UBC Social, Ecological Economic Development Studies (SEEDS) Student Reports

Algae Bioreactor System for the UBC Power House

Gang Chen

Alessandro Deviato

Simon Kras

University of British Columbia

CHBE 484

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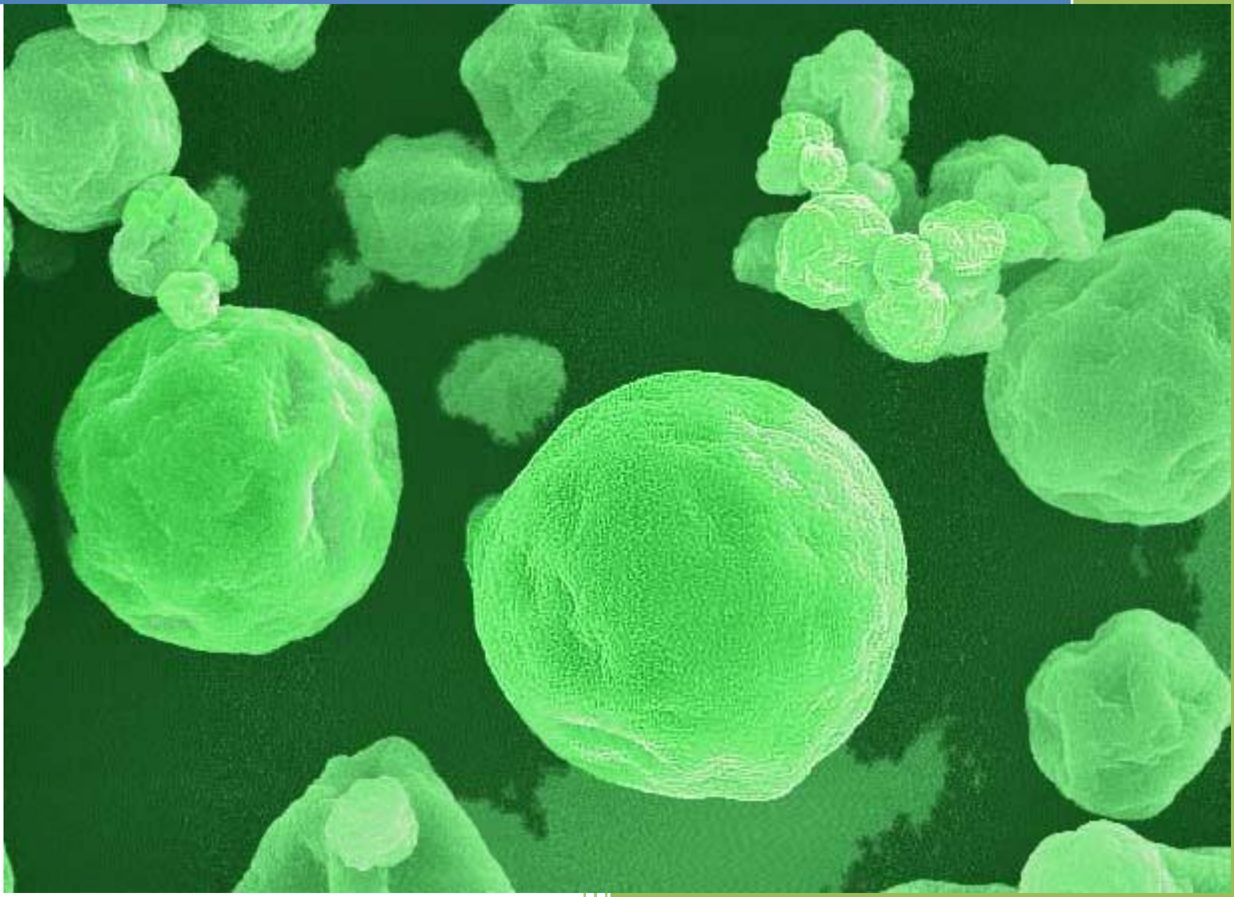

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Alessandro Deviato

Simon Kras

University of British Columbia

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EXECUTIVE SUMMARY

In the last 20 years, the use of algae bioreactors has been gaining popularity. Fuel produced by algae bioreactors can be in the form of methane or in the form of lipids, which can be converted to biodiesel.

Certain species of algae such as *Botryococcus Braunii* and *Chlorella vulgaris* have especially high lipid contents when starved of nutrients and are therefore ideal candidates for biodiesel production. The major requirements of all photoautotrophic species, including algae, are light, carbon dioxide and nutrients. All three requirements are naturally available, making open-air bioreactors the most common type. However, closed photo-bioreactors (PBRs) are becoming increasingly common, since they provide increased exposure to sunlight, increased growth rates, and consequently, increased production on a given area of land. CO_2-rich flue gas can be used fairly readily by closed PBRs to increase the rate of production by providing a source of heat and carbon.

A study was done in 2008 to assess the feasibility of a closed PBR situated on the roof of the Leonard S. Klinck (LSK) building at UBC, using flue gas from the UBC powerhouse. In her study, Christine Hung suggested that a PBR using *B. Braunii* would be economically feasible, in large part due to production of biodiesel. In this study we have sought to consider whether using different algal species, or incorporating wastewater as a reactor medium would improve the performance of the proposed PBR. We have provided a short background of microalgae production, conducted an analysis concerning the use of *Chlorella vulgaris*, *Nannochloropsis oculata* and *Scenedesmus sp*, and determined the cost of pumping wastewater from the current sewer system to a PBR on the roof of the LSK building.

We are unable to replicate Hung's calculations, and based on our analysis, the proposed PBR is not economically feasible. The expected annual revenue for *B. Braunii* is $32,600, and the annual expense instalments are $1.1 million. *Scenedesmus sp*. was deemed to be the best performer with expected annual revenue of $70,000.

The capital and operating costs over a ten year period associated with pumping wastewater from the existing sewage lines to the proposed PBR are $8,700 annually.

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1.0 INTRODUCTION

Renewable energy is currently the subject of intense research due to the focus on reducing greenhouse gas (GHG) emissions, and finding energy alternatives to fossil fuels. Biofuels are a promising renewable energy source that has attracted attention in recent years. However, first generation biofuels primarily obtained from food crops and oil seeds are limited in their capacity due to their extensive land requirement, often competing with agricultural land use (Reinhardt G et al., 2008). These concerns have steered scientific and engineering research towards intensive biomass productions through non-food organisms such as microalgae.

The basis for this report is the undergraduate thesis created by Christine Hung in 2008, which examines the feasibility of an algae bioreactor fed by the UBC powerhouse flue gas. The motivation of this literature-based study is to address a few of the items left pending by Hung in her thesis. A brief introductory background will be provided on algae bioreactors, followed by an examination of the feasibility of using different algal species at UBC. The use of wastewater as a growth medium will also be examined.

2.0 BACKGROUND

2.1 How a Bioreactor Works

According to researcher T.M. Mata, a bioreactor is defined as a system in which a biological conversion or reaction is achieved (Mata et al, 2009). Therefore, a photo-bioreactor is a reactor in which phototrophs (microbial, algal or plant cells) are cultivated or utilized to carry out a photo-biological reaction. Although this definition may be valid for both closed and open-culture systems, for the purpose of this article the definition is limited to the close-culture systems.

Photo-bioreactors (PBRs) are flexible systems that can be optimized according to the biological and physiological characteristics of the particular algal species being used, allowing for species' selection based on the desired products. In a PBR, direct exchange of gases and contaminants (i.e. microorganisms, dust) between the grown cells and atmosphere are limited or not allowed by the reactor's walls. In addition, a large amount of light must cross the transparent reactor walls.

2.2 Biodiesel Process Using Algal PBRs

Error! Reference source not found. shows a schematic representation of the algal biodiesel process. It starts with the selection of algae species, followed by the design and implementation of PBRs for algae growth. After the PBRs, the biomass harvesting, processing and oil extraction are the typical unit operations for biodiesel production unit.

Depending on the local conditions and available materials PBR's design varies in size, shape, construction materials, inclination and agitation type. PBRs can be classified on the basis of both design and mode of operation. Generally, vertical tubular or flat-plate reactors are relatively cheap, easy to clean up, and have a large illumination surface, high mass transfer, and good mixing with low shear stress (Diane Greer, 2009). Those advantages play an important role in productivity. Limitations include the cost and complex construction. In addition, since diameter and height cannot be too large, a significant number of units are necessary to process the desired amount of waster water and flue gas.

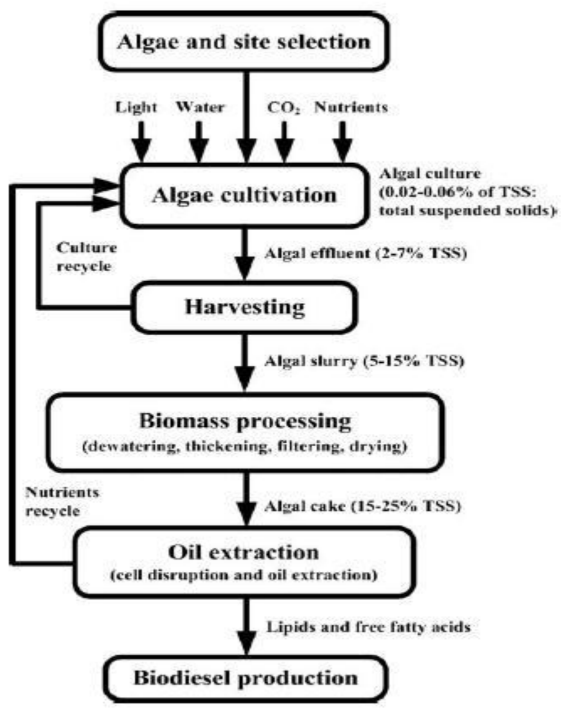


Figure 1. Schematic of biodiesel process with PBRs (Source: T.M. Mata et al, 2010)

2.3 Successful Implementations

2.3.1 Environmental Applications

Production of biodiesel and other bio-products from algae can be more environmentally sustainable, cost-effective and profitable if combined with processes such as wastewater and flue gas treatments.

Flue gas CO_2 emissions as algae nutrient

Flue gases from power plants are responsible for more than 7% of the total world CO_2 emissions from energy use (Kadam KL., 1997), providing a CO_2-rich source for algae cultivation and a potentially more efficient route for CO_2 bio-fixation. Therefore, the use of flue gas emissions from fuel-fired power plants as a source of CO_2 for algae growth is expected to contribute to reducing CO_2 emissions and may offer a promising alternative to current GHG emissions mitigation strategies.

Wastewater nitrogen and phosphorous as algae nutrients

Aslan and Kapdan used the algae *C.vulgaris* for nitrogen and phosphorus removal from wastewater with an average removal efficiency of 72% for nitrogen and 28% for phosphorous (from 3 to 8 mg/L NH4+ and 1.5-3.5 mg/L PO4-3).

2.3.2 Specialty Chemical and Bioactive Compounds

Depending on the algae species, various high-value chemical compounds can be extracted such as pigments, antioxidants, b-carotenes, polysaccharides, triglycerides, fatty acids, vitamins, and biomass, which are largely used as bulk commodities in different industrial sectors (e.g. pharmaceuticals, cosmetics, nutraceuticals, functional foods, and biofuels).

Algae applications in human health

Traditionally, nutritional supplements derived from plants have been used and dominate the marketplace. However, the health benefits of aquatic microorganisms such as algae are still being investigated and their recognition and appreciation has been only within the last three to four decades, largely linked to the introduction of probiotic supplements (Barrow C, Shahidi F., 2008). Microalgae are treated as having a protein quality and value greater than other vegetable sources (e.g. wheat, rice, and legumes), but poorer than animal sources (e.g. milk and meat).

Algae for aquaculture and animal feed

So far, microalgae culture has been more successful for food source and feed additive in the commercial rearing of many aquatic animals (i.e. rearing larvae and juveniles of many commercially important fish) both freshwater and marine (T.M. Meta et al., 2010).

3.0 OPTIMIZATION OF A UBC ALGAE PHOTOREACTOR

3.1 Previous feasibility analysis

Previous research has suggested that it may be economically viable to use an algae bioreactor to capture flue gases from UBC's powerhouse in order to produce biodiesel (Hung, 2008). Hung proposed an airlift PBR using *Botryococcus braunii*, operating at 25°C. Several issues were left for future consideration including the following:

1. The heat transferred from the flue gas to the medium was not sufficient to maintain the 25°C design temperature of the PBR. The option of bypassing the powerhouse's economizer in order to capture more heat was brought up for further consideration.

2. *B. Braunii* is a relatively slow growing species of algae. Faster growing species such as *Chlorella vulgaris* were suggested for future consideration.

3. The effects of light in the reactor, potentially causing photoinhibition due to excessive exposure, were not considered, and may be worth investigating.

4. Detailed hydrodynamical analysis of a PBR was not carried out, and was considered to be an issue worthy of bench-scale or full scale testing.

5. Seasonal discrepancies in production capacity and flue gas availability were not considered, and the possibility of CO_2 sequestration in winter months to supplement biodiesel production in the sunny summer months was suggested.

6. The possibility of illumination systems such as optical fibres was presented, allowing the system to be placed indoors and kept warmer.

7. The production of methane and hydrogen were left for future consideration, as was the possibility of capturing oxygen to improve the powerhouse efficiency.

Other issues which were left unaddressed, but not mentioned by Hung include:

1. Means of cooling the bioreactor during the summertime, when the PBR may overheat, resulting in cell damage and reduced productivity.
2. In order to house a bioreactor farm on the rooftop of the Leonard S. Klinck building, major structural improvements would likely be required. The cost of these improvements was not considered in Hung's economic analysis.
3. The conversion and separation processes necessary to obtain biodiesel from an algae feedstock were not accounted for in the economic analysis.
4. There are numerous other species of algae to consider besides *B. braunii* and *C. vulgaris*.
5. The nutrient requirements of the PBR were not accounted for in the economic analysis.

Based on the scope of this report, item 4 from the above list was chosen as a focal topic. In addition to *Chlorella vulgaris*, two other promising species of algae were considered: *Nannochloropsis oculata* and *Scenedesmus sp.* Item 5 will also be addressed with a focus on the use of secondary wastewater effluent for nutrient supplementation.

3.2 Hydrocarbon Yield with varying species of algae

In order to determine the economic viability of a PBR using various species of algae, an attempt was made to reproduce the calculations carried out by Hung (2008), using *B. braunii* as an algal species.

These verifications did not agree with the values obtained by Hung. The calculated annual hydrocarbon yield was 22.3 m^3 (compared to the value of 37 m^3 obtained by Hung). The projected income was $32,600 (compare with $4.77M obtained by Hung). Detailed calculations are shown in Appendix A.

Based on a specific growth rate of 0.60/day (Ratchford and Fallowfield, 1991) and a lipid content of 20% (Mata, 2009), *Scenedesmus* species performed the best, with an annual hydrocarbon yield of 45.13 m^3 and a revenue of $70,000 per year. *C. vulgaris* performed comparably to *B. braunii*, and *N. oculata* performed less favourably.

Since the capital and operating costs for the system are $1.1 million per year (Hung, 2008), the PBR is clearly not economically viable as designed. In addition, based on calculations found in the next section, the cost of the new sewer line would add $8,700 annually over a ten year period. It should also be noted that the cost of any structural upgrades to the Leonard S. Klinck building in order to resist greater loads at the rooftop have not been accounted for.

3.3 Secondary wastewater effluent as a growth medium


Figure 1: Raceway bioreactor

Wastewater can often be used as a source of nutrients for a PBR (El Hamouri, 2003). Domestic wastewater is considered to be nutrient poor, with typical nitrogen and phosphorus concentrations of 10-15 μg/L and 0.5-1 μg/L respectively in secondary effluent. *Scenedesmus sp*. was proposed by Xin et. al (2010) due to its low nutrient requirements. Since nutrient starvation can benefit biodiesel production in a bioreactor by forcing algae to produce more lipids, a nutrient poor medium may in fact be optimal (Mata et al., 2009).

4.0 TRANSPORTING WASTEWATER TO UBC POWER HOUSE

The implementation of a bioreactor above the Power House requires an addition to the current UBC sewer system to divert wastewater. The current sanitary sewer system in place at UBC is quite intricate. The Northern campus, which is of primary interest to the project, consists of three main trunks that are fed from smaller capillary lines attached to surrounding buildings and two large pump catchments (Alpin & Martin, 2001 as cited in Grant et al., 2001). These three main gravity driven trunks and the two catchments join to a single sewer that runs north towards

Northwest Marine Drive and feeds into the City of Vancouver's Spanish Banks Interceptor. The city interceptor line eventually runs to the Iona Island Wastewater treatment facility (*North Campus Neighbourhood Plan*, 2004).

4.1 Design of Sewer Line Addition

The wastewater, which is used to supply the algae with nutrients, will be diverted off one of the existing main sewer trunks in north campus. Due to the physics of pulling a liquid, it is only possible to raise a column approximately ten metres when placing the pump on top of the roof. Since the UBC Power House is within this height range, it is advised that the wastewater should be pumped up from the bottom rather than pulled up from the top to maximize efficiency. After the wastewater is pumped to the roof of the Power House, where the bioreactor is located, it will return to a gravity powered path down from the roof and back into the same main sewer trunk that it originated from (Figure 3 on the following page).

It should be noted that ideally the supply of nutrients should come from secondary effluent, which in the future could be directed from a UBC wastewater treatment facility. For this project and the simplicity of calculations it is assumed that the wastewater can come directly from the existing sewer lines.

According to the 2009 Edition of the UBC Technical Guidelines the following must be met when constructing new sanitary sewer lines:

- Sanitary sewers shall be designed using Peak Wet Weather Flow (PWWF), which is the Peak Dry Weather Flow (PDWF) plus 500 litres per diameter of pipe (m) per length of pipe (m) per day.
- Sewer lines not driven by gravity require special permission from UBC Utilities accompanied with an explanation, pump capacity (L/s) at operating head (kPa), a diagram showing pump curve and elevations which pump functions.

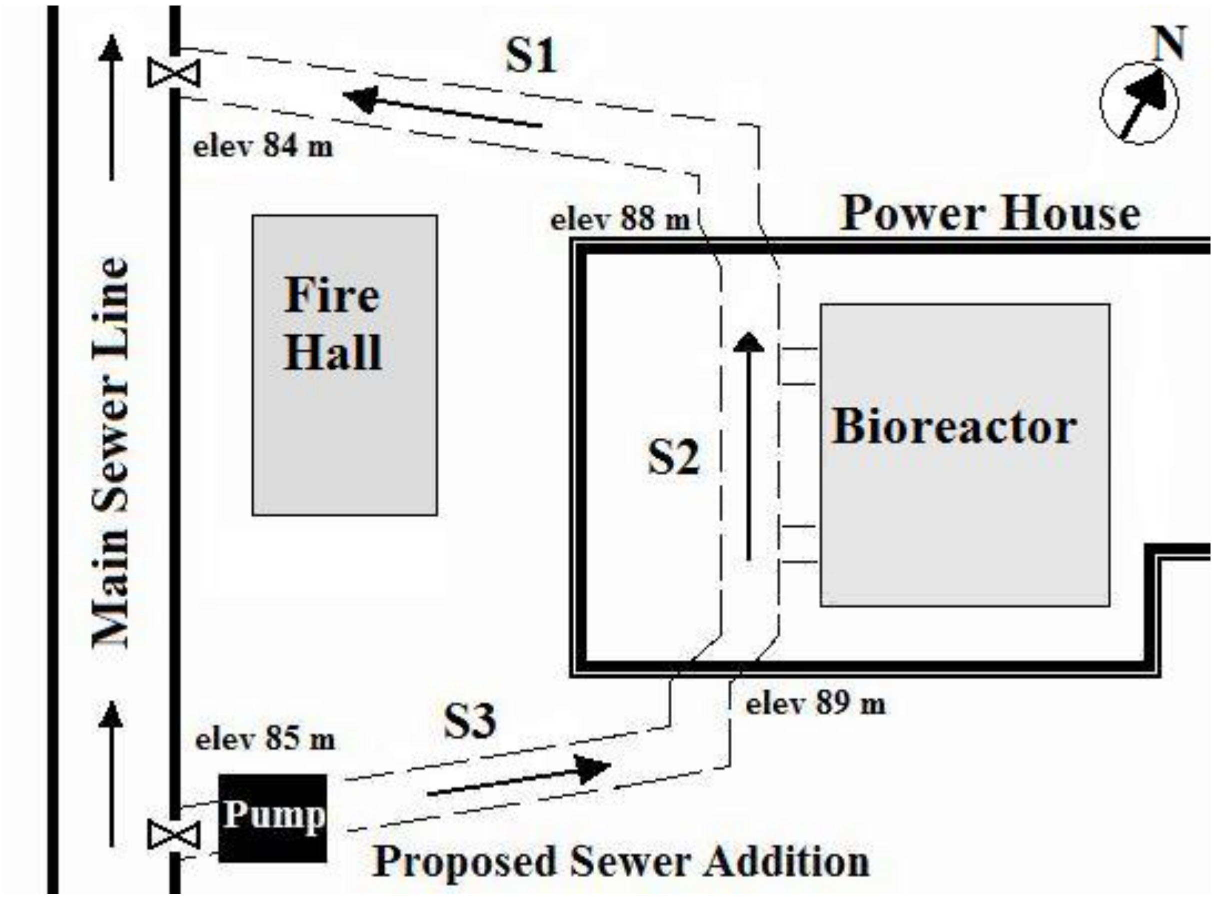


Figure 3. Diagrammatic top-view representation of proposed sewer addition to supply Power House Bioreactor with constant supply of fresh wastewater. (Not to scale)

- Gravity sewers are sized using the Manning's Formula with an "n" value of 0.011 for PVC and 0.013 for concrete. During peak flow, the depth should not exceed 50% with a minimum flow velocity of 0.6 m/s.
- Minimum pipe size for industrial/research areas is 250 mm and a minimum of 150 mm size shall be used for connectors.
- Regardless of pipe slope and capacity, downstream size shall be equal or larger diameter. No downsizing.
- All service connections shall be installed with a manhole.
- PVC piping is preferred for all piping under 450 mm.

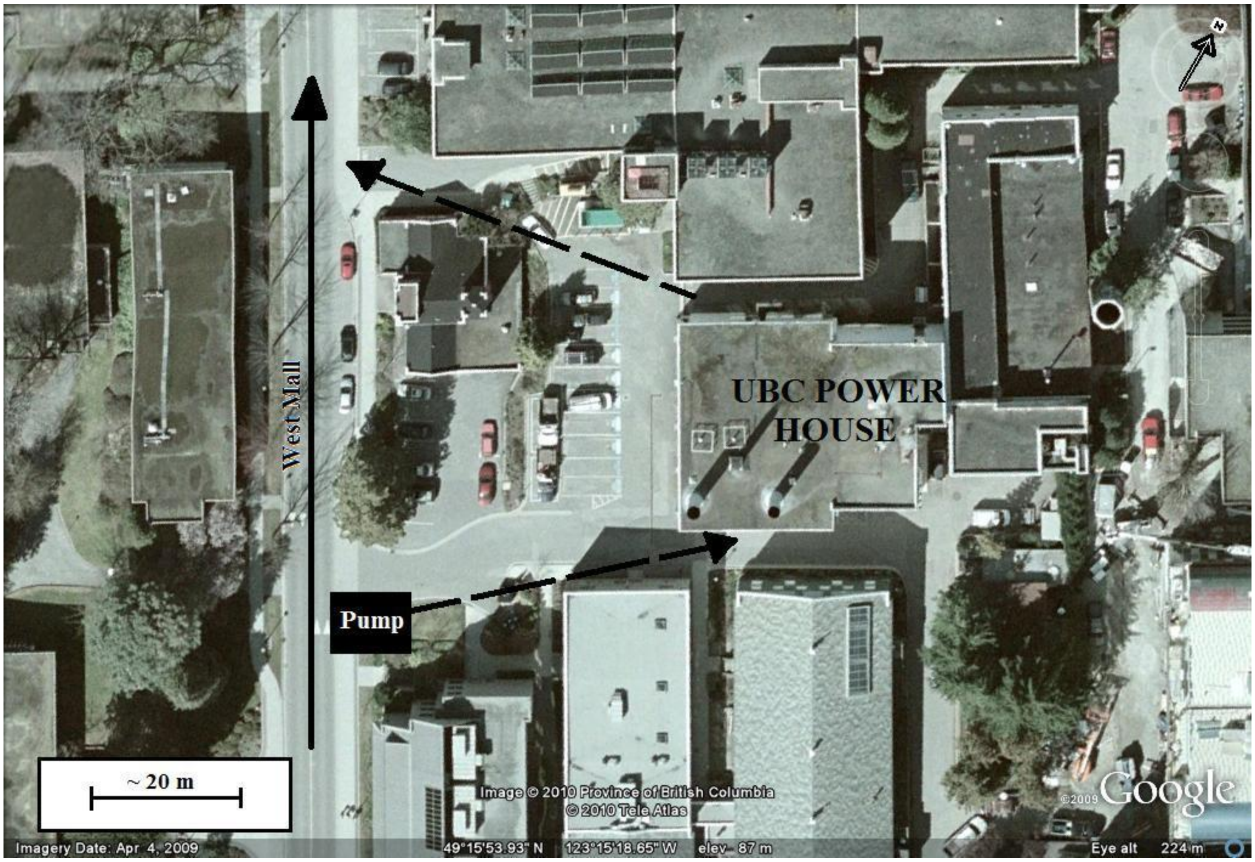


Figure 4. Actual satellite top-view of proposed sewer addition site. (Google Earth, 2010)

The minimum diameter of piping is required for S1, the gravity driven section, is 8.58 mm (Appendix A). Peak wastewater flows vary greatly throughout the day, even as much as an eight to one difference (An, 1999). To account for these peak flows, and to have a uniform piping system with the existing one, a final pipe diameter of 300 mm is used. Although the pipe size is less than 450 mm, reinforced concrete will be used in section S1 and S3 to conform with the existing underground sewer lines. The exposed S2 section, which will run out of the ground over the Power House and back into the ground, will be made of insulated PVC piping to reduce temperature fluctuations caused by the climate. UBC (2009) also states that there must be a maintenance manhole at each branch connection; therefore two manholes will be necessary, one at each of the connecting points on the existing main sewer trunk.

4.2 Price Analysis of Materials

Table 1 is a materials price breakdown based off of Hanson Pipe & Precast Corporation, and Northland Distributing & MFG Incorporated. From Google Earth 2010, the following measurements were deduced to calculate pipe costs; S_1 = 64m, S_2 = 55m (includes pipe running the height of the building and across the roof), & S_3 = 61m (Figure 4).

Table 1. Materials price breakdown for the proposed sewer addition to transport wastewater to the roof of the UBC Power House

Item [Diameter in mm]	Length/piece [m]	Units	Unit Price [$]	Total [$]
Reinforced Concrete Pipe [300 mm]	2.29	56	62.10	3477.60
Insulated PVC Pipe [300 mm]	0.305	182	35.80[a]	6515.60
Concrete Connector [300 mm]	-	2	247.90	495.80
PVC Connector [300 mm]	-	6	189.50	1137.00
Concrete Elbow [300 mm]	-	4	335.00	1340.00
Insulated PVC Elbow [300 mm]	-	2	170.66[a]	341.32
Insulated PVC Tee [300 mm]	-	2	307.84[a]	615.68
Maintenance Holes [1200mm]	2.0[b]	2	1684.50	3369.00
TOTAL		**256**		**$17,292.00**

[a] Prices interpolated from smaller pipe sizes. [b] Depth of Maintenance Hole.

4.3 Price Analysis of Construction

Lim, Lee, and Park (2009) created equations to estimate the total construction cost of wastewater piping lines. A simplified version of their equations is used to calculate the proposed sewer addition to the UBC Power House.

$$Construction\ Cost_{TOTAL} = (Piping + Materials + Labour + EXP + OH + PRO)_{COST}$$

$$Piping_{COST} = \sum Pipe_{COST} = \sum Concrete_{PIPING} + \sum PVC_{PIPING}$$

$$Piping_{COST} = Pipe_{S_1} + Pipe_{S_3} + Pipe_{S_2}$$

$$Materials_{COST} = \sum Extra\ Materials = Elbows + Connectors + Tees + Man\text{-}holes$$

$$Labour_{COST} = \sum_{S\#} DL = DL_{S_1} + DL_{S_2} + DL_{S_3}$$

$$DL_{S\#} = ([a]_{dl} A + b_{dl}) \cdot l_{S\#}$$

$$EXP_{COST} = \alpha \cdot (Piping_{COST} + Labour_{COST})$$

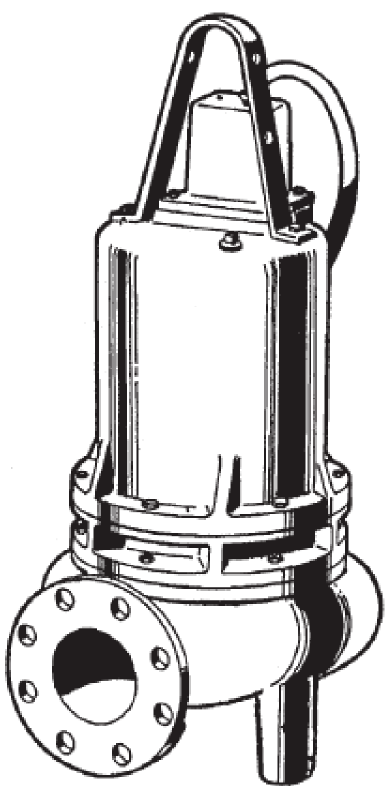
$$OH_{COST} = \beta \cdot (Piping + Labour + EXP)_{COST}$$

$$PRO_{COST} = \gamma \cdot (Piping + EXP + OH)_{COST}$$

4.4 Pump Sizing

To size a pump that is sufficient to push the wastewater across a 61 m sewer, up a slope of 0.066, then vertically 12 m to the roof of the Power House, while maintaining an exit velocity equal to that of the pipe velocity, it is necessary to determine the head loss across this path. The following equation is used to determine the required pump head needed to achieve this task (Finnemore & Franzini, 2002).

$$h_p = \Delta z + \frac{V^2}{2g} + \sum h_L$$



Using this equation, the pump head required to maintain the same average flow of 12.0 lps through the new addition is 17.0 m. Taking this into consideration, it is recommended to use a 4 inch submersible horizontal discharge sewage pump. The following is a particular model made by Barnes®, which will perform close to optimum efficiency during average flow while still allowing operation at higher flows that are closer to the peak.

Figure 5. Image of the recommended pump. Series: 4SE-L 4.5 – 15HP, 1750 RPM, 60Hz

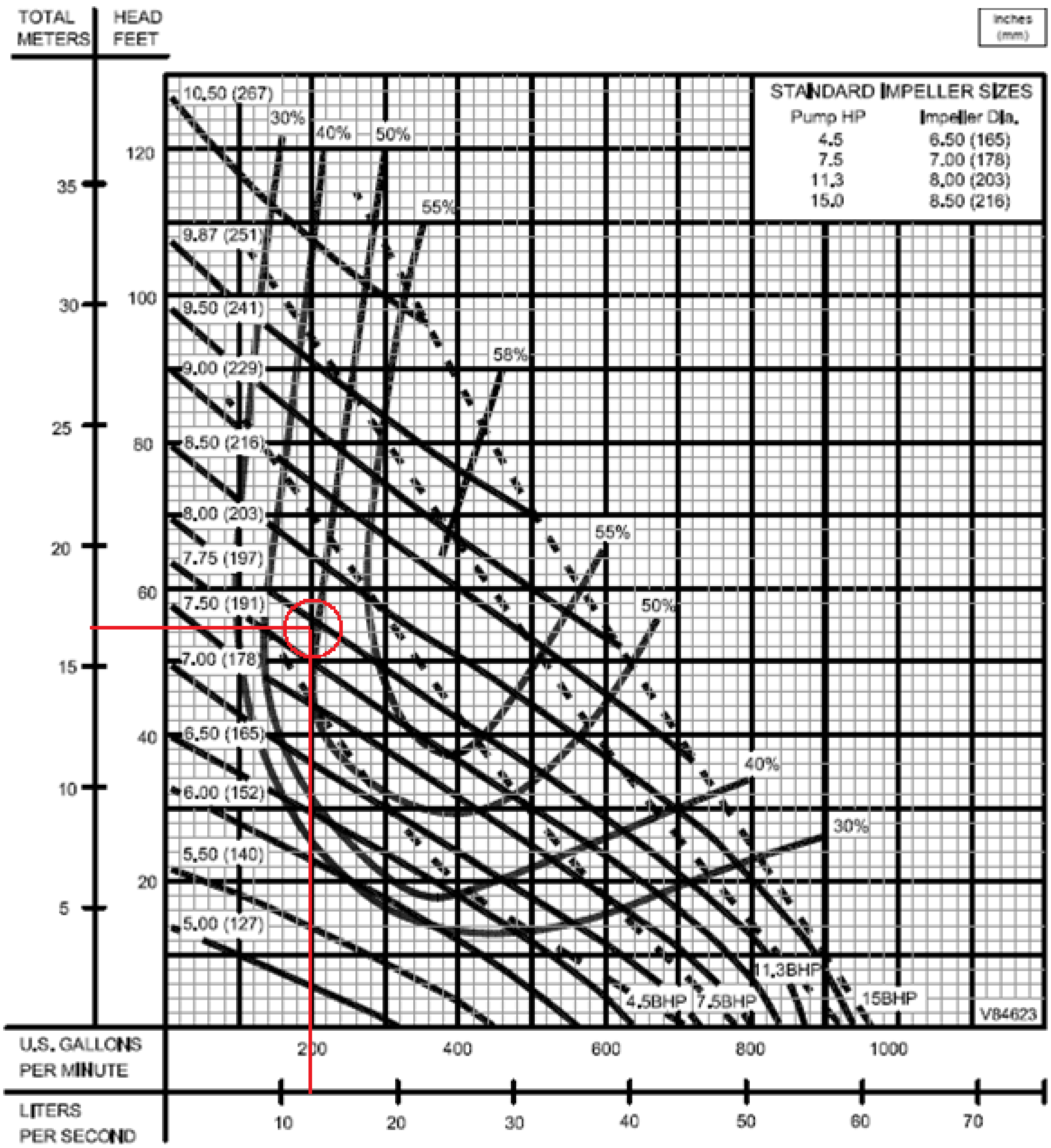


Figure 6. Pump Curve for the Barnes® Series: 4SE-L 4.5 – 15HP, 1750 RPM, 60Hz with the operating point highlighted in red, showing 50% efficiency.

4.5 Total Cost

The electricity costs are calculated (Appendix A) based on the fact that the pump runs at 15 hp (11.19 kW). A total cost figure is calculated based on the materials, construction, pump requirement for the proposed sewer, and year round electricity to operate the pump. A final cost of approximately sixty-five thousand dollars is needed for the set up and operation of the pump (see Table 2 and 3).

Table 2 & 3. Total cost breakdown including materials of pipe, labour, construction expenses, contractor's overhead, contractor's profit and pump. Parameters used in the study.

Variable	Cost [$]	Percent of Cost [%]
Piping	9993.20	15.48
Materials	7298.80	11.30
Labour	29738.08	46.05
EXP	7946.26	12.31
OH	2383.88	3.69
PRO	2032.33	3.15
Pump	2990.00	4.63
Electricity (per year)	2193.26	3.40
TOTAL	**$64,575.81**	100%

Parameter	Value
a_{dl}	2106.3
b_{dl}	16.326
α	0.2
β	0.05
γ	0.1

[c] Price taken from a pump comparable in performance to the Barnes® Series: 4SE-L 4.5 – 15HP, 1750 RPM, 60 Hz

5.0 OPPORTUNITIES FOR FUTURE WORK

Given that the cost of a PBR for UBC is prohibitive, it may be worth considering a raceway bioreactor. Although this type of system requires more land, it can handle much greater volumes, and requires a lower capital expenditure.

Algae metabolism is a complex topic, as discussed in Section 2, and Vancouver-based pilot scale studies are recommended to determine the optimal species of algae to use in a secondary wastewater effluent medium.

Converti (2009) compares *C. vulgaris* and *N. oculata* at various temperatures and nitrogen concentrations and finds that both species have the highest yield at low NaNO3 concentrations. However, the lowest concentrations studied were 75 mg/L for *N. oculata* and 375 mg/L for *C. vulgaris*. Lipid yields varied very little for *N. oculata* between 15°C and 25°C. It is possible, therefore, that no additional heat would need to be supplied to the system designed by Christine Hung if *N. oculata* were used. *C. vulgaris* showed the highest lipid yield at 25°C based on a study range of 25°C to 35°C. Although at 25°C *C. vulgaris* had approximately double the maximum yield of *N. oculata*, determining whether *C. vulgaris* can be cultivated at temperatures below 25°C requires further research.

6.0 CONCLUSION

The aim of this paper is to provide a greater understanding of bioreactor processes, to shed some light on optimal algae species and lastly, to design and explore the feasibility of constructing a sewer system to supply the bioreactor with wastewater.

In calculating the annual production of the bioreactor some discrepancies are found in Hung's work. There is a 14.7% difference in the hydrocarbon production volume calculated by Hung (37 m^3) and the value calculated in this report (22.3 m^3). The projected annual income is $32,600, which is much lower than Hung's value of $4.77-million. Between the three species studied, *B. braunii*, *N. oculata* and *Scenedesmus*, the latter performed the best, with an annual yield of 45.13 m^3 and annual revenue of $70,000. A sewer line design was proposed to supply the Power House with nutrient rich wastewater. The proposed design has a capital cost of $65,000 and an annual electricity cost of $2,200. The cost of the sewer line over a ten year period adds $8,700 to the $1.1-million annual instalment forecasted by Hung. The addition of a photo-bioreactor on the UBC Power House roof is therefore not considered feasible.

Further research should be considered; including assessing the viability of a raceway pond and/or nutrient extraction operation using algae. Pilot tests should be carried out to determine the optimal algae species for flue gas capture in Vancouver's climate using UBC's wastewater effluent.

7.0 NOMENCLATURE

PWWF = Peak Wet Weather Flow

PDWF = Peak Dry Weather Flow

EXP = construction expenses for piping

OH = contractor’s overhead for piping

PRO = contractor’s profits for piping

$DL_{S\#}$ = direct labour cost associated with section of piping

a_{dl} = regression parameter for direct labour cost for piping

b_{dl} = regression parameter for direct labour cost for piping

A = cross sectional area of pipe [m^2]

$l_{S\#}$ = length of pipe section

α = coefficient for construction expenses

β = coefficient for contractor’s overhead

γ = coefficient for contractor’s profits

h_L = head loss

h_f = head loss due to friction

h_e = head loss due to entrance and exit

h_b = head loss due to bends

f_{con}= friction factor for concrete piping

f_{PVC} = friction factor for PVC piping

k_e = exit loss coefficient

k_b = bend loss coefficient

e_{con} = absolute roughness for concrete pipe

e_{PVC} = absolute roughness for PVC pipe

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APPENDIX A

SAMPLE CALCULATIONS

CALCULATIONS

1. Manning Equation to calculate minimum pipe diameter for gravity driven section, S_1.

- With 50% depth as outlined by UBC Technical Guidelines, therefore $P_w = P/2$
- Velocity equals a minimum of 0.6 m/s as outlined by UBC Technical Guidelines

$$V = \frac{1}{n} R_h^{\frac{2}{3}} s^{\frac{1}{2}}$$

$$R_h = \frac{A}{P_w} = \frac{2A}{P} = \frac{2\pi D^2}{4\pi D} = \frac{D}{2}$$

$$s = \frac{rise}{run} = \frac{(88 - 84)m}{(64 - 0)m} = 0.0625$$

$$V = \frac{1}{n} \left(\frac{D}{2}\right)^{\frac{2}{3}} s^{\frac{1}{2}}$$

$$D_{min} = \frac{(Vn)^{\frac{3}{2}} 2}{s^{\frac{3}{4}}} = \frac{(0.6 \cdot 0.011)^{\frac{3}{2}} \cdot 2}{0.0625^{\frac{3}{4}}} = 0.00857898\ m = 8.58\ mm$$

2. Peak Wet Weather Flow (PWWF)

- Peak Dry Water Flow is taken as the peak design flow of the "N-158" manhole from the 2012 Sanitary Model Data (Alpin & Martin, 2001)
- Infiltration is taken from the same data set

$$PWWF = PDWF + Infiltration$$

$$PWWF = (44.8\ \mathrm{L/s} + 13.9\ \mathrm{L/s}) * \left(\frac{1m^3}{1000L}\right)$$

$$PWWF = 0.0587 \frac{m^3}{s}$$

3. Pump head required to lift water through S3 and onto the roof of the Power House(½ S2) maintaining the same velocity of 12.0 lps as in average flow (Alpin & Martin, 2001)

$$h_p = \Delta z + \frac{V^2}{2g} + \sum h_L$$

$$h_L = \Delta z + \frac{V^2}{2g} + h_{f,S_3} + h_{f,S_2} + h_{ent} + h_{b,concrete} + h_{b,PVC}$$

- The wastewater is assumed to have a density of 1150 kg/m^3
- V = 0.16977 m/s (based off of average flow through main trunk & D=300mm)
- e_{con} = 0.0015 mm; $e_{PVC} \approx 0$; all k values (Finnemore & Franzini, 2002);
- v_{sewage} = 1.1555e-06 m^2/s. Assumed to be the same as water at 15ºC.
- $f_{con} = f_{PVC} \approx 1.57$ (Moody Diagram in Appendix B)

$$h_p = z_1 - z_2 + \frac{V^2}{2g} + f_{con}\frac{L_{S_3}}{D}\frac{V^2}{2g} + f_{PVC}\frac{0.5L_{S_2}}{D}\frac{V^2}{2g} + k_e\frac{V^2}{2g} + k_{b,45º}\frac{V^2}{2g} + k_{b,90º}\frac{V^2}{2g}$$

$$h_p = (101m - 85m) + \frac{(0.16977\text{m/s})^2}{2 \cdot 9.81\ \text{m/s}^2} \cdot \left[1 + \frac{1}{0.3m}(2.43 \cdot 61m + 2.19 \cdot 0.5 \cdot 55m) + 0.5 + 0.42 + 0.25\right]$$

$$h_p = 17.02\ m$$

4. Electricity costs for operating the pump year round

- Electricity costs taken extrapolated from data: Vancouver
  - 7 kW/month = $82.64
  - 20 kW/month = $393.31

$$Power_{PUMP} = 15\ hp \cdot \frac{1\ kW}{1.34\ hp} = 11.19\ kW$$

$$Electricity_{COST} = \frac{\$82.64}{month} + \frac{\$393.31 - \$82.64}{20\ kW - 7\ kW} \cdot (11.19\ kW - 7\ kW) \cdot \frac{12\ months}{year}$$

$$Electricity_{COST} = \$2{,}193.26 \frac{}{} year$$

	Value	Description
X (kg/m3)	6	Biomass concentration
V_L (m3)	0.232	Liquid volume in bioreactor
N	505	Number of bioreactors in system
Y_CO2 / Y_biomass	1.88	Mass CO2 consumed per unit biomass produced
Eta	64.00%	Percent of lipids produced which are converted to biodiesel
rho_HC (kg/m^3)	667	Mass density of HC
C_biodiesel ($/litre)	1.304	Value per litre of biodiesel
C_CO2 ($/ton)	25	Value per ton of CO2 in carbon credits

The parameters used in Hung, 2008 were left unchanged. The specific growth rate was adjusted based on the algae species of interest.

	Value	Equation/Source
Botryococcus braunii		
Specific growth rate mu (1/s)	3.48E-06	Hung 2006
Lipid content	30.00%	
Biomass production rate (kg/s/reactor)	4.84E-06	$Q_{biomass} = \mu X V_L$
Total biomass produced per year (kg)	77199	$Q_{total} = Q_{biomass} N \left(86400 \frac{s}{day}\right)\left(365.25 \frac{days}{yr}\right)$
Total HC produced (m^3)	22.22	$HC = \frac{Q_{total}(\% Lipids)\eta}{\rho_{HC}}$
Value of HC ($)	$28,977.89	
CO2 captured (tons)	145.13	$Q_{CO_2} = Q_{total} \frac{Y_{CO_2}}{Y_{biomass}}$
Value of CO2 credits ($)	$3,628.37	
Total revenue	$32,606.26	
Chlorella vulgaris		
Specific growth rate mu (1/s)	1.00E-05	Ratchford and Fallowfield, 1992
Lipid content	10.00%	
Biomass production rate (kg/s/reactor)	1.39E-05	$Q_{biomass} = \mu X V_L$
Total biomass produced per year (kg)	221837	$Q_{total} = Q_{biomass} N \left(86400 \frac{s}{day}\right)\left(365.25 \frac{days}{yr}\right)$
		$HC = \frac{Q_{total}(\% Lipids)\eta}{\rho_{HC}}$

Total HC produced (m^3)	21.29	
Value of HC ($)	$27,756.60	
CO2 captured (tons)	417.05	$Q_{CO_2} = Q_{total} \frac{Y_{CO_2}}{Y_{biomass}}$
Value of CO2 credits ($)	$10,426.35	
Total revenue	$38,182.96	

Nanochloropsis oculata

Specific growth rate mu (1/s)	6.94E-06	James and Al-Khars, 1989
Lipid content	10.00%	
Biomass production rate (kg/s/reactor)	9.66E-06	
Total biomass produced per year (kg)	153955	
Total HC produced (m^3)	14.77	
Value of HC ($)	$19,263.08	
CO2 captured (tons)	289.44	
Value of CO2 credits ($)	$7,235.89	
Total revenue	$26,498.97	

$$Q_{biomass} = \mu X V_L$$

$$Q_{total} = Q_{biomass} N \left(86400 \frac{s}{day}\right)\left(365.25 \frac{days}{yr}\right)$$

$$HC = \frac{Q_{total}(\% Lipids)\eta}{\rho_{HC}}$$

$$Q_{CO_2} = Q_{total} \frac{Y_{CO_2}}{Y_{biomass}}$$

Scenedesmus sp.

Specific growth rate mu (1/s)	1.06E-05	Ratchford and Fallowfield, 1992
Lipid content	20.00%	
Biomass production rate (kg/s/reactor)	1.48E-05	
Total biomass produced per year (kg)	235148	
Total HC produced (m^3)	45.13	
Value of HC ($)	$58,844.00	
CO2 captured (tons)	442.08	
Value of CO2 credits ($)	$11,051.93	
Total revenue	$69,895.93	

$$Q_{biomass} = \mu X V_L$$

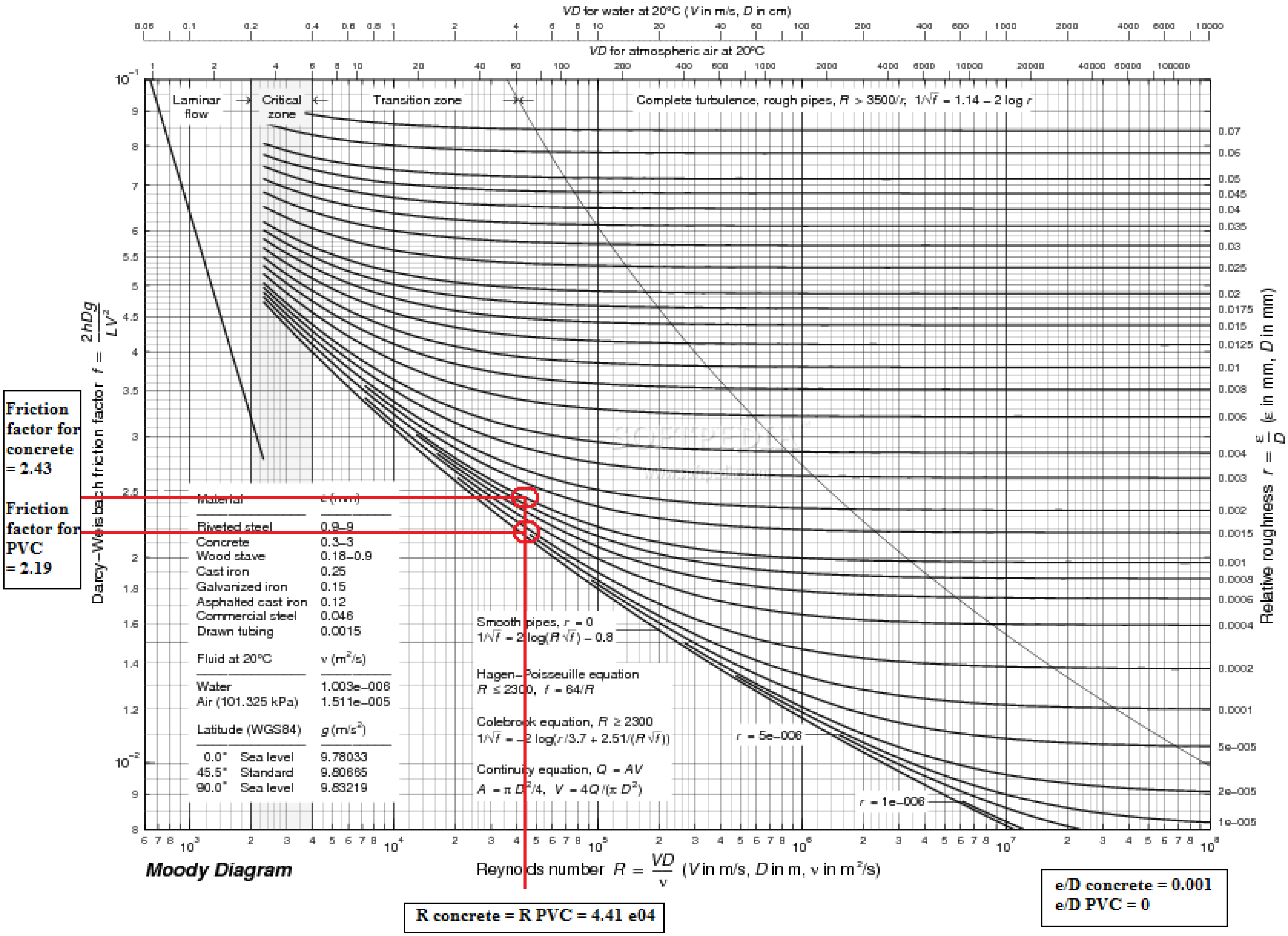
$$Q_{total} = Q_{biomass} N \left(86400 \frac{s}{day}\right)\left(365.25 \frac{days}{yr}\right)$$

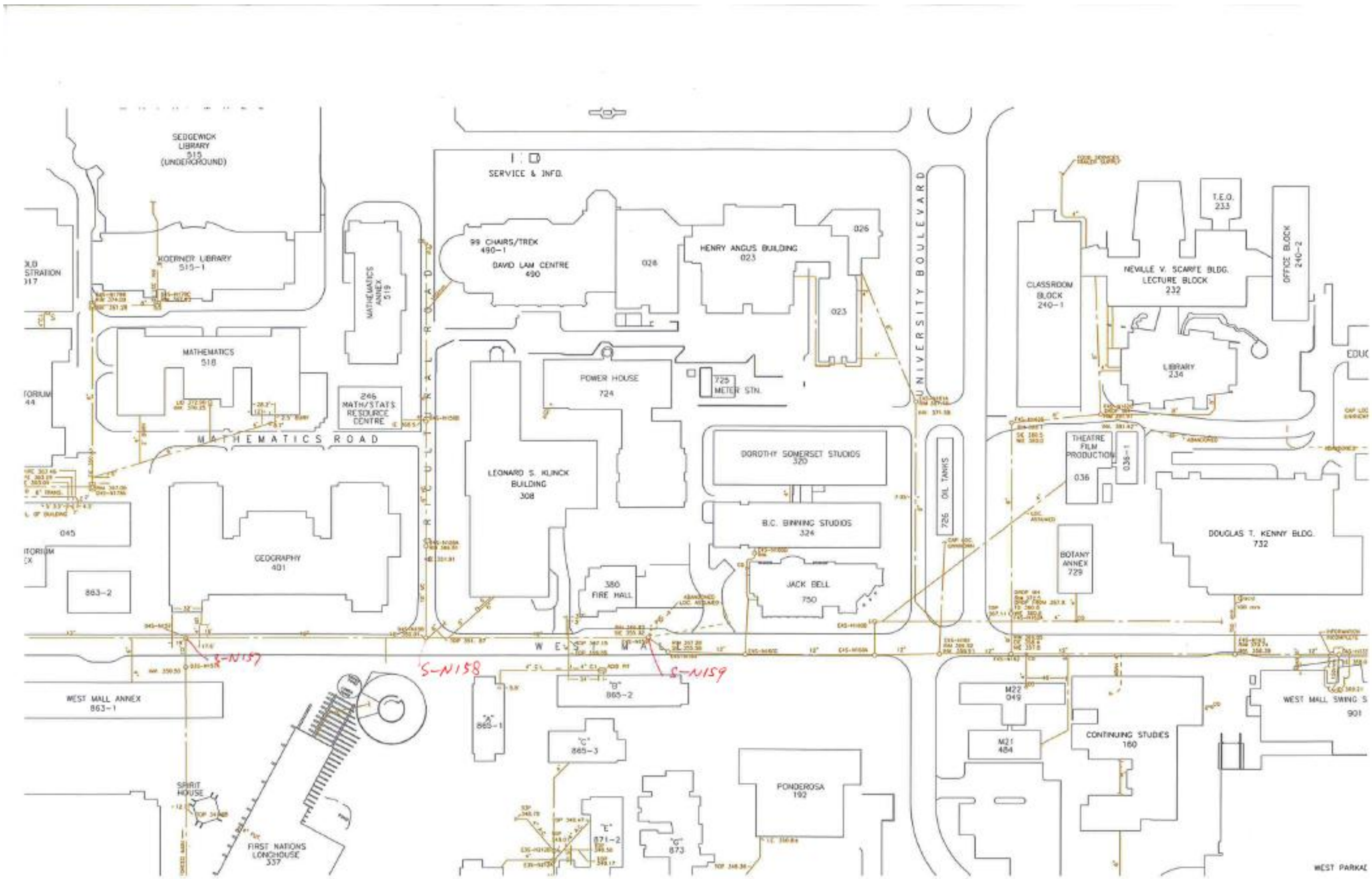
$$HC = \frac{Q_{total}(\% Lipids)\eta}{\rho_{HC}}$$

$$Q_{CO_2} = Q_{total} \frac{Y_{CO_2}}{Y_{biomass}}$$

APPENDIX B

FIGURES & DATA


VD for water at 20°C (V in m/s, D in cm)
VD for atmospheric air at 20°C
Laminar flow
Critical zone
Transition zone
Complete turbulence, rough pipes, R > 3500/r, 1/√f = 1.14 – 2 log r
Darcy–Weisbach friction factor f = 2hDg / LV²
Relative roughness r = ε/D (ε in mm, D in mm)
Material ε (mm)
Riveted steel 0.9–9
Concrete 0.3–3
Wood stave 0.18–0.9
Cast iron 0.25
Galvanized iron 0.15
Asphalted cast iron 0.12
Commercial steel 0.046
Drawn tubing 0.0015
Fluid at 20°C ν (m²/s)
Water 1.003e–006
Air (101.325 kPa) 1.511e–005
Latitude (WGS84) g (m/s²)
0.0° Sea level 9.78033
45.5° Standard 9.80665
90.0° Sea level 9.83219
Smooth pipes, r = 0
1/√f = 2 log(R √f) – 0.8
Hagen–Poisseuille equation
R ≤ 2300, f = 64/R
Colebrook equation, R ≥ 2300
1/√f = –2 log(r/3.7 + 2.51/(R √f))
Continuity equation, Q = AV
A = π D²/4, V = 4Q/(π D²)
r = 5e–006
r = 1e–006
Moody Diagram
Reynolds number R = VD/ν (V in m/s, D in m, ν in m²/s)
Friction factor for concrete = 2.43
Friction factor for PVC = 2.19
R concrete = R PVC = 4.41 e04
e/D concrete = 0.001
e/D PVC = 0


SEDGEWICK LIBRARY 515 (UNDERGROUND)
SERVICE & INFO.
99 CHAIRS/TREK 490-1
DAVID LAM CENTRE 490
HENRY ANGUS BUILDING 023
KOERNER LIBRARY 515-1
MATHEMATICS ANNEX 519
MATHEMATICS 518
246 MATH/STATS RESOURCE CENTRE
MATHEMATICS ROAD
POWER HOUSE 724
725 METER STN.
UNIVERSITY BOULEVARD
CLASSROOM BLOCK 240-1
NEVILLE V. SCARFE BLDG. LECTURE BLOCK 232
T.E.O. 233
OFFICE BLOCK 240-2
LIBRARY 234
THEATRE FILM PRODUCTION 036
DOROTHY SOMERSET STUDIOS 320
726 OIL TANKS
LEONARD S. KLINCK BUILDING 308
B.C. BINNING STUDIOS 324
DOUGLAS T. KENNY BLDG. 732
BOTANY ANNEX 729
GEOGRAPHY 401
380 FIRE HALL
JACK BELL 750
863-2
WEST MALL
S-N157
S-N158
S-N159
WEST MALL ANNEX 863-1
"B" 865-2
"A" 865-1
"C" 865-3
M22 049
M21 484
CONTINUING STUDIES 160
WEST MALL SWING S 901
SPIRIT HOUSE
FIRST NATIONS LONGHOUSE 337
"E" 871-2
"G" 873
PONDEROSA 192
WEST PARKAD

UBC MASTER SERVICING PLAN – TECHNICAL REPORT APPENDIX C

Sanitary Model Data North Campus 2012

Pipe Manholes Up	Down	Description	External File	Pump Rate (lps)	Meas Flow (lps)	Grade (%)	Mannings n	Dia (mm)	Area+Addnl	Population
N157	N156					1.132	0.013	300	0+	0
N157A	N157	receives pump flow				3.509	0.013	250	0+	0
N158	N157					0.531	0.013	300	0+	0
N159	N158					1.784	0.013	300	0+	0
N160	N159					0.938	0.013	300	0+	0
N161	N160					0.461	0.013	300	0+	0
N162	N161					0.526	0.013	300	0+	0
N163	N162					0.360	0.013	300	0+	0
N164	N163					0.568	0.013	300	0+	0
N165	N164					0.398	0.013	300	0+	0

ZONING: population density (pers/unit) / Industrial flow (l/unit/day)

ZONING:	Res-S	Res-F	Class	Offic	Libry	Resrh	Mixed	Other	Medic	Animl	Assm	Food	Hosp	5-wr	10-wr
Infiltr	1.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Code	0	0	90	90	90	90	90	90	4	10	16	15	7	5	10
	persn	persn	studt	workr	persn	persn	persn	persn	sqm	sqm	NASM	NASM	sqm	sqm	sqm
N157	.	.	.	76	.	.	.	.	.	.	.	.	.	.	.
N157A	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N158	.	.	.	97	79	.	.	.	.	.	.	741	.	.	.
N159	.	.	.	76	.	21	641	92	.	.	.	.	.	.	.
N160	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N161	.	.	.	747	.	.	896	.	.	.	.	.	.	.	.
N162	.	.	1169	145	53	.	.	.	.	.	.	.	.	.	.
N163	.	.	546	6	.	358	.	.	.	.	.	.	.	.	.
N164	.	.	113	58	.	.	.	6	.	.	.	.	.	.	.
N165	.	.	.	14	.	87	.	.	.	.	.	.	.	.	.

ZONING: population density (pers/unit) / Industrial flow (l/unit/day)

ZONING:	15-wr	25-wr	3-wr	Base	FHstd		F-Cor	F-Rsh	Fcomm	MH-ea	MH-th	MH-ga	MH-mc	MHvst	MHcom
Infiltr	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.4	1.4	1.0
Code	15	25	3	0	0	0	22	12	51	0	0	0	0	0	0
	sqm	sqm	sqm	ha	persn	ha	cpop	sqm	sqm	persn	persn	persn	persn	persn	persn
N157	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N157A	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
N158	.	.	.	1.0	.	.	.	.	.	.	.	.	.	.	.
N159	.	.	.	1.0	.	.	.	.	.	.	.	.	.	.	.
N160	.	.	.	.	.	.	633	.	.	.	.	.	.	.	.
N161	.	.	.	2.0	.	.	.	.	.	.	.	.	.	.	.
N162	.	.	.	1.0	.	.	.	.	.	.	.	.	.	.	.
N163	.	.	.	1.0	.	.	.	.	.	.	.	.	.	.	.
N164	.	.	.	.	.	.	3154	.	.	.	.	.	.	.	.
N165	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Up	EXISTING.... Dia (mm)	Capacity (lps)	REQ'D Dia (mm)	PROPOSED.... Dia (mm)	Capacity (lps)	Vfull (mps)	Vpart (mps)	Q/Qf	DESIGN FLOWS.... Infiltr (lps)	DW Avg (lps)	Peak (lps)
N157	300	102.9	220	300	102.9	1.5	1.4	0.44	14.1	12.0	45.2
N157A	250	111.4	9	250	111.4	2.3	0.0	0.00	0.0	0.0	0.0
N158	300	70.5	253	300	70.5	1.0	1.1	0.64	13.9	12.0	44.8
N159	300	129.2	199	300	129.2	1.8	1.7	0.33	12.8	11.6	43.0
N160	300	93.7	218	300	93.7	1.3	1.3	0.43	11.6	10.8	39.9
N161	300	65.7	248	300	65.7	0.9	1.0	0.60	11.6	10.6	39.5
N162	300	70.1	227	300	70.1	1.0	1.0	0.48	9.5	8.9	33.3
N163	300	58.0	231	300	58.0	0.8	0.8	0.50	8.4	7.5	28.9
N164	300	72.9	202	300	72.9	1.0	0.9	0.35	7.3	6.5	25.4
N165	300	61.0	207	300	61.0	0.9	0.8	0.37	7.1	5.6	22.8

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