# Upflow Anaerobic Sludge Blanket (UASB), Summer 2017

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[I only read through the big ideas in the report and the organization and structure of information is very clear. I think you did a great job transitioning from your first set of experiments to next and using previous results to justify the decisions you made.]

**Abstract**

Briefly summarize your previous work, goals and objectives, what you have accomplished, and future work. (100 words max) If you have a question, please use the help menu ("?") on the top bar to search for help or ask us a question.

## Introduction

*Due to the very similar nature the work between the Spring and Summer 2017 UASB teams, the following Introduction and Literature Review reproduced from the Spring 2017 UASB team report.*

The contamination of ground and surface water sources by wastewater has adverse environmental and health affects. First, the biological degradation of wastewater by aerobic microbes lowers the dissolved oxygen content in natural waterways, preventing aquatic life from thriving and potentially creating dead zones. Additionally, it increases waterborne fecal matter content and increases the risk of exposure to pathogens (Chong et al., 2012). The latter is of particular concern to individuals in the global south, as communities downstream of wastewater outfalls often have inadequate drinking water treatment.

Wastewater can also be an opportunity for energy recovery. According to recent estimates, the energy potential of wastewater and biosolids is more than ten times the energy needed for treatment (Ghoneim et al., 2016). Most wastewater treatment facilities in the US do not optimize the recovery of energy and resources from biosolids (Ghoneim et al., 2016). While it is important to develop wastewater treatment technology to optimize current wastewater treatment for all individuals, the focus of this research was on small communities in the global south. Such communities do not have widespread wastewater infrastructure, and therefore much of the wastewater is left untreated.

Currently in the United States, effective municipal wastewater treatment facilities have long retention times, require large land areas, and have a high fixed cost per capita (Chong et al., 2012). Due to economy of scales, small systems have even higher fixed costs per capita and these high fixed costs make conventional wastewater treatment systems inaccessible for small communities. Many cities in the global south forgo wastewater treatment altogether due to the high cost and instead discharge untreated wastewater to the environment (Chong et al., 2012). Research and development of small-scale and decentralized wastewater treatment methods should be prioritized in order to make wastewater treatment accessible for all communities.

Upflow Anaerobic Sludge Blanket (UASB) reactors are conventionally used as a preliminary wastewater treatment process to clarify wastewater by removing suspended solids and reducing organic matter (Chong et al., 2012). UASB reactors rely on gravity to clarify wastewater, biological processes to remove organic matter and convert it to biogas, and are less energy intensive than other forms of preliminary wastewater treatment that use aerobic processes. A byproduct of the biological processes in UASB reactors is methane. Methane is a potent greenhouse gas, but if collected, can be used as a fuel or burned and safely released into the atmosphere.

In January 2017, a novel pilot scale UASB reactor design was created by AguaClara for the EPA People, Prosperity and the Planet (P3) Student Design Competition proposal. This reactor was designed to improve the accessibility of wastewater treatment for small communities. The proposed UASB reactor design identified five areas to improve conventional reactor design: (1) plate settlers, (2) submerged gas collection lid, (3) sludge weir, (4) submerged exit launder, and (5) fabrication methods. Of these design modifications, the Summer 2017 UASB Team researched and tested the impact of plate settlers and a sloped exit weir on improving granule retention rate.

# Literature Review

## Conventional Wastewater Treatment Options

Municipal and industrial wastewater can be treated via biological, chemical oxidation, or thermal oxidation treatment processes. Biological treatment is commonly used because the latter two treatment options require higher capital investment and operational costs (Mittal, 2011). The two main types of biological treatment are the activated sludge process and anaerobic digestion. As shown in Figure 1, when compared to the activated sludge process, anaerobic digestion yields less sludge and reduces energy input (Mittal, 2011). Although there are some drawbacks to anaerobic digestion such as long solids retention time (SRT) and insufficient nutrient removal, the reduced energy input renders it the most feasible technology for communities in the global south (Chong et al., 2012).

| Parameter | Aerobic Treatment | Anaerobic Treatment |
|---|---|---|
| Process Principle | • Microbial reactions take place in the presence of molecular/ free oxygen<br>• Reactions products are carbon dioxide, water and excess biomass | • Microbial reactions take place in the absence of molecular/ free oxygen<br>• Reactions products are carbon dioxide, methane and excess biomass |
| Applications | Wastewater with low to medium organic impurities (COD < 1000 ppm) and for wastewater that are difficult to biodegrade e.g. municipal sewage, refinery wastewater etc. | Wastewater with medium to high organic impurities (COD > 1000 ppm) and easily biodegradable wastewater e.g. food and beverage wastewater rich in starch/sugar/ alcohol |
| Reaction Kinetic | Relatively fast | Relatively slow |
| Net Sludge Yield | Relatively high | Relatively low (generally one fifth to one tenth of aerobic treatment processes) |
| Post Treatment | Typically direct discharge or filtration/ disinfection | Invariably followed by aerobic treatment |
| Foot-Print | Relatively large | Relatively small and compact |
| Capital Investment | Relatively high | Relatively low with pay back |
| Example Technologies | Activated Sludge e.g. Extended Aeration, Oxidation Ditch, MBR, Fixed Film Processes e.g. Trickling Filter/Biotower, BAF, MBBR or Hybrid Processes e.g. IFAS | Continuously stirred tank reactor/digester, Upflow Anaerobic sludge Blanket (UASB), Ultra High Rate Fluidized Bed reactors e.g. EGSBTM, ICTM etc. |

Figure 1: Comparison of activated sludge (aerobic) and anaerobic treatment technologies for wastewater. (Chong et al., 2012)

## Details of Anaerobic Digestion

After several weeks of anaerobic digestion, dense aggregates of anaerobic microorganisms, called granules, naturally form and perform methanogenesis (Abbasi and Abbasi, 2012; Rittmann and McCarty, 2013). Methanogenesis is the process by which organisms, known as methanogens, convert organic matter to methane (Rittmann and McCarty, 2013). Formation of granules is preferred since granules have a high settling capacity, promoting compact design, and high biomass concentration in reactors (Kreuk and Bruin, 2004).

Upflow anaerobic sludge blanket (UASB) reactors are one example of high-rate anaerobic digesters. UASBs are used as primary clarification of wastewater, and therefore require post-treatment options such as trickling filters and secondary clarifiers to achieve ideal reduction of chemical oxygen demand (COD), suspended solids (SS), and nutrients (Abbasi and Abbasi, 2012). High-rate anaerobic digesters, such as UASBs, are designed to operate at short hydraulic retention times (HRT) and long solids retention time (SRT) to increase loading capacity and improve sludge stabilization (Chong et al., 2012). Due to these

advantages, UASB reactors were chosen as the basis for preliminary wastewater treatment design for communities in the global south.

## Conventional UASB Reactor Design

A conventional UASB reactor is shown in the Figure 2 below. The major components of a UASB reactor are the inlet system, sludge blanket, gas-liquid-solid separator system (GLSS), and exit weir.

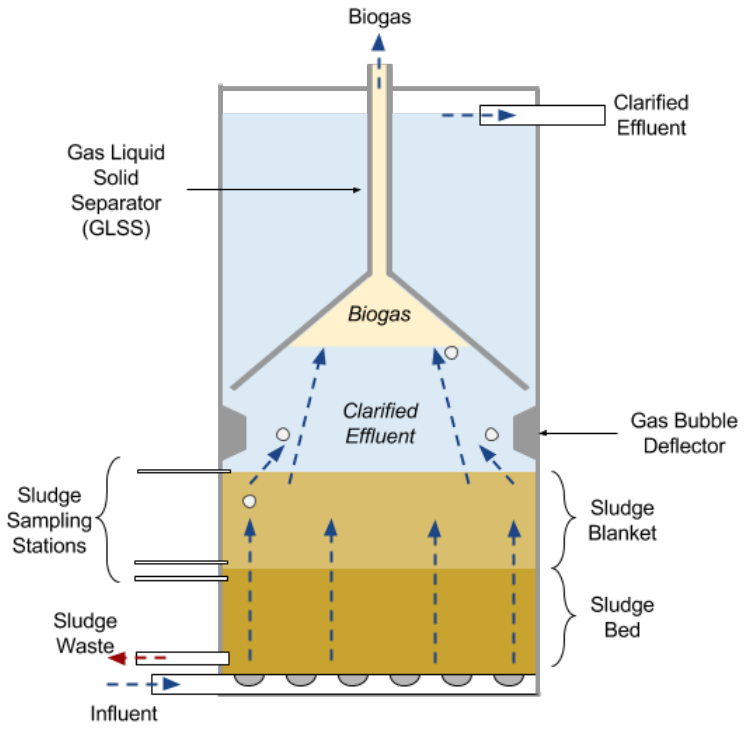


Figure 2: Schematic of a conventional UASB reactor. Important components of the reactor are labeled.

### Problems with Conventional Reactor Design

Conventional UASB reactors utilize GLSS to collect biogas (carbon dioxide and methane) that is produced during anaerobic digestion (Narnoli and Mehrotra, 1997). Since methane is a potent greenhouse gas, the biogas should be captured to reduce negative environmental impacts (Chong et al., 2012). GLSS are submerged funnels that function as a three-phase separator, where biogas is deflected to the funnel and either harvested for energy or burned before it is emitted into the atmosphere (Chong et al., 2012). Conventional UASB reactors are not gas-tight systems because the free-surface of water is open to the atmosphere.

When sludge escapes the sludge blanket and accumulates at the water surface open to the atmosphere, it forms a filamentous layer of bacteria (Lettinga and Holshoff Pol, 1991). This is problematic because the exit weir skims the water surface. In traditional UASB design, the effluent outlet is located at this gas-water interface, allowing for bacteria and other solids carried up by gas bubbles to escape untreated.

## Sludge Blanket

Anaerobic bacteria are crucial to the functionality of UASB technology. However, due to the size of the bacteria, an efficient upflow velocity would easily washout free-floating bacteria. To successfully process organic waste, UASB reactors heavily rely on the accumulation, concentration, and conglomeration of a large population of these bacteria in order to form diverse microbial community known as granules. Proper granulation and retention of these granules in a reactor is imperative to maximize the removal of COD and BOD and increase the overall effectiveness of UASB technologies (Subramanyam, 2013).

To maintain a specified sludge bed height, granule retention in the sludge bed is important. Granule retention and settling in the sludge bed is the result of the density difference between granules and

water. Compared to the density of water, $1000\frac{kg}{m^3}$, granule densities are slightly higher, within the range of $1000\frac{kg}{m^3}$ to $1050\frac{kg}{m^3}$ (Liu et al., 2006). According to Liu et al., higher density granules have large diameters which has a positive correlation with settling velocity (Liu et al., 2006). This average of granule densities from multiple wastewater treatment UASB reactors with associated settling velocities is shown below in Table 1.

Table 1: Densities and settling velocities observed by Liu et al. (2006)

| Types of wastewater | Granule diameter (mm) | Density (kg $m^{-3}$) | Settling velocity (m $h^{-1}$) | Reynolds number |
|---|---|---|---|---|
| Sample 4 | 0.7 | 1030 | 25.3 | 5.22 |
| Beet sugar factory 2[a] | 0.8 | 1082 | 53.6 | 11.91 |
| Sample 1 | 1.2 | 1050 | 54.6 | 18.05 |
| Sample 2 | 1.3 | 1040 | 55.2 | 19.95 |
| Sample 3 | 1.4 | 1040 | 60.5 | 23.53 |
| Distillery wastewater[b] | 1.5 | 1039 | 52.9 | 22.04 |
| Potato processing[c] | 1.86 | 1057 | 97.8 | 47.81 |
| Beet sugar factory 1[d] | 1.9 | 1038 | 83.3 | 43.73 |
| Wastepaper plant[e] | 2.2 | 1042 | 98.9 | 60.44 |

[a] Beet sugar factory 2 (Suiker Unie, Roosendaal, The Netherlands)
[b] Distillery wastewater (Nedalco, Bergen opZoom, The Netherlands)
[c] Potato processing plant (Aviko, Steenderen, The Netherlands)
[d] Beet sugar factory 1 (Central Suiker Maatschappij Breda, The Netherlands)
[e] Wastepaper processing plant (Papierfabrick Roermond, The Netherlands)

The mathematical settling model created by Liu et al. simply assumes that the granules are perfectly spherical and constant average density of the granules in determining settling velocity (Liu et al., 2006). It does not account for instances of biogas formation on the surface of granules, thus altering density properties. This is a topic that needs to be further explored as granules can rise along with biogas as it is formed.

# Previous Work

Since 2013, AguaClara has been working on developing novel wastewater treatment systems for communities in the global south. Over the past 4 years, a number different teams have worked on designing and implementing a number of different high-rate bioreactors that utilize large microbial communities packed in granular sludge to remove organic matter and other nutrients from synthetic sources of wastewater. In (Fall 2015), the Upflow Anaerobic Sludge Blanket team was formally established to investigate the effectiveness of a settled sludge bed in treating wastewater. Since then, much progress to push the boundaries of AguaClara wastewater technology.

In Spring 2016, four new reactors were designed with a 0.05 mm/s upflow velocity. These reactors were then inoculated with granular sludge taken from the Budweiser brewery in Syracuse in Summer 2016 by Andrew Kim. The reactors were run over that summer to acclimate then to an environment of synthetic wastewater until steady state was reached. Biogas production was also measured and characterized.

In Fall 2016, work was done to improve the synthetic wastewater solution to prevent clogging as well as update operational setup to improve function of the lab bench. A fluoride tracer test was also conducted to determine the hydraulic residence time through. From that experiment, it was determined that HRT through the sludge blanket was 4 hours.

In January 2017, a grant proposal was submitted by Serena Takada and Subhani Katugampala for the EPA P3 design competition. The proposal outlined a redesign of the conventional UASB reactor to make it modular and easily scalable by incorporating AguaClara concepts and technologies derived from the 1 L/s plant. As of Summer 2017, AguaClara has been informed that the project will likely be funded.

In Spring 2017, work commenced on testing the efficacy of two of the proposed design changes. One of the changes was to introduce a removable gas capture device and utilize a water seal in order to make it gas tight. It was determined that a gas tightness can be achieved by a removable lid as long as it was sufficiently tall. Another design proposal that was tested was utilizing plate settlers to maintain high biomass concentration. Due to low microbial activity and biogas production, however, it could not be definitely determined whether plate settlers would be useful in the redesigned UASB reactor.

# 1 Granule Settling Experiment

## 1.1 Methods

### Purpose of Experiment

The design of this experiment was to determine the impact of plate settlers on solids retention and potential granule escape. To do this, a cross section of the proposed reactor design and conventional design were modeled as shown in Figure 3. Based on the results of the experiment, the reactor design that produced better effluent equality will be used to influence the overall geometry of a full scale AguaClara UASB reactor.

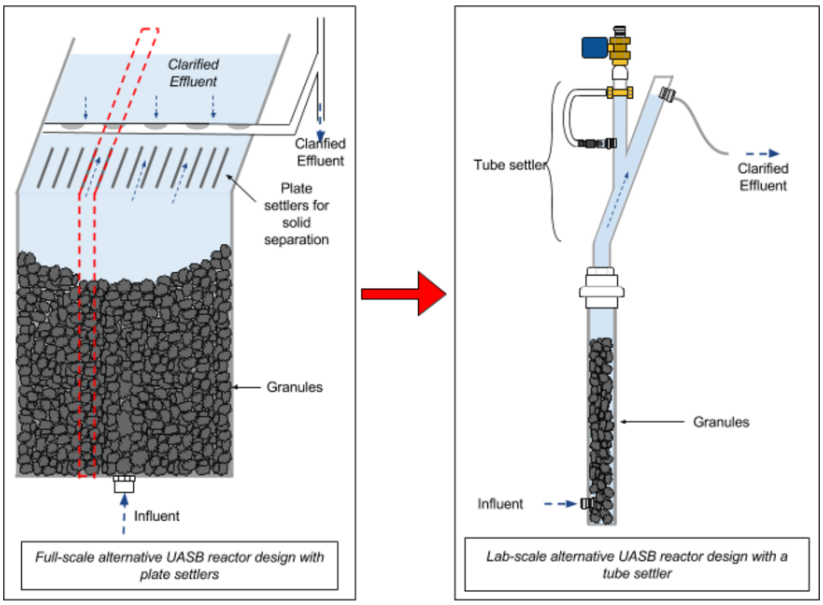


Figure 3: Schematic of the proposed UASB reactor and the lab scale reactor. The design of the lab scale reactor is based on a cross section of the proposed full scale reactor

[I think it will be helpful to include any challenges in fabrication of the apparatus and how future teams can build their own if they want to. I'm also not sure if it's considered a cross section of the full scale reactor because I think that implies a horizontal cross section? I'm not sure, but it might be good to double check that.]

### Experimental Design and Changes

The Spring 2017 UASB had previously hypothesized that regular biogas production in a full scale UASB would destabilize and become a potential point for granule washout. Due to the lack of microbial activity and biogas production, the results were inconclusive. To mitigate this problem, pressure sensors and solenoid valves were reintroduced. [How do pressure sensors and solenoid valves mitigate the problem?] Two reactor tops were fabricated to correctly model the 60 degree angle that is typically used in AguaClara plate settler designs as well as capture biogas as shown in Figure 4. Two other reactor tops were also fabricated to model conventional reactor designs. With the equipment and ProCoDA, a volumetric way of measuring biogas production can be achieved and used to to to determine if microbial activity had reached steady state as based on Andrew Kim's data from Summer 2016.

The previous semester's team also utilized a visual method of interpreting the quality of collected effluent water. While this would suffice in determining whether larger particles and granules were washed out, it was not a highly accurate method of measuring effluent quality. In order to get quantitative confirmation on water quality, effluent was collected as shown in Figure 5 and measured daily using a handheld turbidimeter.

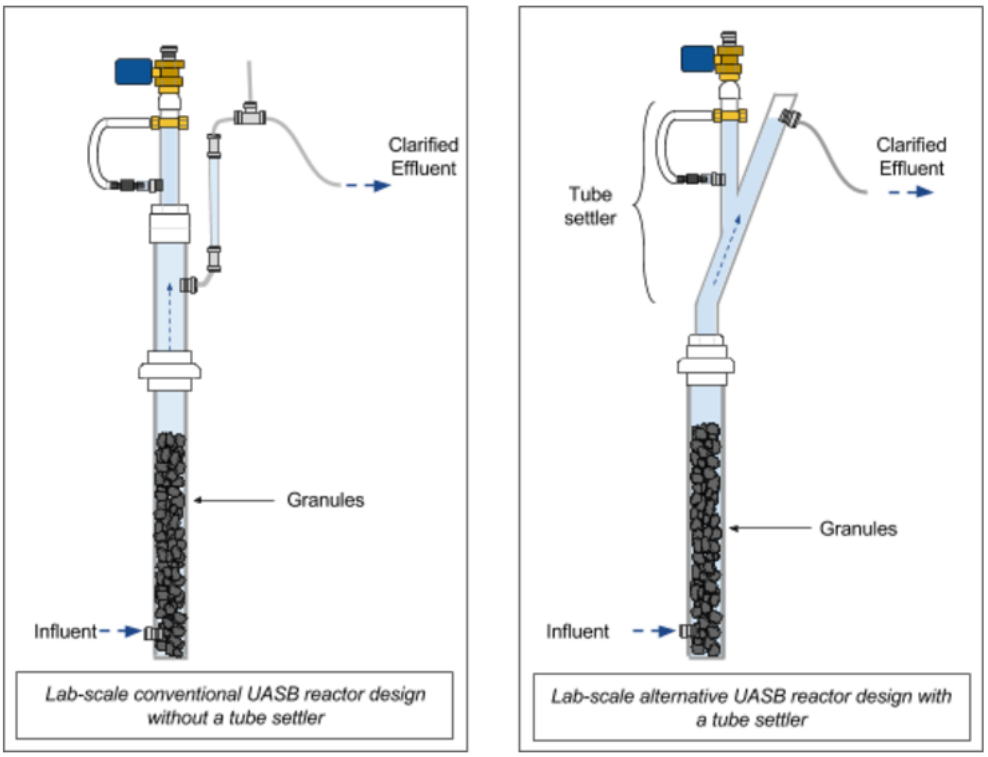


Figure 4: Design of the conventional reactor versus the design of the alternative reactor. The alternative reactor includes a 60 degree bend to model plate settlers traditionally used by AguaClara.

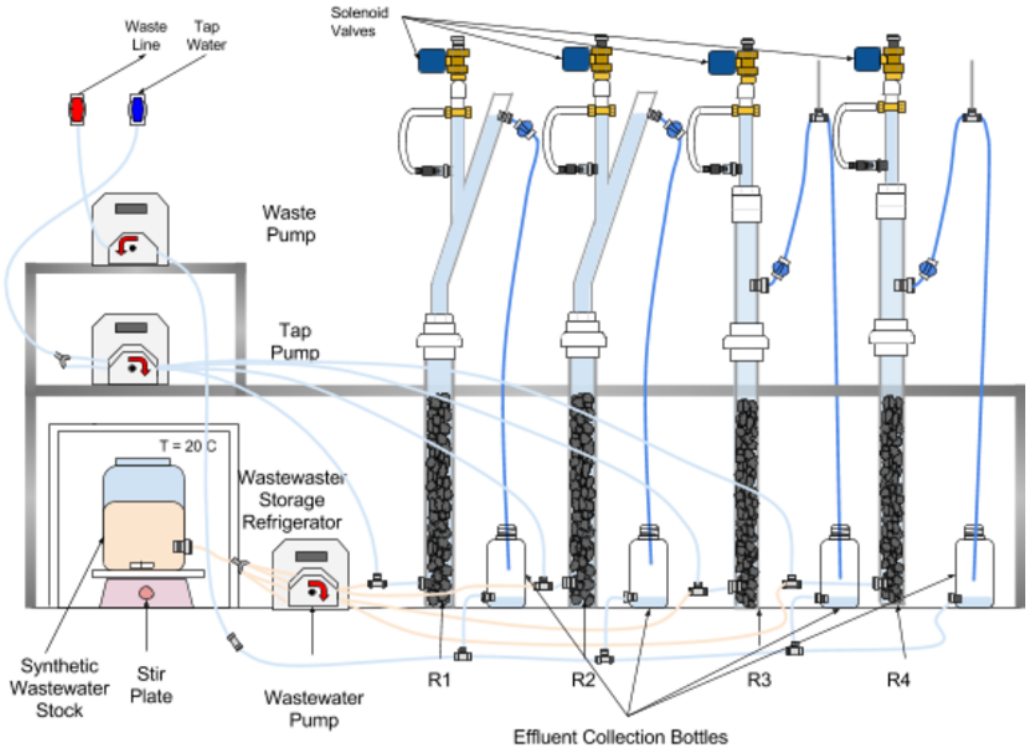


Figure 5: The bench setup for the lab scale UASB reactors. Solenoid valves were added to the reactors in order to quantitatively monitor biogas production. individual effluent collection bottles were also added to better measure effluent quality from each reactor.

### Procedure

The reactors were brought to steady state operation as detailed in Lab Scale UASB Operational Manual. Once stability in biological activity was achieved, all four reactors were run with 7300 mg COD/L-day of synthetic wastewater stock at an organic loading rate of 6 g COD/L-day for approximately three days. Effluent turbidity and biogas collection data was then measured after each day. [Perhaps reference the manual where you explain how you created your wastewater stock?]

## 1.2 Results

[Might be helpful to include a sentence or two to establish that R1, R2 and R3, R4 were the same apparatus or include it in the table instead of the area?] Due to clogging issues in the pump tubing that deliver synthetic wastewater stock to the reactors, Reactor 2 and Reactor 4 [reactors 2 and 4?] were not provided with the calculated amount of wastewater stock on Day 1 as shown in Figure 2. The two reactors produced biogas that lead to 0 and 3 offgassing events [per day?] with an average effluent turbidity of 0.72 NTU and 2.14 NTU, respectively. Reactor 1 and Reactor 3 were able to produce 28 and 40 offgassing events with an average effluent turbidity of 5.61 NTU and 17.02 NTU respectively. Similar results were obtained during Day 2 of the experiment as shown in Figure 3. Gradual clogging eventually limited the the performance of each reactor over the length of the experiment as shown in Figure 4.

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fraction | Events/day | Area (cm^ | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 28 | 1.96037 | 219.5614583 | 164.6710937 |
| R2 | 1 | 0 | 1.96037 | 0 | 0 |
| R3 | 1 | 40 | 1.96037 | 313.6592261 | 235.2444196 |
| R4 | 1 | 3 | 1.96037 | 23.52444196 | 17.64333147 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 4.95 | 6.82 | 5.07 | 5.613333333 | |
| R2 | 0.72 | 0.73 | 0.71 | 0.72 | |
| R3 | 18.88 | 17.11 | 15.09 | 17.02666667 | |
| R4 | 2.07 | 2.47 | 1.89 | 2.143333333 | |

Table 2: Biogas production (mL/day) measured against effluent turbidity on Day 1 of the Granule Settling Experiment

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fracti | Events/day | Area (cm^2) | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 15 | 1.960370163 | 117.6222098 | 88.21665735 |
| R2 | 1 | 0 | 1.960370163 | 0 | 0 |
| R3 | 1 | 47 | 1.960370163 | 368.5495907 | 276.412193 |
| R4 | 1 | 9 | 1.960370163 | 70.57332588 | 52.92999441 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 3.04 | 2.28 | 3.71 | 3.01 | |
| R2 | 0.38 | 0.36 | 0.36 | 0.366666667 | |
| R3 | 23.84 | 23.97 | 24.1 | 23.97 | |
| R4 | 0.65 | 0.59 | 0.53 | 0.59 | |

Table 3: Biogas production (mL/day) measured against effluent turbidity on Day 2 of the Granule Settling Experiment

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fraction | Events/day | Area (cm^2) | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 12 | 1.96037016 | 94.09776784 | 70.57332588 |
| R2 | 1 | 0 | 1.96037016 | 0 | 0 |
| R3 | 1 | 45 | 1.96037016 | 352.8666294 | 264.6499721 |
| R4 | 1 | 18 | 1.96037016 | 141.1466518 | 105.8599888 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 6.82 | 5.63 | 6.97 | 6.473333333 | |
| R2 | 0.56 | 0.61 | 0.56 | 0.576666667 | |
| R3 | 59.36 | 58.36 | 58.92 | 58.88 | |
| R4 | 0.87 | 0.81 | 0.83 | 0.836666667 | |

Table 4: Biogas production (mL/day) measured against effluent turbidity on Day 3 of the Granule Settling Experiment

## 1.3 Analysis

Based on data from Day 1 of experimentation, there is a significant difference in effluent quality when biogas is being produced. Comparing R1 and R3, reactors that were properly ~~delivered~~delivering synthetic wastewater stock, with R2 and R4, reactors that did not produce biogas due to clogging, the average turbidity was significantly higher in the reactors that had consistent biogas production. Biogas production indeed suspends granules and other particles enough for them to be washed out of the reactors rather than settle back after gas bubbles pass. Day 1 also shows that plate settlers are an effective means of retaining solids and other particulate biomass. Comparing R1, a reactor with plate settlers, and R3, a reactor without plate settlers, R1 had much lower effluent turbidity. This implies that particles suspended by biogas production are able to settle in the tube settler, preventing further washout. (Add More)

Data from Day 2 reaffirmed these results. Comparing the data between R1 and R2, and between R3 and R4, when biogas was produced, there were more suspended solids washed out of the reactors. This led to higher turbidity reading and lower effluent quality. In comparing R1 and R3, average turbidity was once again lower in the reactor with the simulated plate settler.

The third day of data collection produced some uncertainty in the results. Due to unforeseen problems with delivery of the synthetic wastewater stock, the performance of R1 degraded and biogas production

dropped while the performance of R4 increased and R1. While performance of the reactors changed, effluent turbidity remained relatively stable compared to the previous days of experimentation. The average effluent turbidity for R1, with plate settlers, was 6.473 NTU while that of R4, without plate settlers, was 0.837 NTU. This inconsistency, however, can be attributed to the size of the granules in R4. While R1 had finer granules that were more easily suspended when biogas moved through the fluidized bed, R4 contained much larger granulated particles that settled almost immediately.

While the data appeared to show that plate settlers may not be necessary in the case of reactors highly developed, matured granules, precluding plate settlers completely from a full scale design may not prove to be effective long term as exemplified by R3. Over the length of the experiment, R3, a reactor that did not have simulated plate settlers and contained smaller granules, experienced continuous decreases in effluent quality. With slow microbial growth rates and long startup times required for proper granulation in conventional UASB reactors, it is impertinent [Did you mean pertinent?] to consider some sort of settling apparatus. However, with challenges in fabricating and high cost of materials, is important to avoid over designing and simplify parts as much as possible.

# 2 Capture Velocity Experiment

## 2.1 Methods

### Purpose of Experiment

Based on the results of the Granule Settling Experiment, it was determined that a settling apparatus was required to improve solid retention and prevent granule escape, however, a full set of plate settlers may not be required. Following this analysis, a conventional reactor design with a sloped exit weir was proposed. Capture velocity, defined as the settling velocity of the slowest settling particle, was determined to be the parameter that needed comparison. It was hypothesized that a sloped exit weir that achieved a capture velocity equal the upflow velocity in the straight section of the reactor would promote settling on par with the alternative reactor design.

### Experimental Design

Due to limited time available to fabricate new reactor tops, two reactors utilized in the Granule Settling Experiment were modified to simulate a straight reactor with a sloped exit weir as shown in Figure 6. Depending on the settling area produced by the tube settlers, different capture velocities would be achieved. Setting area of the tube settlers was calculated using the following equation:

$$A_{Settling} = (Lcos(\alpha) + \frac{\pi}{4}\frac{S}{sin(\alpha)}) * S \tag{1}$$

where L is the length of the tube settler, $\alpha$ is the angle of the tube settler, and S is the diameter of the tube. Capture velocity can then be determined by the following equation:

$$V_{capture} = \frac{V_{up}A}{A_{Settling}} \tag{2}$$

[Did not define the other variables.] where $V_{up}$ is the upflow velocity through the straight section of the reactor, and A is the area of the base of the reactor. The calculated capture velocities in the Alternative Design V1 with a full tube settler and Alternative Design V2 with a reduced tube settler were 0.00671 mm/s and 0.023 mm/s as shown in Table 5. Since only modification to existing reactors were made, the desired capture velocities for experimentation could not be achieved, however, a good basis for comparison was still achieved. Aside from these modification, no other changes were made to the existing reactors or bench setup.

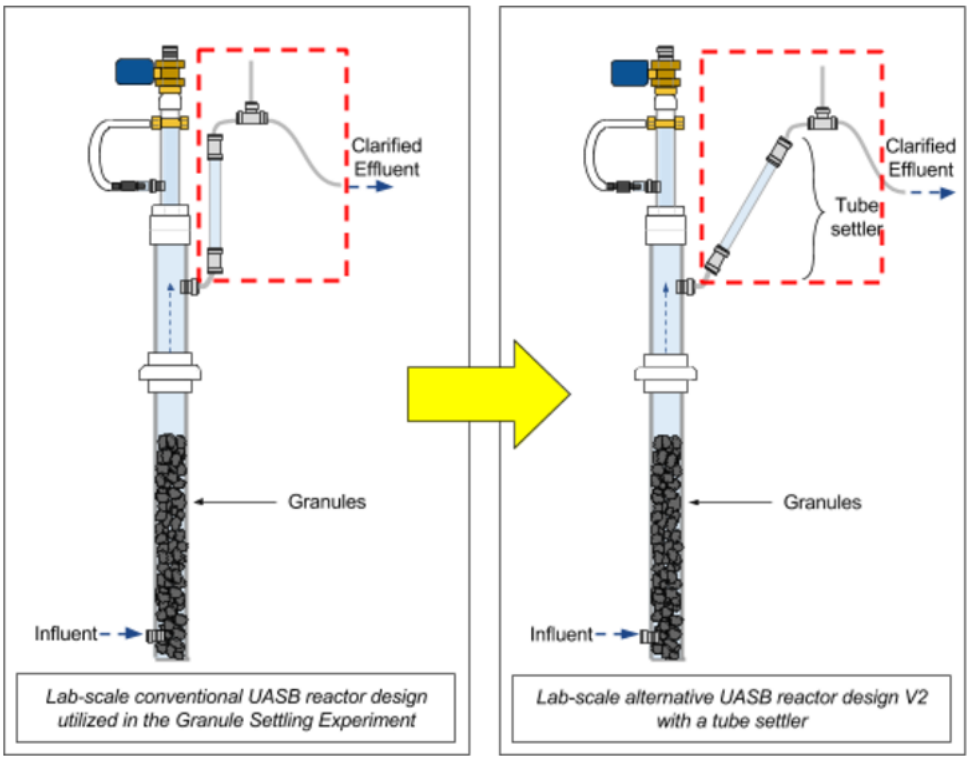


Figure 6: Changes made to the conventional reactor design used in the Granule Settling Experiment. A sloped exit weir was created to determine the effectiveness utilizing higher capture velocity on solid retention.

| Capture Velocity Experiment Parameters | | | | |
|---|---|---|---|---|
| | **R1** | **R2** | **R3** | **R4** |
| **Upflow Velocity, $V_{up}$ (mm/s)** | 0.05 | 0.05 | 0.05 | 0.05 |
| **Base Area, A (cm^2)** | 5.11 | 5.11 | 5.11 | 5.11 |
| **Flow Rate, Q (mm^3/s)** | 25.54 | 25.54 | 25.54 | 25.54 |
| **Settling Area, $A_S$ (cm^2)** | 38.06 | 38.06 | 10.91 | 10.91 |
| **Capture Velocity (mm/s)** | 0.00671 | 0.00671 | 0.023 | 0.023 |

Table 5: The capture velocities determined by the parameters of the existing experimental design

**Procedure**

The reactors were first brought to steady state operation as detailed in Lab Scale UASB Operational Manual. Once stability in biological was achieved, all four reactors were run with 7300 mg COD/L-day of synthetic wastewater stock at an organic loading rate of 6 g COD/L-day for approximately two days. Effluent turbidity and biogas collection data was then measured after each day. Due to the variance in turbidimeter readings, vials were measured three times and averaged.

## 2.2 Results

During Day 1, there was consistent biogas production in three of the four reactors. R1 produced 11 offgassing events while producing an effluent turbidity of 2.783 NTU as shown by Table 6. R3 and R4 produced a similar number of offgassing events with 15 and 13 respectively while producing an average effluent turbidity of 2.71 NTU and 1.39 NTU. Similar results were produced after Day 2 of the experiment. R1 experienced 35 offgassing events and produced an average effluent turbidity of 1.050 NTU as shown by Table 7. R3 and R4 experienced 26 and 27 offgassing events respectively while producing average effluent turbidity of 1.837 NTU and 1.08 NTU.

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fraction | Events/day | Area (cm^2) | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 11 | 1.960370163 | 86.25628717 | 64.69221538 |
| R2 | 1 | 2 | 1.960370163 | 15.6829613 | 11.76222098 |
| R3 | 1 | 15 | 1.960370163 | 117.6222098 | 88.21665734 |
| R4 | 1 | 13 | 1.960370163 | 101.9392485 | 76.45443636 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 2.60 | 2.97 | 2.78 | 2.783333333 | |
| R2 | 2.61 | 2.63 | 2.59 | 2.61 | |
| R3 | 2.65 | 2.94 | 2.56 | 2.716666667 | |
| R4 | 1.37 | 1.42 | 1.39 | 1.393333333 | |

Table 6: Biogas production (mL/day) measured against effluent turbidity after Day 1 of the Capture Velocity Experiment.

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fraction | Events/day | Area (cm^2) | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 35 | 1.960370163 | 274.4518228 | 205.8388671 |
| R2 | 1 | 16 | 1.960370163 | 125.4636904 | 94.09776782 |
| R3 | 1 | 37 | 1.960370163 | 290.1347841 | 217.6010881 |
| R4 | 1 | 26 | 1.960370163 | 203.878497 | 152.9088727 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 0.96 | 1.09 | 1.1 | 1.05 | |
| R2 | 1.00 | 1.06 | 0.99 | 1.016666667 | |
| R3 | 1.87 | 1.86 | 1.78 | 1.836666667 | |
| R4 | 1.07 | 1.06 | 1.11 | 1.08 | |

Table 7: Biogas production (mL/day) measured against effluent turbidity after Day 2 of the Capture Velocity Experiment.

## 2.3 Analysis

The results from the Capture Velocity Experiment suggest that there is no significant difference between utilizing a capture velocity of 0.023 mm/s or 0.00671 mm/s. More importantly, this implies that a capture velocity on the same order of magnitude as the upflow velocity is sufficient in allowing granules and other particulate matter to settle back into the reactor. This is highly unusual as AguaClara drinking water technologies utilize a standard capture velocity of 0.12 mm/s which is approximately ten times less than the upflow velocity in smallest sedimentation tank.

One reason for this occurrence may be the low upflow velocity through the reactor. Since the bed of granules is settled at an upflow velocity of 0.05 mm/s, particles that are suspended due to biogas production can still settle due to their higher density. This may suggest a capture velocity as high as the 0.05 mm/s can still achieve reliable settling in a full scale design. Furthermore, these high capture velocities, relative to upflow velocity, highly simplify design as a smaller settling area is needed to achieve proper settling. This implies that conventional reactor retrofitted with a sloped exit weir, with the potential to hold plate settlers to reduce capture velocity, can be utilized as shown in Figure 7, rather than a full AguaClara sedimentation tank with a system of plate settlers. These results highly simplify design and fabrication work for future teams as well as reduce the overall cost of the proposed AguaClara UASB reactor.

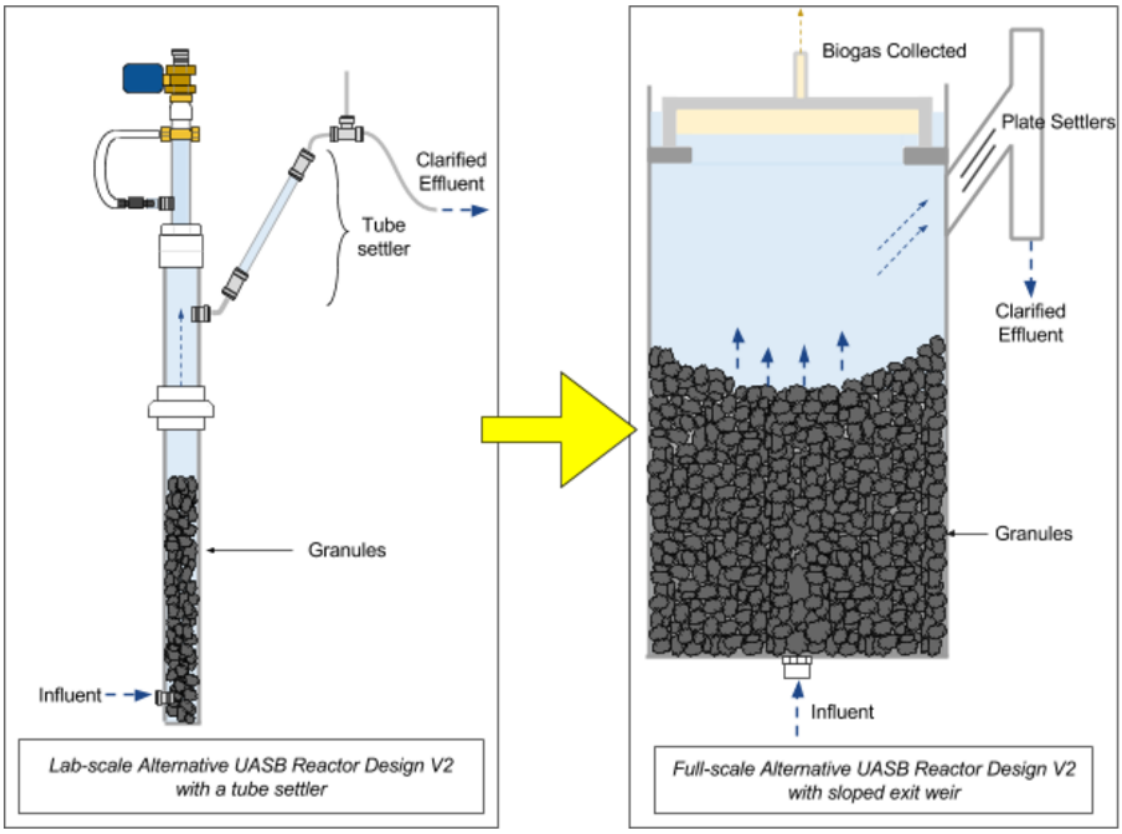


Figure 7: A modified version of the AguaClara UASB proposed in the EPA P3 Design competition proposal. Rather than having a full system of plate settlers and a bend in the body of the reactor, a sloped exit weir with plate settler is utilized to help maintain granules and other solids

## Conclusions

The granule settling experiment from Spring 2017 has reached a conclusive result. Due to high capture velocity relative to the upflow velocity, a full system of plate settlers will not be required of a full scale UASB reactor. There is no substantial impact from drastically decreasing capture velocity. Rather, a smaller settling apparatus such as a sloped exit weir can achieve the the similar solid retention rates. More specifically, it was established that a 0.023 mm/s capture velocity can be utilized to increase effluent turbidity. It is with these conclusions, that the Summer 2017 UASB team recommend that future UASB teams move forward with fabrication of the revised full-scale design.

## Future Work

With the geometry of a full scale UASB reactor finalized, future teams should focus on fabricating a pilot scale plant. Funding from January 2017's EPA grant is tentatively set to arrive this coming fall so the pilot scale plant can commence. Contact between a local wastewater treatment facility such as the Ithaca Wastewater Treatment Facility should be established for pilot scale testing with true wastewater.

Further work also needs to be conducted on a gas capture apparatus. While the Spring 2017 UASB team establishes the effectiveness in using semi-submerged lid to collect biogas, specifics on the fate of any collected biogas was not determined. Based on the method of disposal or usage of the biogas, designs will need to be adjusted to reflect the desired fate. Current lab scale gas collection simply releases biogas into the atmosphere which is undesirable on a full scale.

Finally, secondary treatment options should be explored within the limits of AguaClara technologies. One proposed idea is to utilize AguaClara flocculation and sedimentation to further remove nutrients and organic matter.

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# Appendix

## Semester Schedule

### Task Map

Task Maps should be created in Microsoft Word and then copy and pasted into the Detailed Task List in Overleaf. Save your word document on Google Drive so that you can make adjustments later in the semester. To Create one, open Microsoft Word. Under Insert, go to Smart Art, click Hierarchy, then Horizontal Hierarchy. Click the arrows on the left side of the box to open up a bulleted list of how your Map is organized. Make sure your map is as large as possible on the page (it may be necessary to increase the font size), then copy and paste it into the Google Doc.

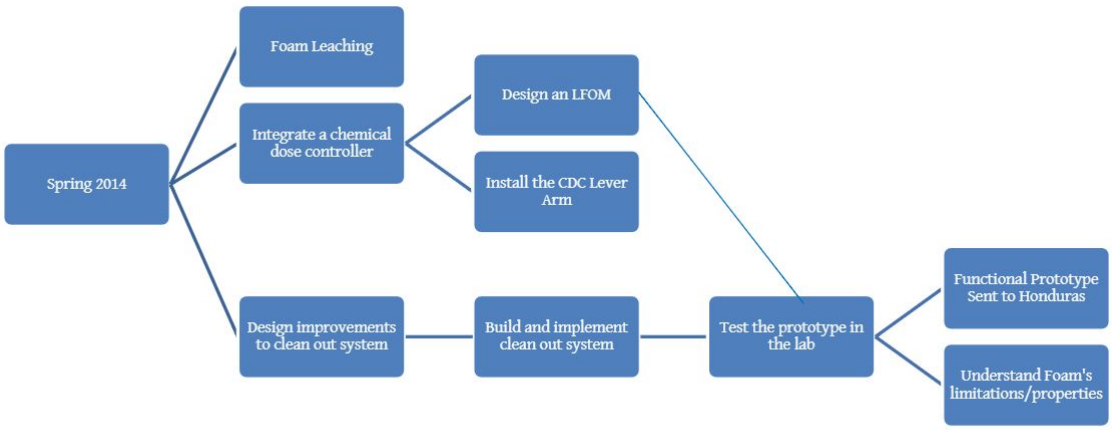



Figure 8: Example Task Map

### Task List

You should keep and update your detailed task list from the first assignment in each of your reports. Denote completed tasks and modify your deadlines to reflect your most recently completed progress and any delays.

1. Task (date) - Individual responsible. Detailed explanation
2. ✓Task (date) - Individual responsible. This is an example of a completed task.

**Report Proofreader:** Team member name

# Lab Scale UASB Operational Manual

*Outline:*



**I. Purpose**

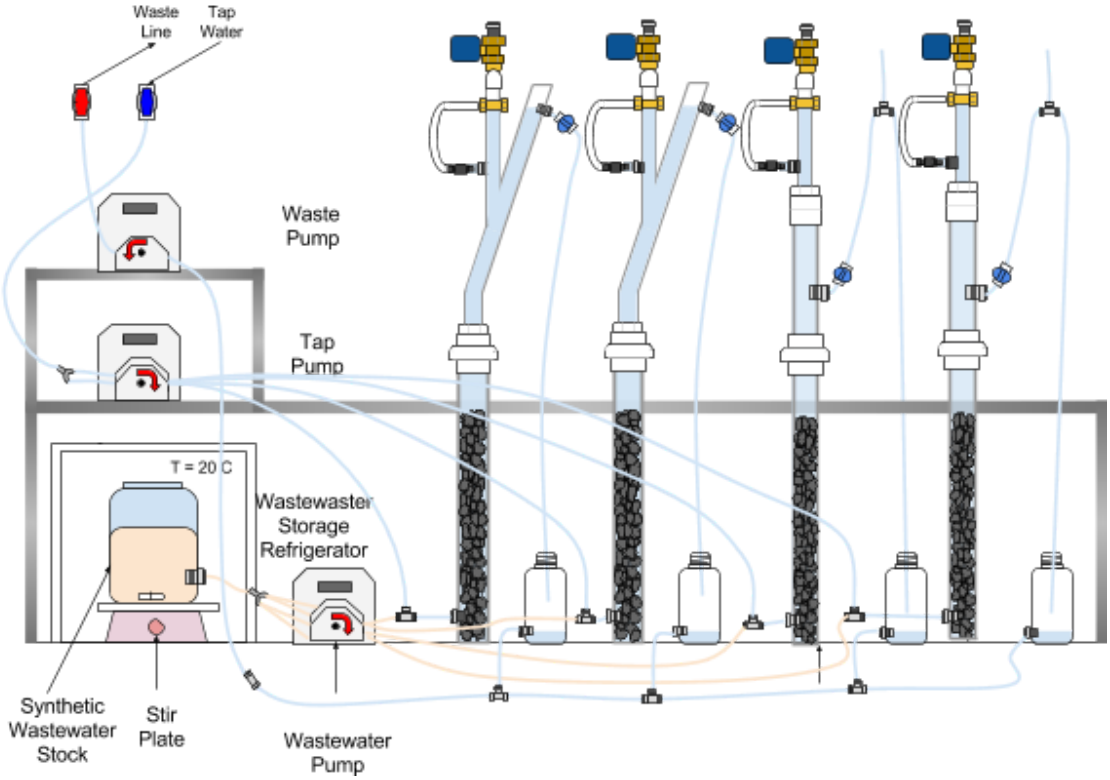
Since its inception in 2013, the AguaClara wastewater subteam has worked to provide a workable, lab-scale model for a number of different wastewater treatment systems. While work on design and experimentation for numerous different iterations of reactors occurred, documentation on how to operate the lab-scale units has not been well kept. The purpose of this manual is to provide a high level overview on the setup and operation of the current lab-scale UASB reactors as of Summer 2017. The hope is to provide future teams with a better foundation on how to utilize an important system should future work and experimentation need to occur on the lab-scale.

**II. Operation**

**A. Overview and Apparatus Setup**

The current reactors were designed by the Spring 2016 UASB Design team. They operate on a manually controlled pump system using low RPM peristaltic pump. The reactors were designed with an upflow velocity of 0.05 mm/s. It was later experimentally discovered by the Fall 2016 team that the hydraulic residence time (HRT) through the granular sludge bed was 4 hours. The gas capture devices are remotely operated through pressure sensors and solenoid valves that are monitored by ProCoDA. More on

how the ProCoDA operates are covered later in the ProCoDA section of this manual.




## B. The Stock Solution

The stock solution is a predominantly carbon-based solution that was specifically designed to mimic wastewater. The original solution was taken from literature, however, due to clogging problems that insoluble constituents and other biological activity caused, the stock solution was modified by the Fall 2016 team.

While the new solution is less prone to clogging, it is not perfect. Caution should still be taken when making synthetic wastewater to ensure that there is no contamination. One of the measures to prolong the life of the wastewater stock is to was all containers with dilute bleach before using them to hold the stock solution. Gloves should also be worn while making the solution as a another precaution. Further steps still need to be taken in order to prevent greater issues in the tubing. To combat biological growth in the synthetic wastewater stock, the stock solution should be placed on in a refrigerator to slow the rate of growth from any possible contaminants. A magnetic stir bar and stir plate should also be utilized to prevent inorganic solutes from precipitating.

Below is the recipe which makes 4L of 7300 mg COD/mL synthetic wastewater stock. This recipe can also be found taped to the chemical cabinet in the AguaClara lab.

<u>Ingredients:</u>
Water, 4 L

Urea, 6.4 g
$NH_4CL$, 0.800 g
Peptone, 1.2 g
$MgSO_4$, 1.58 g
$KH_2PO_4$, 1.22 g
$FeSO_4$-$7H_2O$, 0.080 g
$CaCl_2$-$2H_2O$, 0.48 g
Glucose, 16.4 g
Yeast extract, 3.6 g
Vegetable oil, 2 g
$CuCl_2$-$2H_2O$, 0.040 g
$MnSO_4$-$H_2O$, 0.008 g
NiSO4-$6H_2O$, 0.020 g
$ZnCl_2$, 0.02 g

**C. Feeding the Reactors**

The microbial community within the reactors require a steady input of synthetic wastewater to ensure proper operational function. Depending on the operational state of the reactors, the organic loading rate (OLR) will change. In order to set the flow rates of the influent lines, calculations need to be made to determine how much synthetic wastewater delivered. These calculations are simplified in the "Reactor Parameters" Google Sheet which can be found in the UASB team folders from Fall 2016 onwards.

*a. Startup and Lag Phase*

After a long period of dormancy, the microbial community will still remain active; however, care needs to be taken when during this start up phase again. After a long period without input, the microbes have diminish ability to process the synthetic wastewater so biogas production will not be at peak level. This is known as the lag phase where metabolic activity is still low.

The microbes will also be unaccustomed to a large organic load and thus must be eased in at a lower OLR. If they are overloaded too early on, the granules may accumulate a large amount of fatty acids which could potentially kill the microbial communities. A proper organic loading rate should be about 3 g COD/L-day in order to work the microbes up.

Care should be taken with the stock concentration as the OLR is decreased. The peristaltic pumps in the AguaClara lab cannot go below 1 RPM. Stock solutions will have to be diluted in order to deliver anything below 6 g COD/L-day when using a stock solution with a 7300 mg COD/L concentration.

The reactor should be run at lower OLR and worked up for approximately 2 weeks to prevent microbial death and granule washout.

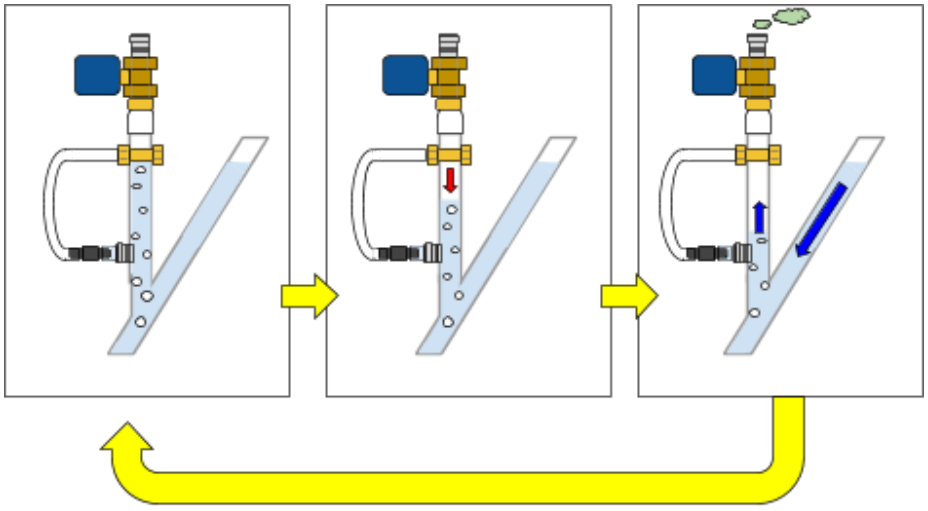
*b. Steady State*

Once the microbes have been worked up to steady state, the reactor can be used for experimentation. At steady state operation, the reactors should receive approximately 6 g COD/L-day. At this OLR, the reactors will produce have approximately 30 offgassing event per day.

## III. Gas Collection and ProCoDA

### A. Overview

When experimenting with the reactors, measuring biogas production is crucial to ensure that synthetic wastewater is being delivered and that the reactors are operating up to capacity. To measure biogas production, the reactors are set up with a small gas collection chamber with a pressure sensor on the side and a solenoid valve at the top of each reactor. At the start of an experiment the solenoid valves should be opened so that pressure equilibrates and the water level in the gas collection chamber will become the same at the effluent line. After the pressure is equalized, the solenoid valves should be closed to create a gas-tight collection chamber. As synthetic wastewater is pumped in and biogas produced, gas bubbles are captured in the chambers and the buildup pushes down the water level. When the water level reaches a certain point measured by the pressure sensors, the solenoid valve opens and equalizes the pressure again. ProCoDA then records the time and which solenoid valve was opened in an Excel file. If synthetic wastewater is being delivered properly, then the process should repeat itself approximately 30-35 times throughout the day in each reactor.



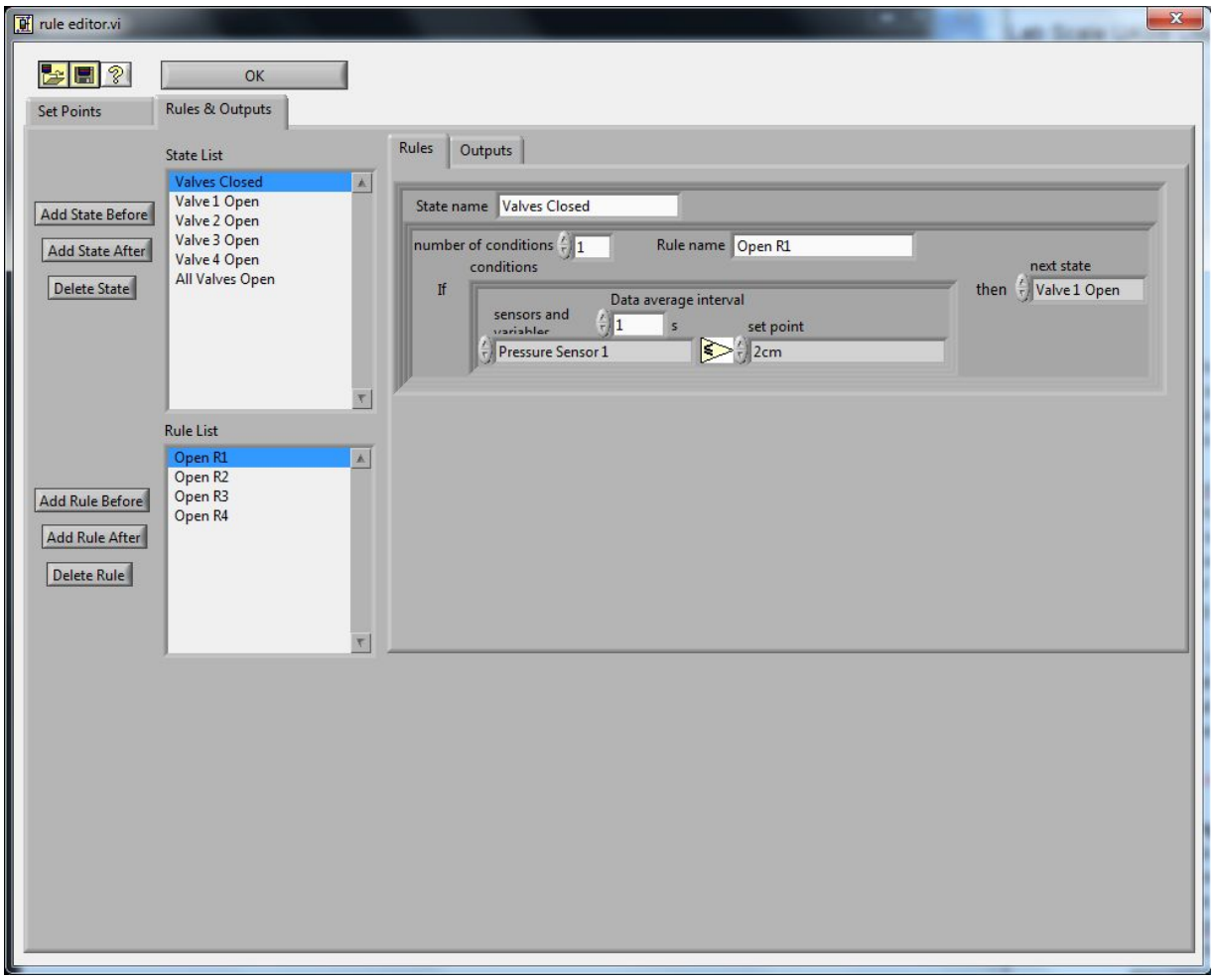
At the start of an experiment, the was level in the gas collection chamber is the same as the effluent line. As biogas is produced and captured in the gas collection chamber, the water level drops. Once the water level drops low enough and the pressure sensor reads 2 cm, the solenoid valve is opens, allowing the pressure to equalize.

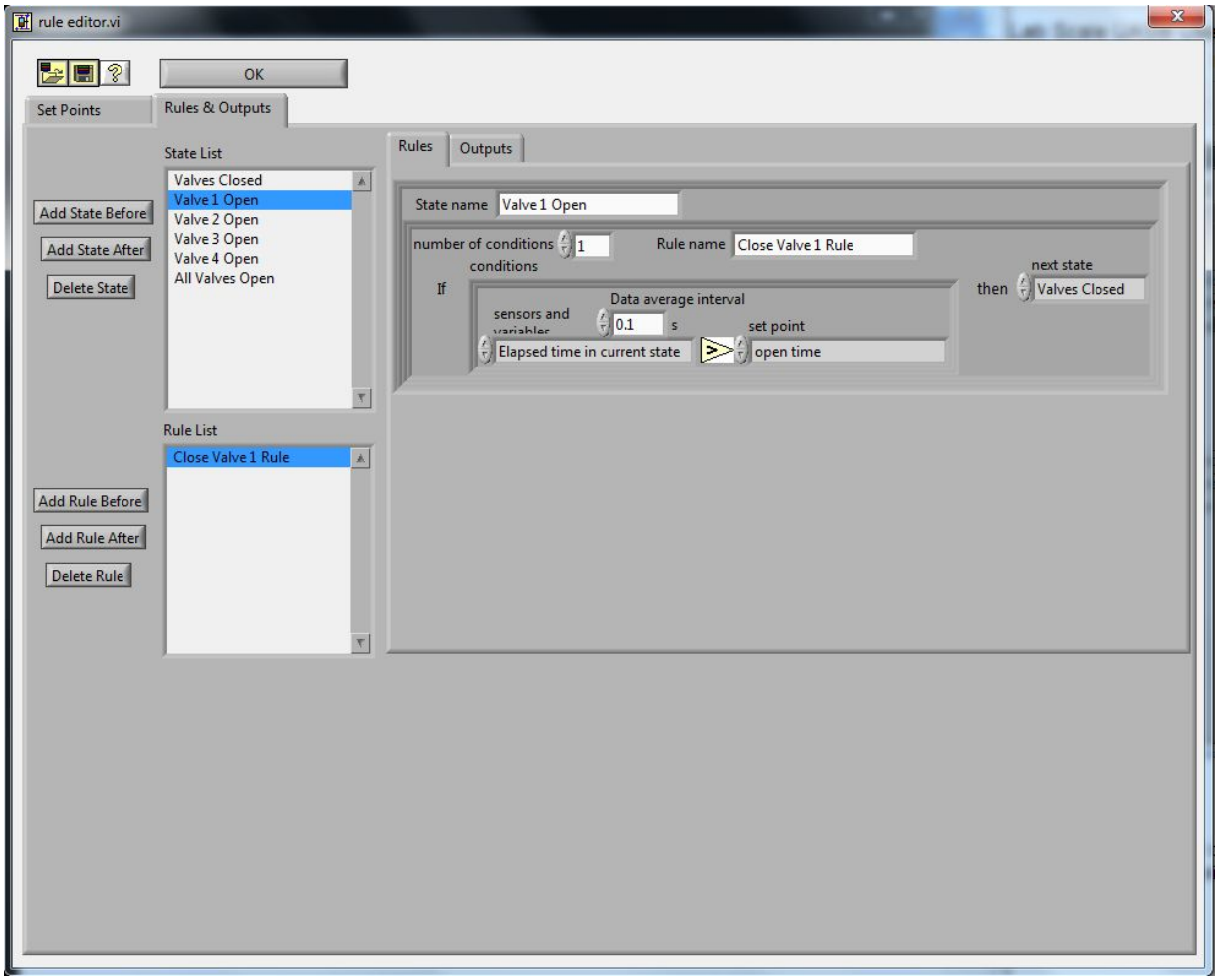
### B. ProCoDA Coding

To remotely control each solenoid valve, ProCoDA is used in conjunction with pressure sensors. When an experiment is first started and the pressure is equalized, the pressure

sensor should read the water level to be around 5 to 6 cm.  As an experiment runs, the pressure sensors continuously monitor the water level as it drops.  When it reaches the 2 cm set point, it triggers one of the Open Reactor rules in ProCoDA to open the solenoid valve associated with that pressure sensor and reactor.

Within ProCoDA, there is one state called “Valves Closed” with four rules that controls the opening of each individual solenoid valve when the water level is read by the pressure sensors to be below 2 cm in of the reactor gas collection chambers.  After one of the valves is opened, one of the “Valve Open” states keeps the valve open for a set amount of “open time.”  When that time has elapsed, the valve is closed until the next offgassing event.






To collect data, the Datalog directory path has to be set to a specific folder on Configurations tab of ProCoDA. Once the path is set and the Mode of Operation is set to automatic under the Process Operation tab, data will automatically be collected on an Excel sheet.

### C. Measuring Biogas Production

Once data is collected, the amount of gas produced can be approximated by the number of off-gassing events. When a valve is opened and the pressure is allowed to equilibrate, the column of water in the gas collection chamber is typically between 5 and 6 cm. ProCoDA is set to open a valve when the water level reaches 2 cm. Since the cross sectional area of the chamber remains constant, the volumetric change can be approximated for a single off-gassing event and then extrapolated for over a day. A range of gas production can be obtained using this method as shown below where the upper range uses 6 cm for the initial height while 5 cm is used for the lower range..

| Off-Gassing Events and Gas Production | | | | | |
|---|---|---|---|---|---|
| Reactor | Day Fraction | Events/day | Area (cm^2) | Upper Range (mL/day) | Lower Range (mL/day) |
| R1 | 1 | 35 | 1.960370163 | 274.4518228 | 205.8388671 |
| R2 | 1 | 16 | 1.960370163 | 125.4636904 | 94.09776782 |
| R3 | 1 | 37 | 1.960370163 | 290.1347841 | 217.6010881 |
| R4 | 1 | 26 | 1.960370163 | 203.878497 | 152.9088727 |
| | | | | | |
| Effluent Turbidity (NTU) | | | | | |
| Reactor | Reading 1 | Reading 2 | Reading 3 | Average | |
| R1 | 0.96 | 1.09 | 1.1 | 1.05 | |
| R2 | 1.00 | 1.06 | 0.99 | 1.016666667 | |
| R3 | 1.87 | 1.86 | 1.78 | 1.836666667 | |
| R4 | 1.07 | 1.06 | 1.11 | 1.08 | |

**D. Problems and Limitations**

General problems with using pressure sensors
Sensitivity of the Pressure Sensors
Backwashing into the other side of the pressure sensors
Need to zero often because of these issues

## IV. Troubleshooting

### A. Influent Line Clogging

Due to its carbon rich nature, the synthetic wastewater stock is very friendly environment for biological growth and activity. Because of the slow flow rate into the reactor and this high conducive environment for growth, clogging is a major issue of the lab scale reactors. There are a number of locations that are prone to clogging. This section provides an overview on the steps to diagnose and remedy a clog

*a. Diagnosing a Clog*

There are two ways to diagnose a clog. The first is when there is very little to no biogas production as determined by the number of offgassing events. Typically, when biological activity has reached steady state, biogas production should lead to approximately 30-40 offgassing events. When this number approaches, or is less than 20, there is an issue in the delivery system that needs to be resolved.

If biogas production cannot be properly measured, the other method of diagnosing a clog is by visual inspection. When plugs of organic matter in the ¼" flexible tubing are visible, then it is highly likely that the wastewater stock is not being delivered to the reactors. In addition, larger plugs in the ¼" tubing typically causes clogging further back in the system in the barbed fittings and the pump tubing.

*b. Non-Invasive Solution for a Clog*

Clogs can be difficult and time consuming to determine their location and fix. Without proper identification of the location of the clog, it can be impossible to

clear the blocked tubing without disassembling the entire system. One of the less invasive methods of clearing a plug is to increase the RPM on the influent wastewater and water lines. If there are any plugs in the ¼" tubing, then a high rate of flow should be able to push through the plug. If there are still problems with biogas production after this, the clog is more likely in the pump tubing which requires a higher degree of care.

c. *Thorough Cleaning*

When non-invasive solutions cannot solve clogging issues, the lines must be taken apart and cleaned individually. Due to the slow growth rate of the anaerobes in the reactors, caution must be taken to ensure the integrity of the granular bed. To prevent any backwashing of granules or other leaking while maintenance is taking place, ***all valves going into and coming out of the reactors must be in the closed position.*** Once all the valves are closed all of the influent pumps should be stopped and flexible tubing should be carefully disconnected and drained to minimize spilling. Then disconnect and remove the pump tubing from the pumps. Remove any barbed fitting, threaded connectors, or push-to-connect fittings.

Using a large 4 L container, create a dilute bleach solution for cleaning. Place all of the tubing and fittings in the dilute bleach solution and soak for approximately 30 minutes. Once the time has passed, dispose of the bleach solution and fill the container with tap water. Let the part soak for another 15 minutes to ensure that all of the bleach solution is out of the tubing. Then attach a threaded ¼" push-to-connect to the sink. Connect a piece of tubing and turn the water on to flush it. Repeat this step for all of the tubing and pump tubing to ensure that there is no residue left in the lines.

Once the parts are dry, the tubing and fittings can be reconnected, and the apparatus can be setup again.

It should be noted that thorough cleaning with dilute bleach should occur once a week in order to ensure smooth operation of the reactors.

**B. Pressure Sensor Issues**

a. *Checking Accuracy*

The pressure sensors in the AguaClara lab measure height of a column of water in centimeters. Because of this characteristic, the pressure sensors can easily be cross checked for accuracy using a basic ruler.

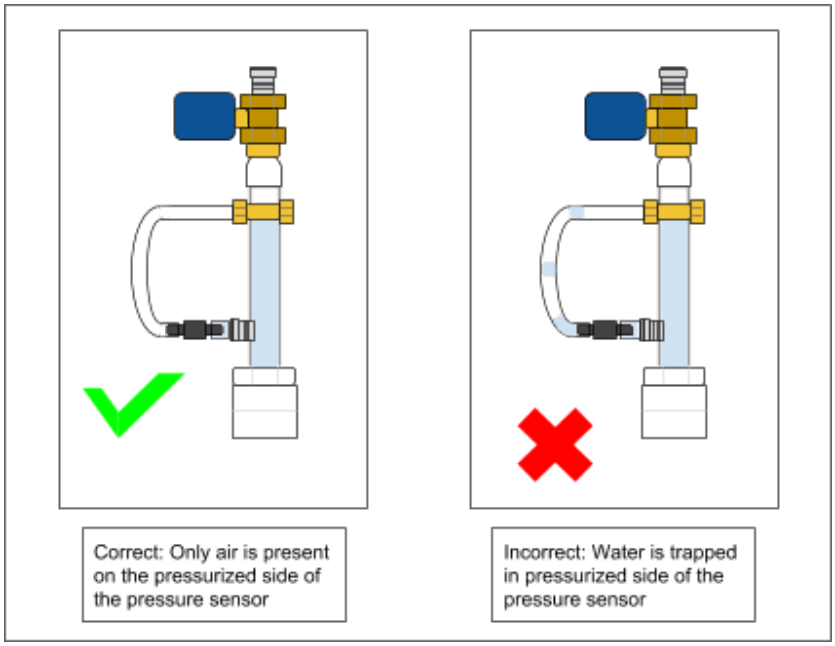
To check the accuracy of the pressure sensors, lineup the end of the ruler with the approximate center of the push-to-connect fitting that attaches the pressure sensor. Compare the measured height to the value shown in ProCoDA. If the value is off by more than a tenth of a centimeter, then the pressure sensor needs

to be adjusted.

b. *Fluid Buildup*

One common issue that arises when running the reactors for a long period is fluid buildup on the wrong side of the pressure sensors. Over time, water liquid from the can escape from the chamber and partially fill the tube connected to the far side of the pressure sensor corresponding to a negative pressure system. This affects the accuracy of the pressure sensors and can skew the data and offgassing events.

To remedy this problem, drag the reactors so that the water level is below the pressure sensors and detach both ends of the pressure sensors from the flexible tubing. Once the water is removed from the tubing, reconnect the apparatus and zero the pressure sensor on ProCoDA.




c. *Sensitivity Degradation*

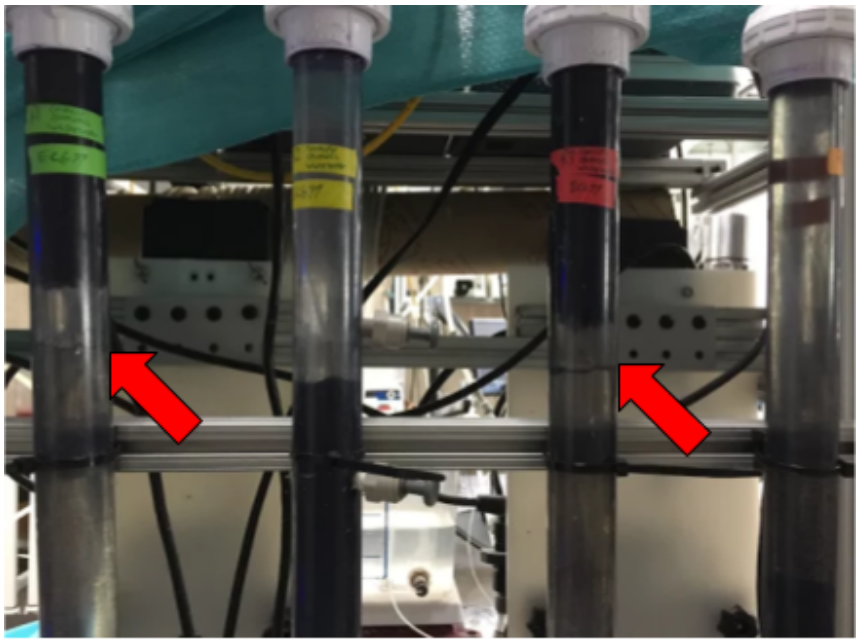
The sensitivity of the pressure sensors can also degrade overtime. In this case, water should be drained until the water level is below the pressure sensor and the pressure sensor zeroed.

## C. Plugs in the Reactors

Due to the high surface area to volume ratio the lab scale design, the reactors are prone to plugs. This occurs due to the densely packed, settled granular bed trapping larger gas bubbles that are produced. The trapped gas then pushes up an entire section of granules rather than moving through the granules.

When this occurs, a mallet with a rubber head should be used to lightly tap on the portion of the reactor where the plug is. The light vibrations from the mallet will allow the granules above the gas bubble to loosen and fall. The tapping should be continued until the plug is dislodged and the biogas is released from under the plug of granules.

Other more invasive methods of clearing these plugs such as placing an agitating rod inside the reactor should be avoided due to the delicacy of the granular sludge. Agitation can lead to the break up of granules and compromise the settled bed and solid retention.



Densely packed granules prevent biogas from escape the settled sludge bed. The buildup of biogas creates plugs of granules that are forced upwards

**VI. Contacts**

Should there be any lapses in the continuity of knowledge from previous UASB team, please see the AguaClara wiki page for a full list of past team members and their NetIDs