbon source determines the route of nitrate reduction (i.e., the competition between denitrification and dissimilatory nitrate reduction to ammonium at low dissolved oxygen concentrations). Thus, it is vital to identify and utilize the optimal carbon source to achieve a high rate of denitrification and to prevent nitrate reduction to ammonia. Even if a high rate of denitrification is achieved, efficiency remains a significant factor that must be considered. Insufficient or excess available carbon will affect the efficiency of the denitrification process (Her and Huang, 1995). Determining the correct carbon dose is vital. As well, the economics of replacement of carbon sources need to be quantified before any decision to change is made.

2.4 Ultrasound Treatment

Numerous researchers have investigated potential improvements to the biodegradability of wastewater. An attractive option for improvement is the use of ultrasonic treatment. Ultrasonic treatment may increase the bio-available carbon concentration (measured as Soluble Chemical Oxygen Demand, SCOD), in the return activated sludge (RAS), with consequent improvement in the denitrification of the wastewater.

Ultrasound is a pressure wave that propagates through a medium with a vast amount of energy dissipation (Chu et al., 2001). This energy can generate gas and vapour bubbles which will then vibrate according to the pressure wave (Monnier et al., 1999). This phenomenon is described as acoustic cavitation. Transient cavitation happens when acoustic power is high, where small gas and vapour bubbles are formed in the low pressure phase, grow and violently collapse in the compression phase resulting in high liquid velocities (Neppiras, 1980, cited in Monnier et al., 1999). The collapse of the bubble will yield mechanical effects in a heterogeneous system resulting in improved physico-chemical processes, cleaning, emulsification and solid disruption (Monnier et al., 1999).

Previous studies have indicated that low frequency ultrasound (20 kHz) coupled with relatively high ultrasonic intensity is suitable for sludge disintegration (Nickel et al., 1999, cited in Gronroos et al., 2005). The ultrasound process leads to cell rupture as a consequence of cavitation and bubble implosion formed in the liquid phase. These induced stresses rupture cells allowing the intracellular components to be released (Bougrier et al., 2005). Microscopic views of secondary sludge showing this phenomenon before and after ultrasonic treatment are presented in Figure 2-5.

NOTE: This figure is included on page 10 of the print copy of the thesis held in the University of Adelaide Library.

Figure 2-5 Microscopic views of secondary sludge (a) Filamentous bacteria before ultrasound treatment; (b) Filamentous bacteria after ultrasound treatment (Reproduced from Purac, 2005)

In relation to cell rupture, Chu et al. (2001) stated that the increase of SCOD is probably a consequence of the release of intracellular components in the sludge body. Their study indicated that although 66% of the total COD in the original sludge is biodegradable, unfortunately the bulk of this COD is associated with the solid phase, rather than the soluble form. Their finding confirmed that the increase of soluble COD is not significant at a low ultrasound power intensities (110 kW/m3), but at a higher power intensities (330 kW/m3), the total COD was transformed into supernatant (soluble) COD. Consequently, the soluble COD increased by approximately 40 times following ultrasonic treatment. Gronroos et al. (2005) also confirmed that ultrasound treatment increases SCOD concentration significantly. Their results demonstrated that maximum rupture was achieved with high intensity and short treatment time rather than low intensity and long treatment time.

Ultrasonic treatment has successfully improved anaerobic digestion. Tiehm et al. (1997) reported that anaerobic digestion following ultrasound pre-treatment of the raw sludge increased biogas production with reduced residence time. This improvement in digester performance was attributed to the increase of SCOD.

These observations suggest that ultrasonic treatment may eliminate the need of external carbon dosing. However, little information on the efficacy of ultrasonic treatment for denitrification of waste activated sludge is available. The data that exists is contradictory particularly as to the present SCOD release due to ultrasound treatment.

Table 2-3 presents the summary of SCOD release determined in various studies. Clearly it is necessary to study the potential SCOD release as a function of sonication time and power intensity. A preliminary economic comparison between a denitrification process using an external carbon source and one using sonicated RAS was performed by Ford (2005). The results obtained were inconclusive due to inconsistencies in the COD measurements. This issue needs resolution.

Table 2-3 Comparison of factor increase in SCOD Release from various studies

Sonication time and intensity	Factor increase	Reference
10 min, 50% amplitude	8 – 40 x	Ford, 2005
10 min, 50% amplitude	2 x	Howland, 2004
20 min, 4W/mL	7.7 x	Mao et al., 2004
120 min, 0.33 W/mL	40 x	Chu et al., 2001

2.5 Research Gaps and Objectives

2.5.1 Research Gap

As outlined in Section 2.3, a wide variety of carbon sources have been utilised for denitrification of activated sludge. The bulk of the carbon sources reviewed produced a high denitrification efficiency and considerably low minimum COD/N ratio. However, a number of widely used carbon sources are toxic and/or expensive. These constraints suggest that the use of methanol, ethanol and acetic acid as carbon sources may not be advisable for treatment of high nitrogen concentration wastewater.

Also, cost benefits maybe derived by using cheaper carbon sources. For example, potato starch is non toxic and readily available, inexpensive carbon source. Unfortunately, little information exists regarding the use of potato starch as a carbon source for denitrification. Furthermore, the solubility of potato starch is very low at room temperature, and thus may lead to major operating concerns (e.g., fouling, plugging).

Ultrasonic treatment of RAS is a proven technology to increase the availability of carbon by cell rupture. However, the optimal operating conditions (i.e., sonication time and intensity) for maximising carbon release are unknown. In both instances, either the use of potato starch or sonicated RAS, a detailed economic evaluation is required to see whether a change in carbon feedstock makes economic sense.

2.5.2 Research Objectives

The objectives of this research are:

- to investigate the solubility of potato starch as a function of concentration
- to investigate the amount of soluble carbon (SCOD) in potato starch, molasses and sonicated RAS
- to investigate the effect of ultrasound treatment on the solubility of potato starch
- to quantify the increase in SCOD following ultrasound treatment of return activated sludge (RAS)

- to compare denitrification performance (i.e., denitrification efficiency) achievable when using molasses, potato starch and ultrasound treated RAS in a laboratory scale bioreactor
- to perform an economic evaluation of the application of potato starch and ultrasonically treated RAS as a carbon source in denitrification

Detailed knowledge will be gained from the above tasks.

3 Materials and Methods

The goal of this research is a preliminary evaluation on two proposed alternative carbon sources for wastewater denitrification in Glenelg WWTP. The two sources are potato starch and ultrasonically treated RAS. The increase in SCOD, the efficiency of nitrate removal and the economic attractiveness of the substitutions are to be evaluated. This section presents key aspects of the experimental design and methodology to be used for the evaluation.

3.1 Materials

The materials used in this research were potato starch which was provided by Smith Snackfoods, a potato chip manufacturing company in Adelaide, South Australia, and return activated sludge (RAS), primary effluent, mix liquor return and molasses, obtained from Glenelg Wastewater Treatment Plant, South Australia.

3.2 Power Output Determination of Ultrasound Device

Sonication studies were performed with a Branson 450 digital sonifier using a 1/4″ (6.35 x 10^{-3} m) micro-tip. The power output of this device needed to be quantified to enable the calculation of the power intensity (W/mL). The output power to the fluid was measured using the calorimeter principle (energy dissipation into water in an insulated container (adapted from Li, 2006)). A well insulated polypropylene bottle filled with distilled water (300 mL) served as the calorimeter. A 3.5 cm thick high density polyethylene (HDPE) was used to insulate the polypropylene (PP) bottle to minimise thermal energy loss. Appendix A summarises the calculation to obtain the thickness of the insulation required. The amplitude of the digital sonifier was from 20% to 70% and the time for the temperature of the water to increase by 5K during ultrasound treatment was recorded. A thermocouple was used for temperature recording. This experiment was performed at each amplitude level for four replicates to obtain average readings. Figure 3-1 illustrates the experimental set up for determining the output power.

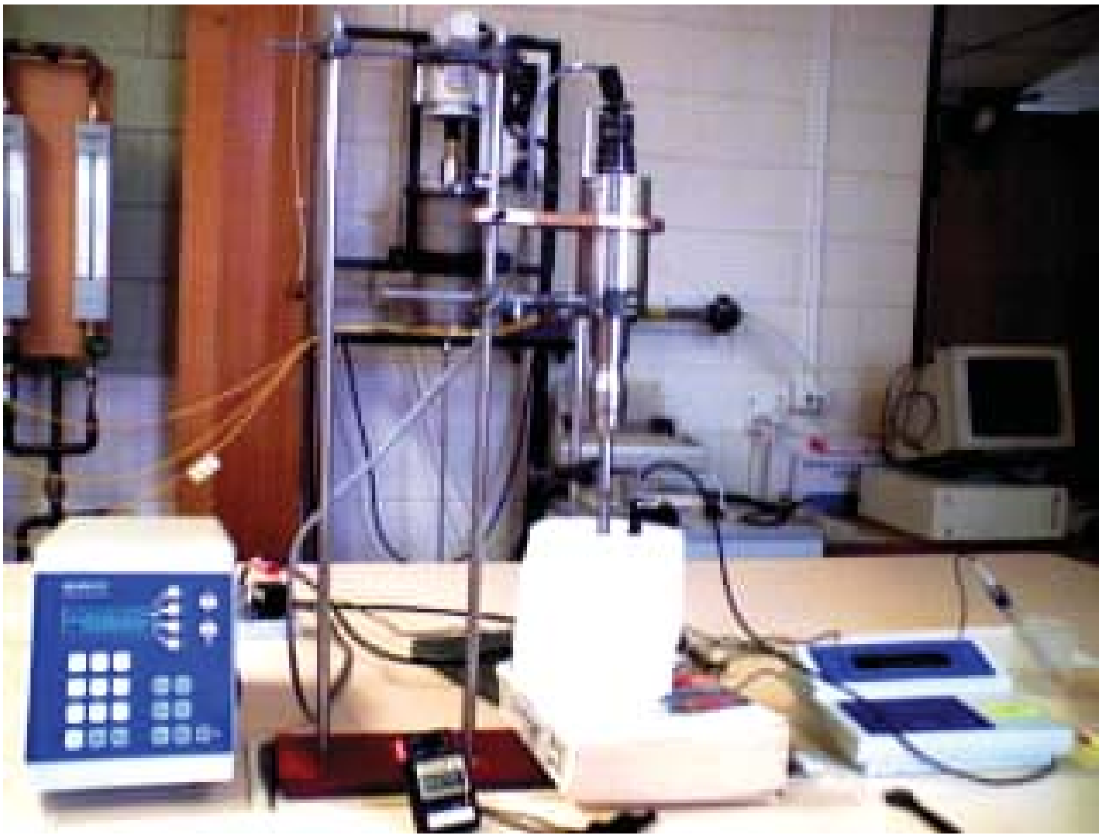

Figure 3-1 Experimental set up for sonicator output power

The energy dissipated by the digital sonifier is ultimately degraded to heat. Hence, the input energy may be estimated using a simple enthalpy balance:

$$\Delta Q = m \times cp \times \Delta T \tag{3-1}$$

where ΔQ is the energy dissipated (J), m is the mass of the water in the simple calorimeter (g), cp is the specific heat capacity of water $\left({}^{J}\!/_{g.K} \right)$, and ΔT is the temperature rise (K).

The output power (W) from the sonicator tip was determined by Equation 3-2:

$$W = \frac{\Delta Q}{t} \tag{3-2}$$

where t is time (s) to achieve 5K temperature rise of 300 mL of distilled water. This output power will be presented as W/mL.

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3.3 Potato Starch Solubility

A first step in the evaluation of potato starch as a carbon source is to determine starch solubility in the wastewater. The solubility of starch in distilled water was assumed to be similar to the solubility in the wastewater. The procedures used to quantify the solubility were adapted from Greenberg et al., 1992. The potato starch obtained from Smiths Snackfoods was pre-dried at room temperature for twenty four (24) hours. An appropriate amount of starch (i.e., 10 g) was suspended in 100 mL distilled water in a beaker. An identical amount of starch was also prepared on a pre-dried and pre-weighed aluminium foil pan to determine the moisture content. The suspension was stirred with a magnetic stirrer for four hours. The suspension was then filtered using a vacuum filter apparatus with a 90 mm diameter Whatman glass fibre filter (GF/C). The vacuum filter apparatus is illustrated in Figure 3-2. Vacuum suction was maintained for approximately three minutes after the filtration was completed. The filtered solids were transferred to a pre-dried and pre-weighed aluminium foil pan. The solids remaining on the funnel were washed with distilled water and poured to the beaker used for mixing. Two millilitres of filtrate was used for SCOD testing (Section 3.6.1). The remaining filtrate and the starch prepared for moisture content were then placed in an oven for twenty four (24) hours in an oven at 105 ± 2^{o}C, cooled in a desiccator and weighed. In order to achieve an average solubility and SCOD result, this test was repeated in three times. The procedure was then repeated for each starch concentration.

Figure 3-2 Vacuum filter apparatus

3.4 Ultrasound Treatment of Return Activated Sludge

This sonication test was undertaken to investigate the amount of SCOD released from the return activated sludge (RAS). The procedure of RAS sonication test was adapted from Howland (2005). The experimental set up is illustrated in Figure 3-3.

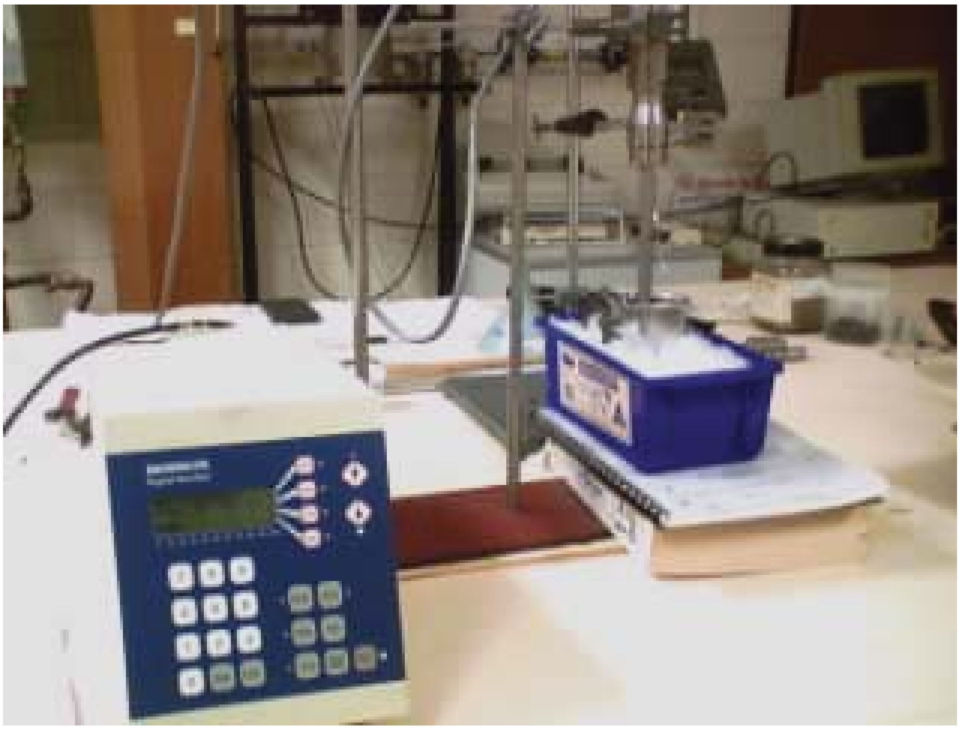


Figure 3-3 Sonication experimental set up

Connections between converter, horn and tip were inspected for tightness, and the retort stand with clamp was also checked to prevent movement while test was performed. A 100 mL sample of RAS was prepared and poured into a 300 mL beaker. The beaker was supported using a clamp and the 1/4″ tip of sonicator was immersed in the solution and located centrally to avoid contact with the beaker walls. The beaker was immersed in an ice bath to minimise the RAS temperature rise. This was required to minimise the possibility of tip breakage caused by excessive heat generation from the tip vibrations. The ultrasound unit (i.e. sonicator) was switched on, and the sonication time and operating amplitude desired were set. Sonication time and operating amplitude were the two independent variables. Ultrasonically treated RAS was then filtered using a vacuum pump, and its SCOD was measured (Section 3.6.3).

Several sonication experiments were conducted without utilising the ice bath to observe the temperature effect. In these tests a 1/8″ tip was always used. Results will be presented in Section 5.3.

3.5 Ultrasound Treatment of Potato Starch

As outlined in Section 2.4, ultrasound can induce transient cavitation leading to solid disruption. The effects of solid disruption on the solubility and SCOD release of potato starch are to be evaluated. Ultrasonic energy was applied to the potato starch in an attempt to improve its solubility and increase the amount of SCOD of potato starch. An appropriate amount of starch (e.g., 5 g) was suspended in 100 mL distilled water in a beaker. An identical mass of starch was also prepared on a pre-dried and pre-weighed aluminium foil pan to determine its moisture content. The suspension was stirred with a magnetic stirrer for 4 hours. The starch suspension was irradiated with ultrasound for 15 minutes at 50% amplitude. An ice bath was used to limit the starch suspension's temperature rise. The suspension was then filtered using a vacuum filter apparatus with a 90 mm diameter Whatman glass fibre filter (GF/C). Vacuum suction continued for approximately 3 minutes after the filtration is completed. The filtered solids were transferred to a pre-dried and pre-weighed aluminium foil pan. The solids remaining on the funnel were washed with distilled water and poured to the beaker used for mixing. Two millilitres of filtrate was used for SCOD test (Section 3.6.1). The remaining filtrate and the starch prepared for moisture content were then placed in an oven for 24 hours at 105 ± 2^{o}C, cooled in a desiccator and weighed. In order to achieve an average solubility and SCOD result, this test was repeated in three replicates.

3.6 Soluble Chemical Oxygen Demand (SCOD) Test

To compare the concentration of bio-available carbon in the molasses, the potato starch and the return activated sludge (RAS), the SCOD was measured. A HACH COD test kit was used. The soluble portion of potato starch and RAS were obtained by filtration following the procedure detailed in Section 3.3. The procedures were adapted from HACH DR/2010 Spectrophotometer Procedures Manual (HACH Company, 2000).

Figure 3-4 COD reactor and portable spectrophotometer

3.6.1 Potato Starch SCOD Test

Two millilitres of the filtrate that was prepared in the potato starch solubility test and ultrasound treatment of potato starch experiment was pipetted to a high range HACH COD vial. The COD test was then conducted following the HACH manual procedure (HACH Company, 2000).

3.6.2 Molasses SCOD Test

Molasses was diluted to a variety of concentrations (e.g., dilutions of 1:100, 1:1000 and 1:10000). Dilution was required because of the limitations of the test kits. After the samples were diluted to an appropriate concentration, the samples' COD were measured using the HACH spectrophotometer following the manufacture's procedure (HACH Company, 2000). The final SCOD is a mean of at least four replicates.

3.6.3 Return Activated Sludge SCOD Test

To identify the effects of ultrasound treatment of RAS, the SCOD released from the RAS before and after ultrasound treatment were measured. Following the sonication and filtration process, 2 mL of the filtrate that was prepared was pipetted to a High Range and High Range Plus HACH COD vial. The COD concentration range of the High Range HACH COD vials may be exceeded, thus High Range Plus COD vials were also utilised (0.2 mL of filtrate was pipetted instead of 2 mL). SCOD test was then performed following the HACH manual procedure (HACH Company, 2000). An SCOD test in molasses and RAS have been previously performed (Ford 2005), however new tests were performed to obtain current SCOD readings and to confirm results.

3.7 Carbon Dosing Test and Denitrification Analysis

In order to compare the denitrification performance of the carbon sources, carbon dosing tests and nitrate removal analysis were performed. The experimental set up is shown in Figure 3-5.

Figure 3-5 Denitrification experimental set up

The main focus of this experiment was to compare molasses, potato starch and sonicated RAS based on the extent to which SCOD was more available for biological uptake. The tests (adapted from Ford, 2005) were carried out as: standards of molasses, potato starch and sonicated RAS were prepared with the same initial SCOD (mg-SCOD/L). Two differing standard SCOD dosage concentrations were chosen; 12.48 and 124.80 mg-SCOD/L. Dosing figures were chosen to match the actual volumetric flow rate of molasses at the Glenelg WWTP denitrification unit, i.e. B and C Plant (refer to Figure 4-1). Each sample was mixed with primary effluent (PE), RAS1 and Mixed

Liquor Return (MLR) in a volume ratio of 1:1:3 respectively. The ratio was based on the flow rates of B and C Plant. A mass balance is provided in Chapter 4. A small volume was taken from each sample to be used for initial SCOD and nitrate testing (time = 0 minutes). The experiment was terminated after 24 hours. The sampling time chosen were t = 0, 30, 60, 120, 180, 240, 300, 360, 420, 1440 minutes. Nitrate concentration was determined using HACH Cadmium Reduction Method 8171 (HACH Company, 2000).

4 System Mass Balance

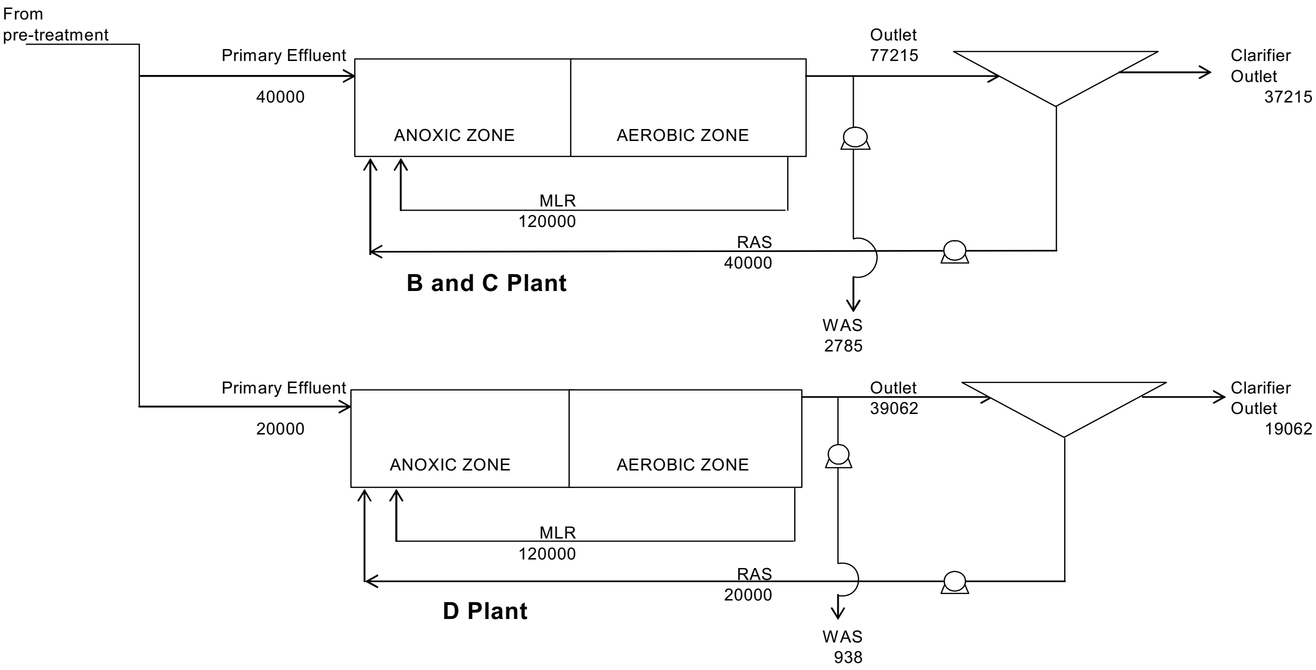


Figure 4-1 Process flow diagram of denitrification process at Glenelg WWTP (figures in m^3/d)

The Glenelg WWTP has three identical denitrification plants in parallel, the B and C Plants and D Plant. The process flow diagram of the denitrification plants is presented in Figure 4-1. The mass balance (m^3/d) of the process was provided by Sweeney (2005^b). Table 4-1 and Table 4-2 provide information of the volumetric flow rates at Glenelg denitrification plants.

Table 4-1 B and C Plant material balance

	Stream							
B&C PLANT Data	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	40,000	120,000	2,785	77,215	40,000	37,215	40,000	40,000

Table 4-2 D Plant material balance

	Stream							
D PLANT Data	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	20,000	120,000	938	39,062	20,000	19,062	20,000	20,000

The flow rates existing in the B and C Plants was chosen as the basis for the denitrification analyses. The composition of mixture in the laboratory scale reactor for denitrification analysis was based on Figure 4-1.

As mentioned in Section 3.7, the mixture content for the denitrification analyses was primary effluent (PE), RAS and Mixed Liquor Return (MLR) at a volume ratio of 1:1:3. As seen in Table 4-1, the volumetric flow rate (m^3/d) of PE: RAS: MLR is 40,000:40,000:120,000 ≈ 1:1:3.

5 Experimental Results and Discussion

This section summarises the results obtained from the experiments carried out. The results are also critically discussed to provide an understanding of the relative merits of the various carbon sources.

5.1 Power Output Determination of Ultrasound Device

The power output from the sonicator tip was determined following the procedure outlined in Section 3.2. The power output was based on 300 g (300 mL) of water. Thus, the power output obtained is in W/300mL. This unit was then converted to W/mL since the results will be used as the basis for the SCOD determination of RAS using V5 Sonix.

The results of this study are summarised in Table 5-1. This data was used to calibrate the sonifier and to generate a power output model for converting from % amplitude to Watts. A best fit line was fitted using the Excel curve fitting options (indicated in Figure 5-1). The fit of the model is high ($R^2 = 0.9994$) as a function of % Amplitude.

The power output appears to increase exponentially with % Amplitude. Standard deviation for this experiment ranges from 0.220 to 0.773. As indicated in Table 5-1, the standard deviation increases with power output. Since power output of the sonifier (sonicator) is related to heat dissipation, one possible reason is with higher power output, a higher thermal energy loss would occur. This error was minimised by using a material with low thermal conductivity (polypropylene) and insulated with HDPE. This allowed the gathering of results with minimum standard deviations.

Based on Figure 5-1, the relationship between the output power and amplitude (%) of the digital sonifier in water is represented by the power model shown below:

$$\mathrm{Y} = 0.0004X^{1.3832} \qquad \mathbf{5\text{-}1}$$

where X is the amplitude (%) of Branson Digital Sonifier 450, and Y is the corresponding power (W/mL). A linear best fit was not used as at 0 % Amplitude should not have a negative value of power output. Calculation details are provided in Appendix B.

With the assumption that properties of wastewater and water are similar, this model is then used to aid the construction of a model for power output scale up of the sonifier.

Table 5-1 Summary of sonicator power output

Power		Standard deviation
Amplitude %	Watt/mL (Watt/m^3)	
70	0.1358 (135.8)	0.2574
60	0.1137 (113.7)	0.1595
50	0.0879 (87.9)	0.1528
40	0.0652 (65.2)	0.1451
30	0.0432 (43.2)	0.0896
20	0.0243 (24.3)	0.0733

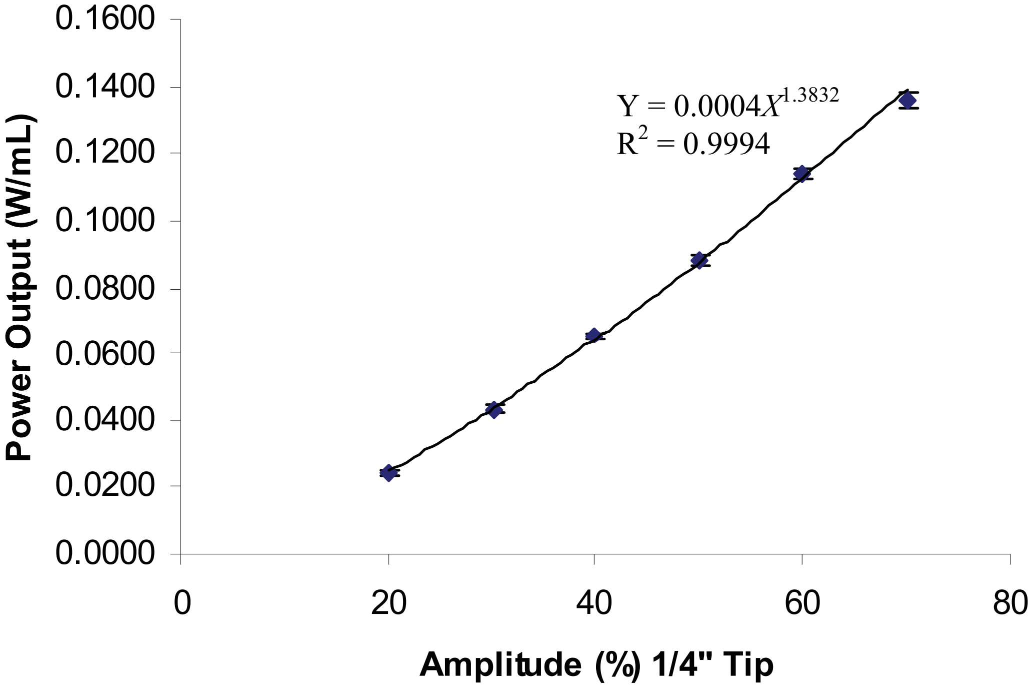


Figure 5-1 Relationship between power output (W/mL) and Amplitude (%)

5.2 Molasses SCOD Test

Multiple tests were performed to measure SCOD of molasses. There was considerable variation in the results. There are two potential cause, batch to batch variations and errors induced by large dilutions. Table 5-2 summarises the result for molasses SCOD. This result will be used as the basis for SCOD dosing using potato starch and sonicated RAS in the denitrification analysis.

Table 5-2 Molasses SCOD data

Average Molasses SCOD, mg-SCOD/L (PTAG cited in Ford, 2005)	Average Molasses SCOD, mg-SCOD/L (experimental)	Standard Deviation, mg-SCOD/L (experimental)
1.20×10^6	1.13×10^6	0.07×10^6

Dilution error were minimised by utilising the same laboratory apparatus and distilled water, and dilution process was performed accurately and carefully to avoid contamination. The SCOD of bulk molasses may be different in every delivery depending on the manufacturer/supplier. However, even when error is minimized, the difference (%) of molasses SCOD to the literature value is 6%.

5.3 Potato Starch and Potato Starch Sonication

This section provides results and discussion about the results obtained for potato starch solubility and soluble COD (SCOD). Results for ultrasound treated potato starch will also be discussed in this section.

5.3.1 Potato Starch Solubility

Several starch concentrations of potato starch were prepared to obtain graphical data on the percent soluble and starch concentration. The maximum solubility obtained from this study is $2.5\% \, ^{W}\!/_{W}$. The result obtained differed slightly to the study obtained by Singh et al. (2003). They reported the solubility of $0.05 \, ^{g}\!/_{g}$ (5%). The two possible causes of the divergence were the use of different potato cultivars and different methodology. The study performed by Singh et al. (2003), involved centrifugation in separating the insoluble portions of the starch (Leach et al., 1959).

Difficulty was experienced in obtaining consistent data. There was always the amount of slight discrepancies in the overall mass balance. The sum of the dissolved and undissolved starch differed slightly from the initial charge. As the solubility experiments involved mixing, filtration, drying, and moisture removal, starch may be lost in each unit operation. Another cause may be the variation in the moisture content of the starch. Careful determination of the moisture content was performed for each concentration to minimise such variation. Solubility test were also performed in multiple batches to obtain consistent data. The results are presented and summarised in Figure 5-2

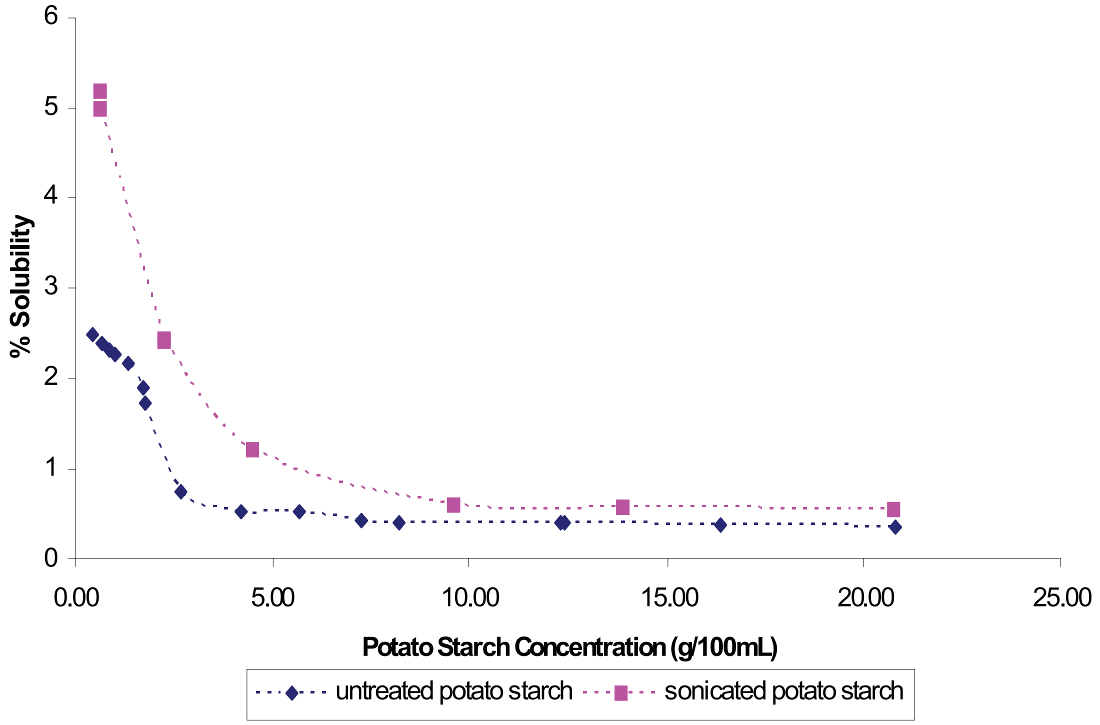


Figure 5-2 Percent dissolved potato starch for different starch concentration

As illustrated in Figure 5-2, the solubility of untreated potato starch at room temperature was extremely low. This may prohibit potato starch as a viable alternative carbon source unless a method for improving the solubility is developed. A potential technology for improving potato starch solubility and SCOD was the application of ultrasonic energy to induce transient cavitation, disrupt and slightly warm the starch particles. Figure 5-2 summarises the comparison of the percent solubility for ultrasonically treated potato starch to the untreated potato starch. Clearly the solubility of sonicated potato starch was increases particularly for low starch concentration. Unfortunately, as the starch concentration increased, the increase in solubility is substantially reduced. The improvement of the potato starch solubility by sonication may result from mechanical vibration in the suspension, leading to fracture of the solid starch particles to produce finer particles. Furthermore, ultrasound energy degrades to heat, hence increasing the temperature of the suspension to approximately 40°C. These heating effects may provide contributed reason for the observed improvement in potato starch solubility.

5.3.2 Potato Starch SCOD Test

Figure 5-3 summarises the amount of SCOD at various potato starch concentration. Clearly, the SCOD increases with increasing potato starch concentration. As indicated in Figure 5-2, the solubility obtained at room temperature is extremely low. However significant SCOD is available.

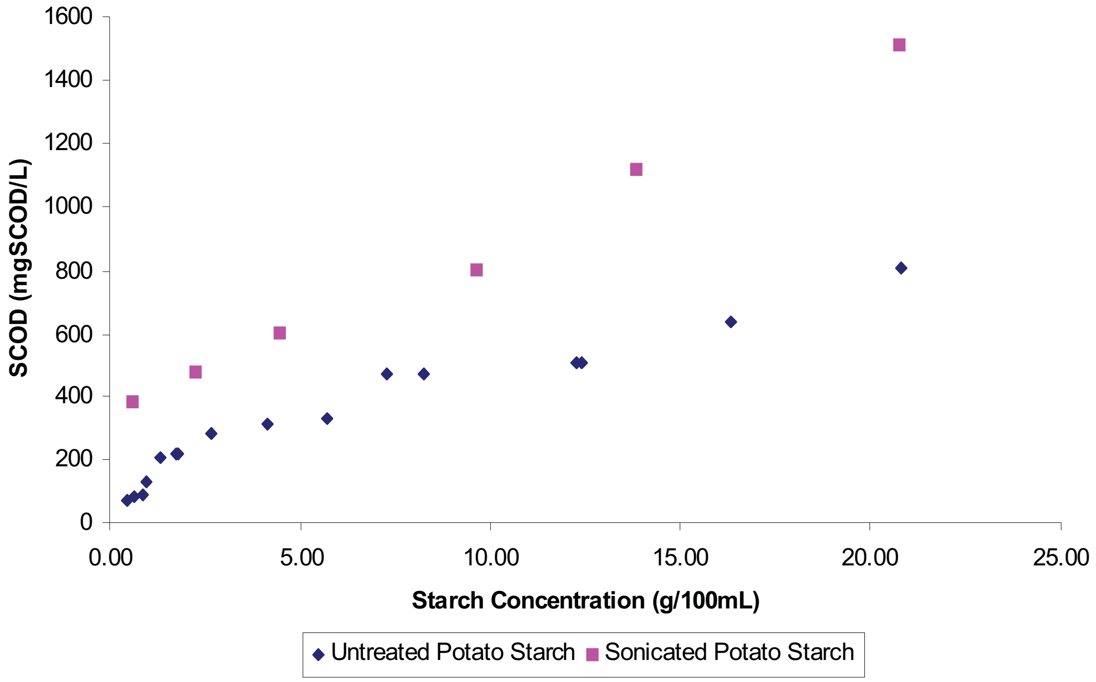


Figure 5-3 SCOD concentration for different potato starch concentration

In this study, the maximum soluble carbon release from potato starch was 809 mg-SCOD/L. If ultrasonic treatment is adopted, a substantial increase of SCOD release is observed. The SCOD released exceeds 1500 mg-SCOD/L. The high SCOD release may be a consequence of cavitation in the suspension, leading to the collapse of starch particles, hence increasing the SCOD. Other possible reason for the increase in the dissolved starch particles may result from particle size reduction and localized heating induced by sonic energy degradation.

Again, increasing the potato starch concentration results in a very low percent solubility, even though higher SCOD concentration was obtained. A possible cause is that the starch suspension has not been saturated by the starch's soluble fraction, even if the amount of soluble starch in that particular concentration has dissolved thoroughly.

As mentioned in Section 5.3.1, temperature rise may cause an improvement in potato starch solubility and SCOD release. A preliminary attempt was carried out to observe the effect of heat treatment in both the solubility and SCOD release in potato starch. Heat treatment with mixing (magnetic stirrer) was performed at approximately 45^{o}C. Unfortunately, the potato starch suspension commenced gelatinisation. Filtration became very difficult, and consistent result could not be achieved. Regarding potato starch as the carbon source, gelatinised starch would not be recommended, as pipe/pump blockage and filtration problems may arise. The mixing in the heat treatment was less intense compared to the ultrasound treatment, since sonication induces rupture. Therefore, it may be concluded that the effect of heat treatment with mixing in relation to improve solubility may not be as significant as ultrasound treatment.

5.4 Ultrasound Treatment of Return Activated Sludge

This section provides results and critical discussion for sonication of return activated sludge (RAS). Laboratory scale investigation on sonication return activated sludge (RAS) was primarily focused on the effect on the release of SCOD. The results provided include the SCOD concentration of untreated and sonicated RAS, as a function of sonication power and treatment time. The goal is to define optimal condition for preliminary design. Table 5-3 presents the SCOD of untreated RAS.

Table 5-3 SCOD of untreated RAS

Previous study RAS SCOD, mg-SCOD/L (Ford, 2005)	Average RAS SCOD, mg-SCOD/L	Standard deviation, mg-SCOD/L	% error to previous study
35.00	35.60	5.60	1.70 %

Results were consistent as confirmed from the low deviation in SCOD reading and minimal % error compared to previous data achieved by Ford (2005). The possible cause of this deviation was the variation of the initial SCOD in the wastewater influent, since sampling was conducted daily. The growth rate of the micro-organism is dependent on the available soluble substrate concentration (Tchobanoglous, 2003). As molasses supplies the external soluble substrate (SCOD) at a fixed rate, the SCOD in the wastewater would vary, where this may affect the SCOD of the RAS

Figure 5-4 shows the results SCOD release versus power per unit volume for ultrasonic treatment of RAS using 1/4″ tip as a function of treatment time. Minimum error was found for these experiments. The R^2 found were all above 0.97 (summarised in Table 5-6). However, since the power output of the sonifier is related to heat dissipation, with a higher power output, a higher thermal energy loss and unstable process would occur for a laboratory scale sonifier. Thus, this may affect the SCOD concentration released from sonicated RAS at a high sonifier power output.

As the sonication process causes heating to the solution, the effect on temperature was also observed in this study. Figure 5-5 shows the sonication results using 1/8″ tip without cooling using ice bath. In Figure 5-4, sonication at a power level of 0.1137 W/mL (60% amplitude) for 30 minutes released about 1600 mg-SCOD/L, whilst in sonication without cooling and same operating condition (Figure 5-5) released about 2000 mg-SCOD/L. A larger tip size would generate a higher SCOD release; however, the experiment that utilised the smaller size tip (1/8″ tip) with no ice bath produced higher SCOD release. Therefore energy degradation and subsequent heating produced a significant effect on the SCOD release.

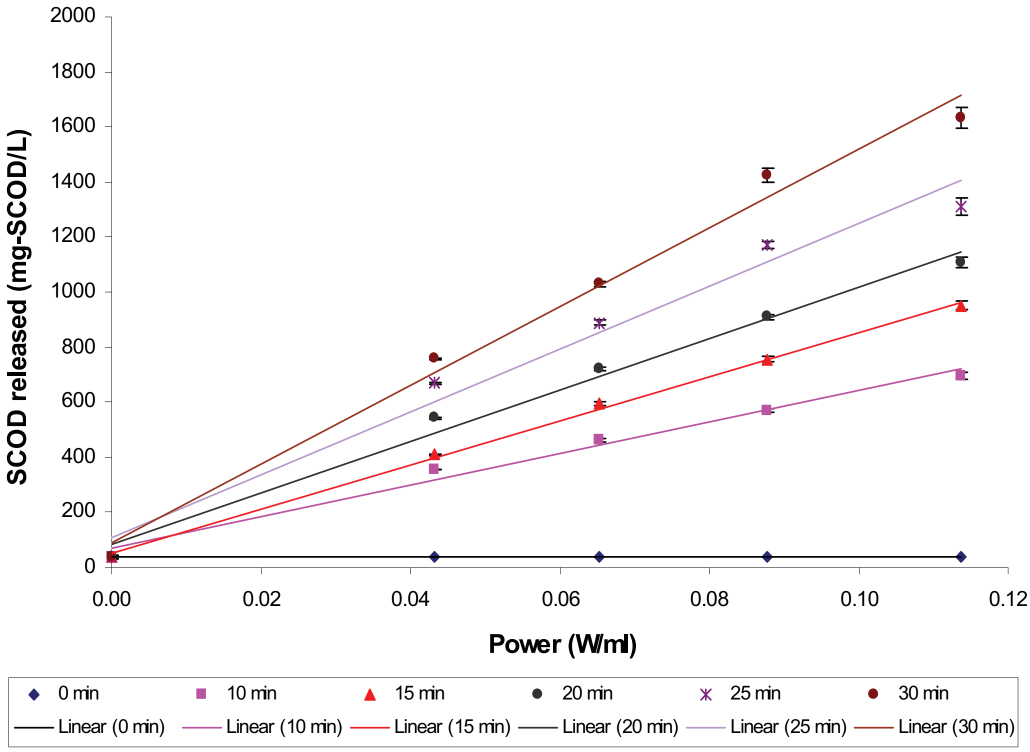


Figure 5-4 SCOD released by ultrasound treatment at various power output (W/mL) and treatment time 1/4″ tip, with ice bath

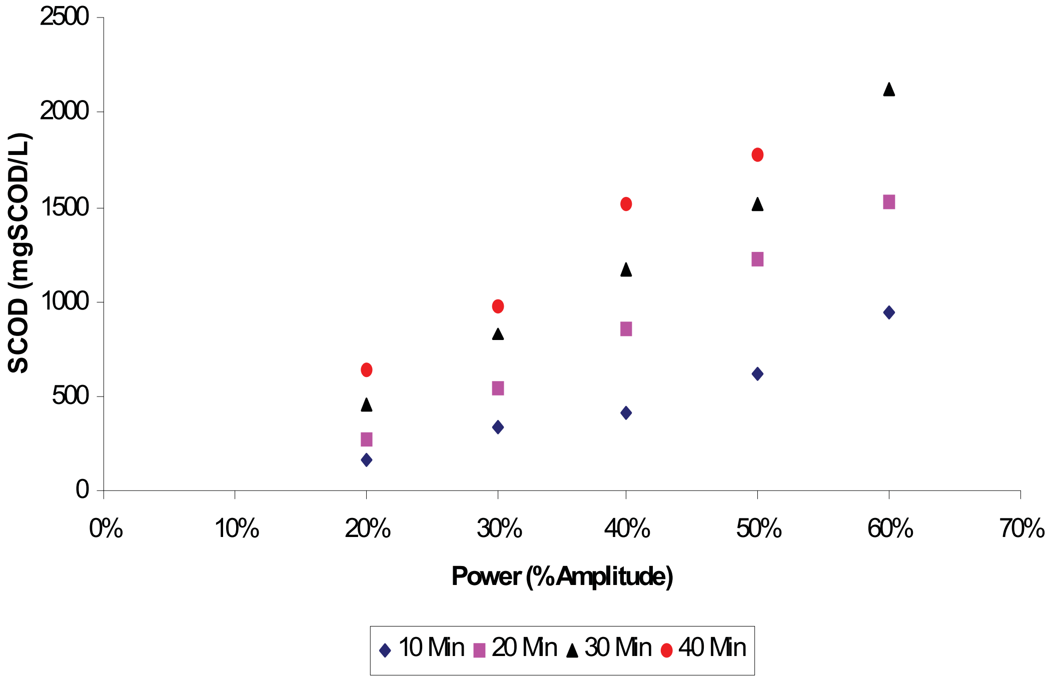


Figure 5-5 SCOD released by ultrasound treatment 1/8″ tip, without ice bath

Cooling of the sludge in ultrasound treatment in wastewater treatment plant would be impractical due to high operating cost. Hence, the SCOD release in the actual wastewater treatment plant may be underestimated. This may reduce the amount of RAS to be sonicated, thus reducing the number of V5 Sonix unit required and therefore reducing the capital costs.

Another objective of this experiment was to obtain a model suitable for scale up to plant scale with a V5 Sonix ultrasound unit. Experimental data using the 1/4″ tip was chosen for scale up. A specification of V5 Sonix power supply is provided in Table 5-4, and specifications for V5 Sonix reactor vessel is provided in Table 5-5 (Rooksby, 2007). One V5 Sonix unit treats approximately 200 m^3/d of sludge.

Table 5-4 Specifications of V5 Sonix power supply

Power Output	3 kW continuous, 19.5 kHz to 20.5 kHz at 1000 V
Power Input	3 phase 480 V, 50/60 Hz, 10 A

Table 5-5 Specifications of V5 Sonix reactor vessel

Number of stack required	5
Volume processed per 24 hours	200 m^3
Maximum working pressure	10 bar (10 atm)
Power Output (specific energy transferred to liquid)	4 – 11.5 W/mL
Retention time	1.5 to 2.0 seconds

The results presented in Figure 5-4 showed that SCOD release increases linearly with increasing power output and treatment time. The increase of SCOD was found to be 8.78 to 44.11 times that of the untreated RAS. These results agreed with the findings of Chu et al. (2001).

Using Microsoft Excel, linear correlations were determined for the relationship between power output and SCOD release. These equations were used to generate a model to predict the SCOD release by a V5 Sonix. Table 5-6 provides the summary of the model obtained.

Table 5-6 Model obtained from ultrasound treatment on RAS sonication experiments

Time, minute	Time, second	Model equation	Y results with X = 7.75 W/ml	R^2
0	0	Y = 35.60	35.60	0
10	600	Y = 5738.8705X + 67.2789	44508	0.9862
15	900	Y = 8049.9662X + 50.0723	62402	0.9982
20	1200	Y = 9374.5964X + 82.2542	72700	0.9888
25	1500	Y = 11396.1879X + 107.3616	88392	0.9764
30	1800	Y = 14339.6740 X + 87.3508	111184	0.9886

The sonicator power output was varied from 4 – 11.5 W/mL (Table 5-5). This study used an average power output (7.75 W/mL) for subsequent scale up and plant reconfiguration. Calculations and details for predicting the SCOD release using the specification of a V5 Sonix is shown in Appendix C.

Figure 5-6 summarises the predicted release using a 7.75 W/mL power output. Clearly, by applying 7.75W/mL power output, more SCOD was released, and increased linearly with time. Since the V5 Sonix has a 1.5 to 2 seconds retention time (2 second retention time was chosen), by using the equation generated from the results and extrapolation, the SCOD release may be calculated. Variable X represents retention time (s), and Y represents SCOD release (mg-SCOD/L) at time X. The SCOD release calculated is 12206 mg-SCOD/L.

Using the calculated SCOD value, two V5 Sonix units are required in the plant. However, based on the RAS flow rates of the plant's current configuration, three units of V5 Sonix are required. The details are provided in Section 6.2.1.1. To avoid the use of an addition sonicator, Option 2 was proposed. The details of Option 2 are given in Section 6.2.2.

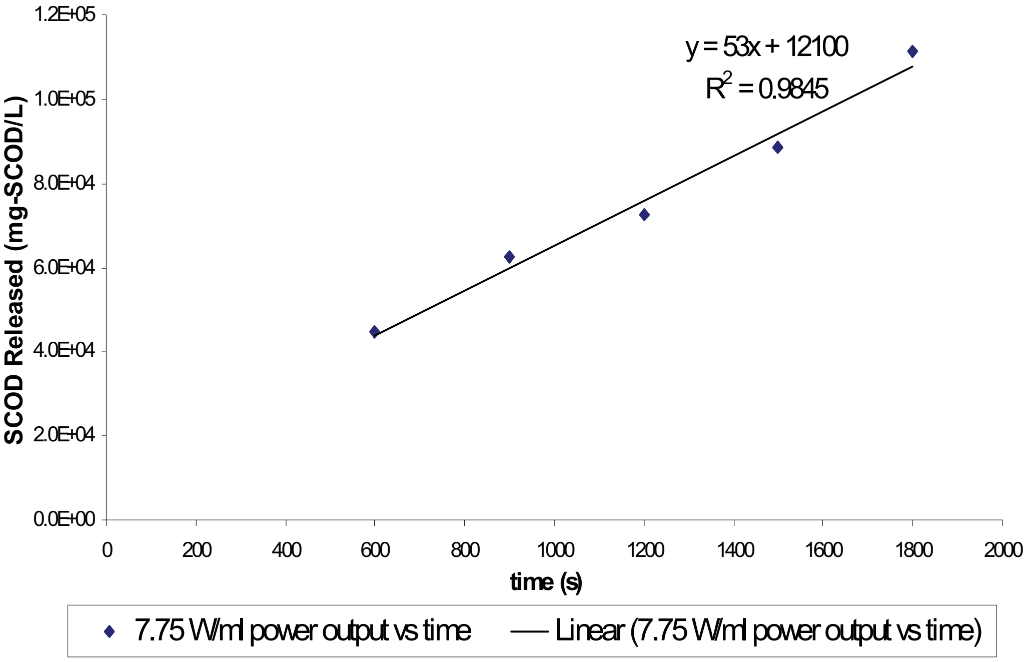


Figure 5-6 Predicted SCOD release using 3kW power output

5.5 Carbon Dosing Test and Denitrification Analysis

Nitrate removal tests were performed to rank the performance of the carbon sources, molasses, potato starch, and sonicated RAS. Two dosing concentrations, low dose (12.48 mg-SCOD/L), and high dose (124.80 mg-SCOD/L) were chosen. Results for both low and high dose are presented in Figure 5-7.

As carbon is a key food source of the micro-organisms, higher food concentration should increase the rate of the reproduction of the micro-organisms. Consequently, the nitrate removal would increase.

The observed plateau in nitrate removal (Figure 5-7) was initially attributed to exhaustion of bio-available carbon, restricting further denitrification process. Consequently, available carbon concentration during the process was monitored and recorded. The SCOD represents the carbon available in the reactor and its time course during the test are presented in Figure 5-8.

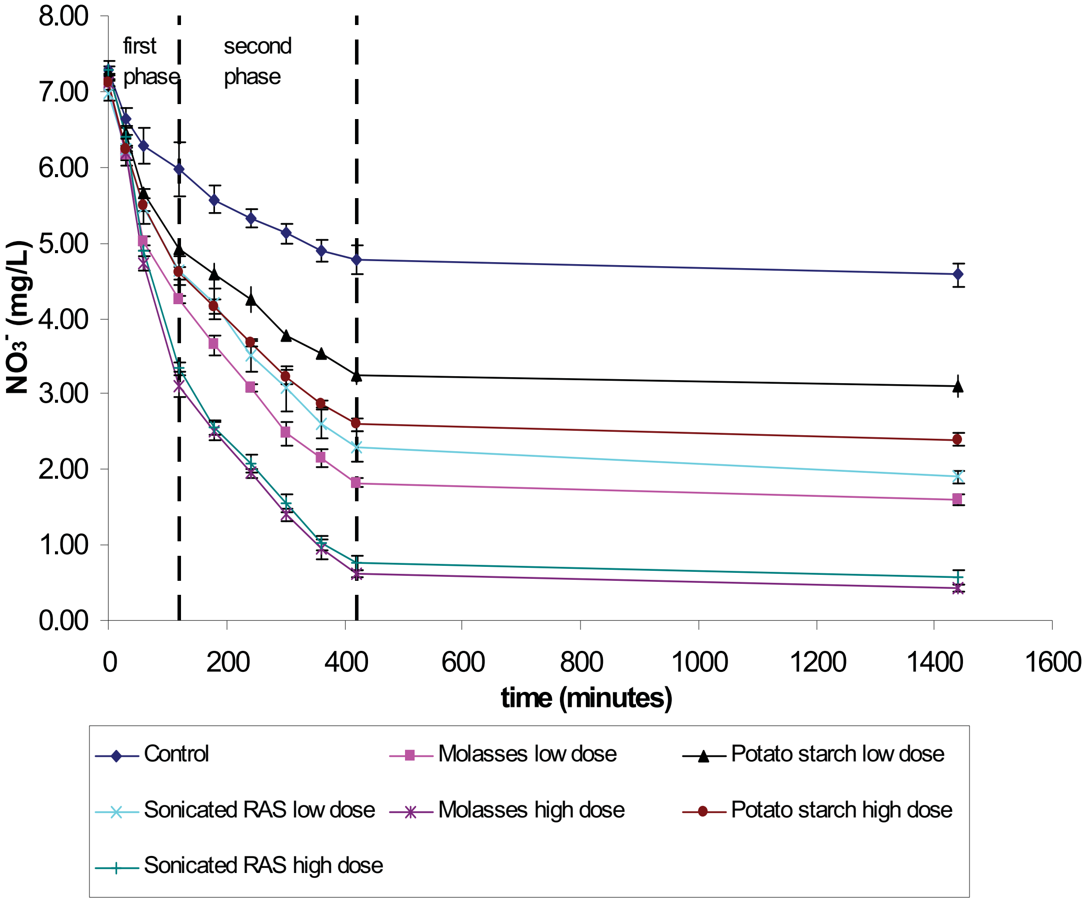


Figure 5-7 Change in nitrate concentration over time in denitrification analyses

As the dosage of carbon is relatively small, the carbon source that exists in the wastewater influent may be preferentially utilized by the micro-organisms initially, before utilizing the externally dosed carbon sources. The dosed carbon source with time becomes more bio-available for the micro-organisms. This may be due to the utilization of the digestible carbon source by the micro-organisms, followed by the more difficult carbon source to digest.

It was expected that the carbon sources would be consumed by the micro-organisms to convert nitrate to nitrogen gas. From Figure 5-8, the carbon concentration (SCOD) was decreasing significantly from t = 0 minutes to approximately t = 400 minutes, and approaching a constant value. Higher carbon uptake was observed for higher SCOD concentration dosed (carbon concentration decreases more steeply compared to low dose)

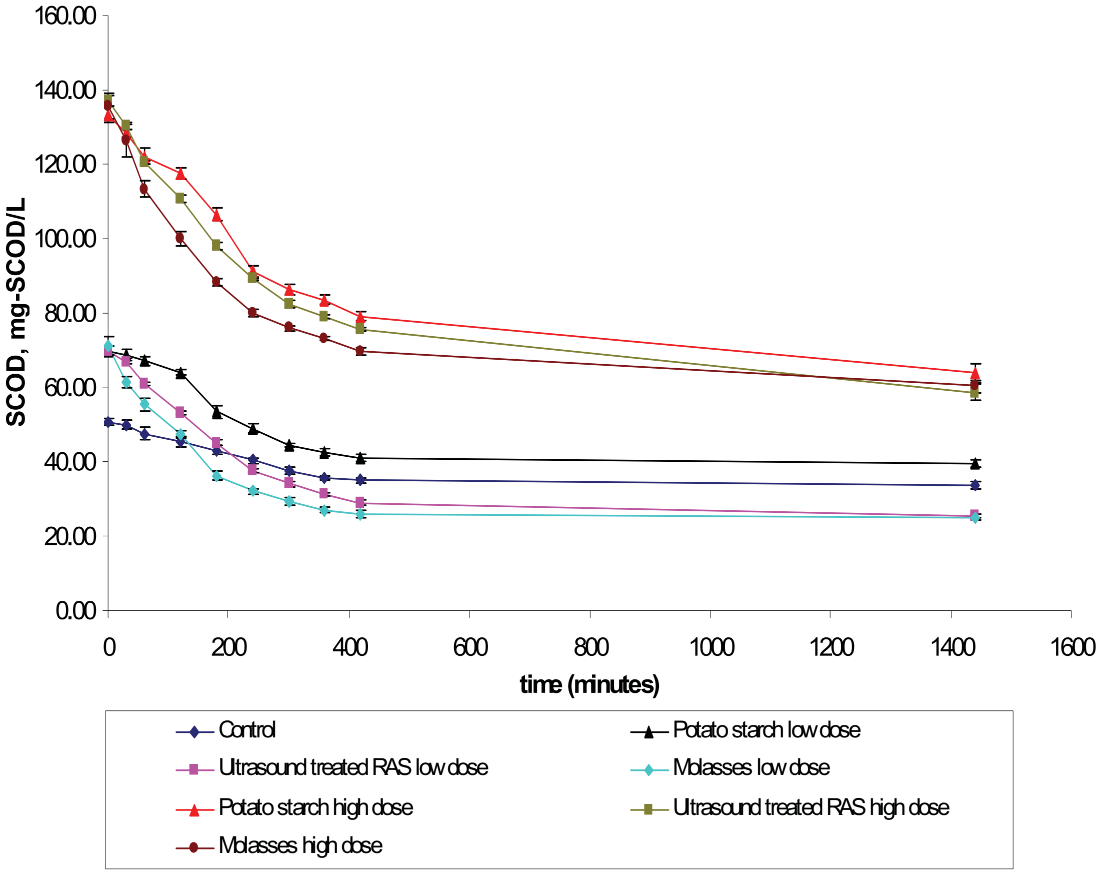


Figure 5-8 Change in SCOD concentration over time in denitrification analyses

For the high carbon dose, the carbon was not consumed by the micro-organisms after approx t = 400 minute. The reason may be caused by the insufficient number of nitrate removal micro-organisms to continue the process. There was no recycle of fresh RAS to the system, hence no external regeneration of the denitrifying micro-organisms.

Other than the quantity of carbon content, the characteristic of the carbon dosed may be one of many factors that influence denitrification performance. Different carbon source have different characteristics. As illustrated in Figure 5-7, the micro-organisms seem to prefer molasses as the carbon source for denitrification process. This is indicated by the high denitrification rate of molasses. The high denitrification rate is the result of the high quantity of readily biodegradable carbon in molasses (Quan et al., 2004).

The denitrification performance of sonicated RAS as a carbon source was similar to that of molasses. This is may be due to the release of intracellular components caused by the sonication (Bougrier et al., 2005) resulting a highly soluble state of carbon release, hence becomes more bio-available (readily biodegradable) for the micro-organisms. Other possible reason is that the sonicated RAS essentially has similar characteristics to the wastewater, thus enhances the digestibility of carbon by the micro-organisms (Chu et. al., 2000).

Results from the nitrate removal analyses showed that potato starch yield the least nitrate removal (Figure 5-7). Potato starch may not be a preferred carbon source for denitrification even when high carbon content is present. This may be caused by the unreadily digestible carbon, since potato starch contains long polymer chains of carbon. The breaking of carbon chains require enzymatic digestion, and would require additional energy. Furthermore, the enzyme produced by the micro-organisms within the wastewater may be insufficient or unsuitable to break the polymer carbon chains. Thus, soluble starch may not be a readily useable carbon for denitrification, which leads to a low nitrate removal rate (nitrate reduction rate).

There are three linear phases in nitrate removal (Griffiths, 1994, cited in Quan et al., 2004). The first phase has the highest denitrification rate, where the micro-organisms utilise the soluble readily biodegradable substrate. The second phase is where the micro-organisms utilise the particulate slowly biodegradable substrate. The third phase is where the micro-organisms utilise the endogenous substrate. This phase has the lowest rate of nitrate reduction. In this experiment, the third phase was neglected, since the nitrate removal process was terminated after approximately t = 400 minutes. The nitrate removal rate (NO_3^-/h) for each carbon dosed is presented in Table 5-7.

Table 5-7 Experimental results of nitrate removal rate using molasses, potato starch and sonicated RAS

	mg-NO_3^-/h			
	Low dose		High dose	
	first phase	second phase	first phase	second phase
Molasses	1.44	0.49	2.01	0.50
Potato starch	1.16	0.34	1.26	0.40
Sonicated RAS	1.18	0.47	1.96	0.52

As seen in Table 5-7, with a higher dose, the denitrification has a higher rate. Molasses has the highest nitrate reduction rate, followed by sonicated RAS, then potato starch. The denitrification rate accomplished using molasses has similar result to the research conducted by Quan et al. (2004). This research emphasised the first two phases, where the first phase has the highest denitrification rate, followed by the slow phase. Thus, the experimental results of this research agreed with the findings by Quan et al. (2004).

The nitrate removal efficiencies using the alternative carbon sources were also determined. The nitrate removal efficiency for each carbon dosed is presented in Table 5-8, and was calculated using Equation 2-5

Table 5-8 Comparison of nitrate removal efficiency using molasses, potato starch and sonicated RAS

Carbon dosed	Low dose (%)	High dose (%)
Molasses	77.54	94.04
Potato starch	57.24	66.32
Sonicated RAS	72.76	92.10

Molasses resulted in the highest denitrification efficiency, followed by sonicated RAS and potato starch, for both high and low dose. Again, this may be due to the quantity of soluble carbon, biodegradability and the characteristic of the carbon source.

Sonicated potato starch was not included in the denitrification analysis as the sonication process was more viable to be used for RAS. Although the SCOD released by both sonicated RAS and sonicated potato starch were comparable, potato starch contains high insoluble fraction, therefore may require post treatment process that will lead to a higher operating cost.

6 FEASIBILITY STUDY AND COSTINGS

This economic analysis aims to determine the feasibility of using sonication (ultrasound treatment) of return activated sludge (RAS) and potato starch to provide alternative carbon source for biological denitrification. Total expenditure estimates for potato starch and sonicated RAS were compared to those for molasses. Expenditure is the sum of total capital cost and total operating cost.

This analysis focuses on estimation of capital investment and the operating cost of the additional plant items which are retrofitted to the existing wastewater treatment. A number of assumptions were required as data on operating cost and some technical data for use of molasses were not available. Capital cost estimation is based on percentage of delivered equipment cost method which typically has ±20 – 30% accuracy. This method accounts for installation, instrumentation and controls, piping, electrical systems and others, including indirect costs. Table 6-1 (Peters et al., 2003) presents average values of the various percentages for typical chemical plants. Wastewater treatment plant was assumed to be in the solid-fluid processing plant category.

As this is an initial economic analysis, prices obtained for unit operations (equipment) were based on previous quotations or approximate cost from the literature. Such data is assumed adequate for this study. The Marshall and Swift Equipment Annual Cost Index were used to correct for time variations and geographic factor. Equation 6-1 (Peters et al., 2003) was applied to update purchase equipment cost to present cost.

$$\text{present cost} = \text{original cost}\left(\frac{\text{index value at present}}{\text{index value at time original cost was obtained}}\right) \qquad \textbf{6-1}$$

The prices quoted were rounded to three significant figures, since the market and raw material prices fluctuate on daily basis. However, the actual prices were used for the calculations. Price quotations from suppliers only provide an approximate estimate of the equipment required to establish the plant. Since price quotes were obtained in US dollars, the fixed capital investment and total capital cost were converted to Australian dollars for comparison to Australian market.

Table 6-1 Ratio factors for capital cost estimation based on delivered equipment cost

	Percent of delivered-equipment cost		
	Solid processing plant	Solid-fluid processing plant	Fluid processing plant
Direct costs			
Purchased equipment delivered	100	100	100
Purchased-equipment installation	45	39	47
Instrumentation and controls (installed)	18	26	36
Piping (installed)	16	31	68
Electrical systems (installed)	10	10	11
Buildings (including service)	25	29	18
Yard improvements	15	12	10
Service facilities (installed)	40	55	70
Total direct plant cost	*269*	*302*	*360*
Indirect costs			
Engineering and supervision	33	32	33
Construction expenses	39	34	41
Legal expenses	4	4	4
Contractor’s fee	17	19	22
Contingency	35	37	44
Total indirect plant cost	*128*	*126*	*144*
Fixed-capital investment	**397**	**428**	**504**
Working capital	**70**	**75**	**89**
Total Capital Investment	**467**	**503**	**593**

Currency conversion data is shown in Table 6-2 (XE Trade, 2007). Table 6-3 (McKetta, 1993; Peters et al., 2001; Chemical Engineering, 1997; Chemical Engineering, 1999; Chemical Engineering, 2004; Chemical Engineering, 2007) presents the combines annual Marshall and Swift Equipment Cost Index.

Table 6-2 Foreign currency exchange

GBP	US$	AU$
1	1.9673	2.5262
0.508306	1	1.2843

The Marshall and Swift index year 2006 (end of year 2006; January 2007) was the latest index obtained at the time the economic analysis was carried out.

Table 6-3 Marshall and Swift Equipment Cost Index

Year	Annual Index
1961	237.2
1991	930.6
1992	943.1
1993	964.2
1994	993.4
1995	1,027.5
1996	1,039.2
1997	1,056.8
1998	1,061.9
1999	1,068.3
2000	1,089.0
2001	1,093..9
2002	1,104.2
2003	1,123.6
2004	1,178.5
2005	1,244.5
2006	1,302.3

Electricity costs (EIA, 2007) are summarised in Table 6-4. The cost for (end of) year 2006 calculated using Table 6-3 and Equation 6-1:

Table 6-4 Electricity cost for industry in Australia

Year	US$/kWh	AU$/kWh
2000	0.045	
2002	0.049	
2003	0.054	
2004	0.061	
2006	**0.067**	**0.087**

$$\mathit{Electricity\ cost}\ 2006 = US\$\ 0.061 \times \left(\frac{1{,}302.3}{1{,}178.5} \right) = US\$\ 0.067$$

Using Table 6-2 to convert to Australian dollars,

$$US\$\ 0.067 \big/ kWh \times \left[1.284289 \frac{AU\$}{US\$} \right] = AU\$\ 0.087 \big/ kWh$$

6.1 Molasses

This section summarises relevant costs and the unit operations (equipments) used for molasses dosing. Total capital investment and operating costs of the molasses dosing are also presented in this section.

6.1.1 Molasses Total Capital Investment

Cost details of the equipment installation and civil work associated with molasses dosing are presented in Appendix E.1, Table E-1. The total cost was **AU$ 561,000** (2004 dollars). This data was provided by United Water International (Kaeding, 2007[a]). The total fixed capital investment in 2006 is estimated to be **AU$ 620,000** using the previous indices.

As stated earlier, the percentage of delivered equipment cost method was employed to calculate fixed capital investment for a solid-fluid processing plant. Using the index in Table 6-1, the fixed capital investment of a solid-fluid processing plant has a multiplier of 4.28. This value was used to estimate the actual purchase cost of equipment for molasses dosing as actual data was not available.

Thus, the purchased equipment cost is $\frac{100}{428} \times AU\$\ 620{,}000 = AU\$145{,}000$.

Again using data in Table 6-1, the percentage of delivered equipment cost for working capital is 75%. As the purchased equipment cost has now been quantified, the working capital required for molasses is $AU\$145{,}000 \times \frac{75}{100} = AU\$109{,}000$. A cost summary in Australian dollars for molasses total capital investment is presented in Table 6-5.

Table 6-5 Summary of molasses capital cost

	Fraction	Cost 2006 (AU$)
Purchased equipments	1.00/4.28	$ 145,000
Fixed Capital Investment	1.00	$ 620,000
Working Capital	0.75 of purchased equipment	$ 109,000
Total Capital Investment		**$ 874,000**

6.1.2 Molasses Operating Cost

Contributions to operating cost include bulk molasses cost, power consumption of molasses rotary pumps and pipe heaters, and maintenance and repair. Details of the calculation for operating cost estimation are provided in Appendix E.2.

6.1.2.1 Bulk Molasses Cost Estimate

The bulk molasses cost estimate (Mackenzie, 2007) requires knowledge of the plant flow rate and price of molasses (Table 6-6).

Table 6-6 Data of molasses pricing

Data	Value	Units
Dosing (plant)	140	L/h
	1226400	L/year
	1716960	kg/year
Cost by mass (AU$, 2006)	$0.35	$/kg
Cost by volume (AU$, 2006)	$0.49	$/L (includes delivery)

The annual cost for bulk molasses based on cost (volume basis) is:

$$AU\$601{,}000 \Big/ year$$

6.1.2.2 Electrical Power Estimate and Cost

Electricity cost estimation was based on the power requirement of molasses rotary pumps and pipe heaters.

6.1.2.2.1 Rotary Pumps

The properties of bulk molasses in Glenelg WWTP are provided in Table 6-7.

Table 6-7 Properties of molasses

Molasses properties	Value	Units
SG (Engineering tool box, 2007)	1.4033	
Viscosity (Transtronic, 2007)	8,700	cp

The density of molasses is 1403.3 kg/m^3. Molasses is a viscous liquid and requires a positive displacement gear pump. A rotary pump was chosen. A typical head value for this a rotary pump is 50,000 ft (15,240 m) (Suppes, G., J., 2002).

Equation 6-2 and 6-3 were used for design calculation of the rotary pump and electric power requirement:

$$brake\ \ kW = \frac{W_S \times m}{\eta \times 1000} \qquad \textbf{6-2}$$

where W_s is the mechanical energy in J/kg, m is the flow rate in kg/s, and 1000 is the conversion factor for W/kW and η is the fractional efficiency. The mechanical energy (W_S) added to the fluid can be expressed using Equation 6-3:

$$W_S = H \times g \qquad \textbf{6-3}$$

where, H is the developed head of the pump (m) of fluid being pumped, and g is the gravitational acceleration. The electric power input (kW) can be expressed by Equation 6-4 (Geankoplis, 1997):

$$electric\ power\ input\ (kW)\ = \frac{brake\ kW}{\eta_e} \qquad \textbf{6-4}$$

where η_e is the motor efficiency. From Table 6-6, the required molasses dose is 140 L/h for the plant. Hence, power input is:

$$m = 0.0546 \frac{kg}{s}$$

$$W_s = 149506.2178 \frac{m^2}{s^2} = 149506.2178 \frac{J}{kg}$$

$$brake\ kW = 13.6051\ kW$$

$$electric\ power\ input = 15.4603\ kW$$

The pump requires a 16 kW motor and assuming 24 hours operation per day, the energy required is:

$$kWh = 16\ kW \times 24\ h/day = 384\ kWh/day$$

6.1.2.2.2 Pipe Heaters

Pipe heaters are used to increase the temperature of molasses in order to reduce its viscosity and to achieve an adequate flow. The total heater length is 66.9 m. (Kaeding (2007b). The heater power output is 12.6 W/m. The average % pipe heat loss to molasses and surrounding is 81.29% (refer to Appendix E.2.2). Using this average percentage pipe heat loss, a rough estimation of the total power requirement is $1.0370\ kW$. Assuming 24 hours operation per day, the power requirement becomes:

$$1.0370\ kW \times 24\ h = 24.8861\ kWh/day$$

6.1.2.3 Annual Electricity Cost

Total electricity consumption (kWh/d) is

Molasses heater energy consumption + molasses rotary pumps

$$24.8861\ kWh/day + 384\ kWh/day = 408.8861\ kWh/day$$

Assuming 365 operating days per year,

$$Electricity\ \cos t = AU\$\ 13{,}000/year$$

The detailed design calculations for molasses operating cost are available in Appendix E.2.

6.1.2.4 Maintenance and Repair

Maintenance and repair was assumed to be 2% of the fixed capital investment (Peters et al., 2003).

Maintenance and repair $= 0.02 \times AU\$\ 620{,}000 = AU\$\ 12{,}400$

6.2 Ultrasound Treatment

An in-line flow-through sonicator (V5 Sonix) was chosen as the ultrasound source for the treatment of RAS. This will necessitate an adjustment in the RAS flow sheet. The sonicator must not be located directly in the RAS stream, as would result disruption to the entire RAS cells (Kaeding, 2006). If this occurs, no denitrifiers will be available to perform denitrification. Hence, a by-pass stream is required to be constructed to split the main RAS stream and to provide a by-pass RAS stream for sonication.

Two options are proposed for the reconfiguration of denitrification plant regarding to the number of V5 Sonix required. These proposals are based on the results described in Section 5.4.

The options are discussed in the following section. A detailed material balance of each option is provided. A detailed summary of the required unit operations, the operating cost and total capital investment are also presented. Detailed calculations are provided in Appendix F.

The process flow sequence and the resulting material balance were based on the operating conditions for the Glenelg WWTP. The reconfiguration for Option 1 introduces a new stream for installation of V5 Sonix. The main RAS streams of each denitrification plants are split in to two streams, the initial stream (RAS 1) and a by-pass RAS stream (RAS 2). V5 Sonix units are installed in the by-pass stream. The reconfigured flow sheet for Plants B and C is presented in Figure 6-1, and the reconfiguration of Plant D is presented in Figure 6-2.

The volumetric flow rates of each stream are summarised in Table 6-8 and Table 6-9. The WAS stream is simply spit. Clearly, flow rates of RAS and MLR are unaltered. Hence, the system material balance and the SRT (sludge retention time) are not affected.

6.2.1 RAS Sonication Option 1

Referring to the material balance shown in Figure 6-1 and Figure 6-2, the V5 Sonix and additional centrifugal pumps required for the total soluble carbon of molasses dosage for Glenelg WWTP Option 1 was initially quantified from the volumetric dosing rate of molasses.

The molasses volumetric dosing rate is 140L/h. One litre of molasses provides 1.13 x 10^6 mg-SCOD (to 3 s.f). From Section 5.4, 1 Litre sonicated RAS using V5 Sonix provides 1.22 x 10^4 mg-SCOD (to 3 s.f). The required sonicated RAS to have the same soluble carbon of 1 L molasses is:

$$\frac{1.13\times 10^6}{1.22\times 10^4} = 92.63\frac{L\ RAS}{L\ molasses}$$

For the whole plant, the required sonicated RAS is:

$$140\,{}^{L\ molasses}\!\!\diagup_{h}\times 92.63\frac{L\ RAS}{L\ molasses} = 13{,}000\,{}^{L\ RAS}\!\!\diagup_{h}$$

$$13{,}000\,{}^{L\ RAS}\!\!\diagup_{h}\times\frac{1\,m^3}{1000\,L}\times\frac{24\,h}{d} = 312\,{}^{m^3\ RAS}\!\!\diagup_{d}$$

For B and C Plants,

$$\frac{2}{3}\times 312\,{}^{m^3\ RAS}\!\!\diagup_{d} = 208\,{}^{m^3\ RAS}\!\!\diagup_{d}\left(8630\,{}^{L}\!\diagup_{h}\right)$$

For D Plant,

$$\frac{1}{3}\times 310.63\,{}^{m^3\ RAS}\!\!\diagup_{d} = 104\,{}^{m^3\ RAS}\!\!\diagup_{d}\left(4310\,{}^{L}\!\diagup_{h}\right)$$

6.2.1.1 Denitrification Plant Reconfiguration Option 1

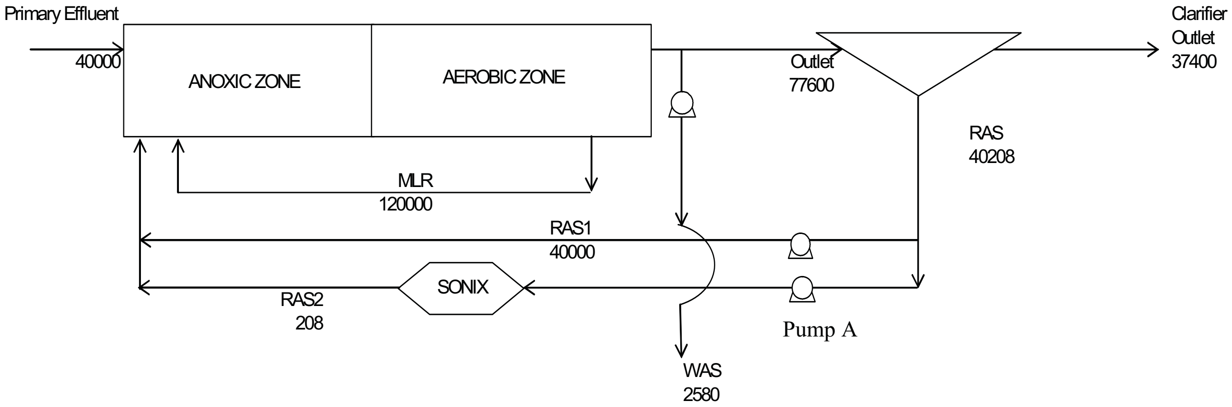


Figure 6-1 Modifications of RAS stream for B and C Plants (figures in m^3/d)

Table 6-8 Summary of B and C Plant material balance Option 1

Stream	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	RAS1	RAS2	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	40000	120000	2580	77600	40200	40000	208	37400	40000	40000

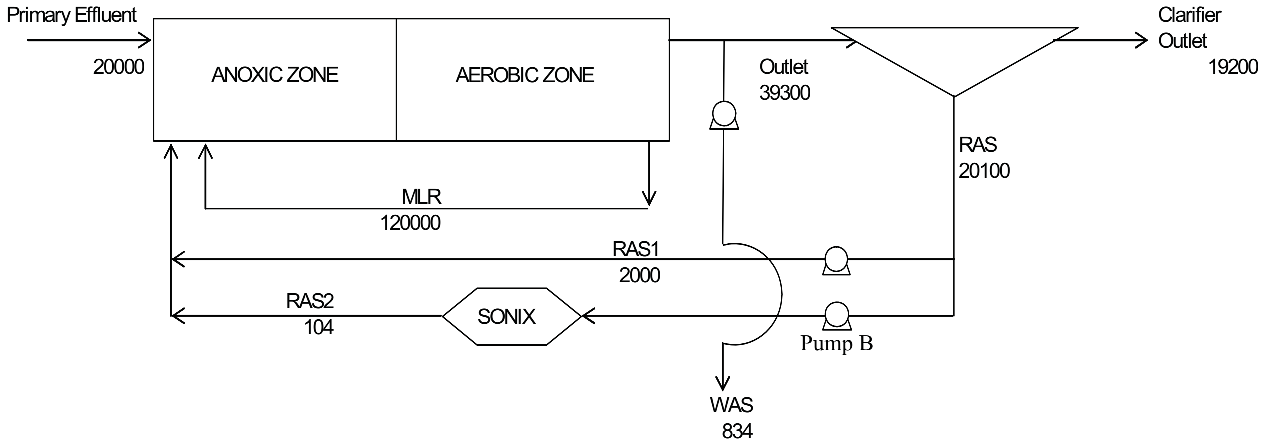


Figure 6-2 Modifications of RAS stream for D Plant (figures in m^3/d)

Table 6-9 Summary of D Plant material balance Option 1

Stream	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	RAS1	RAS2	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	20000	120000	834	39300	20100	2000	104	19200	20000	20000

6.2.1.1.1 V5 Sonix

The total RAS required to be sonicated is 312 m^3/d. Referring to Table 5-5, one V5 Sonix unit is able to treat 200 m^3/day of sludge. Hence, two V5 Sonix units are required. Unfortunately, the flow rate of Plants B and C exceeds the limiting capacity of a single unit V5 Sonix unit. Therefore, a total of three units are necessary, two V5 Sonix units are required for Plants B and C, and one V5 Sonix unit for Plant D (Appendix F.1.1). The purchase cost for three V5 Sonix units (including 10% delivery cost) is **US$ 1,230,000**.

6.2.1.1.2 Centrifugal pumps

The output flow rate of centrifugal pumps was matched to the capacity of each denitrification plant. Two additional RAS centrifugal pumps are required for this option (Appendix F.1.2). Plants B and C requires a single centrifugal pump with a capacity of 270 m^3/d and a 7 kW motor. Plant D requires a centrifugal pump with a capacity of 135 m^3/d and a 6 kW motor. These pump capacity includes a design margin of 30%.

The total purchase cost for centrifugal pumps (including 10% delivery cost) is **US$ 13,400**.

6.2.1.2 Sonicated RAS Operating Cost – Option 1

This section provides the operating cost for the unit operations listed in Section 6.2.1. Maintenance and repair for the unit operations are also included. Detailed operating cost calculations are given in Appendix F.2.

6.2.1.2.1 V5 Sonix

Three V5 Sonix units are required for proposed process. The total energy consumption is 1080 ${kWh}/{d}$ and the resulting energy cost is $US\$\ 26{,}600/{year}$

6.2.1.2.2 Centrifugal Pumps

Two centrifugal pumps were proposed, one for the combination of Plants B and C, and one for Plant D. Table 6-10 presents the design basis.

Table 6-10 Values of assumption used for centrifugal pump cost

Assumptions	Value	Units
Maximum allowable pressure (Peters et al., 2003)	1035	kPa
Viscosity	<0.1	Pa.s (kg/m.s)
Density at 25^{o}C	1035	kg/m^{3}

The pump for Plant B and C requires a 7 kW motor whilst that for Plant D requires a 6 kW motor. The total power is 13 kW or $312\,{}^{kWh}\!/_{d}$. The annual power cost is $US\$\,7{,}700\,{}/_{year}$.

6.2.1.2.3 Maintenance and Repair

Maintenance and repair costs were assumed to be 2% of the fixed capital investment. Maintenance and repair cost for RAS sonication Option 1 is $US\$\,107{,}000$.

6.2.1.3 Sonicated RAS Total Capital Investment – Option 1

The proposed ultrasound devices are located in the RAS by-pass stream. The by-pass stream required additional pumps. The required equipment for RAS sonication is summarised in Table 6-11 and Table 6-12 shows the summary of capital cost estimation for ultrasound treatment (sonication) of RAS Option 1. Detailed design calculation and purchase cost estimation for the unit operations are available in Appendix F.1.

Table 6-11 Summary of purchased equipments for RAS sonication Option 1

Summary RAS	Price US Dollars
V5 Sonix (3 units)	$ 1,121,372
V5 Sonix delivery	$ 112,137
Centrifugal Pump	
B&C Plant	$ 6,841
D Plant	$ 5,307
10% delivery	$ 1,215
Sub Total	$ 1,246,872

Table 6-12 Summary of capital cost estimation for RAS sonication Option 1

DIRECT COST	Fraction of delivered equipment	Cost (US$)
Purchased equipments	1.00	$ 1,246,872
Purchased equipments installation	0.39	$ 486,280
Instrumentation and controls (installed)	0.26	$ 324,187
Piping (installed)	0.31	$ 386,530
Electrical equipment (installed)	0.1	$ 124,687
Buildings (including services)	0.29	$ 361,593
Yard improvements	0.12	$ 149,625
Service facilities (installed)	0.55	$ 685,780
Total Direct Cost	3.02	**$ 3,765,554**
INDIRECT COST		
Engineering and supervision	0.32	$ 398,999
Construction expenses	0.34	$ 423,937
Legal expenses	0.04	$ 49,875
Contractor's fee	0.19	$ 236,906
Contingency	0.37	$ 461,343
Total Indirect Cost	1.26	**$ 1,571,060**
Fixed Capital Investment	4.28	**$ 5,336,613**
Working Capital	0.75	**$ 935,154**
Total Capital Investment		**$ 6,271,768**

Using currency conversion from Table 6-2, the total fixed capital investment of Option 1 RAS ultrasound treatment (sonication) is **AU$ 6,850,000**, and the total capital cost is **AU$ 8,050,000**.

6.2.2 RAS Sonication Option 2

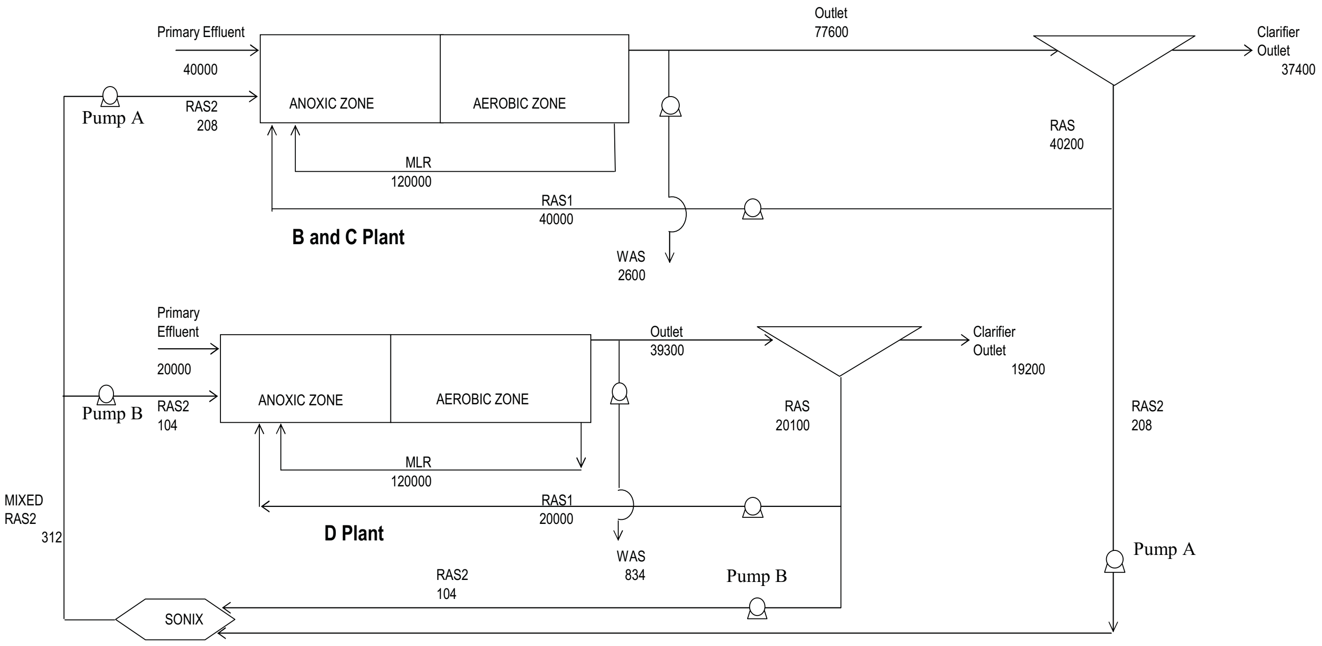


Figure 6-3 Flow diagram of combined RAS2 streams (figures in m^3/d)

RAS Sonication Option 2 combines the by-pass RAS stream from all denitrification plants to reduce the number of sonicators required. The plant reconfiguration for Option 2 is presented in Figure 6-3.

6.2.2.1 Denitrification Plant Reconfiguration Option 2

The plant reconfiguration Option 2 has the same concept to the plant reconfiguration Option 1, thus the system material balance and the SRT would not be greatly affected.

Table 6-13 Summary of B and C Plant material balance Option 2

Stream	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	RAS1	RAS2	Mixed RAS2	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	40000	120000	2600	77600	40200	40000	208	312	37400	40000	40000

Table 6-14 Summary of D Plant material balance Option 2

Stream	Primary Effluent	Mix Liquor Return	Waste Sludge	Outlet	RAS	RAS1	RAS2	Clarifier Outlet	BALANCE IN	BALANCE OUT
Volumetric flow, m^3/d	20000	120000	834	39300	20100	20000	104	19200	20000	20000

Whilst number of sonicators is reduced, this option requires four additional RAS centrifugal pumps. Since there are no changes in the flow rates, the same motor specifications were used. Operating details follow. Detailed operating cost estimates are provided in Appendix F.5.

The overall material balance based on Figure 6-3 is summarised in Table 6-13 and Table 6-14, the total flow of the by-pass RAS stream is 312 m^3/d.

6.2.2.1.1 V5 Sonix

Each sonicator can process 200 m^3/day of sludge, thus

$$\text{V5 Sonix units required} = \frac{312\ \text{m}^3/\text{d}}{200\ \text{m}^3/\text{d}} = 1.56 \approx 2\ \text{units}$$

The total purchase cost for two V5 Sonix units (including 10% delivery cost) is **US$ 822,000**.

6.2.2.1.2 Centrifugal Pumps

Based on Figure 6-3, four additional RAS centrifugal pump are necessary. Plants B and C requires two centrifugal pump units with a capacity of 270 m^3/d and 7 kW motor. Plant D requires two units of centrifugal pumps with a capacity of 135 m^3/d and a 6 kW motor.

The total purchase cost for centrifugal pumps (including 10% delivery cost) is **US$ 26,700**.

6.2.2.2 Sonicated RAS Operating Cost – Option 2

This section summarises the operating cost including repair and maintenance for the required equipments in Option 2 (Section 6.2.1). Detailed operating cost calculations are available in Appendix F.2.

6.2.2.2.1 V5 Sonix

Two V5 Sonix units are required with a total energy consumption of $720\,{}^{kWh}\!/\!_{d}$ and an associated cost of $US\$\,17{,}700\,/_{year}$.

6.2.2.2.2 Centrifugal Pumps

The pump for Plant B and C requires two 7 kW motor whilst that for Plant D requires two 6 kW motor. The total power is 26 kW or $624\,{}^{kWh}\!/\!_{d}$. The annual power cost is $US\$\,15{,}400\,/_{year}$.

6.2.2.2.3 Maintenance and Repair

Maintenance and repair was assumed to be 2% of the fixed capital investment and for Option 2 is $US\$\,72{,}700$.

6.2.2.3 Sonicated RAS Total Capital Investment – Option 2

Table 6-15 and Table 6-16 summarize the purchased equipment cost and total capital cost for Option 2. Detailed design calculation and purchase cost estimation for the unit operations are available in Appendix F.4.

Table 6-15 Summary of purchased equipments for RAS sonication Option 2

Summary RAS	Price US Dollars
2 V5 Sonix (2 units)	$ 747,582
V5 Sonix delivery	$ 74,758
Centrifugal Pump	
B&C Plant	$ 13,681
D Plant	$ 10,615
10% delivery	$ 2,429
Sub Total	$ 849,065

Table 6-16 Summary of capital cost estimation for RAS sonication Option 2

DIRECT COST	Fraction of Delivered Equipment	Cost (US$)
Purchased equipments	1.00	$ 849,065
Purchased equipments installation	0.39	$ 331,135
Instrumentation and controls (installed)	0.26	$ 220,757
Piping (installed)	0.31	$ 263,210
Electrical equipment (installed)	0.1	$ 84,907
Buildings (including services)	0.29	$ 246,229
Yard improvements	0.12	$ 101,888
Service facilities (installed)	0.55	$ 466,986
Total Direct Cost	3.02	**$2,564,177**
INDIRECT COST		
Engineering and supervision	0.32	$ 271,701
Construction expenses	0.34	$ 288,682
Legal expenses	0.04	$ 33,963
Contractor's fee	0.19	$ 161,322
Contingency	0.37	$ 314,154
Total Indirect Cost	1.26	**$1,069,822**
Fixed Capital Investment	4.28	**$3,633,999**
Working Capital	0.75	**$ 636,799**
Total Capital Investment		**$4,270,797**

Using currency conversion (Table 6-2), the fixed capital investment of Option 2 RAS ultrasound treatment (sonication) is **AU$ 4,670,000**, and the total capital cost is **AU$ 5,490,000**.

6.3 Potato Starch

The second alternative investigated was the use of potato starch as external carbon dosing. Figure 6-4 presents the plant configuration using this carbon source.

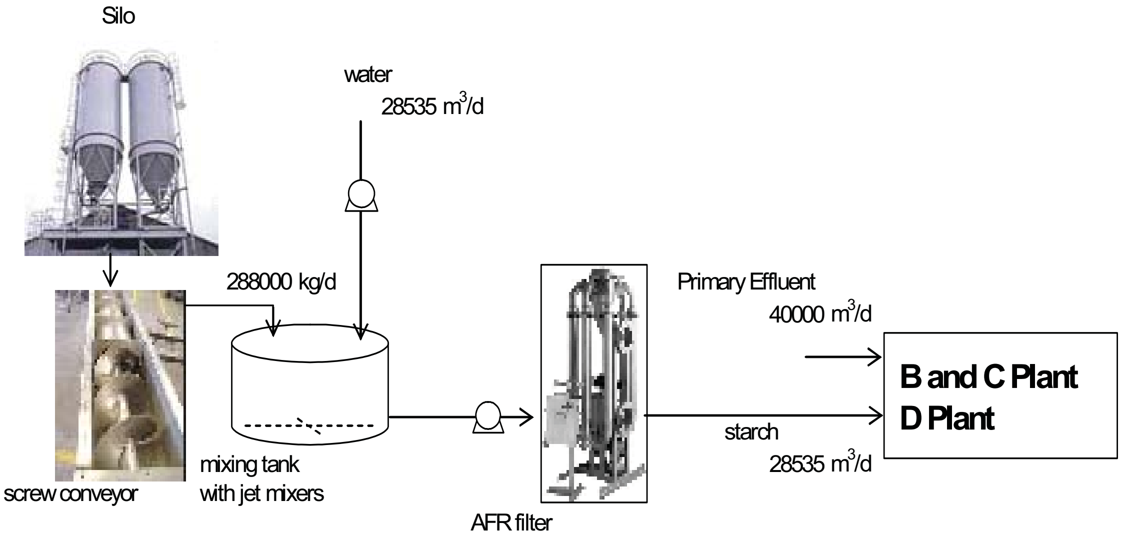


Figure 6-4 Plant reconfiguration for starch as external carbon dose

6.3.1 Potato Starch Mass Balance

Again, the available soluble COD of potato starch must be equivalent to that for molasses. The molasses volumetric dosing rate is 140 L/h. A litre of molasses provides 1.13 x 10^6 mg-SCOD. From earlier experimental results, the solubility of potato starch is very low. The proposed concentration used for carbon dosing is 10 g/L (2% solubility) since a higher suspension concentration would have less solubility.

One litre of this potato starch suspension provides 133 mg-SCOD and the required ratio is

$$\frac{1.13 \times 10^6}{133} = 8500 \frac{L\ potato\ starch\ suspension}{L\ molasses}$$

The resulting flow rate of potato starch is:

$$\frac{140\ L\ molasses}{h} \times \frac{8500\ L\ (potato\ starch\ suspension)}{L\ (molasses)}$$

$$= \frac{1.19 \times 10^{6}\ L\ potato\ starch\ suspension}{h} = \frac{1190\ m^{3}\ \ potato\ starch\ suspension}{h}$$

The required mass flow rate of potato starch suspension is

$$\frac{10\ g}{L} \times 1.19 \times 10^{6}\ L\ (potato\ starch\ suspension) \big/ h = 1.19 \times 10^{7}\ g \big/ h$$

$$= 12{,}000\ kg \big/ h$$

Assuming a weekly delivery cycle, the mass of potato starch required per week is:

$$12{,}000\, kg \big/ h \times 24 = 288000\, kg \big/ d \times 7\ d \big/ week = 2{,}020{,}000\, kg \big/ week$$

Giving 30% allowance, the mass of potato starch per week is:

$$2{,}020{,}000\, kg \big/ week \times \frac{130}{100} = 2{,}630{,}000\, kg \big/ week$$

6.3.2 The Reconfigured Flow Sheet Using Potato Starch as External Carbon Source

Additional process items include potato starch powder storage tanks, screw conveyor, starch mixing tanks, filtration units and centrifugal pumps. The total capital investment and operating costs for this process follow.

6.3.2.1 Potato starch powder storage tank (silo)

Relevant design calculations are provided in Appendix G.1.1. Required available storage volume per week is $2{,}180\ m^{3}$ (58,000 gallons). Based on available tank size and to simplify the design calculations, an API, cone roof, and field fabricated, at atmospheric operating pressure tank was chosen. The material chosen is carbon steel and API.

The purchase cost for the storage tank (including 10% delivery) is **US$ 300,000**.

6.3.2.2 Mixing Tank

The properties of the starch suspension were assumed to be similar to water, as the solid concentration is low (10 g/L). Therefore, the tank design was based on water storage tanks. A prestressed cylindrical concrete tank was chosen given the large volume required. The design was based on the method of Creasy (1961).

Detailed design calculations are provided in Appendix G.1.2. The required dimensions were 40 m diameter and 5 m depth with a wall thickness of 1.1 m. The tank was proposed to be buried in the ground with fixed wall-foot type, in order to resist further stresses from the mixing process.
The purchase cost for the concrete mixing tank (including 10% delivery) is **US$ 205,000**.

6.3.2.3 Jet Mixers

Given the size of the tank, mixing with impeller is impractical. Hence, the use of jet mixers is proposed. A total of eighty jet mixers are required. The jet mixer size is 3 with detailed design calculation given in Appendix G.1.3. The proposed jet mixer arrangement is illustrated in Figure 6-5. This arrangement was determined to be optimal in a project conducted by Mixing Systems, Inc. (2007). Arrows indicate the flow direction.

The cost of jet mixers is insignificant compared to other unit operations. The cost of jet mixers is dominated by the cost of the centrifugal pump providing the pressurised flow (Peters et al., 2003). With 10% delivery cost, the purchase cost is **US$ 47,900**.

A more detailed capital cost was obtained from GEA jet pumps (Engelhart, 2007) for jet mixers. The price for eighty jet mixer units type 17.1 size 5-80 including 10% delivery cost is **US$ 53,400**.

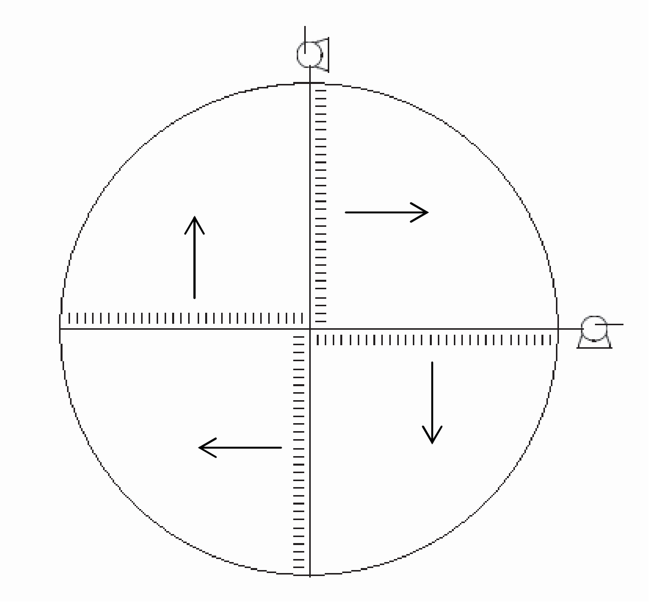


Figure 6-5 Proposed jet mixer arrangement

6.3.2.4 Screw Conveyor

A screw conveyor was chosen to transport potato starch powder as it has the ability to handle dusty, fibrous and sticky solids (Peters et al., 2003). The conveyor transports the potato starch powder to the mixing tank. A 0.23 m screw diameter (Appendix G.1.4) is proposed and single screw conveyor would suffice. The purchase cost (including 10% delivery) is **US$ 26,400**.

6.3.2.5 Centrifugal Pumps

Two identical centrifugal pumps are required for this plant reconfiguration. One centrifugal pump is required to supply water in to the mixing tank, and another is required to transport the mixed starch slurry to the AFR filters. The required flow rate of the water and potato starch slurry is 1190 m^3/h (0.33 m^3/s). As the slurry concentration is low, its density was assumed to be identical to that of water. Each pump requires a 187 kW motor.

The purchase cost for two centrifugal pumps including motors (plus 10% delivery cost) is **US$ 112,000**.

6.3.2.6 AFR Filter

The potato starch sent to the denitrification plant must be completely dissolved. Hence filtration equipment to remove undissolved starch is required. AFR filters were chosen, since this filter is compact with 150 micron retention and capable of handling up to 454 m^3/h flow rates (Eaton, 2007). Unfortunately, no general design methodology is available for AFR filters. Personal communication with the supplier generated data on the type and specification of suitable filtration equipments for the proposed process. Their full AFR filter specification is attached in Appendix H. The design flow rate of potato starch slurry is 1190 m^3/h and three AFR filter units are required.

The purchase cost of the AFR filters with the controller (including 10% delivery cost) is **US$ 348,000**.

6.3.3 Potato Starch Operating Cost

This section summarises operating cost for this option including maintenance and repair. Detailed calculations are presented in Appendix G.2.

6.3.3.1 Jet Mixers

The total energy required for the jet mixers is $1728\,{}^{kWh}\!/_{d}$. The annual operating cost for eighty jet mixers is $US\$\ 42{,}300.00\,/_{year}$.

6.3.3.2 Screw Conveyor

A single screw conveyor is required. The power requirement for a screw conveyor is given in Equation 6-5 (Peter et al., 2003).

$$P = 0.07 \times m^{0.85} \times L \tag{6-1}$$

where P is the power requirement (kW), m is the mass flow rate of solid (kg/s), and L is the length of conveyor (m). The resulting daily energy consumption (kWh) is $140.16\,{}^{kWh}\!/_{d}$, and the annual electricity cost for six screw conveyors is $US\$\ 3{,}430\,/_{year}$.

6.3.3.3 AFR Filters

Three AFR filters are required for this process. The required power input for a single unit of AFR filter is $0.345\,kW$. Total electricity cost per day is $US\$\,1.66/d$. The total annual energy cost for the AFR filters is $US\$\,606/year$.

6.3.3.4 Centrifugal Pumps

Two identical centrifugal pumps are required for this proposed plant reconfiguration. The total required power for the pumps is 264 kW and the annual energy cost is $US\$\,155{,}000/year$.

6.3.3.5 Maintenance and Repair

Maintenance and repair was assumed to be 2% of the fixed capital investment (Peters et al., 2003) and annual contribution is $US\$\,195{,}000$.

6.3.4 Potato Starch Total Capital Investment

Table 6-17 presents a summary of the individual cost contributions of units required for this operation.

Table 6-17 Summary of potato starch capital cost

Summary Potato Starch	Price US$
Storage Tank	$ 812,564
Jet mixers (80 units)	$ 48,480
Concrete tank	$ 245,000
Centrifugal Pump	$ 149,751
Filtration (US$)	$ 316,611
Screw conveyor	$ 23,588
Waste Disposal	$ 450,504
Total	$ 2,046,498
10% delivery	$ 204,650
Total	$ 2,251,148

A land contribution was required for the large concrete mixing tank, storage tank (silo) and screw conveyors, since it is not available in the existing plant.

The AFR filtration unit requires an air compressor or blower to supply 5 cfm (140 L/min) air at 60-120 psi (4 bar). This was not included in the capital cost estimation. It was assumed that a source of air was available in the existing plant.

The total capital cost for potato starch as alternative carbon source is significantly larger than the capital cost of molasses plant but the operating cost of both carbon sources were similar. Whilst potato starch is a feasible carbon source, it is not economic.

The detailed design calculation and purchase cost estimates for the unit operations are given in Appendix G.1. Table 6-18 summarises the capital cost estimates for potato starch as the external carbon source for biological denitrification.

Table 6-18 Summary of capital cost estimation for potato starch

DIRECT COST	**Fraction of Delivered Equipment**	**Cost (US$)**
Purchased equipments	1.00	$ 2,251,148
Purchased equipments installation	0.39	$ 877,948
Instrumentation and controls (installed)	0.26	$ 585,299
Piping (installed)	0.31	$ 697,856
Electrical equipment (installed)	0.1	$ 225,115
Buildings (including services)	0.29	$ 652,833
Yard improvements	0.12	$ 270,138
Service facilities (installed)	0.55	$ 1,238,132
Land	0.06	$ 135,069
Total direct cost	3.08	**$ 6,933,536**
INDIRECT COST		
Engineering and supervision	0.32	$ 720,367
Construction expenses	0.34	$ 765,390
Legal expenses	0.04	$ 90,046
Contractor's fee	0.19	$ 427,718
Contingency	0.37	$ 832,925
Total Indirect Cost	1.26	**$ 2,836,447**
Fixed Capital Investment		**$ 9,769,983**
Working Capital	0.75	**$ 1,688,361**
Total Capital Investment		**$ 11,458,344**

Using Table 6-2 for currency conversion, the fixed capital investment for potato starch in Australian Dollars is **AU$ 12,500,000**, and the total capital cost is **AU$ 14,800,000**.

7 COMPARISON OF THE ALTERNATIVE CARBON SOURCES EXPENDITURE

This section summarises the total expenditure for each alternative carbon source with comparison to molasses. The total expenditure includes both capital investment combined with annual operating costs. In this study, a plant life of 20 years was assumed.

7.1 RAS Sonication Option 1 versus Molasses

The key expense of RAS Sonication Option 1 is the three sonicator units to produce a soluble carbon (SCOD) source from the RAS stream. The capital estimate for this process is AU$ 8,050,000. This estimate is significantly greater than for the current molasses dosing. The capital cost of the current process is AU$ 874,000.

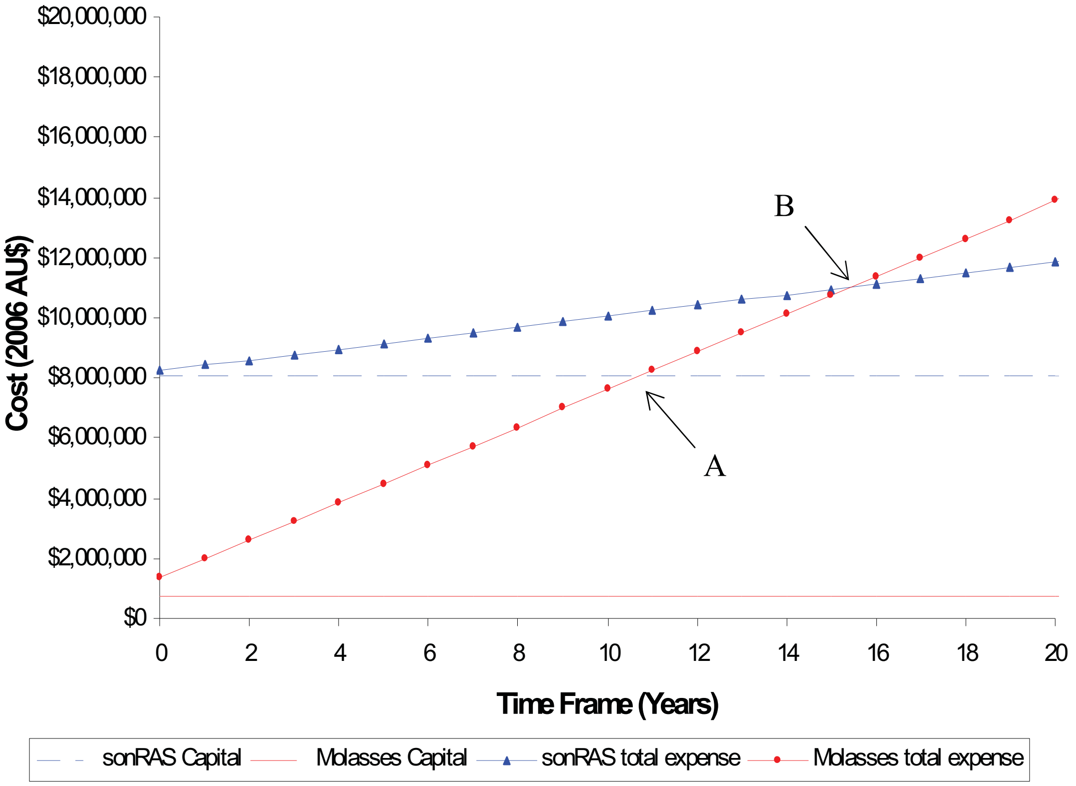


Figure 7-1 Comparison of capital cost and total expenditure for molasses and RAS sonication Option 1

Although RAS Option 1 requires a high capital cost, but its annual operating cost estimate is significantly lower than that for molasses dosing. This reduced operating cost is the key feature of the alternative process. Figure 7-1 presents a comparison of capital cost and annual expenditure of RAS sonication option 1 compared with the current use of molasses.

The "SonRAS Capital" line represents the capital investment for RAS Sonication Option 1. Point A represents the payback period for RAS sonication option 1 (approximately 11 years), whilst Point B represents the break even point (approximately 15 years). Following 15 years, RAS sonication option 1 would have a lower annual expenditure. This alternative process would gain significant savings from the molasses expenditure.

The feasibility of the alternative process is dependent to the life span of the plant and the time frame of utilising the selected carbon source. However, since the payback period and the break even point are well over 5 years, this may not be a feasible option to replace molasses dosing.

7.2 RAS Sonication Option 2 versus Molasses

The key component of RAS Sonication Option 2 is two units of sonicators to increase the soluble carbon (SCOD) of the RAS stream. The required unit of sonicators was able to be reduced by combining the RAS stream from both denitrification plant (B and C Plant and D Plant). However, this required a larger number of centrifugal pumps. The capital cost estimation for this process is AU$ 5,480,000. Although additional pumps were required, the capital cost and expenditure of RAS sonication option 2 is lower to that of option 1. Since option 2 has less costs and investment, this may be an attractive choice to substitute molasses dosing.

Figure 7-2 illustrates the comparison of annual expenditure of RAS sonication option 1 to molasses. Although the capital cost estimated for RAS sonication option 2 is also well above the investment of molasses dosing, it is seen clearly that the total expense is well below molasses dosing.

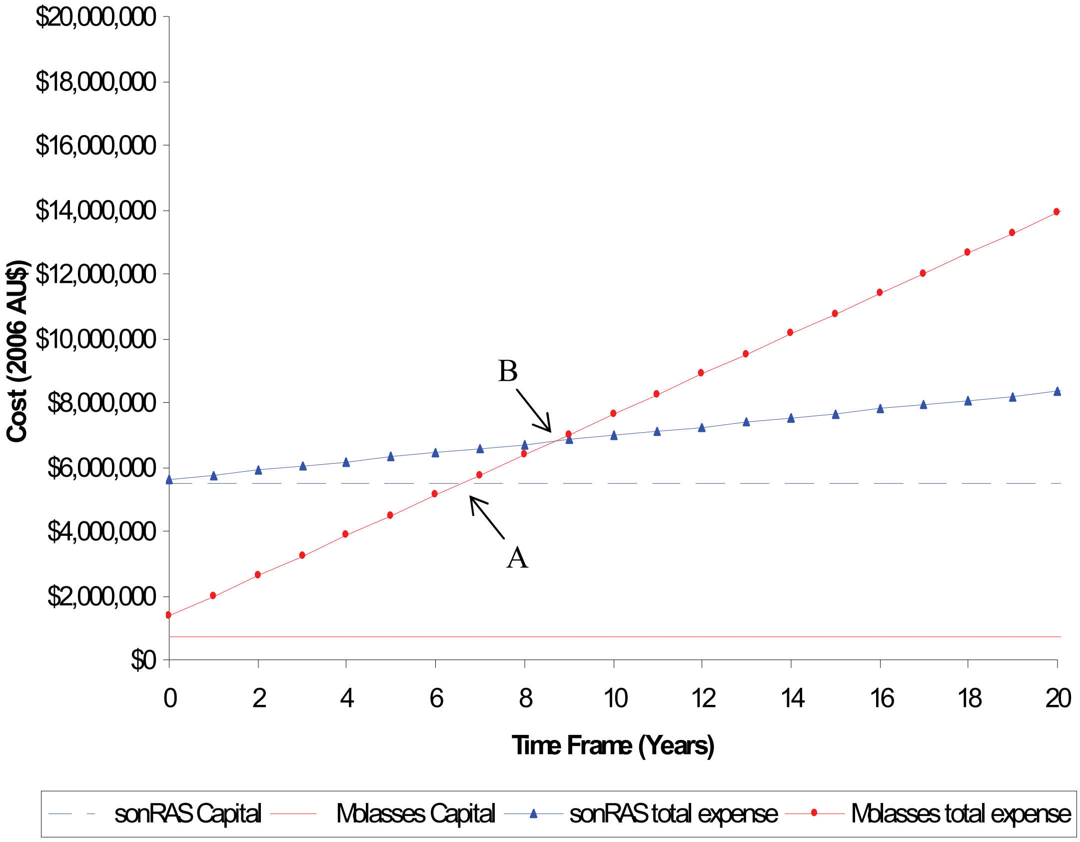


Figure 7-2 Comparison of capital cost and total expenditure for molasses and sonicated RAS Option 2

Point A represents the payback period of RAS sonication option 2 (approximately 6.5 years), which is nearly half the time frame of RAS Sonication Option 1. Additionally, the break even point (Point B) is approximately 8 years. Following eight years, RAS sonication Option 2 would have a lower annual expenditure. This alternative process would have more time to gain significant savings from the molasses expenditure. Thus for a projected life of 20 years, this alternative process may be feasible. Since the payback period and the break even point are close to 5 years, this may be a considerable choice to substitute molasses dosing.

7.3 Potato Starch versus Molasses

The key factor of potato starch as an external carbon source is its solubility. From the experimental results obtained, the solubility of potato starch at room temperature is very low. This results to the requirement of a very high flow rate of potato starch suspension in order to have the equivalent SCOD as molasses (Appendix G). With a very high flow rate, the required unit operations, such as mixing tanks, conveyor, filtration process and pumps attract extremely high purchase cost and operating cost.

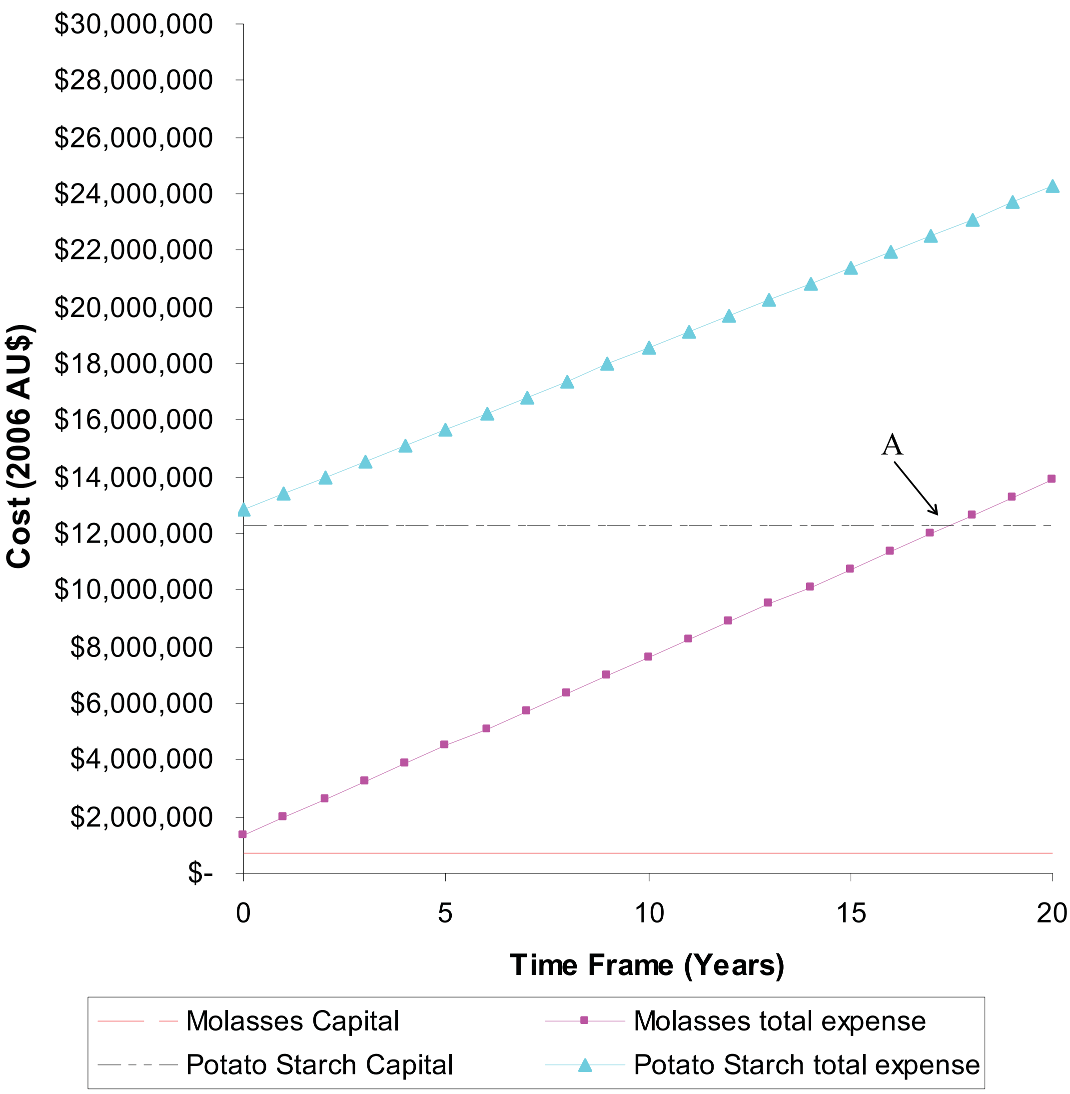


Figure 7-3 Comparison of total expenditure for molasses and potato starch

The capital cost estimation for this process is AU$ 14,800,000. Figure 7-3 illustrates the comparison of annual expenditure of potato starch to molasses dosing. It is seen clearly that the capital cost and total expense of potato starch as external carbon source is well above molasses dosing. The payback period (point A) would be approximately 18 years. However, since the operating cost is approximately similar for both molasses and potato starch, the break even point would be excessively long and exceed the time frame of the project (approximately 103 years).

In addition, this option requires a high volumetric flow rate of potato starch to be dosed to the denitrification plant. The tank may not have the capacity to hold this extra flow. Thus, the denitrification plant may require reconfiguration, which will lead to an additional cost in the capital investment.

The current conclusion made is this process is not feasible. This may be feasible if the solubility of potato starch is improved with reduced mixing time. Sonication of potato starch was performed in this research. However, due to the higher SCOD release from return activated sludge to potato starch, the implementation of ultrasound treatment to RAS was favoured. A possible option to improve potato starch is the use of enzymatic digestion.

8 CONCLUSION

The important conclusions that can be drawn from this research are:

- The solubility and soluble carbon in potato starch vary according to the concentrations prepared. The experimental results showed that the solubility and soluble carbon content is low in comparison to molasses and sonicated RAS.
- Molasses provided the highest soluble carbon release (SCOD), followed by sonicated RAS and potato starch respectively.
- Ultrasound treatment on RAS has lead to 5.6 to 68.4 times the release of the SCOD in untreated RAS, dependant on the sonication intensity and treatment time.
- Ultrasound treatment on potato starch has shown improvement on the solubility and SCOD release from potato starch, however, due to economic considerations, ultrasound treatment would be more viable to be applied to RAS.
- The highest denitrification efficiency for both low and high dosage concentration was achieved by using molasses followed by ultrasound treated RAS and potato starch respectively.
- The highest denitrification rate for both low and high dose was achieved by using molasses, followed by ultrasound treated RAS and potato starch respectively.
- For the economic analysis, molasses has the least capital cost compared to sonicated RAS and potato starch. However, sonicated RAS has the least operating cost compared to molasses and potato starch. Thus, with the savings from molasses operating cost, sonicated RAS may have a payback period of approximately 6.5 years, and a break even point approximately 8 years. Due to this, sonicated RAS may be an attractive substitute for molasses.
- Potato starch was found to be unfeasible, which is caused by the low solubility that leads to a high capital and operating cost.

9 RECOMMENDATIONS FOR RELEVANT FUTURE RESEARCH

- To investigate the denitrification kinetics for molasses and the proposed carbon source including potato starch and sonicated RAS.
- To investigate methods for improving the solubility of potato starch. Enzymatic digestion may be a possible option.
- To perform denitrification analyses in a larger and improved batch laboratory scale bioreactor.
- To investigate denitrification analyses in a continuous laboratory bioreactor and/or pilot plant.
- To perform a more detailed design calculation with accurate design properties and information of the unit operation required, thus more accurate capital cost estimation may be achieved.

Appendix A – Calculation of Insulation Thickness

This appendix summarises the assumptions and calculations to obtain the minimum insulation thickness to prevent heat loss. The material of the calorimeter used is polypropylene, and the material used for insulation is polystyrene. The top view of the calorimeter with the polystyrene and polypropylene layers is shown in Figure A-1.

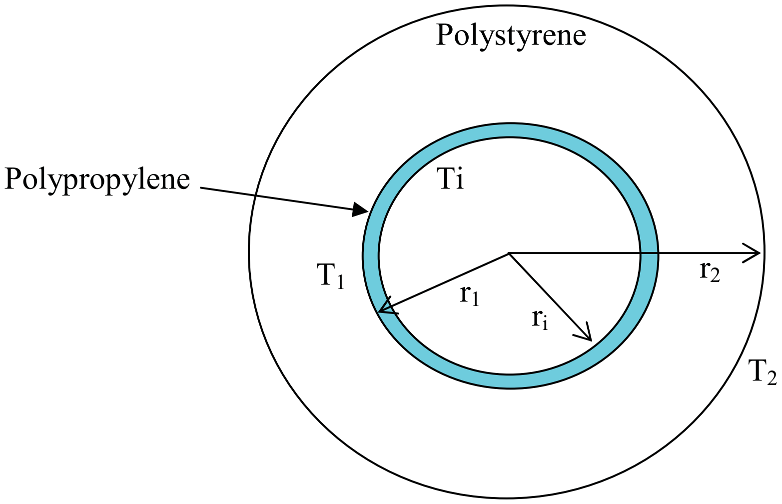


Figure A-1 Top view of calorimeter

The thermal conductivity (Holman, 2002) of polypropylene and polystyrene are summarised in Table A-1 and the dimensions of polypropylene are summarised in Table A-2. Water was used as the media for the temperature rise. 300 grams (300 mL) of water was used and the heat capacity of liquid water, cp, is 4.182 J/g.K (Geankoplis, 1997). It was assumed that only conductive heat transfer was taking place in the system, therefore the convective heat transfer from the air and water were neglected. Assuming steady state conditions, heat in = heat out (q in = q out).

Table A-1 Thermal conductivity of polypropylene and polystyrene

Properties	Polypropylene	Polystyrene
Thermal Conductivity, k	0.16 W/m.K	0.14 W/m.K

Table A-2 Dimension of polypropylene used

Dimensions	Value	Units
Length, L	0.0952	m
Inner radius, r_i	0.0447	m
Outer radius, r_1	0.0450	m
$T_{i,\ \text{maximum assumed}}$	35	°C
T_0	25	°C

Equation 3-1 was used to calculate the energy dissipated to water using assumptions that the sonifier may increase the temperature of water to 40°C, and the ambient temperature was 25°C. However, the temperature difference was set to 5K, as it was necessary to find out the amount of energy required to increase the water temperature of 5°K. Below is a sample calculation for *ΔQ* (energy). The results for *ΔQ* and *W* are shown in Table A-3.

$$\Delta Q = 300 \times 4.182 \times 5$$
$$\Delta Q = 6273\ J$$

Table A-3 Approximate time to achieve 5K of water temperature rise

Amplitude %	T_0, °C	T_1, °C	ΔT, °C or K	t, s	Q, Joules	Power, Watt/300mL
70	25	30	5	158	6273	39.7025
60	22.7	27.7	5	200	6273	31.3650
50	22.3	27.3	5	253	6273	24.7945
40	22.5	27.5	5	327	6273	19.1835
30	22.7	27.7	5	498	6273	12.5964
20	22.9	27.9	5	1108	6273	5.6616

Preliminary experiment without insulation was carried out to indicate the approximate time to increase the water temperature of 5K. Equation 3-2 was then used to calculate the output power.

Below is a sample calculation for 70% amplitude.

$$Power\ \left(W/_{300ml}\right) = \frac{\Delta Q}{t}$$

$$Power = \frac{6273}{158} = 39.7025\ Watt/_{300ml}$$

The calculated heat out (W) was then used to calculate the temperature of the outer surface of the polypropylene (T_1), using log mean surface area (A_{lm}). The sample calculation is shown below:

Using data from Table A2, the inner (A_i) and outer (A_1) surface area of the polypropylene container are 0.0267 and 0.0269 m^2 respectively.

Calculating A_{lm1}

$$A_{lm1} = \frac{A_1 - A_i}{\ln\left(A_1/_{A_i}\right)} \qquad \textbf{A-1}$$

$$A_{lm1} = 0.0268\ m^2$$

In order to calculate T_1, the resistance (R_1) of polypropylene must be calculated. Equation A-2 shows the equation for calculating R_1 (Geankoplis, 1997)

$$R = \frac{\ln\left(r_{outer}/_{r_{inner}}\right)}{2 \times \pi \times k_{material} \times L} = \frac{r_{outer} - r_{inner}}{k_{material} \times A_{lm}} = \frac{r_1 - r_i}{k_{polypropylene} \times A_{lm1}} \qquad \textbf{A-2}$$

Using the data from Table A-1 and A-2,

$$R_1 = 0.09\ K/_{W}$$

Since $q_{in} = q_{out}$ in all layers, R_1 may be used to calculate T_1 using Equation A-3.

$$q_{in} = q_{out} = q = \frac{\Delta T}{R} = \frac{T_i - T_1}{R_1} = \frac{T_1 - T_2}{R_2} \qquad \textbf{A-3}$$

Therefore rearranging Equation A-3,

$$T_1 = T_i - (q \times R_1) \qquad \textbf{A-4}$$

Using data from Table A-2 and values for *q* and R_1,

$$\mathrm{T_1} = 31.4\ °\mathrm{C}$$

Therefore obtaining ΔT_1

$$\Delta \mathrm{T_1} = 3.6\ \mathrm{K}$$

Using Equation A-3 to check the q_{out} from polypropylene layer = *q*,

$$\mathrm{q_{pp}} = \frac{\Delta \mathrm{T_1}}{\mathrm{R_1}} = \frac{3.5602}{0.0897} = 39.7\ \mathrm{W}$$

<u>Calculating ΔT_2,</u>

$$\Delta T_2 = T_1 - T_2$$
$$\Delta T_2 = 6.5\ \ K$$

<u>Rearranging equation A-3 to calculate R_2:</u>

$$R_2 = \frac{\Delta T_2}{q_{pp}}$$
$$R_2 = 0.16\ {}^{K}\!/_{W}$$

<u>Using Equation A-2, r_2 may be calculated:</u>

$$ln\left({}^{r_2}\!/_{r_1}\right) = 0.0136$$

$$r_2 = 0.0457\ \ m$$

The required minimum insulation thickness for experiments at 70% amplitude is

$Thickness_{min} = r_2 - r_1 = 0.0616 \ \ cm$

The required minimum insulation thickness obtained was very small. However, for a longer duration of sonication, the higher the temperature would increase. For the duration of 1108 seconds for 20% amplitude, the required minimum insulation thickness is 0.68 cm.

Since only conductive heat transfer that was taken into account, it was chosen to increase the thickness to 3.50 cm to overcome the affect of other heat transfer mechanisms. Results are displayed in Table A-4

Table A-4 Summary of results for insulation thickness

q_{in}=q_{loss}	A_i	A_1	A_{lm1}	R_1	T_1	ΔT_1	ΔT_2	q_{pp}	R_2	$ln(r_2/r_1)$	(r_2/r_1)	r_2, m	thickness$_{min}$, cm	A_2
39.7025	0.0267	0.0269	0.0268	0.0897	31.4398	3.5602	6.4398	39.7025	0.1622	0.0136	1.0137	0.0457	0.0616	0.0273
31.3650				0.0897	32.1874	2.8126	7.1874	31.3650	0.2292	0.0192	1.0194	0.0459	0.0873	0.0275
24.7945				0.0897	32.7766	2.2234	7.7766	24.7945	0.3136	0.0263	1.0266	0.0462	0.1199	0.0277
19.1835				0.0897	33.2798	1.7202	8.2798	19.1835	0.4316	0.0362	1.0368	0.0467	0.1658	0.0279
12.5964				0.0897	33.8704	1.1296	8.8704	12.5964	0.7042	0.0590	1.0608	0.0478	0.2737	0.0286
5.6616				0.0897	34.4923	0.5077	9.4923	5.6616	1.6766	0.1405	1.1508	0.0518	0.6791	0.0310

Appendix B – Calculation of Sonicator Power Output

This appendix summarises the assumptions and calculations to obtain the sonicator power output. Table B-1 to Table B-4 represents the raw data obtained for sonicator power output experiment.

Equation 3-1 was used to calculate the energy (*ΔQ*) using the simple insulated calorimeter (Appendix A). It was found that *ΔQ* is fixed at 6273 J. To obtain the power output in Watts, Equation 3-2 was used. Sample calculation is given below using the raw data set 1, for 70 % Amplitude:

$$Power = \frac{6273}{151} = 41.54\,{Watt}/{300ml} = 0.138\,{Watt}/{ml}$$

Table B-1 Raw data (set 1)

Amplitude %	T_0, °C	T_1, °C	ΔT, °C (K)	t, s	Q	W/mL
70	24.7	29.7	5	151	6273	0.138
60	25.3	30.3	5	181	6273	0.116
50	25.7	30.7	5	241	6273	0.087
40	26.4	31.4	5	326	6273	0.064
30	26.7	31.7	5	493	6273	0.042
20	27.1	32.1	5	826	6273	0.025

Table B-2 Raw data (set 2)

Amplitude %	T_0, °C	T_1, °C	ΔT, °C (K)	t, s	Q	W/mL
70	25.3	30.3	5	154	6273	0.136
60	25.6	30.6	5	183	6273	0.114
50	25.4	30.4	5	232	6273	0.090
40	25.3	30.3	5	312	6273	0.067
30	25.4	30.4	5	470	6273	0.044
20	25.3	30.3	5	859	6273	0.024

Table B-3 Raw data (set 3)

Amplitude %	T_0, ^oC	T_1, ^oC	ΔT, ^oC (K)	t, s	Q	W/mL
70	24.9	29.9	5	158	6273	0.132
60	24	29	5	187	6273	0.112
50	24	29	5	240	6273	0.087
40	23.8	28.8	5	327	6273	0.064
30	23.8	28.8	5	485	6273	0.043
20	23.6	28.6	5	879	6273	0.024

Table B-4 Raw data (set 4)

Amplitude %	T_0, ^oC	T_1, ^oC	ΔT, ^oC (K)	t, s	Q	W/mL
70	24.9	29.9	5	153	6273	0.137
60	24	29	5	185	6273	0.113
50	24	29	5	239	6273	0.087
40	23.8	28.8	5	318	6273	0.066
30	23.8	28.8	5	488	6273	0.043
20	23.6	28.6	5	881	6273	0.024

Table B-5 Converted calculated data to W/mL

	W/mL					
Amplitude %	Set 1	Set 2	Set 3	Set 4	AVERAGE	STDEV
70	0.14	0.14	0.13	0.14	**0.14**	0.003
60	0.12	0.11	0.11	0.11	**0.11**	0.002
50	0.09	0.09	0.09	0.09	**0.09**	0.002
40	0.06	0.07	0.06	0.07	**0.07**	0.001
30	0.04	0.04	0.04	0.04	**0.04**	0.001
20	0.03	0.02	0.02	0.02	**0.02**	0.001

The data in Table B-5 was used to obtain the relationship between % Amplitude and power output (W/mL). The relationship is presented as Equation 5-1. The average power output (W/mL) was also used to generate the graphical presentation of SCOD released versus power output given in Figure 5-4 in Section 5.4.

Appendix C – V5 Sonix SCOD Release Prediction Model

This appendix provides the calculation steps to predict the SCOD release using specification data of V5 Sonix given in Table 4-4 and Table 4-5.

Figure 5-4 shows the experimental data of RAS sonication, varying intensity and treatment time. From this experimental data, linear equations were developed. Using these linear equations, a graph SCOD release versus time for V5 Sonix was generated, where X represents the power output (W/ml) and Y represents the SCOD release for a particular X value.

Summary of the linear equations can be seen in Table 5-6 in Section 5.4.

Sample calculations are given below.

For time = 10 minutes, $Y = 5738.87X + 67.2789$

X is the power output of the V5 Sonix, is set to 7.75 W/ml. Therefore giving SCOD release (Y):

$$Y = (5738.87 \times 7.75) + 67.2789$$

$$Y = 44500 \ {}^{\text{mg} - \text{SCOD}}\!/_{\text{L}}$$

For time = 25 minutes, $Y = 11396.19X + 107.3616$

$$Y = (11396.19 \times 7.75) + 107.3616$$

$$Y = 88400 \ {}^{\text{mg} - \text{SCOD}}\!/_{\text{L}}$$

Table C-1 shows the summary of calculated Y actual values.

Table C-1 Summary of calculated Y actual values

Time, min	Time, s	Model Equation	X	Y	$Y_{actual} = Y - Y_0$
0	0		0	$y_0 = 35.6$	
10	600	$Y = 5738.8705X + 67.2789$	7.75	44543.5253	44507.9253
15	900	$Y = 8049.9662X + 50.0723$	7.75	62437.3104	62401.7104
20	1200	$Y = 9374.5964X + 82.2542$	7.75	72735.3763	72699.7763
25	1500	$Y = 11396.1879X + 107.3616$	7.75	88427.8178	88392.2178
30	1800	$Y = 14339.6740X + 87.3508$	7.75	111219.8243	111184.2243

From the results obtained, a graphical presentation of SCOD versus time (s) was generated, and a linear equation was established. Figure 5-6 was used to distinguish the SCOD release at 2 seconds treatment (retention) time.

The linear equation obtained was Y = 53.1144X + 12099.9286 with and $R^2 = 0.9845$
Input X = 2 seconds,

$$Y = (53.1144 \times 2)\ +\ 12099.9286$$

$$Y = 12200\, {mg - SCOD} \big/ L$$

Therefore, after sonication at 3 kW (7.75 W/ml) for 2 seconds, the SCOD release obtained was 12200 mg-SCOD/L. Summary of values obtained at 3 kW (predicted) sonication process are shown in Table C-2.

Table C-2 Summary of values obtained using linear model equation for sonication at 3 kW

Model	Y = 227.8089X + 16759.2608
X, time	2 seconds
Y, mg-SCOD/L	12200 mg-SCOD/L
AVERAGE RAS SCOD concentration	35.6 mg-SCOD/L
Factor increase	343 times

Appendix D – Laboratory Scale Denitrification Analyses

As stated in Section 3.7, the mixture content for the analysis includes primary effluent (PE), RAS and Mixed Liquor Return (MLR) with a volume ratio of 1:1:3. This ratio was used for the mixture fraction in a 1 L laboratory scale denitrification reactor.

The total flow of the denitrification plant (B and C Plant) is:
40,000 + 40,000 + 120,000 = 200,000 m^3 wastewater/d (200,000,000 L wastewater/d)

Since the volume ratio is 1:1:3, for a 1 L reactor becomes 0.2 L: 0.2 L: 0.6 L ≈ 1 L.
(Scaling 200,000,000 L wastewater/d ≈ 1 L)

Molasses dosing for whole plant is 140 L/h.
As the PE of B and C plants is 40,000 m^3/d and PE of D Plant is 20,000 m^3/d, the molasses dosing for B and C Plant is 2/3 of 140 L/h (correspondence with Ian Mackenzie). Therefore molasses dosing for B and C plant is 92.134 L/h (2,211.216 L/d).

For 1 L laboratory scale reactor, the required molasses dosing is

$$\frac{2{,}211.216 \;\; L \;\; molasses/day}{200{,}000{,}000 \;\; L \;\; wastewater/day} = 0.00011 \frac{L \;\; molasses}{L \;\; wastewater} = 0.011 \frac{mL \;\; molasses}{L \;\; wastewater}$$

1 L molasses provides 1,130,000 mg-SCOD.

Soluble carbon in molasses (mg-SCOD/d) is $2{,}500{,}000{,}000\ \mathrm{mg-SCOD}/_{\mathrm{day}}$

Therefore, the SCOD required for 1 L wastewater is $12.48\ \mathrm{mg-SCOD}/_{\mathrm{L\ wastewater}}$

High molasses dosing of 124.80 mg-SCOD/L (10 times of the original dosing) wastewater was also carried out. Sonicated RAS and potato starch dosing for laboratory scale denitrification were based on the actual molasses dosing rate in the plant. It was obtained that 12.48 mg-SCOD/L of molasses was dosed for 1 L wastewater. Thus, 12.48 mg-SCOD/L of soluble carbon were prepared from both sonicated RAS and potato starch. Dilutions were required to obtain the target concentration. Higher dosages of molasses, sonicated RAS and potato starch (124.80 mg-SCOD/L) were also prepared.

Appendix E – Economic Analysis - Molasses

As stated in Chapter 6, this economic analysis solely estimates the capital cost and operating cost of the additional major unit operations to the existing Glenelg Wastewater Treatment Plant.

E.1 Fixed Capital Cost Estimation

This section provides the details and information regarding costs and the unit operations (equipments) used in molasses dosing. Table E-1 summarises the details of the fixed capital investment (Kaeding, 2007[a]).

Table E-1 Details of molasses fixed capital investment

PRELIMINARIES	Rate
Site specific project quality plan	$3,020.00
program of works	$3,886.00
Site establishment and cleanup	$3,571.00
Total Preliminaries	**$10,477.00**
WORKS AS SPECIFIED	
Earthworks	
Earthworks and base preparation for concrete bund	$5,903.00
Truck loading bay including bitumen and kerbing	$8,506.00
Reinstatement including paving	$1,655.00
All other works as specified	-
Services	
Potable water and effluent washwater services	$5,763.00
Instrument air services	$2,935.00
Storm water services	$1,699.00
Electrical Services	-
All other works specified	-
Civil Works	
Concrete bund, plinths, earthing system and associated works	$25,652.00
Supply and installation of concrete and veranda for control panel	$3,742.00
All other works as specified	-

Table E-1 Details of molasses fixed capital investment (continued)

Mechanical Works	
Supply and installation of pumpsets	$15,176
Supply and installation of valves including actuators as specified	$12,757.00
Supply and installation of pipework and associated fittings	$10,468.00
Supply and installation of tank	$59,852.00
Supply and installation of platforms, stairs, kickboards handrails and associated works	$28,787.00
Supply and installation of eyewash station and hose points	$998.00
supply and installation of sump transfer pump	$1,027.00
all other mechanical works as specified	
Electrical Works	
Supply and installation of electrical service including interfacing to existing switchboard	$21,582.00
Supply and installation of LCP with VSDs and associated works	$46,801.00
Supply and installation of local fitting station control panel	$2,822.00
Supply and installation of general power and lighting, earthing system and lightning protection	$11,583.00
Supply and installation of cables, conduits, cable pits, cable ladders and fixings and associated works	$25,205.00
Supply and install trace heating on molasses pipework	$2,438.00
All other electrical works as specified	-
Instrumentation and Control Works	
Supply and installation of inline magnetic flowmeters, 4 off	$8,011.00
Supply and installation of nitrate analysers and associated works, 3 off, including security / vandal proofing	$132,910.00
Supply and installation of tank level instrument	$2,057.00
Supply and install automation and control of actuated valves	-
Supply and installation of cables, conduits, cable pits, cable ladders and fixings and associated works	$14,503.00

Table E-1 Details of molasses fixed capital investment (continued)

Supply and installation of Controllers, Programmable Logic Controller and associated programming	$40,659.00
Supply and installation of SCADA works including programming and screens	$11,000.00
Supply and installation of Ethernet cables and interfacing	$4,752.00
Supply and installation of handwired alarms to Master RTU	$17,424.00
Other	
Testing and Commissioning in accordance with the specification and to confirm functionality operation of the installation	$12,092.00
Pre-Construction Documentation, As Constructed Drawings	$4,318.00
Operation and Maintenance manuals	$6,336.00
Operator training	$807.00
Fixed Capital Investment (2004 dollars)	**$560,700.00**

E.2 Molasses Operating Cost Estimation

E.2.1 Bulk molasses cost

The current dose and price of molasses is summarised in Table 6-6 (Mackenzie, 2006). Cost per litre of molasses is AU$ 0.49. Required dosage is 140 L/h. Assuming 24 hour operation per day and 365 working days per year, the annual cost of bulk molasses is:

$$\text{AU\$ } 0.49 \Big/ \text{L} \times 140\ \text{L} \Big/ \text{h} \times 365\ \text{d} \Big/ \text{year} \times 24\ \text{h} \Big/ \text{d} = \text{AU\$ } 600{,}936.00 \Big/ \text{year}$$

E.2.2 Electricity cost estimation

The electricity cost include power requirement for molasses pipe heaters and rotary pumps. Data on molasses pipe heaters was provided by Keading (2007^b). The details of this information are attached in Appendix H.2.

Assuming the properties of molasses in Glenelg WWTP similar to that given in Table 6-7, the electricity cost estimation is as follows:

Using SG molasses = 1.4033 cp (Engineering tool box, 2007), the density of molasses is

$$\rho_{molasses} = 1403.3\, {kg}\!/\!{m^3}$$

Molasses pipe heaters

Total heater length is 66.9 m. The heater power output is 12.6 W/m (1.26 x 10^{-2} kW/m). The average % pipe heat loss is 81.29 %. Data provided in Table E-2 (Kaeding, 2007^b).

Table E-2 Molasses pipe heater details

Length (m)	**Power output (W/m)**	**Pipe heat loss (W/m)**	**%heat loss**
7.7	12.6	7.2	57.14
2	12.6	19.4	153.97
1.6	12.6	7.2	57.14
4.4	12.6	8.4	66.67
7.7	12.6	7.2	57.14
2	12.6	19.4	153.97
1.6	12.6	7.2	57.14
4.4	12.6	8.4	66.67
4.6	12.6	8.4	66.67
5.9	12.6	7.2	57.14
2	12.6	19.4	153.97
1.6	12.6	7.2	57.14
4.4	12.6	8.4	66.67
17	12.6	8.4	66.67
∑ = 66.9			Mean = 81.29

Using the average percentage heat loss, a rough estimation of the power requirement is:

$$\frac{100\%}{81.29\%} x12.6\ {W}\!/\!{m} = 15.50\, {W}\!/\!{m} = 1.55 \times 10^{-2}\, {kW}\!/\!{m}$$

The total power requirement is

$$1.55 \times 10^{-2}\, {kW}\!/\!{m} \times 66.9\ \ m = 1.04\ \ kW$$

Assuming 24 hours daily operation, the power requirement becomes:

$$1.04\ \ kW \times 24\ \ h = 25\ \ {kWh}\!/\!{day}$$

Molasses rotary pump

$$m = 140\frac{L}{h} \times \frac{1\ m^3}{1000\ L} \times 1403.3\frac{kg}{m^3} \times \frac{1h}{3600\ s} = 0.0546\frac{kg}{s}$$

A typical head value for this a rotary pump is 50,000 ft (15,240.1853 m) (Suppes, G., J., 2002)

Calculating Ws using Equation 6-3:

$$W_s = H \times g$$

$$W_s = 149506.2178\ \frac{m^2}{s^2} = 150,000\frac{J}{kg}$$

The efficiency of rotary pumps (η) varies from 40 to 85% (Peters et al., 2003). Assuming the pump efficiency, η = 60%, using Equation 6-2 to calculate the brake kW:

$$brake\ \ kW = \frac{W_s \times m}{\eta \times 1000}$$

$$brake\ \ kW = 14\ \ kW$$

Using Figure E-1 (Peters et al., 2003), the motor efficiency (η_e) for the brake power = 88% Calculating the electrical power input (kW) using Equation 6-4:

$$electric\ \ power\ \ input\ \ (kW) = \frac{brake\ \ kW}{\eta_e}$$

$$electric\ \ power\ \ input = 16\ \ kW$$

From the calculation results above the pump requires a 16 kW motor.

Assuming 24 hour daily process, the kWh for the rotary pump:

$$kWh = {}^{384\ \ kWh}\!\big/_{day}$$

NOTE: This figure is included on page 89 of the print copy of the thesis held in the University of Adelaide Library.

Figure E-1 Efficiencies of three phase motors (Reproduced from Peters et al., 2003)

Annual electricity cost

The annual electricity cost is:

Molasses heater energy consumption + molasses rotary pumps = $409\ \text{kWh}/\text{day}$

With $\text{AU\$}\ 0.087/\text{kWh}$, the annual electricity cost is $\text{AU\$}\ 13{,}000/\text{year}$

From Table 6-5, the purchased equipment cost is **AU$ 620,000.**

Maintenance and repair was assumed to be 2% per year of the fixed capital cost:

$$\frac{2}{100} \times \$620{,}000 = \$12{,}400$$

The total annual operating cost is:

Bulk molasses cost + electricity cost + maintenance and repair = $\text{AU\$}626{,}000/\text{year}$

Table E-3 provides the summary of total expenditure of molasses dosing projected for 20 year period.

Table E-3 Total expenditure of molasses projected for a 20 year period

year	Fixed Capital Investment	Operating cost	Total
0	$ 728,200	$ 626400	$ 1,354,600
1	$ 728,200	$ 1,252,800	$ 1,981,000
2	$ 728,200	$ 1,879,200	$ 2,607,400
3	$ 728,200	$ 2,505,600	$ 3,233,800
4	$ 728,200	$ 3,132,000	$ 3,860,200
5	$ 728,200	$ 3,758,400	$ 4,486,600
6	$ 728,200	$ 4,384,800	$ 5,113,000
7	$ 728,200	$ 5,011,200	$ 5,739,400
8	$ 728,200	$ 5,637,600	$ 6,365,800
9	$ 728,200	$ 6,264,000	$ 6,992,200
10	$ 728,200	$ 6,890,400	$ 7,618,600
11	$ 728,200	$ 7,516,800	$ 8,245,000
12	$ 728,200	$ 8,143,200	$ 8,871,400
13	$ 728,200	$ 8,769,600	$ 9,497,800
14	$ 728,200	$ 9,396,000	$ 10,124,200
15	$ 728,200	$ 10,022,400	$ 10,750,600
16	$ 728,200	$ 10,648,800	$ 11,377,000
17	$ 728,200	$ 11,275,200	$ 12,003,400
18	$ 728,200	$ 11,901,600	$ 12,629,800
19	$ 728,200	$ 12,528,000	$ 13,256,200
20	$ 728,200	$ 13,154,400	$ 13,882,600

Appendix F – RAS Sonication

This section provides the details of the additional unit operations proposed for the ultrasound treatment (sonication) of return activated sludge (RAS). This appendix also summarises the assumptions and elaborates the design calculations to obtain the capital cost investment and operating cost.

F.1 RAS Sonication Equipment Purchase Cost Estimation – Option 1

The additional equipments required for the denitrification plant modification Option 1 are V5 Sonix and centrifugal RAS pumps. This is based on the process flow diagram presented in Figure 6-1 and Figure 6-2.

F.1.1 V5 Sonix

The experimental results of molasses SCOD is 1,128,454.33 mg-SCOD/L. Using the data summarised in Table 6-6 (MacKenzie, 2006) and experimental results from sonication experiments in Section 5.4, the amount of RAS required to be sonicated to achieve the same SCOD concentration as molasses was able to be calculated.

Molasses dosing for the whole wastewater treatment plant is 140 L/h. The wastewater treatment plant consists of B and C plant, and plant D. According to MacKenzie (2006), two thirds of the molasses dose is supplied to B and C plants.

Referring to the material balance shown in Figure 6-1 and Figure 6-2, the amount of RAS required to be sonicated to achieve the same molasses SCOD is 310.6306 m^3/d. Based on Table 5-5 (Rooksby, 2007) in Section 5.4, one unit of V5 Sonix is able to treat 200 m^3/d of RAS.

V5 Sonix unit required for B and C Plant is

$$\text{V5 Sonix required} = \frac{207.1\,\mathrm{m}^3/\mathrm{day}}{200\,\mathrm{m}^3/\mathrm{day}} = 1.0355 \approx 2 \text{ units}$$

For D Plant,

$$\text{V5 Sonix required} = \frac{103.5\,\text{m}^3/\text{day}}{200\,\text{m}^3/\text{day}} = 0.5175 \approx 1\ \text{unit}$$

Thus, the required V5 Sonix for the denitrification plant is 3 units. The price for 1 unit V5 Sonix is GBP 190,000 (Rooksby, 2007). Using the foreign currency exchange given in Table 6-2 (XE Trade, 2007), the price of one V5 Sonix unit in US dollars is US$ 373,790.80.

Therefore the cost for three units of V5 Sonix is

$3 \times \text{US}\,\$373{,}790.80 = \text{US}\,\$1{,}121{,}372.40$

An additional cost for delivery is 10%

Thus, total purchased cost for 3 V5 Sonix units is:

$\text{US\$}\,1{,}121{,}372.40 + \text{US\$}\,112{,}137.24 = \text{US\$}\,1{,}230{,}000$

F.1.2 Centrifugal Pump

Centrifugal pump are often used to convey return activated sludge (RAS). Centrifugal pumps can handle the debris and stringy materials constituted in RAS (ECY, 2007). Centrifugal pumps are simple, inexpensive and have low maintenance cost. TEFC (totally enclosed fan cooled) motor are used for wastewater centrifugal pumps (Direct Industry, 2007). The motor specification above was used to calculate the pump electricity cost. Several assumptions were made as some data that were not available and to simplify the calculations. The viscosity of RAS was assumed to be similar to water.

The density of activated sludge (Schuler and Jang, 2007) is **1035 kg/m^3**: Assuming the characteristics of sonicated RAS are suitable for the pump operating conditions, Figure F-1 was used to obtain the head (H, units in meter) of the liquid. 30% allowance was taken into account in the design calculations.

- **Plants B and C**

The flow rate of the activated sludge is 207 m^3/day (8.6286 m^3/h; 2.40 x $10^{-3} m^3/s$). With 30% allowance, the flow rate becomes:

$$\frac{130}{100} \times 207.0871 \, \mathrm{m^3/day} = 269.2132 \, \mathrm{m^3/day} \left(11.2172 \, \mathrm{m^3/h}; 3.1159 \times 10^{-3} \, \mathrm{m^3/s}\right)$$

Using Figure F-1, the head of the liquid (RAS) is 90 m. From Figure F-2, the pump efficiency chosen is 50%.

NOTE: This figure is included on page 93 of the print copy of the thesis held in the University of Adelaide Library.

Figure F-1 Normal operating ranges for commercially available pumps (Reproduced from Peters et al., 2003)

Calculating Ws using Equation 6-3:

$$W_s = H \times g$$

$$W_s = 883 \frac{\mathrm{J}}{\mathrm{kg}}$$

Calculating the mass flow rate

$$m = 269.2132 \frac{\mathrm{m^3}}{\mathrm{day}} \times 1035 \frac{\mathrm{kg}}{\mathrm{m^3}} \times \frac{1 \, \mathrm{day}}{24 \, \mathrm{h}} \times \frac{1 \, \mathrm{h}}{3600 \, \mathrm{s}} = 3.2249 \frac{\mathrm{kg}}{\mathrm{s}}$$

NOTE: This figure is included on page 94 of the print copy of the thesis held in the University of Adelaide Library.

Figure F-2 Efficiencies of centrifugal pumps (Reproduced from Peters et al., 2003)

Calculating the brake kW using Equation 6-2,

$$\text{brake kW} = \frac{W_s \times m}{\eta \times 1000}$$

$$\text{brake kW} = 5.6\ \text{kW}$$

Using Figure E-1, the η_e is 0.855. Calculating the electric power input (kW) using Equation 6-4,

$$\text{electric power input (kW)} = \frac{\text{brake kW}}{\eta_e}$$

$$\text{electric power input} = 7\ \text{kW}$$

From the calculation results above the pump requires a 7 kW motor.

Using Figure F-3 (Peters et al., 2003), purchased cost for the required centrifugal pump less motor for B and C Plant (Pump A) is US$ 2,000.00

NOTE: This figure is included on page 95 in the print copy of the thesis held in the University of Adelaide Library.

Figure F-3 Purchased cost of diaphragm, centrifugal, and rotary pumps (Reproduced from Peters et al., 2003)

NOTE: This figure is included on page 95 in the print copy of the thesis held in the University of Adelaide Library.

Figure F-4 Purchased cost of electric motor (Reproduced from Peters et al., 2003)

To minimise corrosion, the material chosen was stainless steel. Material adjustment factor for stainless steel is 2.4. Therefore, the purchase price of the centrifugal pump for B and C plant (Pump A) becomes $2.4 \times \text{US\$ } 2{,}000.00 = \text{US\$ } 4{,}800.00$

As stated above, the motor proposed for the design is a TEFC (totally enclosed fan cooled) with power requirement of 7 kW. Using Figure F-4, the motor price is US$ 1,000.00.

Thus, the total price for one unit of centrifugal pump for B and C Plant (Pump A) is
$US\$\ 4{,}800.00 + US\$\ 1{,}000.00 = US\$\ 5{,}800.00$

- **Plant D**

The flow rate of the activated sludge is 103.5435 m^3/day (4.3143 m^3/h; 1.20 x 10^{-3} m^3/s). With 30% allowance, the flow rate becomes:

$$\frac{130}{100} \times 103.5435 \ \mathrm{m^3/day} = 134.6066 \ \mathrm{m^3/day} \left(5.6086 \ \mathrm{m^3/h} ; 1.5579 \times 10^{-3} \ \mathrm{m^3/s}\right)$$

Following the same design steps, using Figure F-1, the head of the liquid (RAS) is 90 m. From Figure F-2, the pump efficiency chosen is 30%.

Calculating the mass flow rate

$$m = 134.6066 \frac{\mathrm{m^3}}{\mathrm{day}} \times 1035 \frac{\mathrm{kg}}{\mathrm{m^3}} \times \frac{1 \ \mathrm{day}}{24 \ \mathrm{h}} \times \frac{1 \ \mathrm{h}}{3600 \ \mathrm{s}} = 1.6125 \frac{\mathrm{kg}}{\mathrm{s}}$$

Calculating the brake kW using Equation 6-2,

$$\text{brake kW} = \frac{W_s \times m}{\eta \times 1000}$$

$$\text{brake kW} = 4.7 \ \text{kW}$$

Using Figure E-1, the η_e is 0.855.Calculating the electric power input (kW) using Equation 6-4,

$$\text{electric power input } (\text{kW}) = \frac{\text{brake kW}}{\eta_e}$$

$$\text{electric power input} = 6\ \text{kW}$$

From the calculation results above the pump requires a 6 kW motor.

Using Figure F-3, purchased cost for the required centrifugal pump less motor for D Plant is US\$ 1,500.00. Stainless steel was chosen, thus the purchased cost for D Plant centrifugal pump (Pump B) becomes:

$$2.4 \times \text{US\$}\,1{,}500.00 = \text{US\$}\,3{,}600.00$$

Using Figure F-4, the price of a 5kW TEFC motor price is US\$ 900.00.

Thus, the total price for one unit of centrifugal pump for D Plant (Pump B) is

$$\text{US\$}\,3{,}600.00 + \text{US\$}\,900.00 = \text{US\$}\,4{,}500.00$$

The total purchase price for the centrifugal pump is US\$ 10,300.00 (2002 US dollars). Converting to 2006 US dollars using Table 6-3 and Equation 6-1:

$$2006\ \text{US\$} = \text{US\$}\,10{,}300 \times \left(\frac{1{,}302.3}{1{,}104.2}\right) = \text{US\$}\,12{,}147.88$$

The total purchase cost for centrifugal pumps (including 10% delivery cost) is **US\$ 13,400**

F.2 RAS Sonication Operating Cost Estimation – Option 1

The operating cost for RAS sonication was assumed to only include power requirements of V5 Sonix and centrifugal pumps, and also maintenance and repair (2% of fixed capital investment). This assumption was taken as this project involved upgrade from an existing plant. Other associated operating costs were neglected as it was assumed to be the same with molasses dosing. Details are provided in the following appendices.

F.2.1 Power Requirement and Electricity Cost for V5 Sonix

From Appendix F.1.1, the required V5 Sonix is 3 units. The specifications of V5 Sonix provided by the supplier are given in Table 5-4 and Table 5-5 in Section 5.4.

The power input (3-phase) required for 1 unit V5 Sonix is:

$$P = 3 \times V \times I$$
$$P = 3 \times 480 \times 10$$
$$P = 14400\ \text{W} = 14.4\ \text{kW} \approx 15\ \text{kW}$$

Since it is a 24 hour continuous process, the energy consumption (kWh) for 1 unit is:

Energy consumption = $15 \times 24 = 360\ \text{kWh}/\text{day}$

For 3 V5 Sonix, the energy consumption is $3 \times 360 = 1080\ \text{kWh}/\text{day}$

Total electricity cost per day is $1080\ \text{kWh}/\text{d} \times \text{AU\$}\ 0.087/\text{kWh} = \text{AU\$}\ 93.96/\text{day}$

Assuming 365 working days per annual, the electricity cost

$$\text{AU\$}\ 93.96/\text{day} \times \frac{365\ \text{days}}{\text{year}} = \text{AU\$}\ 34{,}300/\text{year}$$

F.2.2 Power Requirement and Electricity Cost for Centrifugal Pump

As calculated, a 6 and 7 kW motor are required for the centrifugal pumps (see Appendix F.1.2)

The total required power for two centrifugal pumps:

6 + 7 = 13 kW

For 24 hours continuous operation, the energy consumption is:

Energy consumption = $13 \times 24 = 312\ \text{kWh}/\text{day}$

Total electricity cost per day is $312\ \text{kWh}/\text{d} \times \text{AU\$}\ 0.087/\text{kWh} = \text{AU\$}\ 27.144/\text{day}$

Assuming 365 working days per annual, the electricity cost

$$\text{AU\$}\ 27.144/\text{day} \times \frac{365\ \text{days}}{\text{year}} = \text{AU\$}\ 9{,}910/\text{year}$$

The total electricity cost per year is

Electricity cost of V5 Sonix + Electricity cost of centrifugal pumps

$$\text{AU\$}\ 34{,}300/\text{year} + \text{AU\$}\ 9{,}910/\text{year} = \text{AU\$}\ 44{,}210/\text{year}$$

F.2.3 Maintenance and repair

As the number of unit operation is minimal, it was assumed to apply maintenance and repair cost of 2% of fixed capital cost.

$$\frac{2}{100} \times \text{AU\$ } 6{,}853{,}759.33 = \text{AU\$ } 137{,}075.19$$

The total operating cost for RAS sonication Option 1 is:

Annual electricity cost + maintenance and repair **= AU$ 181,000**

Table F-1 provides the summary of RAS sonication Option 1 operating costs.

Table F-1 Summary of operating cost estimation Option 1

Item	Value	Unit
power input 1 unit V5 Sonix	14.4	kW
rounded	**15**	**kW**
24 hours running time	360	kWh
for RAS pumps		
RAS pump A	7	kW
RAS pump B	6	kW
24 hours running time (Centrifugal pumps)	312	kWh
24 hours running time (5 V5 Sonix)	1080	kWh
TOTAL kWH-24 hr	1392	kWh
cost per kWh	0.087	$/kWh
Electricity cost	120.51	$/d
Electricity cost per annum	**AU$ 43,985.19**	
Maintenance and repair per annum	**AU$ 137,075.19**	
Total operating cost per annum	**AU$ 181,278.15**	

F.3 Total Expenditure for Option 1

Table F-2 provides the summary of total expenditure of RAS sonication Option 1 projected for 20 year period.

Table F-2 Total expenditure sonication RAS Option 1 projected for a 20 year period

Year	Total Capital Investment (AU$)	Operating cost (AU$)	Total (AU$)
0	$ 8,050,000	$ 181,000	$ 8,240,000
1	$ 8,050,000	$ 363.000	$ 8,420,000
2	$ 8,050,000	$ 544,000	$ 8,600,000
3	$ 8,050,000	$ 725,000	$ 8,780,000
4	$ 8,050,000	$ 906,000	$ 8,960,000
5	$ 8,050,000	$ 1,090,000	$ 9,140,000
6	$ 8,050,000	$ 1,270,000	$ 9,320,000
7	$ 8,050,000	$ 1,450,000	$ 9,500,000
8	$ 8,050,000	$ 1,630,000	$ 9,690,000
9	$ 8,050,000	$ 1,810,000	$ 9,870,000
10	$ 8,050,000	$ 1,990,000	$ 10,000,000
11	$ 8,050,000	$ 2,180,000	$ 10,200,000
12	$ 8,050,000	$ 2,360,000	$ 10,400,000
13	$ 8,050,000	$ 2,540,000	$ 10,600,000
14	$ 8,050,000	$ 2,720.000	$ 10,800,000
15	$ 8,050,000	$ 2,900,000	$ 11,000,000
16	$ 8,050,000	$ 3,080,000	$ 11,100,000
17	$ 8,050,000	$ 3,260,000	$ 11,300,000
18	$ 8,050,000	$ 3,400,000	$ 11,500,000
19	$ 8,050,000	$ 3,630,000	$ 11,700,000
20	$ 8,050,000	$ 3,800,000	$ 11,900,000

F.4 RAS Sonication Equipment Purchase Cost Estimation – Option 2

The additional equipments required for the denitrification plant modification Option 2 are V5 Sonix and centrifugal RAS pumps. This is based on the process flow diagram presented in Figure 6-3.

F.4.1 V5 Sonix

Referring to the plant reconfiguration shown in Figure 6-3 and the mass balance for Option 2, the amount of RAS required to be sonicated to achieve the same molasses SCOD is 310.6306 m^3/d. It was stated in the previous chapter that one unit of V5 Sonix is able to treat 200 m^3/d of RAS.

V5 Sonix unit required for plant reconfiguration Option 2 is

$$\text{V5 Sonix required} = \frac{310.6306 \, {m^3}/{day}}{200 \, {m^3}/{day}} = 1.5532 \approx 2 \text{ units}$$

From the calculation above the required V5 Sonix for the denitrification plant is 2 units.

Thus, the cost for 2 units of V5 Sonix is

$$2 \times \text{US } \$373{,}790.80 = \text{US } \$747{,}581.60$$

An additional cost for delivery is 10%

Thus, total purchased cost for 2 V5 Sonix is:

$$\text{US\$ } 747{,}581.60 + \text{US\$ } 74{,}758.16 = \text{US\$ } 822{,}000$$

F.4.2 Centrifugal Pump

Referring to Figure 6-3, four additional centrifugal pumps are required. The same assumptions taken for Option 1 were again applied and 30% allowance was taken into account in the design calculations.

- **B and C Plants**

The flow rate of the activated sludge is 207.0871 m^3/d (8.6286 m^3/h; 2.40 x $10^{-3} m^3$/s). Referring to the plant reconfiguration shown in Figure 6-3, the flow rates of the RAS by-pass streams are identical, thus two identical pumps were selected. One unit centrifugal pump is required for the RAS by-pass stream to transfer RAS from the clarifier output to the V5 Sonix, and one unit centrifugal pump from the V5 Sonix to the anoxic zone of B and C Plant.

Since the RAS bypass flow rates are similar to the plant reconfiguration Option 1, the specifications of the centrifugal proposed for Option 1 was adopted. Therefore, the total price for the required centrifugal pump for B and C Plant (Pump A) is

$$(\text{US\$ } 4{,}800.00 + \text{US\$ } 1{,}000.00) \times 2 = \text{US\$ } 11{,}600.00$$

- **D Plant**

The flow rate of the activated sludge is 103.5435 m^3/d (4.3143 m^3/h; 1.20×10^{-3} m^3/s). Referring to the plant reconfiguration shown in Figure 6-3, the flow rates of the RAS by-pass streams (RAS 2) are identical. Two identical centrifugal pumps were selected. One unit centrifugal pump is required for the RAS by-pass stream to transfer RAS from the clarifier output to the V5 Sonix, and one unit centrifugal pump from the V5 Sonix to the anoxic zone of D Plant.

Since the RAS bypass flow rates are similar to the plant reconfiguration Option 1, the specifications of the centrifugal proposed for Option 1 was adopted. Therefore, the total price for the required centrifugal pump for D Plant (Pump B) is

$$(\text{US\$ } 3{,}600.00 + \text{US\$ } 900.00) \times 2 = \text{US\$ } 9{,}000.00$$

The total purchase price for the centrifugal pump is US$ 10,300.00 (2002 US dollars). Converting to 2006 US dollars using Table 6-3 and Equation 6-1:

$$2006 \text{ US\$} = \text{US\$ } 20{,}600 \times \left(\frac{1{,}302.3}{1{,}104.2} \right) = \text{US\$ } 24{,}295.76$$

The total purchase cost for centrifugal pumps (including 10% delivery cost) is **US$ 26,700.**

F.5 RAS Sonication Operating Cost Estimation – Option 2

The operating cost for RAS sonication Option 2 was assumed to only include power requirements of V5 Sonix and centrifugal pumps, and also maintenance and repair (2% of fixed capital investment). Details are provided in the following sub-chapters.

F.5.1 Power Requirement and Electricity Cost for V5 Sonix

From Appendix F.4.1, the required V5 Sonix is 2 units. The specifications of V5 Sonix provided by the supplier are given in Table 5-4 and Table 5-5 in Section 5.4.
Power input (3-phase) required for 1 unit V5 Sonix is:

$$P = 3 \times V \times I = 3 \times 480 \times 10 = 14400 \text{ W} \approx 15 \text{ kW}$$

Since it is a 24 hour continuous process, the energy consumption (kWh) for 1 unit is:

Energy consumption = $5\text{kW} \times 24 \text{ h} = 360 \, {}^{\text{kWh}}\!/_{\text{day}}$

For 2 V5 Sonix, the energy consumption is $2 \times 360 = 720 \, {}^{\text{kWh}}\!/_{\text{day}}$

Electricity cost for year 2006 calculated in Appendix F.2.1 is AU$ 0.087/kWh.
Total daily electricity cost for two units of V5 Sonix:

$$720 \, {}^{\text{kWh}}\!/_{\text{day}} \times {}^{\text{AU\$ } 0.087}\!/_{\text{kWh}} = {}^{\text{AU\$ } 62.64}\!/_{\text{day}}$$

Assuming 365 working days per annual, the electricity cost

$$ {}^{\text{AU\$ } 62.64}\!/_{\text{day}} \times \frac{365 \text{ days}}{\text{year}} = {}^{\text{AU\$ } 22{,}863.60}\!/_{\text{year}}$$

F.5.2 Power Requirement and Electricity Cost for Centrifugal Pump

As calculated, one 7 kW motor is required for B and C Plants, and one 6 kW motor for D Plant. Since the required centrifugal pump for plant reconfiguration Option 2 is twice the required centrifugal pumps for Option 1 (Appendix F.4.2), assuming 365 working days per annual, the electricity cost is (624 kWh/d):

$$\left({}^{\text{AU\$ } 27.144}\!/_{\text{day}} \times \frac{365 \text{ days}}{\text{year}} \right) \times 2 = {}^{\text{AU\$ } 19{,}815.12}\!/_{\text{year}}$$

The total electricity cost per year is
Electricity cost of V5 Sonix + Electricity cost of centrifugal pumps

$$ {}^{\text{AU\$ } 22{,}863.60}\!/_{\text{year}} + {}^{\text{AU\$ } 19{,}815.12}\!/_{\text{year}} = {}^{\text{AU\$ } 42{,}687.72}\!/_{\text{year}}$$

F.5.3 Maintenance and repair

As the number of unit operations is minimal, it was assumed to apply maintenance and repair cost of 2% of fixed capital cost.

$$\frac{2}{100} \times \text{AU\$ } 4{,}667{,}108.09 = \text{AU\$ } 93{,}342.16$$

The total operating cost for RAS sonication is

Annual electricity cost + maintenance and repair **= AU$ 136,000.**

Table F-3 provides the summary of RAS sonication operating cost Option 2.

Table F-3 Summary of operating cost estimation Option 2

Item	**Value**	**Unit**
power input 1 unit V5 Sonix	14.4	kW
rounded	**15**	**kW**
24 hours operation	360	kWh
for RAS pumps		
2 x RAS pump A	7	kW
2 x RAS pump B	6	kW
24 hours operation(Centrifugal pumps)	624	kWh
24 hours operation (5 V5 Sonix)	720	kWh
TOTAL kWh-24 hr	1344	kWh
cost per kWh	0.087	$/kWh
Electricity cost	116.928	$/d
Electricity cost per annum	**AU$ 42,687.72**	
Maintenance and repair per annum	**AU$ 93,342.16**	
Total operating cost per annum	**AU$ 136,029.88**	

F.6 Total Expenditure for Option 2

Table F-4 provides the summary of total expenditure of RAS sonication Option 2 projected for 20 year period.

Table F-4 Total expenditure sonication RAS Option 2 projected for a 20 year period

Year	Total Capital Investment (AU$)	Operating cost (AU$)	Total (AU$)
0	$ 5,480,000	$ 136,000	$ 5,620,000
1	$ 5,480,000	$ 272,000	$ 5,760,000
2	$ 5,480,000	$ 408,000	$ 5,890,000
3	$ 5,480,000	$ 544,000	$ 6,030,000
4	$ 5,480,000	$ 680,000	$ 6,170,000
5	$ 5,480,000	$ 816,000	$ 6,300,000
6	$ 5,480,000	$ 952,000	$ 6,440,000
7	$ 5,480,000	$ 1,090,000	$ 6,570,000
8	$ 5,480,000	$ 1,220,000	$ 6,710,000
9	$ 5,480,000	$ 1,360,000	$ 6,850,000
10	$ 5,480,000	$ 1,500,000	$ 6,980,000
11	$ 5,480,000	$ 1,630,000	$ 7,120,000
12	$ 5,480,000	$ 1,770,000	$ 7,250,000
13	$ 5,480,000	$ 1,900,000	$ 7,390,000
14	$ 5,480,000	$ 2,040,000	$ 7,530,000
15	$ 5,480,000	$ 2,180,000	$ 7,660,000
16	$ 5,480,000	$ 2,310,000	$ 7,700,000
17	$ 5,480,000	$ 2,450,000	$ 7,930,000
18	$ 5,480,000	$ 2,580,000	$ 8,070,000
19	$ 5,480,000	$ 2,720,000	$ 8,210,000
20	$ 5,480,000	$ 2,860,000	$ 8,340,000

Appendix G – Potato Starch

This section provides the details of the additional unit operations proposed for potato starch as the alternative external carbon source. This appendix also summarises the assumptions and elaborates the design calculations to obtain the capital cost investment and operating cost.

G.1 Potato Starch Equipment Purchase Cost Estimation

The additional equipments required for the denitrification plant modification using potato starch as external carbon source are potato starch powder storage tank, screw conveyor, mixing tanks and centrifugal pumps. This is based on the process flow diagram presented in Figure 6-4.

G.1.1 Potato Starch Powder Storage Tanks

From Section 6.3.1, the required mass of potato starch per week is $2{,}596{,}697.6253\,{}^{\text{kg}}\!\big/_{\text{week}}$. The specific density of potato starch was assumed to be 1.55 g/mL (International Starch Institute, 2007). The required volume of the storage tank for 1 week is:

$$\frac{2596697.6253\ \text{kg}}{\frac{1.55\ \text{g}}{\text{mL}}\times\frac{10^6\ \text{mL}}{\text{m}^3}\times\frac{1\ \text{kg}}{1000\ \text{g}}}=1675.2888\ \text{m}^3$$

Giving 30% allowance of the potato starch storage tank volume:

$$1675.2888\ \text{m}^3\times\frac{130}{100}=2177.8754\ \text{m}^3$$

The purchase cost for the storage tank (Matche, 2007) in 2003 US dollars is US$ 275,745.10. Converting to 2006 US dollars using Table 6-3 and Equation 6-1

$$2006\ \text{US\$}=\text{US\$}\ 233{,}800\times\left(\frac{1{,}302.3}{1{,}123.6}\right)=\text{US\$}\ 270{,}984.10$$

With 10% delivery cost, the purchase cost becomes **US$ 298,000.**

G.1.2 Mixing Tank

From Section 6.3.1, the required flow rate of potato starch is $\frac{1.1890\times10^{6}\ \text{L potato starch suspension}}{\text{h}}=1{,}200\ \text{m}^3\!/\text{h}$. Four hours mixing time is required to maintain the potato starch slurry in suspension. Thus, the mixing tank volume required for steady state operation:

$$\frac{1.1890\times10^{6}\ \text{L potato starch suspension}}{\text{h}}\times 4\ \text{h}=4..7559\times10^{6}\,\text{L}\approx 4{,}800\ \text{m}^3.$$

Since the required volume is very large, it was proposed to use prestressed concrete closed tanks. According to Creasy (1961), the economical depth of open water storage tanks is 15 ft (4.6 m). This guidance was used for the tank design (Figure G-1). Open tank was chosen for simplified design calculation and with the assumption that rain water would not affect the SCOD concentration of the starch slurry as the starch slurry is processed under high flow rate operation.

NOTE: This figure is included on page 107 of the print copy of the thesis held in the University of Adelaide Library.

Figure G-1 Economical depth of concrete storage tanks (Reproduced from Creasy, 1961)

Calculating the dimension of the tank with tank volume = 4800 m^3 (1,060,000 gallons) and the required tank depth, h = 4.6 m, gives the tank diameter, *d*:

$$d=\sqrt{\frac{V}{0.25\times\pi\times h}}$$

$d = 37\ \text{m}\ (122\text{ft}; 1{,}456.69\ \text{in})$

with a 10% of free board allowance, the tank depth, h = 5 m (16.5 ft; 196.85 in)

Recalculating new tank volume,

$\text{V} = 0.25 \times \pi \times d^2 \times \text{h}$

$\text{V} = 5400\ \text{m}^3\ (1{,}200{,}000\ \text{gallons})$

The next step of designing the tank was to calculate the wall thickness. The design equation presented was adopted from Gray, 1960 using British Units.

Maximum pressure at bottom wall, p is

$p = 62.5 \times \text{h}$

$62.5 \times 15\text{ft} = 937.5\ {}^{\text{lb}}\!/_{\text{ft}^2}\left(4578\ {}^{\text{kg}}\!/_{\text{m}^2}\right)$

The tension to be resisted, T is

$$\text{T} = \frac{p \times \text{D}}{2}$$

$$\text{T} = \frac{937.5 \times 122}{2} = 57187.5\ \text{lb}\ (25939.8\ \text{kg})$$

Assuming the tensile strength of steel for water retaining structures is 12,000 lb/in^2 and a modular ratio of 15 (Gray, 1960), the tensile strength of concrete is

$$\frac{12000\ {}^{\text{lb}}\!/_{\text{in}^2}}{15} = 800\ {}^{\text{lb}}\!/_{\text{in}^2}$$

Assuming the tension of steel in the wall of the tank (Gray, 1960) is 12,000 lb/in^2, the area (A_{st}) of steel in tension is:

$$\text{A}_{\text{st}} = \frac{\text{T}}{\text{p}_{\text{st}}} = \frac{57187.5}{12000} = 4.8\ \text{in}^2$$

The stress recommended in the code of practice (Gray, 1960) for water retaining structures is 190 lb/in^2, however for this design, the permissible stress used will be 150 lb/in^2 (Creasy, 1961). Therefore, the wall thickness of the tank, assuming the width of member in the tank, b = 12 in, is

$$150\ {}^{\text{lb}}\!/_{\text{in}^2} = \frac{\text{T}}{(12 \times \text{d}) + [(\text{m} - 1) \times \text{Ast}]}$$

$$150\ {}^{\text{lb}}\!/_{\text{in}^2} = \frac{57187.5}{(12 \times \text{d}) + [(15 - 1) \times 4.8]}$$

The wall thickness, d is 41.89 in (3.5 ft; 1.1 m)

The maximum ring tension for the above design is (Creasy, 1961)

$$150\,{}^{\mathrm{lb}}\!/_{\mathrm{in}^2} = \mathrm{w} \times \mathrm{H} \times \left[\frac{\mathrm{D}}{2t}\right]$$

where w is the density of liquid assuming water 0.032 lb/in^3 (63 lb/ft^3; 1000 kg/m^3), H is the depth of the tank (in), D is the tank diameter (in), and t is the wall thickness (in). In order to verify the above results, the ring tension using $t = 41.89$ in:

$$\mathrm{f_r} = 0.032 \times 196.85 \times \left[\frac{1456.69}{2 \times 41.89}\right] = 123.23\,{}^{\mathrm{lb}}\!/_{\mathrm{in}^2}$$

Since the ring tension 123.23 lb/cu.in is less than the maximum allowable ring tension (150 lb/in^3), the wall thickness is therefore satisfactory.

The cost of unmounted ground level prestressed concrete tank (assuming design with semi-sliding wall-foot type) is given in Figure G-2.

NOTE: This figure is included on page 109 of the print copy of the thesis held in the University of Adelaide Library.

Figure G-2 Purchase cost of concrete tanks (Reproduced from Creasy, 1961)

The cost shown in this diagram includes site stripping, excavation, contract preliminaries and trimming for fitting (approximately 20%). With the use of this diagram, the purchase cost for one unit of 1.2 million gallon open concrete tank is £12,000.00 (in 1961). However, a fixed wall-foot was proposed for the design. This will affect the cost of approximately 10% increase to the cost of semi-sliding wall-foot type. Therefore the tank cost with fixed wall-foot is: 1.1 × £ 12,000.00 = £ 13,200.00

Since the tank will be mounded to the ground, another cost factor was employed to obtain higher accuracy of the cost. The cost trend for mounded tank is shown in Figure G-3.

NOTE: This figure is included on page 110 of the print copy of the thesis held in the University of Adelaide Library.

Figure G-3 Cost trend of mounded tank (Reproduced from Creasy, 1961)

The tank diameter calculated was 122 ft. Using Figure G-3, the relative cost is 130%. Since the relative cost obtained was for 1 million gallon capacity, converting the percentage relative cost to 1.2 million gallons

$$\text{cost equipment A} = \text{cost equipment B} \times \left(\frac{\text{capacity equipment A}}{\text{capacity equipment B}} \right)$$

$$\text{relative cost} = 130\% \times \left(\frac{1.2 \text{ million gallons}}{1.0 \text{ million gallons}} \right)$$

$$\text{relative cost} = 156\%$$

Thus, the cost of the tank is:

156% x £ 13,200.00 = £ 20,592.00

Converting to 2006 US dollars using Table 6-2 and Table 6-3:

1961 US$ = £ 20,592.00 x 1.9673 US$/£ = US$ 40,510.64

$$2006\ \text{US\$} = \text{US\$}\ 40{,}510.64 \times \left(\frac{1{,}302.3}{237.2}\right) = \text{US\$}\ 222{,}416.00$$

With 10% delivery cost, the purchase cost becomes **US$ 245,000.00**.

G.1.3 Jet Mixers

With the large dimensions calculated in the tank design, impeller mixers would not be sufficient to achieve homogenous mixing. Therefore, jet mixers were proposed to be utilized. The mixing time required is 4 hours (Section 3.3). It was assumed that 4 hours mixing time should dissolve the soluble fraction of the starch.

To obtain a good mixture and homogeneity, approximately 25 – 100 m^3 liquid content per mixer is required for low profile tanks (ANA, 2007). Taking the average value of 62.5 m^3 per mixer, with a 5400 m^3 tank volume, the number of jet mixers required is:

$$\frac{4800\ m^3}{62.5} = 76.8 \approx 80\ \textit{jet mixers}$$

The price for 80 jet mixer units type 17.1 size 5-80 is with 10% delivery cost is **US$ 53,400**.

The cost of jet mixers is quite small compared to other unit operations. Principally, the cost of jet mixers is the cost of the centrifugal pump which delivers the pressurised flow (Peters et al., 2003).

Calculating the total delivered flow to the jet mixers (m^3/h) (Engelhardt, 2007), assuming this equation covers for preliminary design:

$$t \approx 0.3 \frac{I_E}{\Sigma V}$$

where t = mixing time (h), I_E is the actual vessel volume (m^3) and $\sum V$ is the total delivered flow to the jet mixers (m^3/h)

$$\Sigma V \approx 0.3\frac{5400\text{m}^3}{4\text{h}}$$

$$\Sigma V \approx 405\ {\text{m}^3}/{\text{h}}$$

The flow of each jet is

$$\frac{405}{80} = 5.1\ {\text{m}^3}/{\text{h}}$$

From the proposed jet mixer arrangement shown in Figure 6-5, one centrifugal pump must cater 40 jet mixers. Therefore, the capacity of one centrifugal pump required is:

$$5.1\ {\text{m}^3}/{\text{h}} \times 40 = 204\ {\text{m}^3}/{\text{h}}$$

Following the same design calculation steps for centrifugal pumps, using Figure F-1, the head of the liquid (potato starch slurry) is 45 m.

Calculating W_s using Equation 6-3:

$$W_s = H \times g$$

$$W_s = 45\ \text{m} \times 9.81\ {\text{m}}/{\text{s}^2}$$

$$W_s = 441.45\ \frac{\text{J}}{\text{kg}}$$

Calculating the mass flow rate

$$m = 204\frac{\text{m}^3}{\text{h}} \times 1000\frac{\text{kg}}{\text{m}^3} \times \frac{1\ \text{h}}{3600\ \text{s}} = 56.67\frac{\text{kg}}{\text{s}}$$

Calculating the brake kW using Equation 6-2 and from Figure F-2, the pump efficiency chosen is 80%.

$$\text{brake kW} = \frac{W_s \times m}{\eta \times 1000}$$

$$\text{brake kW} = \frac{441.45\ {\text{J}}/{\text{kg}} \times 56.67\ {\text{kg}}/{\text{s}}}{0.8 \times 1000}$$

$$brake\ kW = 31.27\ kW$$

Using Figure E-1, the η_e is 0.88. Calculating the electric power input (kW) using Equation 6-4,

$$\text{electric power input}\left(\text{kW}\right)=\frac{\text{brake kW}}{\eta_e}$$

$$\text{electric power input}\left(\text{kW}\right)=\frac{31.27}{0.88}=35.5\text{ kW}$$

From the calculation results above the pump requires a 36 kW motor.

Using Figure F-3 (Peters et al., 2003), purchased cost for the required centrifugal pump less motor is US$ 6,000.00. Stainless steel was chosen, thus the purchased cost for the centrifugal pump becomes:

$$2.4\times\text{US\$ }6{,}000.00=\text{US\$ }14{,}400.00$$

Using Figure F-4 (Peters et al., 2003), the price of a 36 kW TEFC motor price is US$ 4,000.00.

The total price for one unit of centrifugal pump with motor is

$$\text{US\$ }14{,}400.0+\text{US\$ }4{,}000.00=\text{US\$ }18{,}400.00$$

Thus, for two units of centrifugal pumps, the total price is US$ 36,800.00 (2002 US dollars). Converting to 2006 US dollars using Table 6-3 and Equation 6-1:

$$2006\text{ US\$}=\text{US\$ }36{,}800\times\left(\frac{1{,}302.3}{1{,}104.2}\right)=\text{US\$ }43{,}500.00$$

With 10% delivery cost, the purchase cost becomes **US$ 47,900.**

The total price for jet mixers including two centrifugal pump units is:

US$ 53,400 + US$ 47,900 = US$ 101,000

G.1.4 Screw Conveyor

The design approach was based primarily on the mass of potato starch required per hour. The screw conveyor must supply 12000 kg/h potato starch to the mixing tank to be mixed with 1200 m^3/h of water.

For 12000 kg/h (3.3333 kg/s), knowing the specific density (1550 kg/m^3), the volumetric flow rate of potato starch (solid powder) is

$$\frac{12000\,{}^{\text{kg}}\!/_{\text{h}}}{1550\,{}^{\text{kg}}\!/_{\text{m}^3}}=7.7419\,{}^{\text{m}^3}\!/_{\text{h}}$$

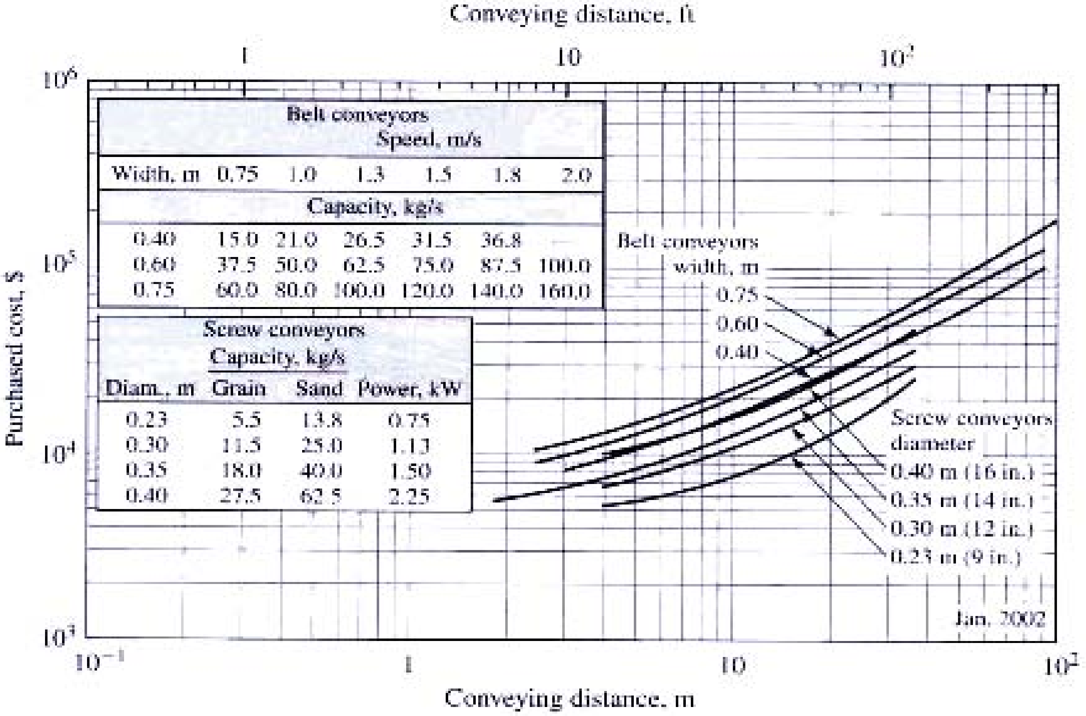
Giving 30% allowance, the flow rate of potato starch becomes

$$7.7419\,{}^{\mathrm{m^3}}\!/_{\mathrm{h}} \times 1.3 = 10\,{}^{\mathrm{m^3}}\!/_{\mathrm{h}}$$

Table G-1 shows the maximum capacity of a screw conveyor for economical service. Potato starch was assumed to be in the Class I material category. To transport a 10 m^3/h capacity, 0.15 m screw diameter was chosen.

NOTE: This figure is included on page 114 of the print copy of the thesis held in the University of Adelaide Library.

Referring to Figure G-4, the next closest available screw diameter is 0.23 m. It was assumed that the conveying distance is 30 m.



Belt conveyors

Width, m	Speed, m/s 0.75	1.0	1.3	1.5	1.8	2.0
	Capacity, kg/s					
0.40	15.0	21.0	26.5	31.5	36.8	—
0.60	37.5	50.0	62.5	75.0	87.5	100.0
0.75	60.0	80.0	100.0	120.0	140.0	160.0

Screw conveyors

	Capacity, kg/s		
Diam., m	Grain	Sand	Power, kW
0.23	5.5	13.8	0.75
0.30	11.5	25.0	1.13
0.35	18.0	40.0	1.50
0.40	27.5	62.5	2.25

Figure G-4 Purchased cost of screw and belt conveyors

The price for one unit screw conveyor is US$ 20,000.00. Converting to 2006 US dollars using Table 6-3 and Equation 6-1

$$2006\text{ US\$} = \text{US\$ } 20{,}000 \times \left(\frac{1{,}302.3}{1{,}104.2}\right) = \text{US\$ } 24{,}000.00$$

With 10% delivery cost, the purchase cost becomes **US$ 26,400.00**

G.1.5 Centrifugal Pumps

The centrifugal pumps discussed in this section refer to the centrifugal pumps required to transport the water for mixing and the soluble starch solution to the denitrification process. Referring to Figure 6-4, two additional centrifugal pumps are required. Following the same design calculation steps, using Figure F-1, the head of the liquid (potato starch slurry) is 45 m.

Calculating W_s using Equation 6-3:

$$W_s = H \times g$$

$$W_s = 45\text{ m} \times 9.81 \,\mathrm{m}/_{\mathrm{s}^2}$$

$$W_s = 441.45\,\frac{\mathrm{J}}{\mathrm{kg}}$$

Calculating the mass flow rate

$$m = 1189\,\frac{\mathrm{m}^3}{\mathrm{h}} \times 1000\,\frac{\mathrm{kg}}{\mathrm{m}^3} \times \frac{1\,\mathrm{h}}{3600\,\mathrm{s}} = 330.2778\,\frac{\mathrm{kg}}{\mathrm{s}}$$

Calculating the brake kW using Equation 6-2 and from Figure F-2, the pump efficiency chosen is 85%.

$$\text{brake kW} = \frac{W_s \times m}{\eta \times 1000}$$

$$\text{brake kW} = \frac{441.45\,{}^{\mathrm{J}}\!/\!_{\mathrm{kg}} \times 330.2778\,{}^{\mathrm{kg}}\!/\!_{\mathrm{s}}}{0.85 \times 1000}$$

$$\text{brake kW} = 171.5307\ \mathrm{kW}$$

Using Figure E-1, the η_e is 0.92.Calculating the electric power input (kW) using Equation 6-4,

$$\text{electric power input}\ (\mathrm{kW}) = \frac{\text{brake kW}}{\eta_e}$$

$$\text{electric power input} = 187\ \mathrm{kW}$$

From the calculation results above the pump requires a 187 kW motor.

Using Figure F-3 (Peters et al., 2003), purchased cost for the required centrifugal pump less motor is US$ 13,000.00. Stainless steel was chosen, thus the purchased cost for the centrifugal pump becomes:

$$2.4 \times \text{US\$ } 13{,}000.00 = \text{US\$ } 31{,}200.00$$

Using Figure F-4 (Peters et al., 2003), the price of a 187 kW TEFC motor price is US$ 12,000.00.

The total price for one unit of centrifugal pump is

$$\text{US\$ } 31{,}200.00 + \text{US\$ } 12{,}000.00 = \text{US\$ } 43{,}200.00$$

Thus, for two units of centrifugal pumps, the total price is US$ 86,400.00 (2002 US dollars). Converting to 2006 US dollars using Table 6-3 and Equation 6-1:

$$2006\text{ US\$} = \text{US\$ }86{,}400 \times \left(\frac{1{,}302.3}{1{,}104.2}\right) = \text{US\$ }101{,}900.67$$

With 10% delivery cost, the purchase cost becomes **US$ 112,000.**

G.1.6 AFR Filters

Referring to Section 6.3.1, the flow rate of potato starch slurry required to be filtered is 1189 m^3/h. From the specification of the AFR filter, one unit of AFR filter is able to process 454 m^3/h. The full specification of this AFR filter is attached in Appendix H. The required AFR is

$$\frac{1189\,\text{m}^3/\text{h}}{454\,\text{m}^3/\text{h}} = 2.6189 \approx 3\text{ units}$$

A quote was obtained by email correspondence with Melissa Murphy and Andrew Garland from Eaton. The price of one unit AFR filter is AU$ 135,540.00. Since all unit operations purchase prices are in 2006 US dollars, converting to 2006 US dollars using currency converter provided in
Table 6-2:

$$3 \times \text{AU\$ }135{,}540.00 = \text{AU\$ }406{,}620.00$$

$$2006\text{ US\$} = \frac{\text{US\$ }406{,}620.00}{1.28429} = \text{US\$ }316{,}610.73$$

With 10% delivery cost, the purchase cost becomes **US$ 348,000**

G.2 Potato Starch Operating Cost Estimation

The operating cost for potato starch was assumed to only include power requirements of jet mixers, screw conveyor, AFR filters, centrifugal pumps, and also maintenance and repair (2% of fixed capital investment). This assumption was taken as this project involved the upgrade from an existing plant. Other associated operating costs were neglected as it was assumed to be the same with molasses dosing. Details are provided in the following sub-chapters.

G.2.1 Jet Mixers

The operating cost for the jet mixers is principally the operating costs of the centrifugal pumps which generate and deliver the pressure required. From Appendix G.1.2, the number of centrifugal pump for the jet mixers required is two units with 36 kW motor each.

The required power for two centrifugal pumps for the jet mixers is 36 kW x 2 = 72 kW.

For 24 hours continuous operation, the energy consumption is:

$$72 \times 24 = 1728 \,{}^{\text{kWh}}\!\!/_{\text{day}}$$

The daily electricity cost is:

$$6336 \,{}^{\text{kWh}}\!\!/_{\text{day}} \times {}^{\text{AU\$ } 0.087}\!\!/_{\text{kWh}} = {}^{\text{AU\$ } 150.34}\!\!/_{\text{day}}$$

Assuming 365 working days per annual, the electricity cost

$$ {}^{\text{AU\$ } 150.34}\!\!/_{\text{day}} \times \frac{365 \text{ days}}{\text{year}} = {}^{\text{AU\$ } 55{,}000.00}\!\!/_{\text{year}}$$

G.2.2 Screw Conveyor

Referring to Appendix G.1.4, six screw conveyors are required. According to the guidelines for the selection of solid transport equipment (Peter and Timmerhaus, 2003), the power requirement for a screw conveyor is given in Equation 6-5. Knowing the mass flow rate (m) is 12000 kg/h (3.3333 kg/s) from Appendix G.1.4, the power requirement (kW) is:

$$P = 0.07 \times m^{0.85} \times L$$

$$P = 5.84 \text{ kW}$$

The daily energy consumption (kWh) is:

$$5.84 \text{ kW} \times 24 \text{ h} = 140.16 \,{}^{\text{kWh}}\!\!/_{\text{day}}$$

The daily electricity cost is:

$$140.16 \,{}^{\text{kWh}}\!\!/_{\text{day}} \times {}^{\text{AU\$ } 0.087}\!\!/_{\text{kWh}} = {}^{\text{AU\$ } 12.19}\!\!/_{\text{day}}$$

Assuming 365 working days per annual, the electricity cost for six screw conveyors is

$$\text{AU\$}\,12.19\Big/_{\text{day}} \times \frac{365\ \text{days}}{\text{year}} = \text{AU\$}\ 4{,}500.00\Big/_{\text{year}}$$

G.2.3 AFR Filters

From the specification of AFR filters given in Appendix H, the service requirements include electrical supply, air and water. However, for the operating cost comparison, only the electrical requirement was observed. Air blowers or compressors and water supply equipment was assumed to be installed in the existing plant. The electrical specifications of the AFR filters are given in Table G-2.

Table G-2 Electrical specification for AFR filters (Garland, 2007)

Electrical specification	Value
Voltage (VAC)	230
Current (Amp)	1.5

The power input required for one unit of AFR filter is

$$P = V \times I = 230 \times 1.5 = 345\ \text{W} = 0.345\ \text{kW}$$

Since it is a 24 hour continuous process, the energy consumption (kWh) for 1 unit is:

$$0.345 \times 24 = 8.28\,\text{kWh}\Big/_{\text{day}}$$

For three units of AFR filters, the energy consumption is

$$3 \times 8.28 = 24.84\ \text{kWh}\Big/_{\text{d}}$$

The daily electricity cost is:

$$24.84\,\text{kWh}\Big/_{\text{day}} \times \text{AU\$}\ 0.087\Big/_{\text{kWh}} = \text{AU\$}\ 2.16\Big/_{\text{day}}$$

The annual electricity cost for three units of AFR filters is

$$\text{AU\$}\ 2.16\Big/_{\text{day}} \times \frac{365\ \text{days}}{\text{year}} = \text{AU\$}\ 790.00\Big/_{\text{year}}$$

G.2.4 Centrifugal Pumps

From the design calculation, 132 kW motor was required for each centrifugal pump. The total required power for two centrifugal pumps is 132 kW x 2 = 264 kW

The daily energy consumption is:

$$264 \times 24 = 6336 \,{}^{\text{kWh}}\!/_{\text{day}}$$

The daily electricity cost is:

$$6336 \,{}^{\text{kWh}}\!/_{\text{day}} \times {}^{\text{AU\$ 0.087}}\!/_{\text{kWh}} = {}^{\text{AU\$ 551.23}}\!/_{\text{day}}$$

The annual electricity cost is:

$$\text{AU\$ 551.23}\!/_{\text{day}} \times \frac{365 \text{ days}}{\text{year}} = \text{AU\$ 202,000.00}\!/_{\text{year}}$$

G.2.5 Maintenance and Repair

It was assumed to apply maintenance and repair cost of 2% of fixed capital cost.

$$\frac{2}{100} \times \text{AU\$ 12,500,000} = \text{AU\$ 250,000}$$

The total operating cost for potato starch as carbon source is

Annual electricity cost + maintenance and repair

261,000 + 250,000 = AU$ 511,000

G.3 Total Expenditure for Potato Starch

Table G-3 provides the summary of total expenditure of potato starch projected for 20 year period.

Table G-3 Total expenditure potato starch projected for a 20 year period

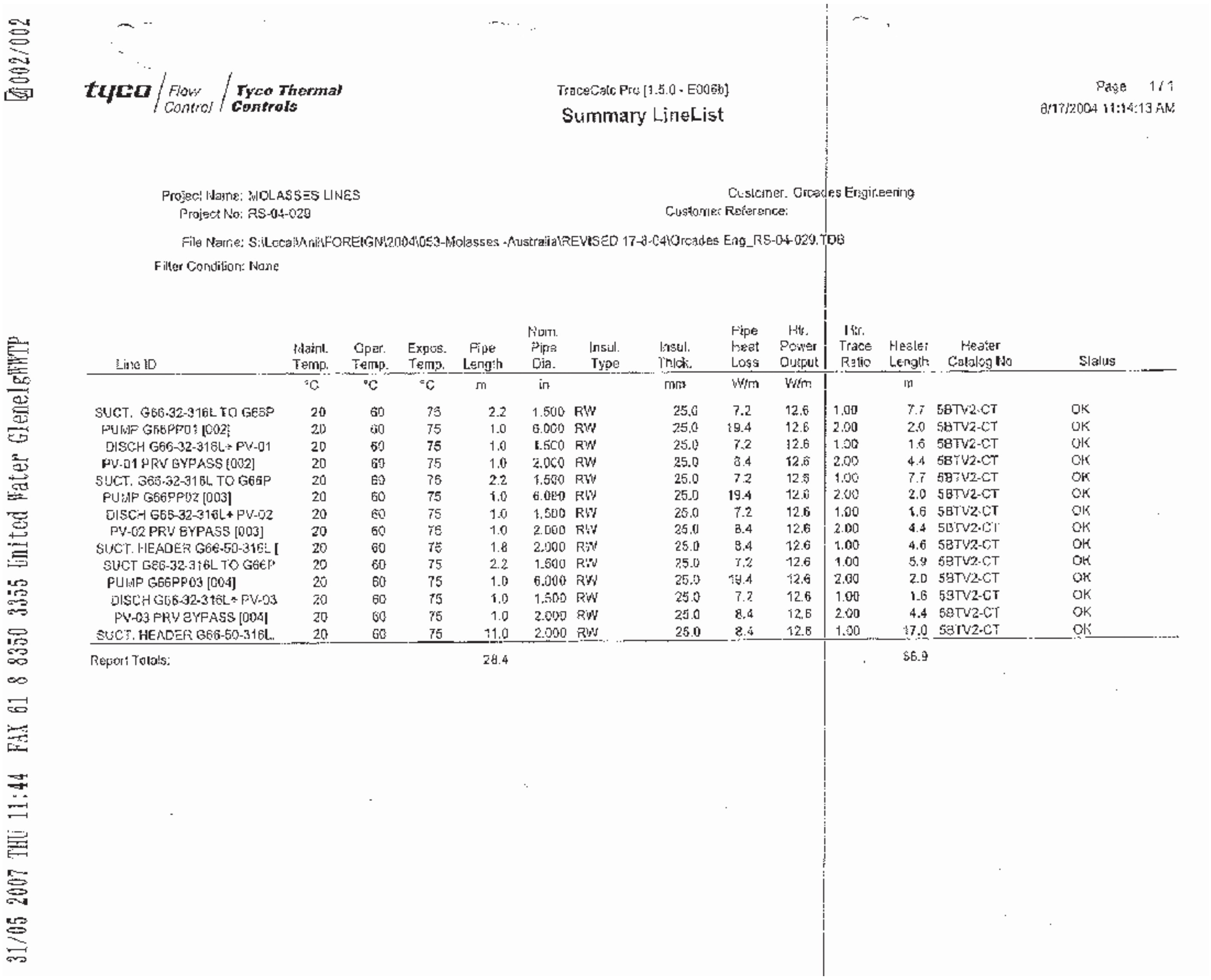
Year	Total Capital Investment (AU$)	Operating cost (AU$)	Total (AU$)
0	$ 12,500,000	$ 512,000	$ 13,100,000
1	$ 12,500,000	$ 1,020,000	$ 13,600,000
2	$ 12,500,000	$ 1,540,000	$ 14,100,000
3	$ 12,500,000	$ 2,050,000	$ 14,600,000
4	$ 12,500,000	$ 2,560,000	$ 15,000,000
5	$ 12,500,000	$ 3,070,000	$ 15,600,000
6	$ 12,500,000	$ 3,590,000	$ 16,100,000
7	$ 12,500,000	$ 4,100,000	$ 16,600,000
8	$ 12,500,000	$ 4,610,000	$ 17,200,000
9	$ 12,500,000	$ 5,120,000	$ 17,700,000
10	$ 12,500,000	$ 5,640,000	$ 18,200,000
11	$ 12,500,000	$ 6,150,000	$ 18,700,000
12	$ 12,500,000	$ 6,660,000	$ 19,200,000
13	$ 12,500,000	$ 7,170,000	$ 19,700,000
14	$ 12,500,000	$ 7,690,000	$ 20,200,000
15	$ 12,500,000	$ 8,200,000	$ 20,700,000
16	$ 12,500,000	$ 8,710,000	$ 21,300,000
17	$ 12,500,000	$ 9,220,000	$ 21,800,000
18	$ 12,500,000	$ 9,740,000	$ 22,300,000
19	$ 12,500,000	$ 10,250,000	$ 22,800,000
20	$ 12,500,000	$ 10,760,000	$ 23,300,000

Appendix H – Attachments

H.1 V5 Sonix Attachments

NOTE: Appendix H.1 is included on pages 122 – 124 in the print copy of the thesis held in the University of Adelaide Library.

H.2 Pipe Heaters



002/002

tyco / Flow Control / **Tyco Thermal Controls**

TraceCalc Pro [1.5.0 - E006b]

Summary LineList

Page 1/1
8/17/2004 11:14:13 AM

Project Name: MOLASSES LINES
Project No: RS-04-029

Customer: Orcades Engineering
Customer Reference:

File Name: S:\Local\Anil\FOREIGN\2004\053-Molasses -Australia\REVISED 17-8-04\Orcades Eng_RS-04-029.TDB

Filter Condition: None

Line ID	Maint. Temp.	Oper. Temp.	Expos. Temp.	Pipe Length	Nom. Pipe Dia.	Insul. Type	Insul. Thick.	Pipe heat Loss	Htr. Power Output	Htr. Trace Ratio	Heater Length	Heater Catalog No	Status
	°C	°C	°C	m	in		mm	W/m	W/m		m		
SUCT. G66-32-316L TO G65P	20	60	75	2.2	1.500	RW	25.0	7.2	12.6	1.00	7.7	5BTV2-CT	OK
PUMP G66PP01 [002]	20	60	75	1.0	6.000	RW	25.0	19.4	12.6	2.00	2.0	5BTV2-CT	OK
DISCH G66-32-316L+ PV-01	20	60	75	1.0	1.500	RW	25.0	7.2	12.6	1.00	1.6	5BTV2-CT	OK
PV-01 PRV BYPASS [002]	20	60	75	1.0	2.000	RW	25.0	8.4	12.6	2.00	4.4	5BTV2-CT	OK
SUCT. G66-32-316L TO G66P	20	60	75	2.2	1.500	RW	25.0	7.2	12.6	1.00	7.7	5BTV2-CT	OK
PUMP G66PP02 [003]	20	60	75	1.0	6.000	RW	25.0	19.4	12.6	2.00	2.0	5BTV2-CT	OK
DISCH G66-32-316L+ PV-02	20	60	75	1.0	1.500	RW	25.0	7.2	12.6	1.00	1.6	5BTV2-CT	OK
PV-02 PRV BYPASS [003]	20	60	75	1.0	2.000	RW	25.0	8.4	12.6	2.00	4.4	5BTV2-CT	OK
SUCT. HEADER G66-50-316L [	20	60	75	1.8	2.000	RW	25.0	8.4	12.6	1.00	4.6	5BTV2-CT	OK
SUCT G66-32-316L TO G66P	20	60	75	2.2	1.500	RW	25.0	7.2	12.6	1.00	5.9	5BTV2-CT	OK
PUMP G66PP03 [004]	20	60	75	1.0	6.000	RW	25.0	19.4	12.6	2.00	2.0	5BTV2-CT	OK
DISCH G66-32-316L+ PV-03	20	60	75	1.0	1.500	RW	25.0	7.2	12.6	1.00	1.6	5BTV2-CT	OK
PV-03 PRV BYPASS [004]	20	60	75	1.0	2.000	RW	25.0	8.4	12.6	2.00	4.4	5BTV2-CT	OK
SUCT. HEADER G66-50-316L	20	60	75	11.0	2.000	RW	25.0	8.4	12.6	1.00	17.0	5BTV2-CT	OK
Report Totals:				28.4							56.9		

31/05 2007 THU 11:44 FAX 61 8 8350 3355 United Water Glenelg WWTP

Figure H-4 Pipe heater details at Glenelg WWTP (Reproduced from Kaeding, 2007^a)

H.3 AFR Filter Specification, Operating Conditions, and Quotation

NOTE: Appendix H.3 is included on pages 126 – 129 in the print copy of the thesis held in the University of Adelaide Library.

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