

CALVIN COLLEGE ENGINEERING DEPARTMENT

BIOburners

Final Design Report

Team 3: BIOburners

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Executive Summary

Team BIOburners designed a biomass gasifier intended to produce synthesis gas capable of providing power to a residence (3-5 kW) and to operate with low levels of tar production (<50 mg tar per cubic meter synthesis gas), high thermal efficiency (75% heat conservation), and high biomass conversion (99%). This gasifier was also to be easy to operate. Finally, in design, BIOburners made certain that their gasifier met safety standards to ensure customer trust and also provided a clean energy alternative to promote good stewardship.

The initial pilot plant was a stratified, double-fire, throatless gasifier. Two heat exchange systems were used to increase thermal efficiency: a counter-current heat exchange system via internal, vertical tubes preheated the air feed and retained the synthesis gas heat, and an external heat exchanger provided steam to drive the water gas reaction, increasing synthesis gas yields. Building the pilot plant was time-intensive, but construction of the unit was completed and the gasifier operated effectively, reaching a temperature of 600°C and producing flammable gases. In light of the problems encountered during operation (which included bridging, air leaks, ash build-up, high levels of tar production, insufficient air feed, and a failure to reach desired temperatures), the pilot plant was redesigned with changes to the manifold system, steam feed, ash grate, and feed hopper.

The team planned to test the composition and tar content of their product gas. The Orsat gas analyzer would have been used to determine the amount of carbon dioxide, carbon monoxide, and oxygen in a synthesis gas sample. A number of standard samples were tested to ensure accuracy of the analytical technique.

While gasifier design and operation were the primary focuses of this project, extensive testing of the redesigned pilot plant would be necessary to optimize the operation of the gasifier. In the following report, BIOburners proposes further work intended to optimize this unit's potential to provide power

from a clean and environmentally friendly fuel source. An experimental schedule was developed for this purpose.

A final consumer product design is also detailed and considered from an economic standpoint. This design is similar to the redesigned pilot plant, but includes a control system to provide a more user-friendly experience and other modifications based on the optimization process. The base gasifier system will be sold for \$6,500 and is only economically viable if free biomass is available.

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1 Project Overview

1.1 Introduction

1.1.1 Project Description

Gasification is a process which converts biomass – such as wood, corn husks, walnut shells, or any other cellulosic-based material – into a combustible gas. The biomass fuel is incompletely burned in an oxygen-poor environment and undergoes four main processes: drying, pyrolysis, combustion, and reduction, as shown in Figure 1-1 below. These processes convert the biomass to a mixture of gases composed primarily of hydrogen and carbon monoxide, which is similar to natural gas in that it is flammable and contains a high fuel credit. Synthesis gas can be burned in an engine or a generator to power a car or provide electricity. Technologies using gasification have been available for nearly 200 years and were in fact employed during WWII due to insufficient petroleum. Most gasifiers function on the industrial scale, but small scale units are also available.

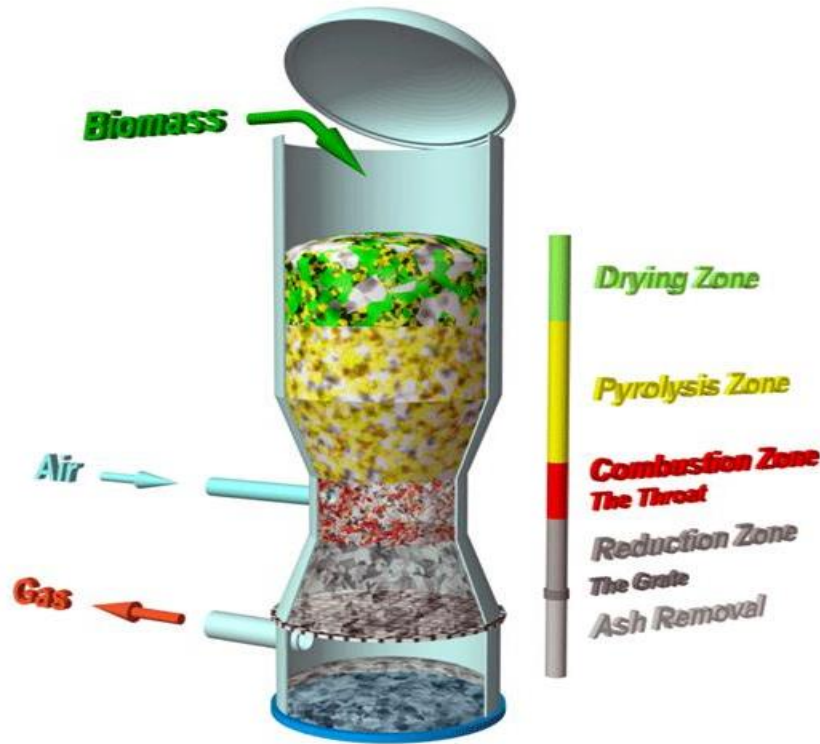


Figure 1-1 Simplified Gasifier Schematic
<http://4.bp.blogspot.com/-li3cM6euyCo/TjJAWq-tlGI/AAAAAAAAAac/Q1NULB3jaFA/s1600/gasification.jpg>

Given the current interest in sources of alternative energy, gasification is an area of increasing popularity and promise. Specifically, BIOburners sees potential for using biomass gasifiers to produce electricity on a home-scale. The goal of this project is to design a gasifier that is highly efficient, easy to use, and environmentally friendly.

The scope of this project is focused on the design of a pilot plant with an eye toward the use of a gasifier by a customer. An initial pilot plant was designed, operated, and disassembled. A modified pilot plant was designed using the observations and problems encountered from testing the first plant. Due primarily to time constraints, extensive gasifier testing was not completed in this project. An experimental plan was proposed to test various operating conditions for the redesigned pilot plant. To meet the needs of the desired consumer (discussed in section 8), a final gasifier product was presented

and its economic viability was considered. Alternative biomass feed sources and feed methods were outside of the project scope. Low tar production was a primary goal of this project. However, if large amounts of tars were produced separations units would be needed. The potential design and implementation of these units were considered outside the scope of this project. These units would be very costly, and the team desires to eliminate the need for them altogether. Additionally, the use of a separation unit increases the bulk of the final design, and since this product is intended for use in a home, a compact design is preferable.

1.1.2 Team Description

Team BIOburners is comprised of four Calvin College seniors studying engineering in the chemical concentration: Nicole Michmerhuizen, Nate Myton, Eric Sager, and Matthew Lomasney.

Nicole Michmerhuizen is pursuing majors in chemical engineering and biochemistry while also running track and cross country. Next year Nicole will be attending graduate school at University of Michigan to pursue a PhD in pharmacology.

Nate Myton is studying chemical engineering and chemistry at Calvin. He loves the outdoors, and when he is not studying you can find him rock climbing, backpacking, or kayaking. After graduation he hopes to find a job internationally where he can continue to stretch himself and experience new things.

Eric Sager is double majoring in chemical engineering and chemistry, but he has a passion for medicine and will be attending medical school at Loma Linda University after graduating from Calvin College. He also loves experiencing other cultures. He spent January of 2013 in China on a school trip and hopes to one day go back.

Matt Lomasney is studying chemical engineering and biochemistry at Calvin College. He has an engineering position at Master Finish, Co. in Grand Rapids, Michigan following graduation. In his spare time Matt loves creating music, especially on his trumpet.

1.1.3 Senior Design Course Description

Engineering 339 and 340 are meant to prepare students for the workplace in a more practical way than other technical courses offered at Calvin College. These two courses seek to teach students to apply the theoretical knowledge they have acquired while at Calvin to not only create a unique design, but also to execute that design and develop a final product. In addition to the design project portion of engineering 339 and 340, these courses educate students in “senior topics,” such as resume building and job searching, project management, presentation and communication skills, ethics in engineering, and Christian Design Norms in engineering. These topics were often presented in form of lectures by engineering faculty or guest speakers. In this way, the courses served as a capstone for the Calvin Engineering education, bringing together liberal arts education, Christian faith, and engineering design.

1.1.4 Calvin College Engineering Department Description

The Calvin Engineering department is composed of four concentrations: Chemical, Civil and Environmental, Electrical and Computer, and Mechanical. The department has fourteen faculty members and approximately 425 engineering students. Calvin Engineering is distinctive because technical courses are combined with a liberal arts curriculum centered on the Christian faith. The liberal arts curriculum benefits the students by expanding the breadth of their education. It teaches students to not only become great engineers, but also to become great people that seek to make a difference in the world. In addition, teaching students how to design in a way that honors God’s Kingdom is at the heart of every Calvin faculty member, and this strongly influences the way that Calvin engineering students approach engineering.

1.1.5 Calvin College Description

Calvin College is a liberal arts college in the Christian Reformed tradition of Christianity. The Calvin College mission statement states, “Through our learning, we seek to be agents of renewal in the academy, church, and society. We pledge fidelity to Jesus Christ, offering our hearts and lives to do

God's work in God's world." (<http://www.calvin.edu/about/mission.html>) Founded in 1876 and located in Grand Rapids, MI, Calvin offers students the opportunity to earn undergraduate degrees in a number of academic programs. About 4000 students are pursuing undergraduate degrees at the college and there are just over 300 full-time faculty members. Calvin also offers graduate programs in education and speech pathology/audiology and is closely affiliated with Calvin Theological Seminary. While many academic programs have very strong reputations and have been accredited or honored at the national level, Calvin also emphasizes engagement with its surrounding community through service opportunities and with culture through a number of student organizations and events. Furthermore, students are encouraged to gain broader international experience through an array of off-campus programs. In all of this, Calvin College remains fully committed to Christian principles, integrating aspects of faith into all activities.

1.2 Gasification Theory

1.2.1 Overview and History

The purpose of gasification is to convert carbonaceous materials into combustible gases to provide energy. The process occurs via oxidation (combustion) reactions in 2 parts, pyrolysis and combustion (discussed below). Gasification involves the conversion of large molecules – such as cellulose, lignin, and hemicellulose – and breaking them down into smaller molecules with high energy bonds such as carbon monoxide and hydrogen gas. These high energy bonds can then be oxidized to produce energy.

A schematic of a biomass gasifier is shown in Figure 2 below.

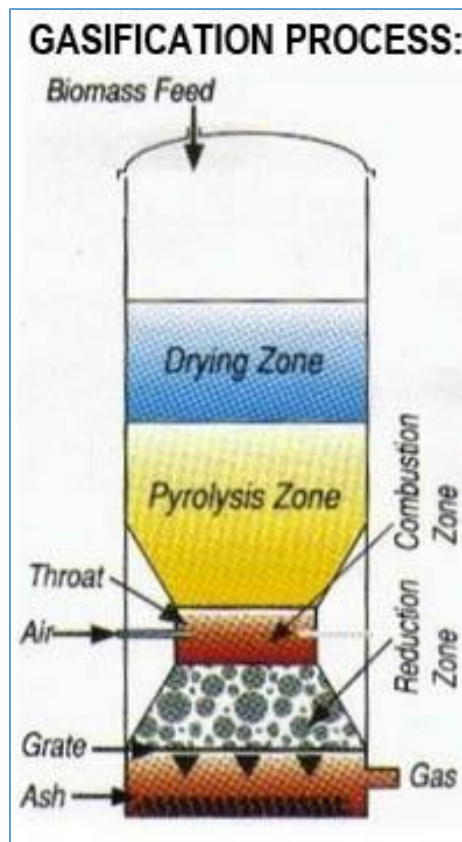


Figure 1-2 Schematic of Biomass Gasifier

<http://blackmountainwoodfuels.blogspot.com/2013/09/biomass-gasification.html>

The reactions that occur in the gasifier are discussed in section 1.2.5 below. There are 2 sections of the gasifier where reactions are taking place: the pyrolysis zone and the combustion zone. The gas produced in the gasifier is then piped out of the reactor and into a generator where it can be further combusted (oxidized) to produce energy in the form of electricity.

Gasification was first developed in the 1800s as means to produce combustible gasses for lighting and cooking (Gasification, 2014). There was more interest in gasification in the early 1900s around the time of World War II due to the shortage of petroleum. Therefore, people began looking for alternative sources of power. During this time, over a million vehicles were operated on gasification products worldwide and large advances were made in the gasification process.

1.2.2 Benefits

The benefits of biomass gasification can be classified in three main categories; renewability, environmental, and sociological. Biomass gasification runs off of wood, grass, and other carbonaceous materials which are continually grown and consumed, and therefore there is not a finite amount of biomass. Conversely, primary methods of producing energy currently rely on fossil fuels, which are rapidly being consumed. Therefore, using biomass gasification as opposed to fossil fuels demonstrates stewardship over the resources we have been entrusted with. Biomass sources absorb carbon dioxide from the environment to grow. Plants accomplish this via photosynthesis and the Calvin Cycle. During gasification the biomass is converted back into CO₂, and therefore there is no net increase in the amount of CO₂ in the universe. Furthermore, other products that could be considered harmful to the environment (tars, nitrous oxides, and sulfurous oxides) are produced in inconsequential amounts compared with fossil fuel usage. Finally, biomass gasification requires no power from the electrical grid. Therefore, it can be used in impoverished nations who have no access to electricity as well as in populations who have suffered a natural disaster that has eliminated sources of electrical energy. Because of these things, biomass gasification shows caring for humanity.

1.2.3 Biomass

Biomass comes in many different forms. Biomass is composed of varying mixtures of three main molecules; cellulose, hemicellulose, and lignin. Varying the amounts of these three components will yield varying compositions of gasification products. Additionally, biomass may be gasified directly or after some additional processing, such as pelletizing or chipping. Pelletized feed contains 4-8% moisture and un-pelletized feed contains 20-60% moisture content (Pellet Fuels Institute, 2011). Therefore, there is more energy contained in pelletized feed per mass; however, when water is produced by the combustion reactions, the unhydrated pellets may swell causing potential bridging problems. Therefore, there is a tradeoff between amount of energy contained in the fuel and the extent of bridging that occurs by using pellets. Interestingly, pelletized feed and raw biomass have similar costs, so cost is not a factor in the decision.

Typical biomasses used in gasifiers include woods, crops, and wastes. Depending on factors such as availability, power requirement, and government regulations, the correct biomass can be chosen for a given application.

1.2.4 Products

Gasification consumes biomass (carbonaceous material) and produces a number of gasses, some combustible and some not. The main products obtained from biomass gasification are presented in

Table 1-1 below (note that compositions will vary depending on the gasifier and type of biomass used):

Table 1-1 Typical Gasification Products

Desired/ Undesired	Chemical State (25°C)	Chemical Species	Composition in Syngas (HMI International, n.d.)
Desired (syngas)	Gaseous	Carbon Monoxide (CO)	24.0%
		Hydrogen (H ₂)	18.0%
		Carbon Dioxide (CO ₂)	6.0%
		Methane (CH ₄)	3.0%
		Nitrogen (N ₂)	48.6%
		Oxygen (O ₂)	0.4%
Undesired (byproducts)	Liquid	Tars (Large Aromatic Hydrocarbons)	>50ppm
		Water (H ₂ O)	0
	Solid	Ash	0
		Charcoal	0

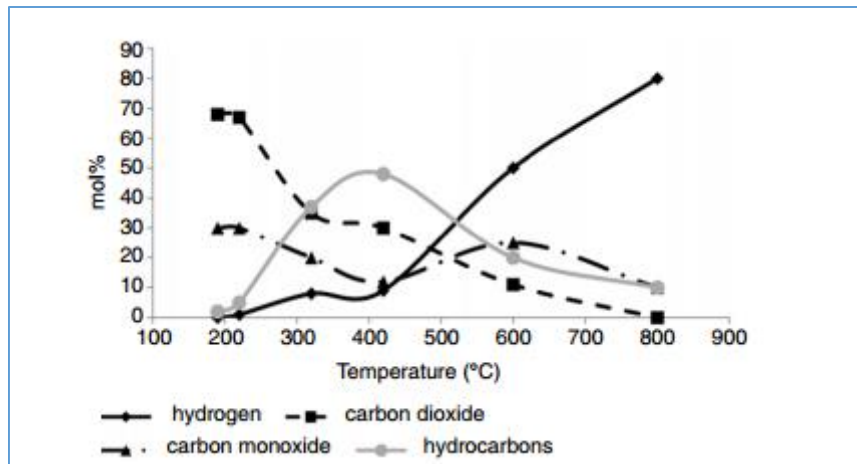


Figure 1-3 Effect of Temperature on Synthesis Gas Product Composition

The desired products are defined as “synthesis gas” or “syngas” for short. The desired products in the syngas are carbon monoxide and hydrogen gas. These are desired because they contain high energy combustible bonds (have relatively high heats of combustion). Therefore, it is desirable to have these gases in as high a concentration as possible. This can be accomplished by a number of factors that will be discussed below. Figure 1-3 above shows how different products are produced in greater amounts at different temperatures inside the reactor.

The main undesirable product is tar. Tars are large aromatic and polyaromatic rings. Tars appear black and highly viscous. The primary composition of tar products from gasification can be seen below in Table 1-2 (Basu, 2010):

Table 1-2 Typical Tar Distribution in Gasification Products

Component	Weight (%)
Benzene	37.9
Toluene	14.3
Other 1 Ring Aromatic Hydrocarbons	13.9
Naphthalene	9.6
Other 2 Ring Aromatic Hydrocarbons	7.8
3 Ring Aromatic Hydrocarbons	3.6
4 Ring Aromatic Hydrocarbons	0.8
Phenolic Compound	4.6
Heterocyclic Compounds	6.5
Other	1.0

These tars are problematic because if the synthesis gas is combusted in an engine to produce energy while containing high concentrations of tars, the engine can easily be damaged. Therefore, it is highly desirable to produce low concentrations of these tars. Methods for how this can be accomplished are discussed below.

Another product of gasification is ash. Ash is not combusted in the reactor, and thus must be removed. This is shown in Figure 1-2 every gasifier must have a means of collecting and disposing of the ash produced during gasification.

1.2.5 Gasification Reactions

1.2.5.1 Pyrolysis

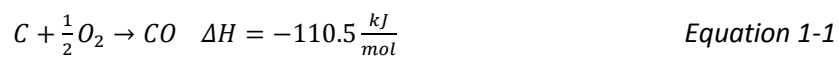
The first part of gasification is pyrolyzation. Pyrolysis takes place in the total absence of oxygen. During pyrolysis, large hydrocarbon molecules, such as cellulose, are converted into smaller molecules in all three phases: solid, liquid, and gas. Pyrolyzation begins at temperatures around 300°C and ends at temperatures around 650 °C (Wikipedia, 2014). The rate at which the biomass is brought through the pyrolysis temperature range will determine the ratio of solid, liquid, and gas products. As discussed

previously, it is undesirable to produce large quantities of liquid tars. Longer residence times in the pyrolysis zone cause higher quantities of desirable gases and lower quantities of undesirable liquid tars to be produced. However, for a given reactor height, increasing the residence time in the pyrolysis zone decreases the energy output. This is because the residence time in the pyrolysis zone is directly related to the biomass combustion rate. The time the biomass resides in the pyrolysis zone is defined as the residence time t_r . Residence times between 5 and 30 minutes are optimal for low productions of tars (Basu, 2010). The graph below displays pyrolysis zone temperatures and the pyrolysis products at different temperatures (Basu, 2010).

1.2.5.2 Combustion

After the pyrolysis zone, the biomass is combusted in what is known as the combustion zone. This is where the heart and soul of biomass gasification takes place. There are a myriad number of reactions that take place in this region of the gasifier, so for the sake of concision, only the most important reactions will be considered.

As mentioned before, the desired product is syngas. This is produced via chemical equation 1-1, presented below. However, chemical equation 1-2 is in competition with equation 1-1.



As seen from equations 1-1 and 1-2 above, the generation of carbon dioxide requires more oxygen than the generation of carbon monoxide. Equation 1-1 is referred to as incomplete combustion (or oxygen poor), while equation 2 is referred to as complete combustion (or oxygen rich). We would like to promote incomplete combustion, and therefore the biomass is burned in an oxygen poor environment. The equivalence ratio is defined as the amount of oxygen feed divided by the stoichiometric amount of oxygen required to obtain complete combustion of the biomass, as seen in equation 1-3. As discussed below, high temperatures are desirable in the reaction, and therefore a balance between equations 1-1

and 1-2 is necessary. Equation 1-2 is more exothermic and provides the heat to sustain the reactor, while equation 1-1 increases the concentration of the desired products in the synthesis gas. Figure 1-4 below shows that increasing equivalence ratio increases the reactor bed temperature.

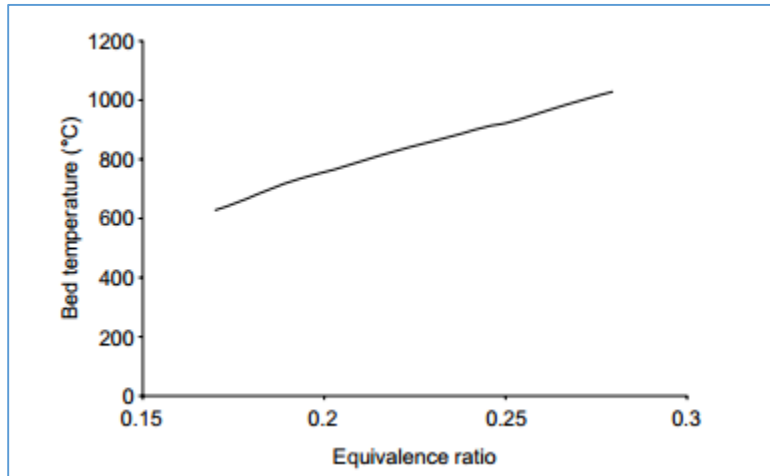


Figure 1-4 Effect of Equivalence Ratio on Bed Temperature

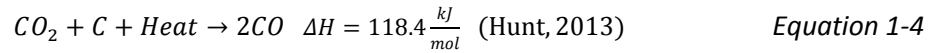
$$ER(\text{Equivalence Ratio}) = \frac{O_2 \text{ Fed}}{O_2 \text{ Required For Complete Combustion}} \quad \text{Equation 1-3}$$

Much research has been performed to determining the optimal equivalence ratio to provide the maximum concentration of desirable products in the synthesis gas. Research shows that the optimal equivalence ratio varies slightly between different gasifiers but is near 25% equivalence in all cases (Basu, 2010). At this equivalence, the reactor is able to achieve high temperatures while still converting the majority of char to carbon monoxide.

1.2.5.3 Boudouard Reaction

This section discusses reactions that occur at elevated temperatures within the gasifier. The Boudouard reaction is shown below in equation 4. This reaction converts carbon dioxide produced via equation 2 into carbon monoxide, thus increasing the combustible products within the synthesis gas. This reaction is endergonic and therefore requires energy input. Because this reaction requires energy as an input, it occurs more commonly at high temperatures, which is supported by Le Chatelier's

principle. Typically, temperatures at which the Boudouard reaction occurs are in excess of 1000 °C (JFE, 2003). Therefore, to increase the synthesis gas product, it is very important to perform the gasification at temperatures at or above 1000°C.



1.2.5.4 Steam Feed

Moisture (water content) is always present in biomass to some extent. This moisture will quickly be converted to steam at the temperatures present within the gasifier. This steam will drive certain reactions. It is important to understand the effect that these reactions have on the synthesis gas product and the gasifier temperature. Equation 1-5 is referred to as the water gas reaction. This reaction is endothermic (requiring energy) and produces carbon monoxide and hydrogen gas. These are both components of synthesis gas, and therefore desirable to produce in high quantities.



Equation 1-6 is known as the water gas shift reaction. It is an equilibrium reaction that converts carbon monoxide and water into carbon dioxide and hydrogen gas. At first it may seem that this reaction decreases the output of synthesis gas as it converts flammable carbon monoxide into carbon dioxide. However, hydrogen gas is produced, which is another combustible component in synthesis gas. Furthermore, the carbon dioxide that is produced can be reformed into carbon monoxide via the Boudouard reaction shown above. Therefore, this reaction also serves to increase the synthesis gas output, especially if coupled with the Boudouard reaction to reconvert the carbon dioxide to carbon monoxide.



Finally, a number of other reactions that occur to lesser degrees. The only other reaction that produces appreciable amounts of combustible products is shown below in equation 7. This reaction converts carbon monoxide and steam into methane and carbon dioxide. This reaction takes desirable

products and forms undesirable products and therefore is not a favorable reaction. Equation 1-7 only occurs at pressures far above that of home-scale gasifiers. Therefore, this reaction only becomes an issue with industrial-sized gasifiers, which utilize pressures in excess of 4 MPa (Wiley-VCH, 2012).



Because this reaction does not occur at the lower pressures that will be used in BIOburner’s design, steam feed is desirable in our gasification process and will only increase the concentration of desirable products in the synthesis gas.

1.2.6 Gasifier Sizing

As mentioned above, the goal of biomass gasification is to produce power. The first step in sizing the gasifier is determining the amount of electrical power required. According to research, feeding $1 \frac{kg}{hr}$ of wood at an optimum equivalence ratio of 0.25 yields power in accordance with the values presented in Table 1-3 below:

Table 1-3 Gasifier Sizing Standards

Gasifier Sizing Standards (ALL Power Labs, 2014)	
Wood Feed	1 kg/hr
SynGas Flow	2.185 m ³ /hr
Heat from Combustion of Gas	3.165 kW
Shaft Work	0.837 kW
Shaft Work	1.12 HP
Electrical Power	0.754 kW

Using these standards, the diameter of the reactor can be calculated using what is known as the specific gas production rate (SGPR). A significant amount of research has been conducted to determine the optimal SGPR. Research suggests that $420 \frac{m^3}{m^2*hr}$ is optimal (Jain, 2006). Therefore, by dividing the synthesis gas flow rate (seen in Table 1-3 above) by the SGPR, the cross-sectional area of the gasifier is obtained. From this value, the required gasifier diameter can easily be determined.

1.3 Project Management

1.3.1 Team Organization

Each team member was equally involved in preliminary research, evaluating design alternatives, designing the gasifier and pilot plant, operating the pilot plant, redesigning the pilot plant, and documentation. Although BIOburners performed many tasks collaboratively, as the project complexity evolved specific roles were assigned to delegate tasks and become more efficient. A description of the roles and assignments appear as follows.

Nate Myton was assigned to be the team manager. He was responsible for delegating tasks and responsibilities to the members of the team. During team meetings, Nate ensured that the team is on task and productive. He also acted as a mediator when conflicts arose within the team. Additionally, Nate was responsible for updating the team website (<http://www.calvin.edu/academic/engineering/2013-14-team3/>) and managing the budget.

Eric Sager was assigned to be the research coordinator. As the research coordinator he was responsible for organizing and maintaining the team's research. Eric was also in charge of delegating research and managing the findings of his teammates. For the final report, it will be his job to review the references and ensure that supporting research is cited when necessary. Eric also took the lead with ensuring that the operating procedures for the gasifier were safe and complete.

Nicole Michmerhuizen was assigned to be the scheduling and budget manager. She reviewed and updated the schedule on a weekly basis, notified the team of upcoming deadlines and ensured the team stayed on schedule. Nicole developed the analytical techniques for the process and together with Eric Sager she developed the operating procedures for the Orsat gas analyzer.

Matthew Lomasney was assigned to be the construction manager. He coordinated with Phil Jasperse to schedule times to work in the metal shop, he reviewed and submitted all material order forms to Bob DeKraker, and he oversaw construction of the gasifier. He also contacted Phil when

construction problems arise to develop a plan for moving forward. Most importantly, Matt was responsible for safety during construction. This included ensuring appropriate use of equipment and ensuring appropriate PPE was worn during operation. Additionally, Matt took meeting minutes and maintained them on the Google Drive.

Figure 1-5 shows the roles of various individuals who supervised team BIOburners during the semester.

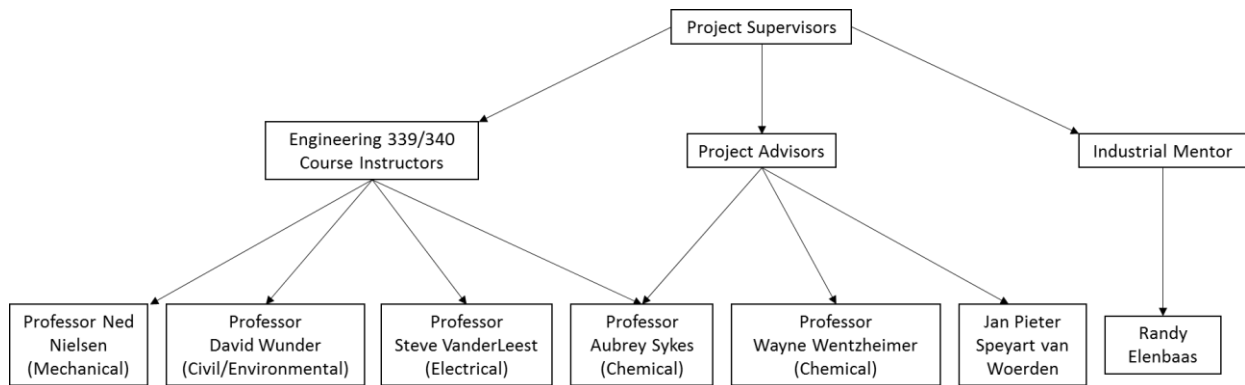


Figure 1-5 Project Supervisors

Jan Pieter Speyart van Woerden (commonly referred to as JP) is a contact of Professor Aubrey Sykes, our faculty advisor during the fall semester. JP proposed the idea for this project and provided insight regarding the design of the gasifier. He is also providing the majority of the funding for the project.

Professor Wayne Wentzheimer served as the faculty advisor for BIOburners during interim and spring 2014.

1.3.2 Schedule

Nicole was in charge of maintaining the schedule. Every week she reviewed the schedule and compared the team’s current and desired progress. She communicated important upcoming deadlines with team members at their weekly team meeting. The team then determined how they could reach deadlines in a timely way. When Nicole notified the team that they had fallen behind schedule, they discussed together if it was possible to modify the schedule in order to meet the original project deadlines or if deadlines needed to be pushed back to ensure that tasks were completed in a quality

manner, however, the final project deadline remained firm. The schedule was updated as necessary based on these discussions and decisions. For example, identifying design alternatives and making design decisions was more involved than the team initially anticipated. This pushed back the construction of the gasifier. To get back on schedule the team began construction during the week of December 17.

At various other points throughout the year, the team also conducted a complete review of the schedule and made major changes that were considered necessary based on the progress of the project and new developments in gasifier design. For example, construction was much more difficult than anticipated due to our lack of fabrication skills, and the startup and testing of the gasifier was delayed significantly. We had initially scheduled three to four weeks to build the gasifier and it took approximately three months. This underestimate forced the team to make difficult decisions regarding what parts of their project were core to their goals and which parts could be eliminated in order to complete the project by the end of the year.

Each team member was expected to commit one hour per week to meetings with project advisors, 2-8 hours to group work, and 0-4 hours to working independently. During the first semester, most of the work was focused on class assignments, design decisions, and calculations. During the second semester, most of the work was focused on reactor construction, testing and operation, and gas analysis methods. Though there were variations from week to week, each team member committed an average of 10-15 hours per week to this project.

1.3.3 Budget

The budget was maintained by Nate. He was responsible for collecting receipts and ensuring that funds are available and are used appropriately. Every two weeks, Nate calculated the amount of money remaining in the budget and compared the expected and actual values of expenses incurred. Mentor Jan Pieter Speyart van Woerden provided a generous donation of funds to complete this project

and the team extends their gratitude to him. Table 1-4 shows the budget for the project and an itemized list of the expenses throughout the year.

Table 1-4 Final Budget

Sources of Funding	
Calvin College	\$ 1,100.00
C.C. ORSAT	\$ 1,400.00
JP Donation	\$ 700.00
Sum	\$ 3,200.00
Expenses	
Materials of Construction	
Stainless Steel Reactor Pipe	\$ 208.49
Stainless Steel Air Tubes	\$ 438.41
Pilot Plant Piping	\$ 256.80
Steam rotameter connections	\$ 10.73
Reducing Bushing	\$ 5.06
1/4" coupling	\$ 2.55
Insulation	\$ 220.00
Instruments	
Thermocouples	\$ 142.00
ORSAT	\$ 1,400.00
Rotometers	\$ 143.50
Dwyer Rotameter	\$ 52.50
Miscellaneous	
ORSAT Chemicals	\$ 170.20
Biomass Pellets	\$ 35.00
Charcoal	\$ 20.00
Gorilla tape	\$ 8.99
Freight Charges	\$ 23.15
Red Caulk	\$ 23.65
Sum	\$ 3,161.03
Funds After Purchases	
	\$ 38.98

1.3.4 Method of Approach

We divided the required research and saved useful documents into a folder in the team Google Drive. Areas of particular interest in the research were highlighted and discussed in group meetings.

While research was most concentrated at the beginning stages of the project, research was continued

with the presentation of new ideas and design decisions. The team initially researched a number of aspects of gasification, using the findings of others as guides and estimates for their design. They also learned about the chemical reactions involved in gasification through their research. As they continued their project, research continued as necessary to test and optimize the design and analyze the synthesis gas.

While making decisions in the fall semester, the team constructed small scale models using plastic and cardboard to visualize the system. Drawings on paper and in AutoCAD were also used to visualize the design. Making detailed models and drawings allowed the team to identify design problems and practical construction concerns before attempting to build the gasifier, such as ease of construction and various connection points, which we could not accurately visualize in our minds. Design decisions were made based on clearly defined criteria which were based on design norms detailed in Section 2.1.



Figure 1-6 Iteratively Testing Designs for Both Constructability and Feasibility

Throughout this process, we spent a significant amount of time collaborating. In some cases, this required summarizing the important portions of a journal article read by a single group member while in other cases it required completing a task in groups of two or four team members. In all of these tasks, we ensured that all members had a sufficient understanding of the design, even if certain areas were more well-understood by specific individuals. Along with this, major decisions were made only after each member of the group was given the opportunity to offer input. Team member relations were

conducted in person, via text message, or by e-mail. Team meetings were scheduled at times that allowed all members to attend. In the case where this was not possible, grace was extended to those who could not attend. In their communications, team members were open, honest, and patient with each other. While still striving to optimize the design of the gasifier, the team also developed the communication skills of not only effective but also Christ-following engineers.

The team also was prepared for meetings with project supervisors. In their communications with their professors and other mentors, they were honest and gracious.

Various team meetings were held throughout the semester at a number of locations on or near the Calvin College campus. In the fall the team held weekly meetings with project advisors Professor Aubrey Sykes and JP at 12:30pm on Wednesdays in the Engineering Building at the team work-station. In the spring the weekly meetings were held with Professor Wentzheimer and JP at 1:30pm on Wednesdays in DeVries Hall. Team meetings were commonly held on Sunday afternoons at Eric Sager's house as well as at other times in the Engineering Building or the Hekman Library. Two meetings were also held with industrial mentor, Randy Elenbaas, who offered valuable advice regarding scheduling and project scope based on his work at Vertellus in Zeeland, Michigan.

Documents were kept in a Google Drive folder available to group members. This folder contained sub-folders entitled Literature & Research, Calculations, Photos & Diagrams, and Assignments. Appropriate materials were placed in each of these folders upon completion. Meeting minutes were also kept in this folder. The Project Proposal and Feasibility Study (PPFS) and Final Design Report were saved on SkyDrive, a Microsoft Word Web App that allows each of the four team members to edit the document simultaneously. Finished materials were published to the team website, and these files were available to the team via the above methods.

1.4 Requirements & Goals

1.4.1 Physical Requirements

A number of requirements were necessary for the design of the gasifier. Many of these requirements were determined by customer needs (eg: the gasifier must be easy to use and safe to operate). The team desires that the gasifier is easy to use so that any individual, no matter their educational or technical background, can operate our gasifier. The gasifier must also be safe so that the users trust the gasifier and are not injured. Ambitious goals and requirements were set at the beginning of the fall semester, however, the team soon realized that these were not achievable in a one year time frame. With that being said, we decided to maintain our initial goals and requirements for the purpose of analyzing the project completion compared to what we initially thought was feasible. A thorough analysis of how the team met the original requirements and goals can be seen in section 2.0. The following list outlines the initial project requirements developed in the fall semester.

The gasifier design shall:

1. Have an outer body temperature cooler than 120°F, in accordance with OSHA standards
2. Include safety measures to prevent injury due to flammable and hazardous gases and high operating temperatures such as a flame arrestor, insulation, and a flame guard
3. Have clear labels on each component of the gasifier that the customer interacts to improve ease of use and safety

1.4.2 Performance Requirements

Specifications were also developed regarding the quantity and quality of synthesis gas produced by the gasifier. In order to provide the energy necessary to power an average home the gasifier shall:

1. Produce between 3 to 5 kW of electrical energy— about 140 mol/hr of standard synthesis gas (molar composition of 25% CO, 12% CO₂, 4% CH₄, 10% H₂, and 49% N₂). This flow rate was calculated from the lower heating values of the combustible gases (Section 1.2).

2. Produce high quality synthesis gas to be used in an internal combustion engine (<50 mg tar per cubic meter of synthesis gas while operating at steady-state (Chopra & Jain, 2007))
3. Fit through an eight foot high garage door so that the gasifier can be transported outside for testing
4. Produce product gas at 75 % efficiency. The standard efficiency achieved in gasifier operations is around 70% (All Power Labs, bk, 2014). Efficiency is determined by determining the amount of energy produced and dividing it by the amount of energy initially contained in the biomass. To determine the energy in the biomass BIOburners used the LHV (lower heating value) of the biomass and multiplied it by the quantity of biomass consumed. This is shown in the Equation 1-8 below. The energy in the product gas is determined by taking the compositions of the synthesis gas products (determined by method in section 5.2) and multiplying them by their heats of combustion. This process is shown in the equation below. Finally, Equation 1-9 shows how the final value for efficiency is determined.

$$15,000 \left(\frac{kJ}{kg} \right) * \text{Quantity of Biomass}(kg) = \text{Energy in Biomass}(kJ) \quad \text{Equation 1-8}$$

$$\text{Volume of Product Gas}(m^3) * \text{Composition of Combustible Material} \left(\frac{m^3}{m^3} \right) * \text{Density} \left(\frac{kg}{m^3} \right) * \Delta H \left(\frac{kJ}{kg} \right) \\ = \text{Energy of Combustible Gas} (kJ)$$

$$\% \text{Efficiency}(\eta) = \frac{\text{Energy of Combustible Gas} (kJ)}{\text{Energy of Biomass} (kJ)} * 100 \quad \text{Equation 1-9}$$

The overall efficiency of the system can be determined by taking into account the conversion from chemical to mechanical energy in the internal combustion engine, and the conversion from mechanical to electrical in the generator. Typical values for these efficiencies are 20% and 95% respectively. Therefore the overall efficiency of the system is found to be 13% as seen in the equation below.

$$\text{Wood To Chemical Energy} (75\%) * \text{Chemical To Mechanical} (20\%) * \text{Mechanical to Electrical} (95\%) = 14.3\%$$

1.4.3 Environmental Requirements

The primary environmental requirement of the biomass gasifier involved the handling of synthesis gas and other products in a safe and environmentally friendly way. The gasifier shall:

1. Not release appreciable amounts of synthesis gas to the environment during operation by completely combusting the synthesis gas product in a flare (reaction shown in Section 1.2.5).
 - a. Produce less than 600g of Carbon monoxide per kilowatt hour (United States Environmental Protection Agency, 2012)
2. Be free from leaks
 - a. Synthesis gas burns with a clear flame, which can only be seen at night. The gasifier will be run at night periodically to check for leaks.
3. Be operated outside in a well-ventilated area to avoid hazardous buildup of carbon monoxide gas

A Hazards and Operability Study (HAZOP) was created for this project after a safety review with Ms. Jennifer Ambrose. The HAZOP can be found in Section 4.8.

1.3.4 Goals

The team has identified several areas where they plan their design can to beyond the requirements laid out above. These goals relate to both the physical design of the gasifier and the performance. The physical design goal is to fit the gasifier on a 42"x42" pallet to allow for easier transportation.

The performance goals are:

1. Produce under 50 mg of tar per standard m³ of synthesis gas
2. Be able to be operated by a single person with minimal training
3. Have a startup time of under 15 minutes
4. Operate using a variety of biomass fuel sources

5. Able to run for 24 hours without direct supervision

1.5 Deliverables

The deliverables for this project include:

1. Final Design Report- Description of entire project.
2. Pilot Plant designed and constructed- Initial design discussed in Section 2.
3. Pilot plant re-designed- Re-design discussed in Section 4.
4. Final product designed- Final Design discussed in Section 7.
5. Team website- Can be found at <http://www.calvin.edu/academics/engineering/2013-14-team3>

1.6 Specifications and Schedule

The major milestones for the project are:

- Completion of Project Proposal Feasibility Study (PPFS) – Dec 9
- Completion of initial design – Feb 3
- Construction of initial pilot plant design – Feb 24
- Testing and optimization of initial pilot plant design – Mar 3
- Construction of revised pilot plant – Mar 24
- Testing and optimization of revised pilot plant – Apr 28
- Presentation at Senior Design night – May 10
- Completion of Final Report – May 19

These milestones were achieved through the tasks listed below:

- Preliminaries and Research
- Pilot Plant Design
- Construction
- Operation
- Pilot Plant Redesign
- Documentation

A complete list of tasks and sub-tasks is included in the Work Breakdown Structure on the team website. (www.calvin.edu/academic/engineering/2013-14-team3/documents/WBS.pdf) Figure 1-7 shows each task and its main subtasks.

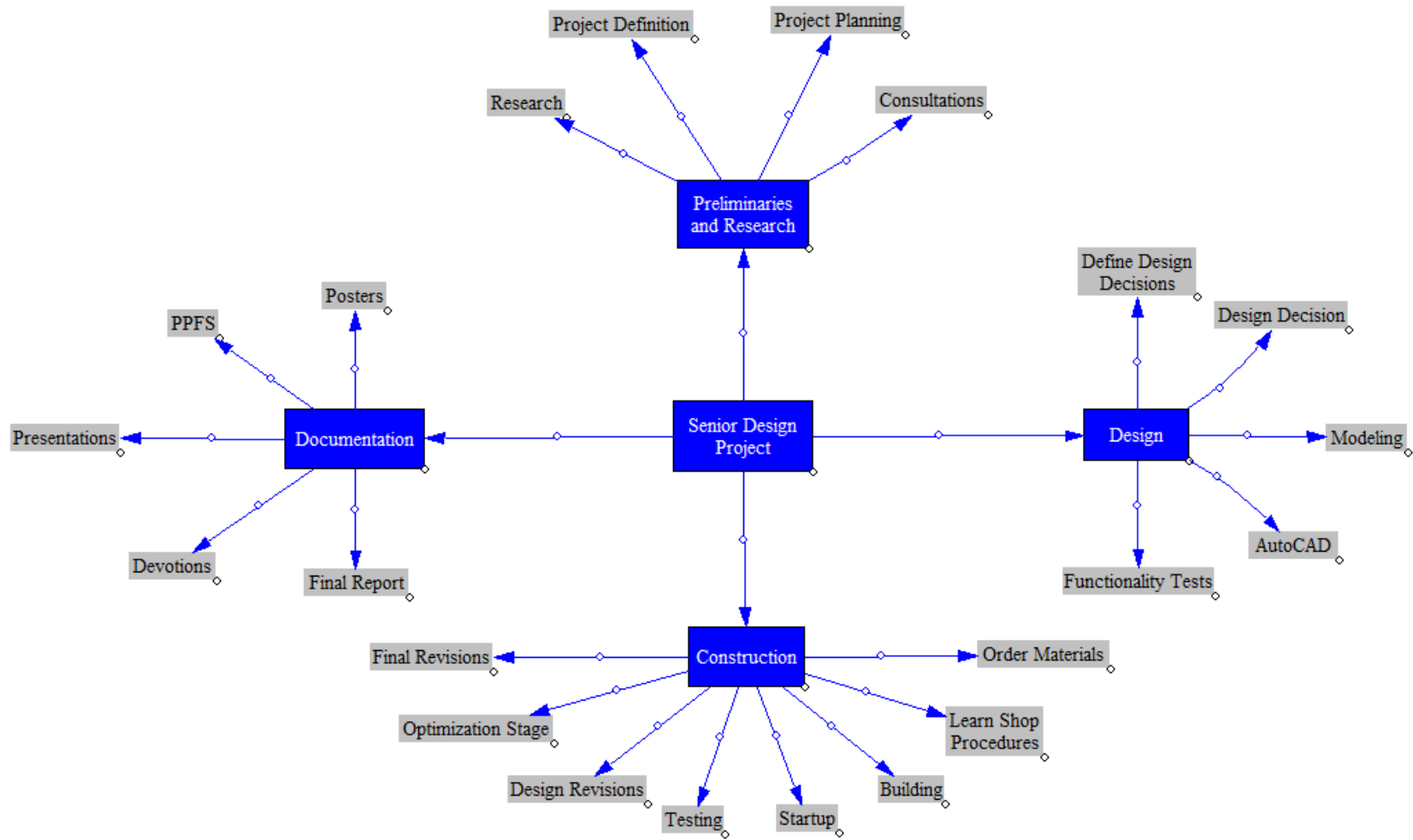


Figure 1-7 Work Breakdown Figure

The anticipated timeline for these tasks changed as the year progressed. When tasks took more or less time than anticipated the schedule had to be updated. Gantt charts were made to schedule the remaining work at several times throughout the year. These Gantt charts can be found on the team website. (www.calvin.edu/academic/engineering/2013-14-team3/downloads.html)

The expected total hours needed to complete the project are estimated at 1450 hours. The actual time required was approximately 1700 hours. A breakdown of the predicted timeline versus the actual timeline is shown in the figure on the following page. There are a number of take-aways from this figure. With the exception of documentation, the team did not correctly predict the time it would take for any part of the project. This was partially to be expected because BIOburners did not have experience with many of the tasks and thus could not accurately predict how long they would take to perform. However, BIOburners did learn the importance of setting an end date and sticking to it. BIOburners spent both September and October in the research section instead of just September as projected. Although could, perhaps, have been more helpful to end this stage of the project earlier and allow more time for later tasks. The other lesson BIOburners learned was that construction takes significantly longer than expected, especially when you are not familiar with it. Construction ended up being the largest task mainly due to numerous problems encountered along the way. Although this did take away from the extensive plan that was initially planned for the preliminary design, BIOburners learned much about construction including; welding using both TIG and MIG, operating the mill, using a lathe, and many more operations, therefore they were pleased with the outcome of the project.

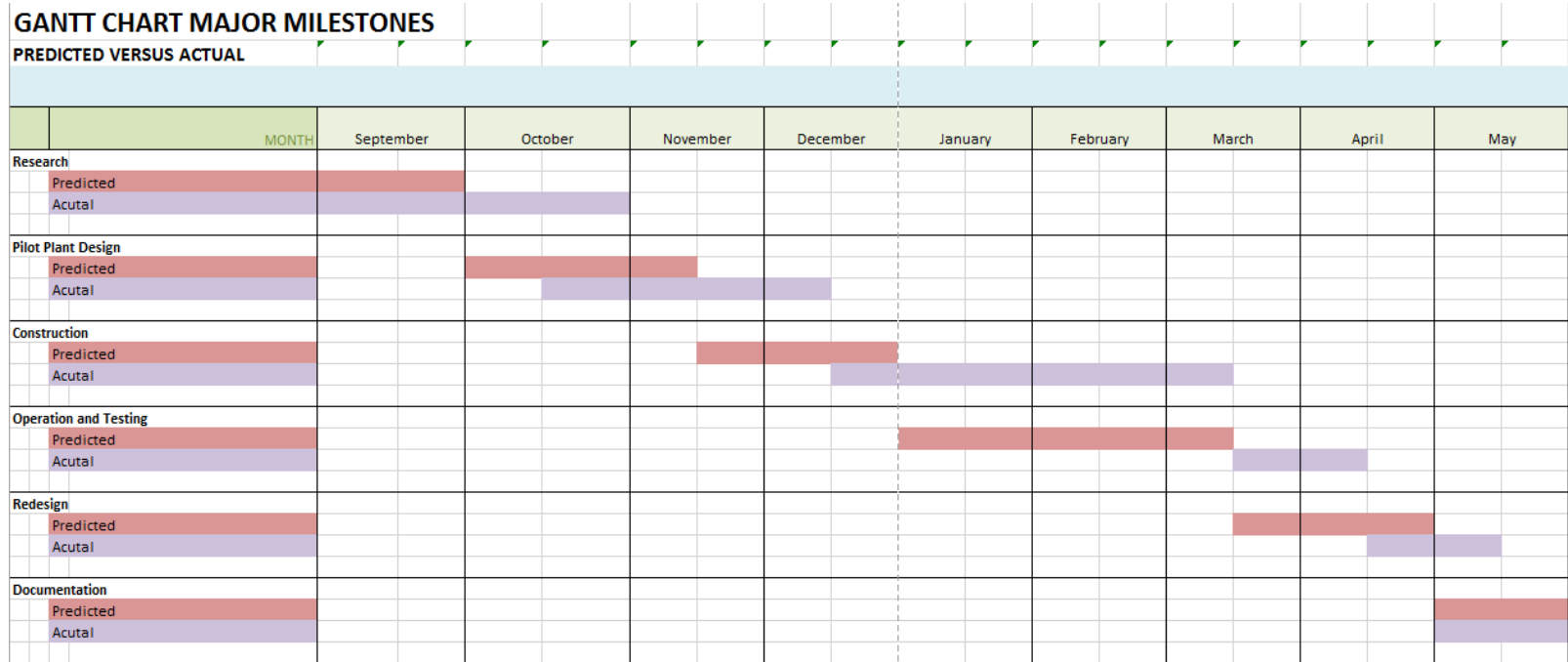


Figure 1-8 Predicted vs Actual Gantt Chart

Gasifier design required a significant portion of the team's time during the fall semester. The original version of the work breakdown structure scheduled very little time for determining design alternatives and making design decisions, but as the semester progressed many possible gasifier designs were presented. Choosing the best design required satisfying a number of requirements as well as avoiding unnecessary complexities. This balance was the focus of many discussions within the team and with mentor JP.

Documentation was another large task that required team member time. Documentation included posters, the Project Proposal Feasibility Study, presentations, and the final design report.

Construction of the gasifier was the largest group of tasks. Construction included ordering materials, building the reactor, testing and optimizing the reactor, and design revisions.

There were also a variety of smaller class-required tasks such as; presentations, website maintenance, job-search goals, and many others.

1.7 Pilot Plant Structure

Figure 1-9 below summarizes the operation of the gasifier pilot plant detailed in this report.

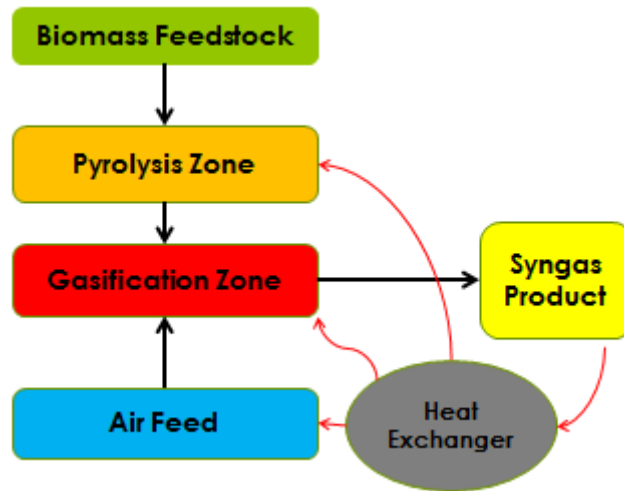


Figure 1-9 System Block Diagram

The reactor and pilot plant were broken into subsections based on the stages of gasification and the primary aspects of the pilot plant design. The biomass feedstock was fed to the reactor from the top. In the final design, the biomass was stored in a hopper, which was fed into the reactor via gravity. After being fed to the gasifier, the feedstock entered the pyrolysis and gasification regions of the reactor and was converted into synthesis gas product. Air was fed to the reactor as a necessary element in gasification. The air was brought down in stainless steel tubes, while the synthesis gas was piped up in adjacent tubes. This counter-current heat exchange system allowed preheating of the air by the synthesis gas product. The air and synthesis gas tubes were surrounded by the body of the reactor, which contained the tubes, biomass, and helped maintain the heat in the reactor. Heat was also transferred from the synthesis gas into the biomass in the reactor, which allowed for the pyrolysis and combustion zones to reach higher temperatures. Additionally, some of the residual heat in the synthesis gas was recaptured in a heat exchanger, which was used to generate steam. This steam was also fed back to the reactor to increase the thermal efficiency of the pilot plant.

The system breakdown seen in Figure 1-9 separates the zones of the system based on their physical location. The feed is located separately from the pyrolysis and gasification zones in space. While keeping sections distinct, this method also integrates the pieces of the reactor design to the feed and products. It is intuitive to think first of the function of design elements and then to consider the arrangement of the components in space.

The team could have alternatively created a block diagram from the viewpoint of the user. In this case, the major blocks would be fuel feed, synthesis gas output, and ash clean-up since these are the components of the gasifier with which users interact. However, this does not include the processes that occur inside reactor, which are critical in this design. As a result, this alternative way of arranging the system architecture in a block diagram was rejected in favor of the breakdown seen in Figure 1-9.

The diagram below in Figure 1-10 is a more detailed block diagram. This diagram also relates each physical component of the design to the design requirements.

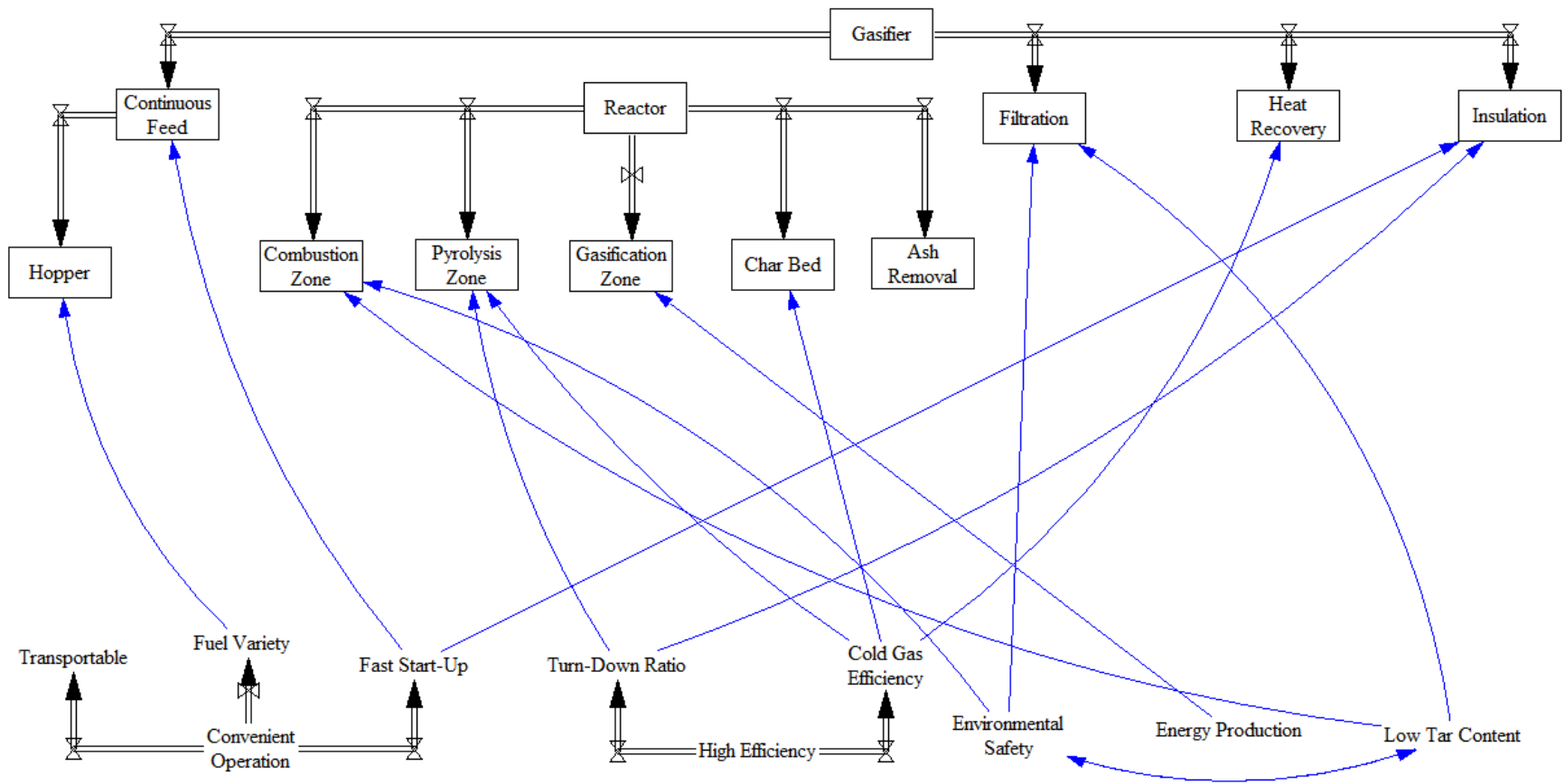


Figure 1-10 Detailed Block Diagram

2 Initial Pilot Plant Design

The first stage of this project was the design of a pilot plant. The design process took place during the fall semester. Many significant alternatives regarding the reactor type, process feeds, heat exchange mechanisms and other sections of the pilot plant were considered using the criterion outlined in Section 2.1 below. This initial pilot plant was constructed primarily during the spring semester. Following construction, operation revealed the successes and shortcomings of this design. Various changes were suggested for both a redesign that could be used in further testing and a final product.

2.1 Primary Design Criterion Overview

Design decisions were made based on a number of key design criterion, and each of these criterion were chosen on the basis of Christian design norms. The three primary design criterion involved in this design relate to the intended features of the gasifier: ease of use, low tar production, and high efficiency.

It is important that the gasifier design is easy to operate, maintain, and repair for the average person. This relates to the design norm of transparency, which requires a design to be easily understood, reliable, and predictable. BIOburners hopes that this gasifier design will be able to operate using various biomass feedstocks although time did not permit them to evaluate the system for more than one type of biomass. This characteristic relates to the design norm of caring because the gasifier will function well regardless of geographic location. BIOburners also recognizes that these design norms are at times in conflict with the team project scope and budget, but strives to implement them whenever possible. In some cases, decision matrices were used to aid in design decisions that involved selecting between alternatives that involved conflicting interests. Chapter 2 outlines the design decisions and presents the decision matrices used for more involved decisions.

BIOburners has defined a highly efficient gasifier as a reactor that converts most of the stored chemical energy in the feedstock into a useable fuel credit in the form of synthesis gas. The target

efficiency is 75% (the calculations necessary to determine the efficiency of the unit are detailed above in 1.4.2). Synthesis gas is composed primarily of carbon monoxide and hydrogen gas (Section 1.2.4). The efficiency of the gasifier will be quantified by evaluating the fuel gas credit as a percentage of the potential energy of the feedstock. This relates to the design norm of stewardship, which requires that the design makes good use of the earth's economic, environmental, and human resources. Ensuring good stewardship has been one of the primary drivers behind this design as it largely dictates the economic feasibility of this product.

Finally, it is also important that the gasifier produces synthesis gas with a low amount of tar. This is important because the synthesis gas will likely be used in an internal combustion engine where tar levels must be under 50 mg/m³ synthesis gas (Chopra & Jain, 2007). High levels of tar will build up in the engine and plug the piping, yielding the engine inoperable. Minimizing tar production also eliminates the need for synthesis gas filtration. This relates to the design norms of stewardship and integrity. A design displaying integrity should be complete and be intuitive to use.

2.2 Reactor Design Decisions

2.2.1 Reactor Bed Type

The first decision in gasifier design involved the choice between a fixed or fluidized bed. In a "fixed" bed gasifier, air flows through a moving bed of solid particles. In a fluidized bed gasifier, air enters at the bottom of the reactor with a high air velocity that suspends biomass particles in the air flow. The vessel diameter increases towards the top of the reactor, which decreases air velocity and recirculates biomass particles. The selected design must be appropriate for the intended scale (3-5 kW). This is the most important criteria due to limited funds and intended project purpose. The other main criteria are that the design is simple and easy to test. This was important to allow the team to build the gasifier before operating and redesigning during the spring semester.

Design Alternative 1: Fixed Bed Gasifier

Advantages:

- Can be scaled to low power production

Disadvantages:

- Lower maximum efficiency
- Greater potential for bridging
- Solid flow mechanics become problematic when scaled

Design Alternative 2: Fluidized Bed Gasifier

Advantages:

- High maximum efficiency
- Can be scaled to produce over 10 MW (Solar Energy Research Institute, 1988)
- Most cost effective for production of over 15 MW (Chopra & Jain, 2007)
- Decreased potential for bridging

Disadvantages:

- Complicated design
- Impractical for small scale production

Selected Design Alternative: Fixed Bed Gasifier

This alternative was chosen because the pilot plant should produce 3-5 kW. There are no recorded instances of fluidized bed gasifiers that produce less than 1 MW of energy. The capital costs required to provide enough air to suspend the particles would be too great to justify the moderate increase in efficiency. A decision matrix displaying the design alternatives and criterion is shown below. Both cost and efficiency are listed as criterion and, as both are important, they are given equal weight. Simplicity definitely plays a role in the decision however not to the extent as the aforementioned criterion.

Table 2-1 Decision Matrix for Reactor Bed Type

	Simple Design	Inexpensive	Efficient	Total
Category Weight	X1	x2	X2	
Fluidized Bed	3	1	5	15
Fixed Bed	5	5	3	21

2.2.2 Air Flow Direction

The second decision involved choosing between a downdraft gasifier, an updraft gasifier, and a hybrid double-fire gasifier. This classification of gasifiers deals with the air entry location. In a downdraft gasifier, the air enters at the top and flows down through the biomass. In an updraft gasifier, the air enters at the bottom and flows up through the biomass. These designs are illustrated in Figure 2-1. In a double-fire gasifier, the oxygen is introduced partway down the packed bed and at bottom of the reactor, and the synthesis gas exits partway between the air feed locations. This design is illustrated in Figure 2-2.

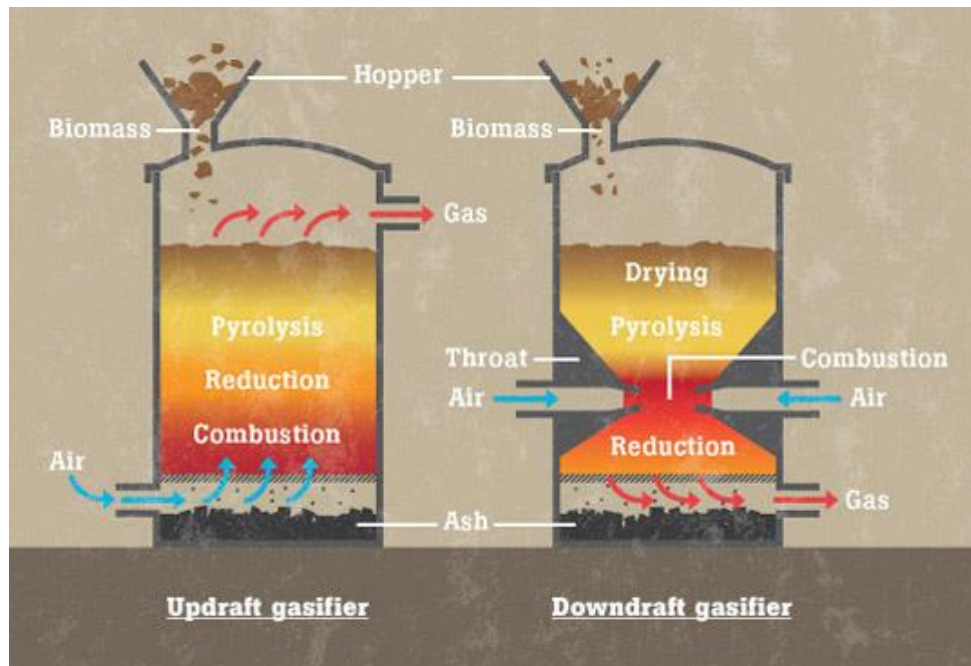


Figure 2-1 Downdraft vs. Updraft Gasifiers.

http://www.ashden.org/images/technologies/Gasifier_2_0.jpg

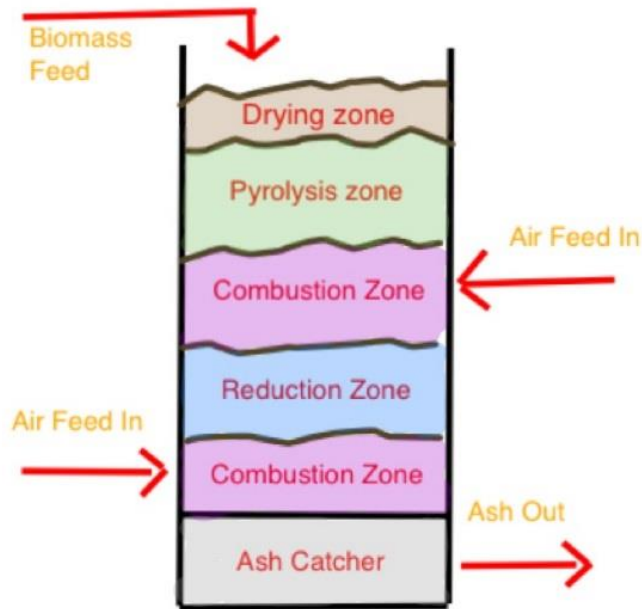


Figure 2-2 Double Fire Gasifier Design

The most important criterion in this decision was low tar production, which aligns with the design norm of stewardship. The second criterion was efficient production. Efficient production refers to maximizing the amount of synthesis gas recovered for a given amount of biomass (thoroughly discussed in Section 1.2.6). Finally, a good design should be able to use a wide range of biomass feed types. This makes the design more transparent because there is less concern about what type of fuel the user feeds; additionally, it makes the design more just because users from around the world can operate the gasifier with whatever biomass is available. While testing with more than one biomass feed was determined to be outside the scope of BIOburners’ design project, this was still an important consideration when choosing the reactor type as others might perform further testing of the gasifier in the future.

Updraft gasifiers are very simple to design and build and are able to gasify a wide range of fuels with high ash and moisture content (up to 15% and 50%, respectively). However, updraft gasifiers generate synthesis gas with a tar content of 50 mg/m³ (Chopra & Jain, 2007). This is because pyrolysis

occurs on top of the packed bed, and in an updraft gasifier the synthesis gas must pass up through this region. This causes the tars produced in pyrolysis to be carried up and away with the synthesis gas before the tars have a chance to be cracked or reduced. Downdraft gasifiers require fuel with lower ash and moisture requirements (under 5% and 20%, respectively) (Chopra & Jain, 2007). However, downdraft gasifiers are capable of producing synthesis gas with tar content as low as 0.015 g/m³ (Basu, 2010). This low tar content is a result of forcing the tar with the air through the hot oxidation zone, where it is reduced. This also improves the efficiency as the tars are reduced to useable fuel gases. Double-fire gasifiers have low tar production, like downdraft gasifiers, but they also have an improved efficiency because the second inlet location for the air provides secondary oxidation and reduction zones.

Design Alternative 1: Updraft Gasifier

Advantages:

- Most simple design and construction
- Widest range of useable biomass feeds

Disadvantages:

- High tar production
- Low efficiency

Design Alternative 2: Downdraft Gasifier

Advantages:

- Lower Tar Production
- Improved efficiency

Disadvantages:

- Narrower range of useable biomass feed

Design Alternative 3: Double-Fire Gasifier

Advantages:

- Low tar production
- Highest efficiency

Disadvantages:

- More complicated

Selected Design Alternative: Double-Fire Gasifier

A double-fire gasifier was selected because it best meets the design criteria of low tar production and high efficiency. This helps better achieve the design norm of stewardship. While this design is more complicated to build, due to the need to construct an addition combustion zone, reduced tar production and increased efficiency justify the added complexity of this design. Although outside the scope of this project and involving additional complexity, exploring the effect of additional fire zones could also be considered (such as a triple-fire or quadruple-fire gasifier).

A decision matrix displaying the design alternatives and criterion is shown below. The most important criterion were tar production and efficiency, as these directly relate to the goals of this project. Other criterion considered were range of feeds and simplicity. These were given less priority because these they are not explicitly stated in the project goals in (Section 1.3.4).

Table 2-2 Decision Matrix for Gasifier Air Feed Type

	Tar Production	Efficiency	Range of Feeds	Design Simplicity	Total
Category Weight	x2	x2	X1	x1	
Updraft	2	5	5	4	23
Downdraft	5	3	4	5	25
Double-Fire	5	5	5	2	27

2.2.3 Reactor Height

The selection of the reactor height involves the following design criteria: cost, flexibility, and tar production. Designs displaying flexibility can be tested more easily for a wide range of variables. Tar production was ranked highest as it directly effects the quality of the synthesis gas produced, followed by flexibility and then cost.

Design Alternative 1: Minimum Required Height

Advantages:

- More cost effective due to less material required

Disadvantages:

- Constrained to design height—cannot increase the height if it is determined that it is too short
- Greater tar production due to less time for the pyrolysis zone (section 1.2)

Design Alternative 2: Maximum Practical Height

Advantages:

- Flexibility for testing and optimizing—can reduce height if desired
- Increased residence time limits tar production (section 1.2)

Disadvantages:

- More expensive

Alternative 1 would result in fast pyrolysis. A shorter reactor decreases residence time in the pyrolysis zone. Faster pyrolysis increases the production of bio-oils, tars composed of carbonyl compounds and aromatics. Fast pyrolysis is ideal for large industrial scale gasifiers, but does not typically work well for smaller applications. Alternative 2 allows for slow pyrolysis. The residence time for slow pyrolysis ranges from 5 to 30 minutes. The products of slow pyrolysis include char, synthesis gas, and small amounts of bio-oil (Basu, 2010)(section 1.2.5.1).

A decision matrix was created to determine the height of the initial pilot plant design and is shown in Table 2-3. The alternatives were evaluated on the basis of cost, pyrolysis time, and flexibility. Pyrolysis time and flexibility were weighted doubly to ensure that the pilot plant was functional and could be used to obtain quality results even if a slightly higher one-time cost was required.

Table 2-3 Reactor Height Decision Matrix

	Cost	Pyrolysis Time (Tar Production)	Flexibility	Total
Category Weight	x1	x2	x2	
Maximum	5	10	10	45
Minimum	8	6	5	30

Selected Design Alternative: Maximum Practical Height

A reactor height of six feet was selected for the preliminary design. This should certainly be sufficient since it is three times taller small-scale gasifiers on the market (ALL Power Labs, 2014). This gasifier height will allow the team to optimize the design more freely, while remaining cognizant of the physical limitations involved. If testing shows that the additional has no effect on tar production, the height will be reduced in future designs (see Section 6.7).

2.2.4 Throat or Throatless

The next design decision considers the inclusion of a throat at the combustion zone of the gasifier. The difference between throated and throatless gasifiers is illustrated by the two designs in Figure 2-1; the updraft gasifier shown is throatless, and the downdraft gasifier has a throat. Design criteria include uniformity of temperature, simplicity of the design, and potential for bridging. The simplicity of the design is the most important criterion since the team has limited construction experience, and temperature, bridging criteria, and tar production are of secondary importance.

Design Alternative 1: Throated

Advantages:

- Higher combustion temperature because it consolidates the area of combustion so that incoming reactant has no choice but to be combusted at the hottest point
- Decreased tar production (Dayton 2002) due to higher temperatures to crack the tars

Disadvantages:

- Difficult to scale up – Cannot adjust throat inside gasifier
- Potential problems with bridging at the throat because it can be hard for biomass to pass through a narrow space without becoming suspended
- Difficult to optimize diameter – Cannot adjust throat inside the gasifier

Design Alternative 2: Throatless

Advantages:

- Can be scaled up with ease – No need to adjust throat
- Simplistic design – Reactor is essentially a cylindrical pipe
- Low potential for bridging – No narrow points in the pipe

Disadvantages:

- Lower combustion temperature – Reactant can travel to cooler locations to combust instead of being forced to combust at one specific location.
- Increased tar production – Lower combustion zone temperatures could cause less tars to be cracked.

Table 2-4 Throat Decision Matrix

	Uniform High Temperature	Design Simplicity	Potential for Bridging	Tar Production	Total
Category Weight	x1	x2	x1	x1	
Throat	5	3	3	4	18
Throatless	3	5	5	2	20

Selected Design Alternative: Throatless

A throatless design was chosen for the initial design because of its relative simplicity and low potential for bridging. This will decrease the combustion temperature and marginally increase the space time in the reactor, which will increase the expected tar production. While this does not achieve good stewardship, it will help the team gain understanding of gasifier operation by removing the potential complexity of bridging. A throat may be considered in the future after BIOburners has a better understanding of how gasifiers operate.

2.2.5 Number of Stages

Another important design decision was the number of stages. Design alternatives include both stratified and two-stage gasifiers. A stratified gasifier (shown in Figure 2-5) combines all gasification processes into one reaction vessel. In a stratified gasifier, the sub-processes (pyrolysis, combustion, reduction, etc.) are divided by their elevation in the reactor. Fresh biomass forms a layer on the top of the reactor where it begins to dry; below this region, pyrolysis occurs, followed by gasification by combustion and reduction. The heat for pyrolysis is provided by the hot gases in the combustion zone, which is located directly below it. In contrast, in a two-stage gasifier pyrolysis and drying occur in a region which is separate from the combustion zone. This is shown in Figure 2-3. In an external two-stage gasifier, the pyrolysis and drying zones are in a separate vessel. The heat required for pyrolysis in this vessel can be obtained via heat exchange from the product gas or from the engine where the synthesis gas is being used. After pyrolysis, the biomass enters the gasification vessel. An internal two-stage gasifier has a similar design that includes distinct areas for the two processes but does not have a separate vessel for combustion. A diagram of this type of gasifier can be seen in Figure 2-4.

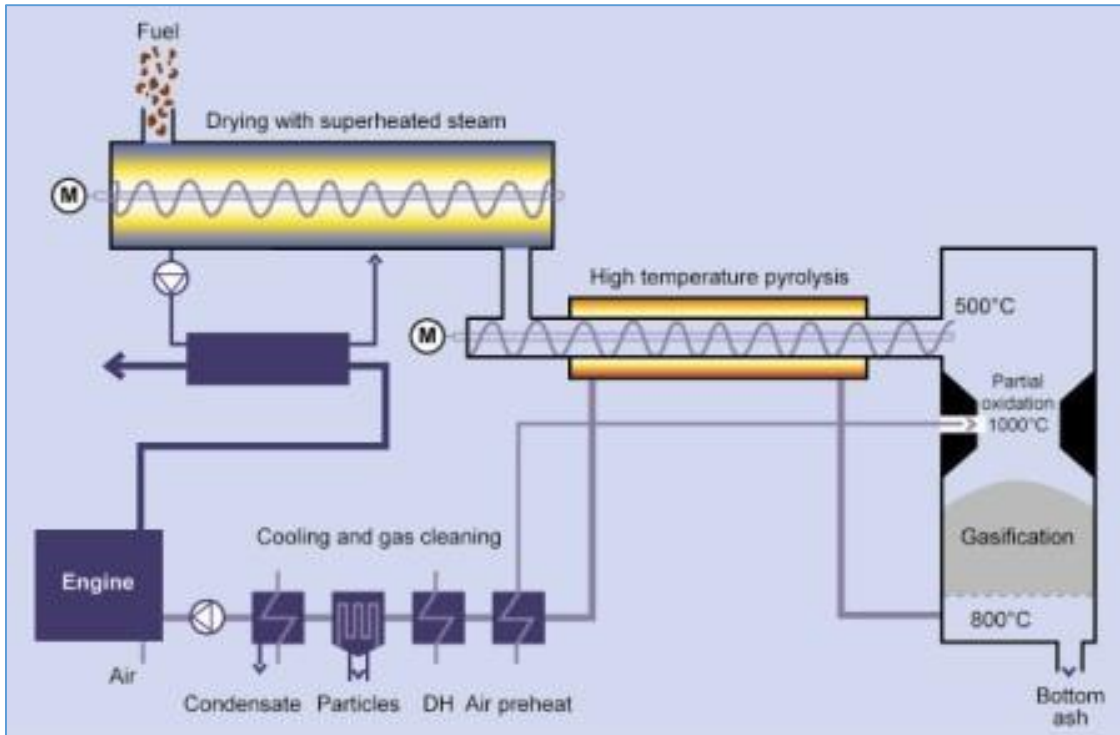


Figure 2-3 Two Stage Gasifier Design
http://www.dallenergy.com/media/fixe_d_bed_upscale_small.jpg

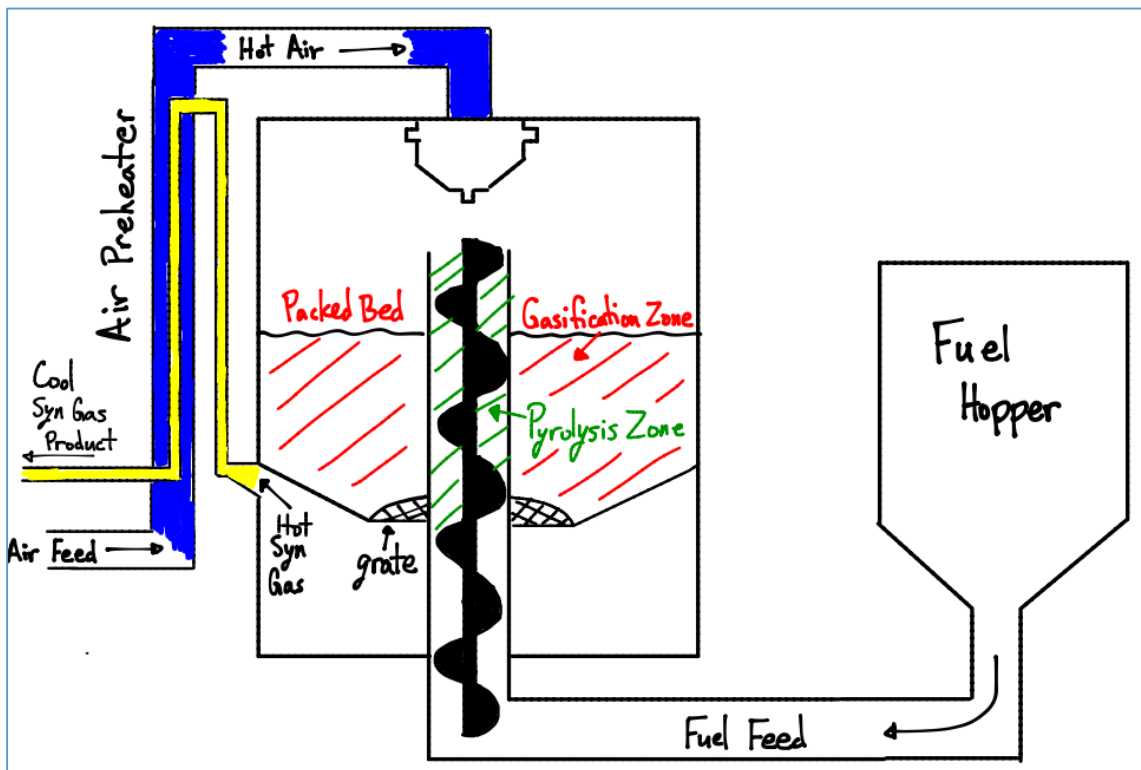


Figure 2-4 Internal Two Stage Gasifier

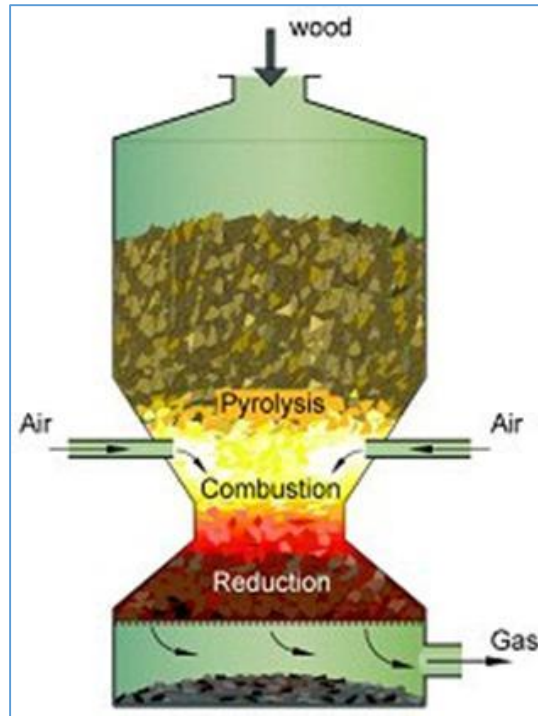


Figure 2-5 Stratified Downdraft Gasifier

<http://tandtunlimited.com/waste-to-energy/>

Critical design criteria for this decision include the difficulty of gasifier construction, required reactor size, tar production, and potential for optimization. Minimizing the time and cost involved in reactor construction was considered of great importance as it will allow the team to spend more time operating the pilot plant. The size of the reactor was also an important criteria, as users will likely operate the gasifier in an area with space constraints. Minimizing tar production improves the stewardship of the design, but the more practical criteria must be obtained before the environmental impacts of the synthesis gas can be considered. A final criterion was the ability to easily optimize the performance of separate portions of the gasifier, such as the pyrolysis or gasification zone without drastically impacting the performance of other regions.

The most important criterion was ease of construction to minimize the time required to fabricate the pilot plant. This criteria was weighted by a factor of three. The cost and size of the reactor were of secondary importance and we weighted by a factor of two. The amount of tar produced and

optimization of individual stages were considered less critical than these practical considerations and were therefore weighted by a factor of one.

Design Alternative 1: Stratified Gasifier

Advantages:

- Simple to build
- Compact
- Many successful and well-documented designs
- Inexpensive

Disadvantages:

- Difficult to optimize performance of individual stages – the only control over the pyrolysis zone temperature and residence time is indirect through changing the conditions in the combustion zone
- Higher tar production: 50 mg/m³ synthesis gas (Chopra & Jain, 2007)

Design Alternative 2: Internal Two-Stage Gasifier

Advantages:

- Individual stage performance can be optimized
- Low tar production: 15 mg/m³ synthesis gas (Chopra & Jain, 2007)
- Compact design

Disadvantages:

- Complex design and construction – Combustion zone and pyrolysis zone must be constructed separately
- Somewhat expensive

Design Alternative 3: External Two-Stage Gasifier

Advantages:

- Individual stage performance can be optimized
- Low tar production: 15 mg/m³ synthesis gas (Chopra & Jain, 2007)

Disadvantages:

- Somewhat complex design and construction
- Expensive
- Large size

Table 2-5 Number of Stages Decision Matrix

	Compact	Inexpensive	Ease of Construction	Tar Production	Optimization of Individual Stages	Total
Category Weight	x2	x2	x3	x1	x1	
Stratified	5	5	5	1	1	37
Internal Two-Stage	1	3	3	5	4	26
External Two-Stage	1	1	1	5	5	17

Selected Design Alternative: Stratified Gasifier

Based on the decision matrix in Table 2-5, the team chose to employ a stratified design because it is the easiest and least expensive to construct. Although the two-stage gasifiers produced less tar and allowed simpler optimization of individual stages, the internal two-stage gasifier was rejected primarily because it is difficult to construct and the external two-stage gasifier was rejected largely on the basis of its large size and high cost.

2.3 Air Feed Considerations

In order to produce the synthesis gas, air must be fed to the reactor to combust the biomass. Synthesis gas is primarily composed of carbon monoxide and hydrogen. In order to produce more carbon monoxide than carbon dioxide, it is necessary to combust the biomass in an air poor environment. The source of this oxygen can be air, pure oxygen, or steam. It is also important for the

oxygen feed system to be safe and well-sealed. This ensures that combustion outside of the reactor is not a potential danger. The most important criterion in determining the type of oxygen feed is safety. Therefore it was given a weighting of 3 in the decision matrix. Other criterion included cost and reactor temperature.

Design Alternative 1: Pure Oxygen Feed

Advantages:

- Higher reactor temperatures due to no diluents

Disadvantages:

- Safety issues due to combustibility
- Relatively expensive compared to air (partially due to regulations). Cost is \$2.00/cubic foot.
- Not as widely available as air

Design Alternative 2: Atmospheric Air Feed

Advantages:

- No capital cost
- Widely available

Disadvantages:

- Diluents decrease the reactor temperature

Design Alternative 3: Steam air mixture in the air feed

Advantages:

- Increased carbon monoxide yield from the following reaction: $\text{H}_2\text{O} (\text{g}) + \text{C} (\text{s}) \leftrightarrow \text{CO} (\text{g}) + \text{H}_2 (\text{g})$
(explained in Section 1.2.5)

Disadvantages:

- Increased heat capacity of the mixture reduces the temperature of the exiting synthesis gas, which may increase tar production

- Difficult to quantitatively test equivalence ratio (fraction of oxygen required for complete combustion) because water in the air affects the measurement of how much air is being fed to the reactor.

Table 2-6 Number of Stages Decision Matrix

	Compact	Inexpensive	Ease of Construction	Tar Production	Optimization of Individual Stages	Total
Category Weight	x2	x2	x3	x1	x1	
Pure Oxygen	5	5	5	1	1	37
Atmospheric Air	1	3	3	5	4	26
Steam Feed	1	1	1	5	5	17

Selected Design Alternative: Steam Air Mixture in the Air Feed

Although atmospheric air was selected as the oxygen source for combustion on the basis of cost and safety at the end of the first semester, design alternative 3 was selected instead after further consideration. Like atmospheric air, this design selection removes the need for compressed, flammable gas storage, which presents obvious safety concerns. Additionally, feeding air instead of pure oxygen reduces the cost and hassle of the process. It was determined that steam must be added to the atmospheric air feed due to the importance of the water shift reaction. To generate steam, a heat exchange system was designed and built to use the thermal energy from the exiting syngas gas. The details of this heat exchange system can be found below in Section 2.2.3.2. When operating the gasifier, however, no steam was produced so atmospheric air was the actual feed for the initial pilot plant as detailed in Section 3.

2.4 Heat Exchange

One of the key ways that this design enables environmental stewardship is by ensuring a high level of thermal efficiency. A heat exchanger between the syngas product and water was developed to accomplish this. There were several design alternatives listed as described below.

2.4.1 Entering Air Feed/Exiting Syngas

The exiting temperature of the synthesis gas is estimated to be between 700 and 800°C. To increase thermal efficiency (defined in Section 1.4.2), the heat contained within this gas needs to be recovered to heat the incoming fuel and air. There are several ways this heat can be recovered. The first design alternative is an external shell and tube heat exchanger, which allows the synthesis gas to exchange its heat with the incoming air. The second design alternative is to surround the entire reactor with a jacket through which the hot synthesis gas must pass through before entering the engine. This allows heat to be transferred through the body of the reactor and back into the biomass. In the third design alternative, vertical tubes are placed inside the reactor. Some of these tubes carry the air down to the combustion zone, while others carry synthesis gas up. This results in countercurrent heat exchange.

Design Criteria:

Each design has several key advantages and disadvantages. There are five major criteria that were used to judge the designs. The first is heat exchange area – the more heat exchange area between the synthesis gas and the biomass, the greater the heat transfer. The second design criterion involves maximizing the temperature difference, which is the driving force for heat transfer. These first two criteria will be weighted the lowest. While they are critically important for good heat exchange, the team completed preliminary evaluations of each design alternative to ensure that each alternative meets the minimum level of heat exchange required. These calculations were performed using an Excel spreadsheet that can be found in Section 12.1 in the Appendix. The third criteria is flexibility, which is significant as there is potential for design changes. This criterion is of moderate importance: while flexibility is useful for the prototyping phase, the team will be open to more rigid designs for our product that would sacrifice flexibility but yield in other areas. The fourth criterion involves reducing the size of the heat exchanger and is of low weight, because it is more of a convenience issue. Finally, the design

must be easy to build. This is the most important criteria because team members have minimal construction experience and must be able to construct and assemble the gasifier fairly quickly to move on to the testing phase. More complex heat exchangers might be considered for the final design, but this criterion was significant in designing the pilot plant for construction. A summary of the heat exchanger criteria is as follows:

- Heat Exchange Area – weighted x1
- Large Temperature Difference – weighted x1
- Flexibility – weighted x2
- Ease of Construction – weighted x3
- Compact – weighted x1

Design Alternative 1: External Shell and Tube

Advantages:

- Large maximum heat transfer area
- High temperature difference
- Isolated from reactor

Disadvantages:

- Difficult to build
- Bulky design requiring more space than alternatives

The shell and tube heat exchanger has the advantage of being separate from the rest of the reactor, which means that the heat transfer area can be as large as deemed necessary. Additionally, since the synthesis gas is transferring heat directly to room temperature air, the temperature difference for heat transfer is high. The shell and tube heat exchanger scores well for flexibility because it is not integrated into the body of the reactor, and consequently it would be simple to make changes to the reactor without changing the overall design. Unfortunately, the shell and tube heat exchanger would be

both expensive and difficult to fabricate (compared to alternatives since it requires an additional, complex unit), so it scores the lowest in that category. The shell and tube heat exchanger results in the least compact overall design because it is not integrated with the reactor body.

Design Alternatives 2: Jacketed Reactor

Advantages:

- Easier to build
- Integrated and compact
- Inexpensive

Disadvantages:

- Limited heat transfer area
- Lower temperature difference

The jacketed reactor provides less maximum heat transfer area than the shell and tube heat exchanger because it is limited by the size of the reactor. It also has a smaller temperature difference than the shell and tube heat exchanger because some of the available heat transfer area is not utilized. Because a reactor jacket integrates the heat exchanger with the reactor, it is also less flexible, and any change to the reactor may necessitate a change to the heat exchanger. On the other hand, this design is much more compact than the shell and tube heat exchanger and should add relatively little to the footprint of the gasifier. Finally, this design is easier to fabricate as it requires significantly fewer welds and fittings than the shell and tube heat exchanger. Additionally, because there is less exposed surface area, the designs require less insulation to maintain thermal efficiency. Finally, using a jacket would increase the complexity of the manifold that controls the air flow into the reactor.

Design Alternative 3: Internal Vertical Tubes

Advantages:

- Easier to build
- Integrated and compact
- Inexpensive

Disadvantages:

- Limited heat transfer area
- Lower temperature difference

The internal tubes design is very similar to the jacket reactor in its advantages and disadvantages. The main difference between the internal vertical tubes and the jacketed reactor lies in the ease of construction. The jacket would be very difficult to construct because the team would need to fabricate a 6' x 6.5" pipe. Conversations with Phil Jasperse, Calvin College machine shop manager, suggest that this would not be practical. Thus, the internal vertical pipe design is the easiest to construct.

Table 2-7 Heat Exchanger Decision Matrix

	Heat Exchange Area	Temperature Difference	Flexibility	Easy Construction	Compact	Total
Category Weight	x1	x1	x2	x3	x1	
Shell and Tube	10	10	10	2	4	50
Jacket	7	7	5	7	10	55
Internal Tubes	7	7	5	9	10	61

Selected Design Alternative: Internal Vertical Tubes

The team chose the third design alternative: a heat exchanger using vertical tubes integrated with the reactor body. In this design the synthesis gas (extracted near the bottom the reactor) will go up through the tubes and will leave through a manifold on the top of the reactor. Placing this manifold at the top of the reactor will provide countercurrent heat exchange between the synthesis gas and the air

and fuel feeds. The details of the manifold system are discussed in Section 2.5. In this design the synthesis gas will also provide heat to the pyrolysis zone. This design will increase thermal efficiency while allowing the gasifier to remain compact and easy to build. The tubes will be spaced very close to each other (as close as physically possible to fabricate necessary welds) and will therefore have minimal biomass between them. Thus, only the biomass within the ring of tubes will significantly impact heat exchange.

2.4.2 Steam Feed/Exiting Syngas

It was determined that the water gas shift reaction would play a crucial role in the production of synthesis gas for the gasifier. In order to carry out this reaction most efficiently, a means of exchanging the heat of the exiting synthesis gas with the water to be evaporated to create the steam feed was designed. There are a number of possible design alternatives for this heat exchanger. The primary consideration for this portion of the BIOburners pilot plant design was ease of construction. While a more complex or aesthetically pleasing heat exchanger might be implemented in the final design, using a heat exchanger that was simple to construct and operate was most important for the team based primarily on constraints in budget and time. An additional consideration for this heat exchanger is that it includes a means of preventing liquid water from entering the reactor, which could cause an explosion and a serious safety issue. This relates to the criterion of flexibility since the water level should be maintained at a specific height or below. The three primary alternatives that the team considered were a constructed metal heat exchanger, a pre-made metal heat exchanger, and a 55-gallon drum. These alternatives were evaluated based on the criteria of flexibility (x1), leak likelihood (x1), ease of construction (x2) and cost (x2) using the decision matrix below in

Table 2-8. Ease of construction and cost were practical considerations that were consequently weighted twice as highly as the other criteria.

Design Alternative 1: Constructed Metal Heat Exchanger

Advantages:

- Most flexible design
- Inexpensive

Disadvantages:

- Requires most construction time
- Greatest likelihood of leaks

Design Alternative 2: Pre-Made Metal Heat Exchanger

Advantages:

- Requires little construction time
- Lower likelihood of leaks

Disadvantages:

- Less flexible design
- More expensive

Design Alternative 3: 55-Gallon Drum

Advantages:

- Requires little construction time
- Lower likelihood of leaks
- Inexpensive

Disadvantages:

- Somewhat flexible design

Table 2-8 Decision Matrix for Steam Feed Heat Exchanger

	Flexibility	Seal Quality	Ease of Construction	Cost	Total
Category Weight	x1	x1	x2	x2	
Constructed Metal Heat Exchanger	3	2	1	3	13
Pre-Made Metal Heat Exchanger	1	3	3	1	12
55-Gallon Drum	2	3	3	3	17

Selected Design Alternative: 55-Gallon Drum

Based on analysis of relevant design criteria in

Table 2-8, a 55-gallon drum was selected for the steam feed heat exchanger. A plastic drum was obtained from Calvin College Physical Plant and could be easily repurposed for use in the pilot plant. This heat exchanger is also not likely to leak. Although it does not offer the flexibility of a heat exchanger constructed specifically for the purposes of the reactor, it will still be able to perform all necessary functions. A hinged door is on one end of the heat exchanger. This door is at a height that liquid water will leak out of the heat exchanger before entering the reactor. Pictures of the heat exchanger are below in Figure 2-6, Figure 2-7, and Figure 2-8. Calculations in Section 12.4.1 of the Appendix indicate that four passes of 1.5" diameter pipe should provide the necessary heat transfer to cool the synthesis gas feed. During the pilot plant redesign more consideration was given to the amount of steam produced and the cooling rate that would result from the steam feed. These calculations are discussed in Section 4.3.



Figure 2-6 Steam Feed Heat Exchanger Interior



Figure 2-7 Steam Feed Heat Exchanger Exterior



Figure 2-8 Steam Feed Heat Exchanger

2.5 Air Manifold System

2.5.1 Two or Three Manifolds

At least two manifolds are required for this gasifier design, one for the air feed and one for the synthesis gas. However, an additional manifold can be used to better manage the ratio of air fed to the top and bottom combustion zone. Because there are no apparent advantages to using a system with two feed manifolds, a design with three manifolds was selected. This design allows better control over the air distribution to the two combustion zones.

2.5.2 Internal or External Manifold System

This decision addressed how manifolds would be attached to the reactor body. The internal manifold system involves welding the manifolds inside the reactor body as shown in Figure 2-9; the external manifold system in Figure 2-10 requires building three separate manifold chambers independent of the reactor body. These chambers will be attached to the reactor body using flanges.

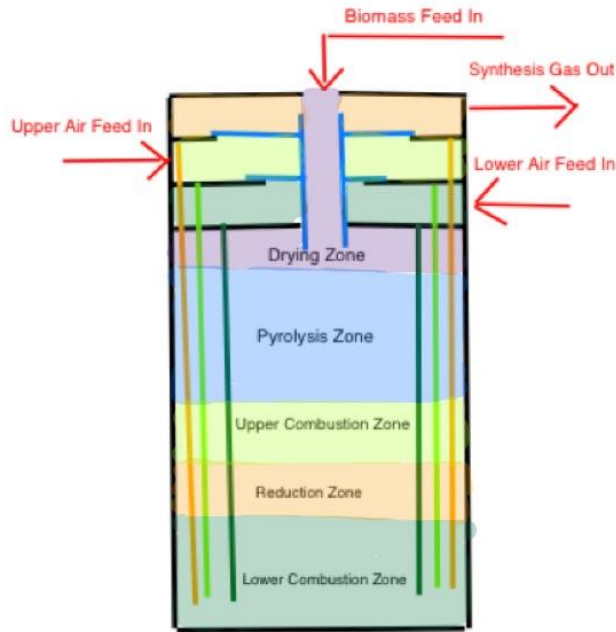


Figure 2-9 Internal Manifold System

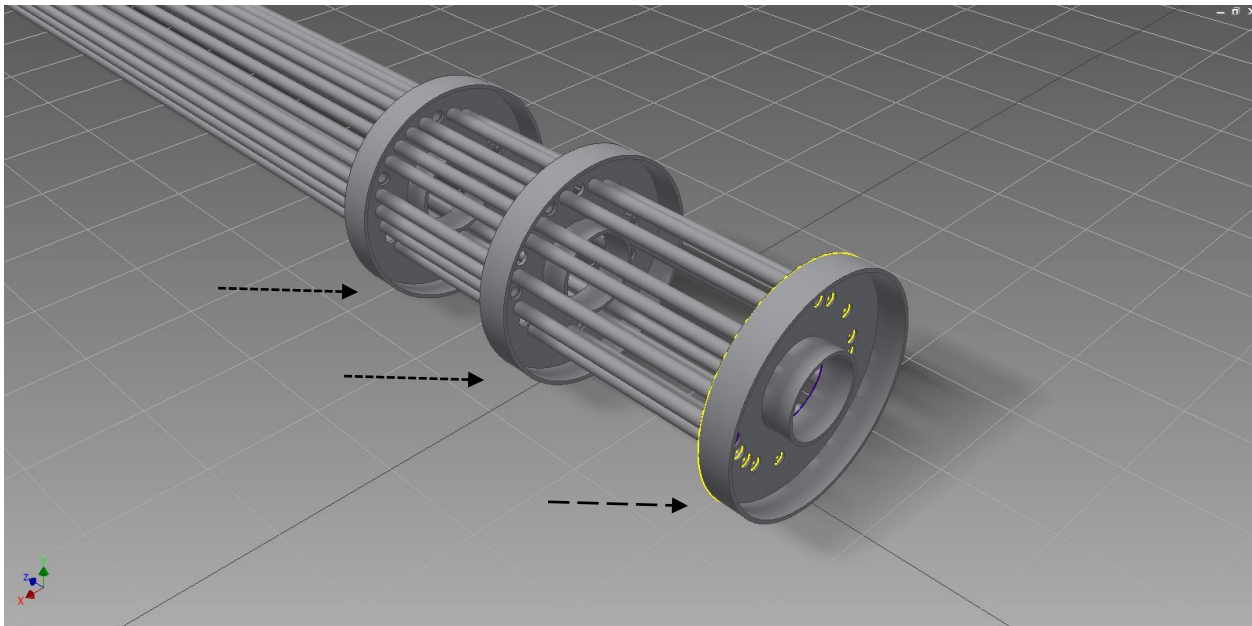


Figure 2-10 External Manifold Design. Dashed arrow for synthesis gas; dotted arrow for dual air feed

The following design criteria were applied to this decision for the team's pilot plant in order of decreasing priority (criterion weight given in parenthesis): flexibility for manifold removal (x3), seal quality (x2), ease of manufacturing (x1). Flexibility was ranked highest because of the strong emphasis

placed on the testing and optimizing portion of this project. The selected design should not prohibit access to the air feed tubes because the air feed locations could need to be modified during testing. Seal quality was ranked second because it is important that the manifold does not leak synthesis gas due to its carbon monoxide content, but the air feed tubes must still be accessible. In the pilot plant, careful welding and the use of a gasket reduced the likelihood of synthesis gas leaks although they were still present to a significant degree (see sections 4 and 5 below for further details regarding this). Ease of manufacturing was deemed important because none of the team members have extensive welding experience and the final design needs to be safe and reliable. However, it was ranked last because the overall safety and flexibility of the design were more important factors and because the final design would be constructed by more experienced individuals. The manifold is a critical part of the design and therefore justifies a greater amount of time spent in manufacturing. Each design criteria was assessed on a scale of 1 to 3 in the decision matrix in Table 2-9.

Design Alternative 1: Internal Manifold System

Advantages:

- Less material costs
- Simpler design

Disadvantages:

- Requires space inside reactor otherwise available for biomass pyrolysis and/or gasification
- Difficult to weld inside the reactor body
- Difficult to maintain seal between manifolds
- Difficult to remove for maintenance and optimizing

Design Alternative 2: External Manifold System

Advantages:

- Flexibility in air feed location
- Easier manufacturing
- Good seal between manifolds

Disadvantages:

- Increased material costs
- More complex design

Table 2-9 Decision Matrix for Internal vs. External Manifold Systems

	Flexibility	Seal Quality	Ease of Manufacturing	Total
Category Weight	x3	x2	x1	
Internal Manifold System	1	2	1	8
External Manifold System	3	3	2	17

Selected Design Alternative: External Manifold System

Based on analysis of relevant design criteria in Table 2-9, an external manifold system is the obvious choice. The increased seal quality improves the safety of the gasifier because synthesis gas leaks will be less likely when a separate manifold chamber is used. This design also relates to the design norms of stewardship and trust because less carbon monoxide will be released to the atmosphere.

2.6 Ash Containment

Ash is produced during gasification of the biomass, which settles to the bottom of the reactor. It is important to separate and retain ash produced during gasification as these particulates cannot pass through an internal combustion engine. Ash is commonly collected below the gasification zone of the reactor. There must also be a convenient way to remove ash buildup periodically, and the team anticipates ash removal will be necessary after 120 hours of operation, depending on which removal method is used. The design criteria used to analyze this decision were cost, storage capacity, and ease

of manufacturing and use. Of these criteria, storage capacity and ease of use were ranked above cost because they best fulfill the design norms of caring and transparency. Ease of manufacturing is also important to ensure that the ash containment mechanism can be fabricated and that air leaks to the gasifier are minimal if present at all. While cost is also a criteria, it is weighted less highly because none of these alternatives would have a significant impact on the total cost of the pilot plant although some are more inherently expensive to construct.

There are four significant design alternatives, three of which also contain a grate. The first of these contains a grate with the bottom foot of the gasifier allocated for ash containment and a side door for ash removal. The second also has a grate, but a pipe with a vacuum attachment for ash removal instead of a side door. The third alternative consists of a duct below the reactor where the ash collects once it has fallen through the grate. This duct has an opening in one end, which allows the ash to be removed periodically after the gasifier has been shutdown. The final alternative, which does not contain a grate, is the external ash removal system. In this system, the synthesis gas enters an open chamber where its velocity is significantly decreased. As it passes through this chamber, the ash settles to the bottom of the unit. After passing through this chamber, the synthesis gas again enters a pipe and then flows to the location where it is burned off or used to provide power.

Design Alternative 1: Grate with Side Door

Advantages:

- Inexpensive and simple design
- Allows easy access to bottom of reactor

Disadvantages:

- Utilizes space in the reactor
- Limited ash storage capacity

Design Alternative 2: Grate with Vacuum Pipe

Advantages:

- Inexpensive and simple design

Disadvantages:

- Takes space in the reactor
- Cannot easily access bottom of reactor
- Limited ash storage capacity

Design Alternative 3: Grate with Ash Removal Duct

Advantages:

- Inexpensive and simple design
- Does not require space inside reactor
- Large ash storage capacity possible

Disadvantages:

- Cannot easily access bottom of reactor

Design Alternative 4: External Ash Settling Unit

Advantages:

- Increased thermal efficiency
- Potentially allows ash removal without gasifier shutdown
- Infinite capacity

Disadvantages:

- Ash may still build up in the reactor
- Expensive and complex design

Table 2-10 Decision Matrix for Ash Containment System

	Storage Capacity	Ease of Use	Ease of Manufacturing	Inexpensive	Total
Category Weight	x2	x2	x2	x1	
Grate with Side Door	1	3	1	2	12
Grate with Vacuum Pipe	1	2	1	1	9
Grate with Ash Removal Duct	2	3	2	3	18
External Ash Settling Unit	3	1	1	2	12

Selected Design Alternative: Grate with Ash Removal Duct

A grate with an ash removal duct was selected as the best design because it best matches the selected design criteria as shown in the decision matrix in

Table 2-10. This alternative allows a large quantity of ash to be collected before shutdown to remove the ash is necessary. Additionally, the design is transparent and simple, as any user of the gasifier can operate this system without any explanation. The ash duct will also be easy to manufacture and will reduce the likelihood of air leaks as compared to the alternatives provided that the door can be tightly sealed to the collection chamber. This alternative is also quite inexpensive to construct, requiring only a sheet of carbon steel for raw materials.

2.7 Grate

The grate can be seen in Figure 2-11. As shown below, all of the 27 manifold tubes were inserted through the grate to better support the grate. The grate was to be positioned roughly 12 cm from the bottom of the reactor and contained concentric circles of 1/4" holes. The grate was made of stainless steel because it would have to withstand temperatures in excess of 1000°C. The purpose of the grate was twofold; it was to support the weight of the biomass as well as allow ash to fall from the bed to be collected in the ash collecting duct.

Air was fed to the lower combustion zone via the bottom air feed tubes shown in Figure 2-11. Some air would travel out of these tubes and through the small holes in the grate where it would then combust directly above the grate. This would ensure that all biomass in the reactor could be combusted. Ash would then fall through the small holes and be collected in a duct beneath the reactor. Based on an estimate that 1% of the biomass is converted to ash (Wood Pellets FAQ, 2011), a duct was fabricated that would not have to be opened during operation but could be emptied when the testing was complete.

The height of the ash grate was chosen so that there would be ample space for the ash to settle downwards. A height of 8 inches was chosen based on the calculations shown in Section 12.3.2 in the Appendix.

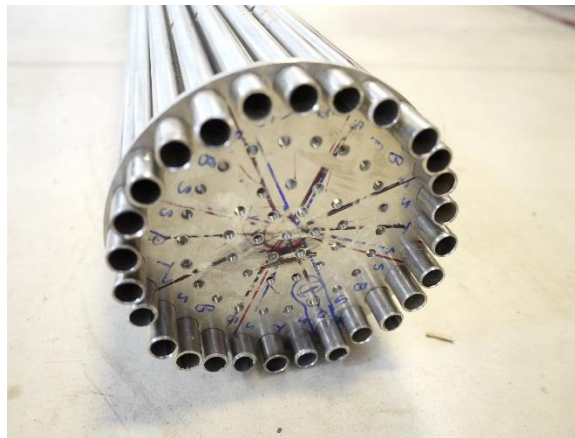


Figure 2-11 Pilot Plant Grate

2.8 Vacuum System

In a gasifier product, a generator is used to create the vacuum that pulls air into the reactor. In the operation of this pilot plant, BIOburners had to develop a similar method to cause air to flow into the reactor. BIOburners could either use a compressed air feed or create a vacuum downstream of the reactor that would suck air in through the air feed holes in the reactor.

With each of these options there were advantages and disadvantages. If the compressed air feed was used, there would be little to no construction required. Additionally using the compressed air feeds would be the less expensive alternative. There were, however, significant disadvantages. By pressurizing the reactor, a potential safety hazard could be created, risking explosions and toxic gas leaks. If the vacuum system design was used, it would require additional construction and roughly \$100. However, by using a vacuum design there would be no possibility of gas leaking out of the system. If there were leaks in the pilot plant, surrounding air would be drawn into the system instead of product gas leaving the system. This option was much safer and therefore BIOburners chose to use the vacuum pump option.

The vacuum system uses the venturi effect to create a pressure difference that results in air flowing into the reactor. Bernoulli's equation, which states that a pressure difference will be created

when air is forced through a constriction, drives the venturi effect. Therefore, in the design of the vacuum system, compressed air was forced through a constriction, which caused the pump to pull a significant vacuum and pull air into the reactor. Although a manometer was never installed, the expected vacuum was between 8 and 20 inches of water. The vacuum value depends also on the compressed air flow rate: the faster the compressed air was fed through the constriction, the stronger the vacuum produced. The completed vacuum pump is shown below in Figure 2-12.



Figure 2-12 Vacuum System

2.9 Flare

The synthesis gas product is composed of carbon monoxide and hydrogen gas as well as nitrogen, carbon dioxide, methane, water, and small amounts of other hydrocarbon tars. This gas is toxic and flammable and therefore must be safely disposed of. The gas will be burned off in a flare to oxidize the carbon monoxide to carbon dioxide, which is much safer and non-toxic. The team considered the possibility of using a pilot light to burn the synthesis gas; however, this can be difficult to construct. Instead, a design was employed in which the gas entered the flare at an angle, causing it to spiral inside the cylinder and double back upon the incoming gas. This design eliminated the need for a pilot light because due to the spiraling nature of the flare the burning synthesis gas doubled back upon the incoming air and ignited it. Therefore, once lit, the flare was self-sustaining. Figure 2-13 below shows the lit flare and the spiraling burn pattern of the synthesis gas.



Figure 2-13 Lit Flare

2.10 Tar Traps

To collect some of the tar that condenses in the pipe between the exiting the manifold and the flare, two mason jars were used. This method is used in the GEK gasifier kit (ALL Power Labs, 2014). The mason jars are easy to install and use. They also allow an estimate of the amount of tar being produced by the system.

2.11 Biomass Fuel Source

When considering the biomass fuel, an important design decision was whether a pelletized or unprocessed biomass feedstock should be used. Various feed stocks are detailed above in Section 1.2.3. The primary criteria for this decision were the cost and availability of the biomass fuel. Choosing an inexpensive and widely available fuel demonstrates the design norm of caring by making the gasifier less expensive to use for all operators. By selecting a widely available biomass source, the gasifier should be functional regardless of the region the gasifier is operated. The consistency in size and moisture content of the feedstock was also critical in this decision and was considered the most important criterion because it allows for better optimization of the gasifier during the testing phase. In a final product for a customer, the gasifier would be tested to ensure that various types of biomass function properly in the gasifier.

Design Alternative 1: Pelletized Feedstock

Advantages:

- Consistent size and moisture content
- Fairly readily available

Disadvantages:

- Expensive
- Must be processed and purchased from external source

Design Alternative 2: Unprocessed Feedstock

Advantages:

- Inexpensive
- Readily available

Disadvantages:

- Variation in size and moisture content

- Bridging

Selected Design Alternative: Pelletized Feedstock

Pelletized biomass feedstock was selected for this design. While these feedstocks are more expensive and less widely available than unprocessed feeds, their use will simplify testing and optimization significantly and still exhibit the design norm of caring by allowing the gasifier to operate with various feeds.

Wood pellets were used during testing because they are readily accessible. While outside the scope of this project, in the future pellets of other types may be explored by other teams. BIOburners expects that different feeds would require oxygen feed ratios to function optimally. Versatility in the biomass feed would help achieve the target for ease of use and would create a more transparent design.

2.12 Pilot Plant Materials of Construction

2.12.1 Metals

The materials of construction considered include aluminum, carbon steel, stainless steel 304, stainless steel 316, and titanium. The most important criterion when choosing the material is its ability to withstand the high temperature conditions in the reactor without deformation or corrosion. The primary consideration, therefore, is the maximum operating temperature of each material. Selecting a material that will withstand temperatures that may reach 1000°C or more will ensure safety for gasifier operators. The cost of the material is also an important criterion and is of secondary importance. Additional criteria included corrosion resistance, workability, and material availability. Corrosion is greatly accelerated at elevated temperatures, which must also be considered when choosing a metal for pilot plant construction. By using an inexpensive material BIOburners shows caring for its customers by ensuring the product is affordable. Material properties were based on information found online from Teadit, Co. (Teadit, 2013) and included in Section 12.1 in the Appendix.

Design Alternative 1: Aluminum

Advantages:

- Inexpensive
- Widely available
- Corrosion resistant

Disadvantages:

- Maximum operating temperature of 460 °C
- Low workability (difficult to weld)

Design Alternative 2: Carbon Steel

Advantages:

- Inexpensive
- Widely available and frequently used
- High workability (easy to weld)

Disadvantages:

- Low corrosion resistance
- Maximum operating temperature of 500 °C

Design Alternative 3: Stainless Steel 304

Advantages:

- Widely available and frequently used
- Moderately inexpensive
- Maximum operating temperature of 760 °C
- Corrosion resistant

Disadvantages:

- Moderate workability (somewhat difficult to weld)

Design Alternative 4: Stainless Steel 316

Advantages:

- Maximum operating temperature of 760 °C
- Corrosion resistant
- Widely available

Disadvantages:

- Moderate workability (somewhat difficult to weld)
- Moderately expensive
- Used less frequently than stainless steel 304

Design Alternative 5: Titanium

Advantages:

- Maximum operating temperature of 1100 °C
- Very corrosion resistant

Disadvantages:

- Less widely available
- Low workability (difficult to weld)
- Expensive

Table 2-11 Materials of Construction Decision Matrix

	Heat Resistance	Inexpensive	Workability	Corrosion Resistance	Availability	Total (High Temp)	Total (Low Temp)
Category Weight	x5	x3	x2	x1 for low temp, x2 for high temp	x2		
Aluminum	1	5	1	4	5	40	31
Carbon Steel	2	5	4	1	5	45	34
Stainless Steel 304	4	3	3	4	3	49	25
Stainless Steel 316	4	2	3	4	2	44	20
Titanium	5	1	2	5	1	44	14

The high temperature total was calculated using all design criteria, while the low temperature total did not take heat resistance into account. Heat resistance was the most important criteria and was weighted by a factor of 5 because it is critical that the design withstands high temperatures. The cost of the materials is also weighted highly (x3) because the materials of construction represent a large portion of the pilot plant cost. Workability and availability were considerations weighted by a factor of 2. Since increased corrosion rates occur at higher temperatures, the corrosion resistance was weighed double in the material used to fabricate regions of the pilot plant subject to high temperatures.

Selected Design Alternatives:

The team used stainless steel 304 in high temperature areas of their design, including the air feed tubes, reactor body, and grate. This metal has the appropriate heat and corrosion resistance while being relatively low cost and widely available. In the lower-temperature areas at the top of the reactor, including the manifold system, carbon steel can be used. This material is appropriate to use at those temperatures and is also widely available, workable, hard, and inexpensive. These choices for materials of construction display concern toward customers' safety and finances. Less expensive and more widely available metals, including carbon steel, were used in various low temperature areas of the reactor.

2.12.2 Reactor Insulation

In order to ensure thermal efficiency, the gasifier must be well-insulated. The two major alternatives for insulation material include a ceramic cast and a ceramic insulation blanket. The thermal efficiency available with each alternative is the most important criterion. Maintaining high thermal efficiency is important for ensuring good stewardship. Insulation material criteria also include durability, cost, and structural integrity. The durability and cost of the insulation are of secondary importance. The durability of the insulation is of importance in achieving trustworthy design. Users will be confident in operating the gasifier if they are not concerned that the insulation will crack and expose hot surfaces.

Insulation materials with high structural integrity are simpler to use because they do not require additional sources of support.

Design Alternative 1: Ceramic Cast

Advantages:

- High thermal efficiency
- High structural integrity

Disadvantages:

- Expensive
- Low durability

Design Alternative 2: Ceramic Blanket

Advantages:

- High thermal efficiency
- Inexpensive
- Durable

Disadvantages:

- Low structural integrity

Selected Design Alternative: Insulation Blanket

A ceramic insulation blanket was chosen as the material for insulation for the gasifier. Both alternatives achieve the same level of thermal efficiency, which ensures good stewardship. In addition, although the insulation blanket requires additional support, it is more durable and more cost-effective than the ceramic cast.

Once the type of insulation was chosen it was important to determine how much insulation was necessary. The team selected Fiberfrax Durablanket upon recommendation by several sales representatives. An important criteria for the insulation was to ensure that operators could touch the

reactor without being burned. Based on an article published by NASA regarding human touch temperature standards (Eugene Ungar, 2014) the team calculated that given the properties of the insulation at 150°C the surface could be touched for 1 second before the operator would experience pain. Even longer contact would be required before an operator would be burned. Based on the thermal conductivity and other manufacturer supplied specifications the team calculated the thickness of insulation necessary to reach a temperature less than 150°C on the outside of the reactor. The calculations showed that 6" of insulation would be required around the combustion zones and 4" would suffice for the pyrolysis zones. The details of these calculations are shown in Section 12.4.4 in the Appendix.

2.13 Feed Hopper

The feed hopper must be a container capable of holding enough biomass to run the gasifier for six or more hours is necessary. Assuming that biomass is consumed at a rate of 2 kg/hour (ALL Power Labs, 2014) and has a density of 700 kg/m³, a volume of at least 17.1 liters is necessary for the feed hopper. Detailed calculations for the sizing of the feed hopper are found in Section 12.3.3 in the Appendix. A second critical criterion for the feed hopper is that it does not have air leaks, which would allow air to enter the system and the flame to travel up the reactor. This criterion is related also to the need for a hopper cover that seals the feed from air but allows the biomass to be refilled immediately.

A potential feed hopper with sufficient volume was found in the engineering building. This container had been used by another senior design team for a previous project. Modifying this feed hopper would require much less time than constructing one from scratch. Consequently, BIOburners decided to operate their gasifier with biomass fed from this hopper.

In order to make this hopper suitable for use in this project, caulk was used to seal any gaps between aluminum panels of the hopper. To address challenges associated with filling the hopper while also not allowing the flame to travel up the reactor, a flat metal plate was used as the hopper cover and

sealed with duct tape. When the biomass needed to be refilled, the tape could be easily removed and the cover was quickly removed while pellets were added to refill the reactor. The cover was then replaced and resealed. As a means of evaluating when the hopper would need to be refilled, a hole was cut in the side of the hopper and covered with Plexiglas. BIOburners never had to refill the hopper during operation of the pilot plant since testing was only performed for short periods of time. However, based on functionality tests performed in the fall semester, the 30 seconds or less that would have been required to refill the feed hopper would not have allowed the flame to travel a significant distance up the reactor. A photograph of the feed hopper is below in Figure 2-14.



Figure 2-14 Feed Hopper

2.14 Support System

A way to stabilize the reactor (a tall, heavy, narrow cylinder) was necessary to ensure that it remained upright and therefore also functional and safe. Flanges were used to bolt the reactor body to

a steel plate, which was bolted to two I-beams. The ash containment system was placed below the steel plate between the I-beams.

Although there are many possible alternatives to this support system, BIOburners chose to use this system because of its flexibility, ease of construction and cost and because it provided adequate support for the reactor. Regarding flexibility, the team considered welding the reactor body to the steel plate, but decided against this alternative. Although the reactor body likely will not be disconnected from the plate during testing, welding did not pose a significant advantage in ease of construction or cost and therefore was not chosen. The materials necessary for this support system were available to BIOburners in the Calvin College machine shop. The fabrication of the support system was also fairly straightforward, which was an additional advantage given the limited metal-working experience of the design team.

2.15 Sampling Apparatus

Samples need to be collected for Orsat analysis of syngas composition and for the determination of tar content. Important considerations included the purity and volume of the samples and the ease with which they could be collected and transported. Operating at a vacuum makes the sampling process somewhat complicated. The final design, which allows the sample to be collected fairly easily despite low pressures, uses two tees, four valves, and two unions to divert the flow from the pipe between the heat exchanger and flare. The sample for tar analysis is collected in a piece of 500 mL round-bottom flask. The glassware can be flushed with syngas prior to collection to ensure a pure and representative sample. This method allows collected sample to be transported easily and quickly to the area where it will be analyzed. The Orsat sample is collected using a piece of metal tubing with a barb at the end. This tube feeds into a piece of rubber tubing connected to the Orsat gas analyzer. Further discussion of the analytical methods used to determine the tar content and composition of the synthesis gas are found in Section 5.

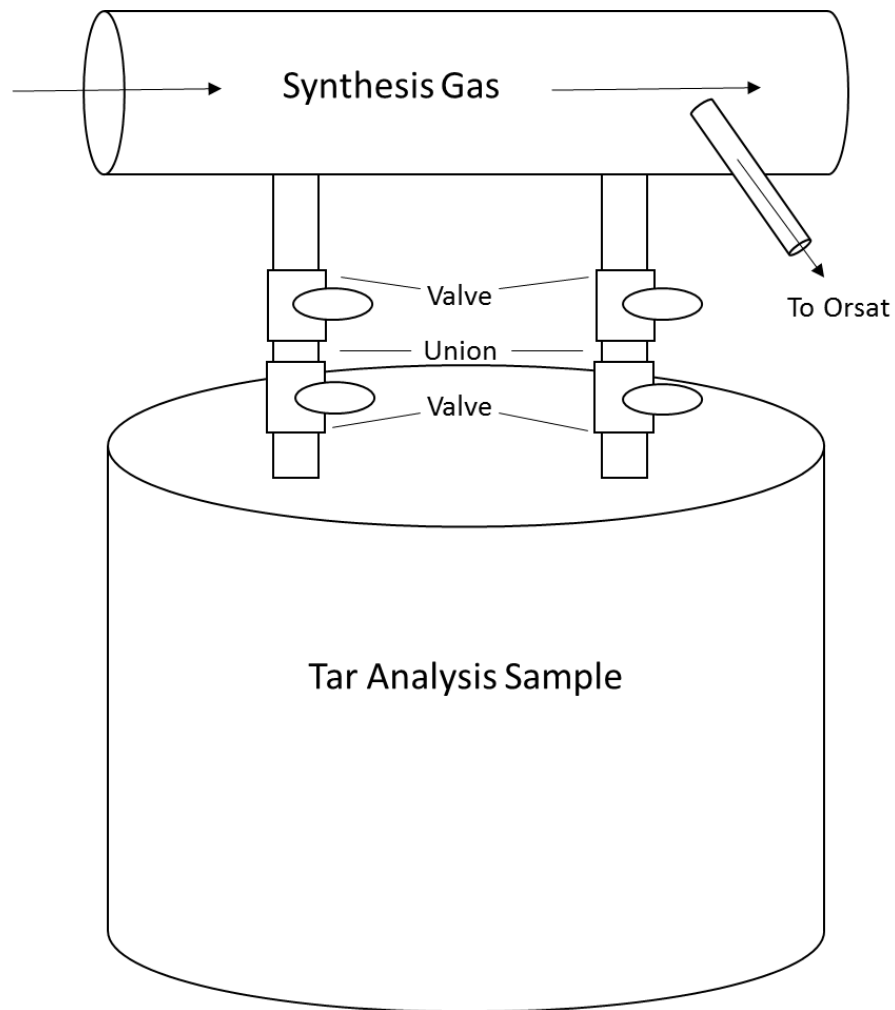


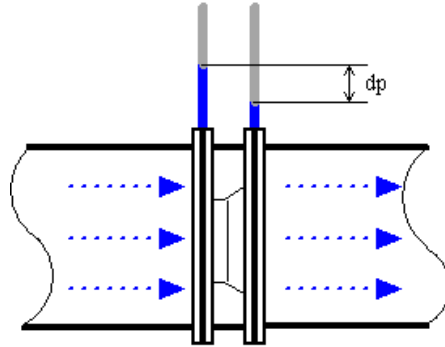
Figure 2-15 Sampling Apparatus Diagram

2.16 Instrumentation

2.16.1 Flow Rates

There were three main options for measuring the flow rates of the incoming air and the exiting product gas. Flow rate can be measured using an orifice plate, a pitot tube, or a rotameter. An orifice plate works by inserting a constriction in the pipe and measuring the pressure drop across it. This pressure drop can be calibrated accurately to the flow rate of the gas in the pipe. A pitot tube is an open-ended tube inserted in the pipe facing into the direction of fluid flow. The moving gas exerts a pressure on the pitot tube, and this pressure can be measured and calibrated to the gas flow rate. A rotameter has a moving float that is suspended by the force of the gas flowing past it. Based on the

height of the float a calibration can be created to determine the flow rate of the gas. Because all of these options were comparable in price, the team chose to use a rotameter because it is the simplest to install and to read.



www.EngineeringToolBox.com

Figure 2-16 Orifice Plate

http://docs.engineeringtoolbox.com/documents/493/orifice_plate.gif

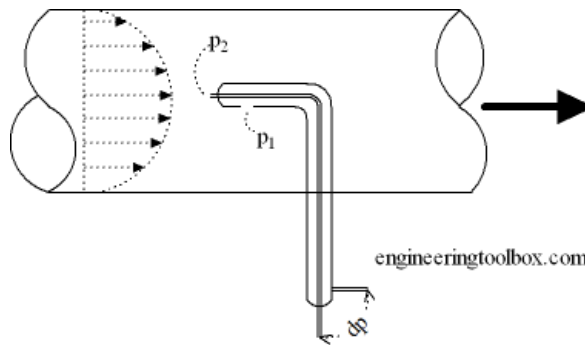


Figure 2-17 Pitot Tube

http://docs.engineeringtoolbox.com/documents/612/pitot_tube.png

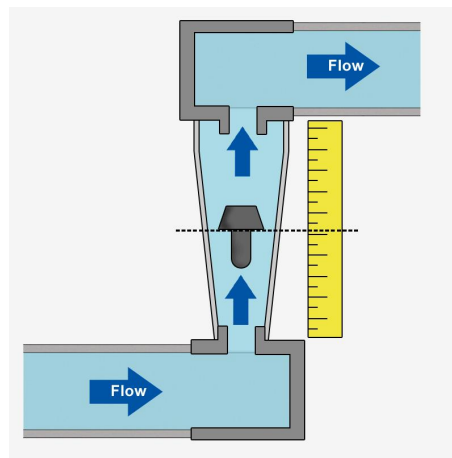


Figure 2-18 Rotameter

http://alicat.com/images/rotameter_big.gif

The synthesis gas rotameter and the steam rotameter were calibrated using air. These calibrations were performed by connecting the rotameter to the shop compressed air to supply a constant flow rate of air. Then the rotameter was held underwater and the air coming out of the water was directed into an inverted graduated cylinder that was also full of water. By measuring the time required to fill the graduated cylinder it was possible to estimate the flow rate of the air and create a correlation between the rotameter reading and the actual flow rate. The rotameters used for the air feeds had gradations for air flow rate, which could be read directly without additional calibration. The data for the calibrations is in Section 12.6 in the Appendix. These calibrations with air can be converted to use with synthesis gas or steam using the correction factor below (Washington University School of Engineering and Applied Science):

$$Correction\ Factor = \sqrt{\frac{PT_{standard}M_{wt\ g}}{P_{standard}TM_{wt\ air}}}$$

where P and T are the actual pressure and temperature, $P_{standard}$ and $T_{standard}$ are the standard temperature and pressure, and $M_{wt\ g}$ and $M_{wt\ air}$ are the molecular weights of the gas in the rotameter and the air, respectively.

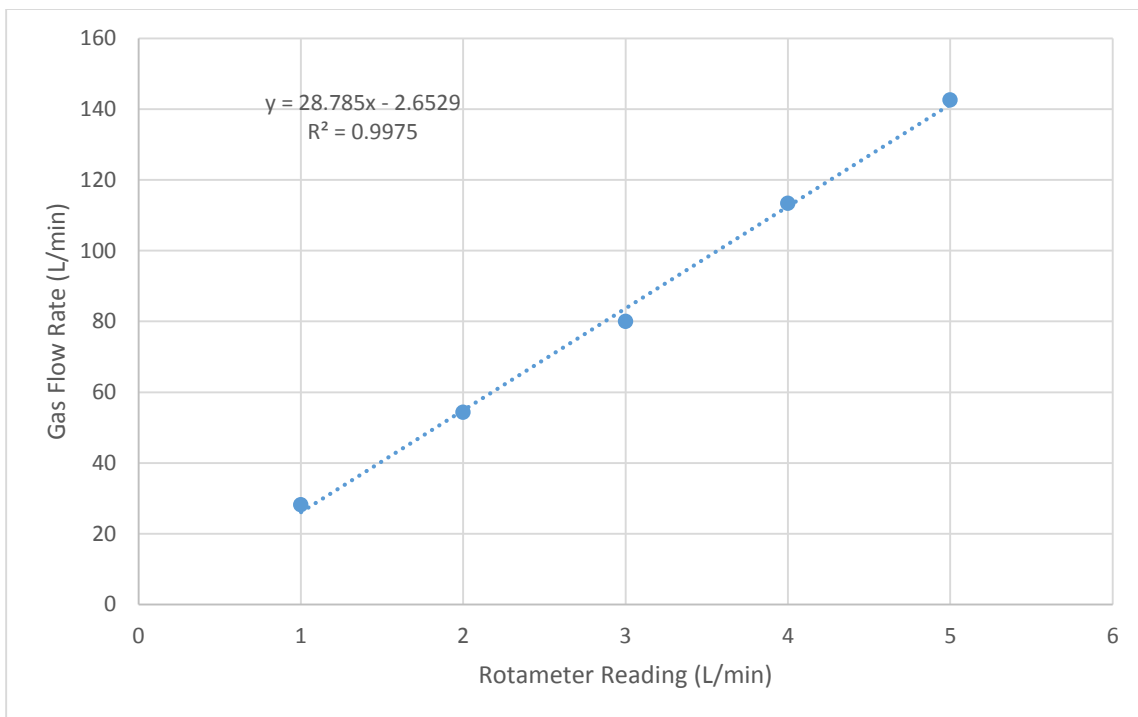


Figure 2-19 Synthesis Gas Rotameter Calibration

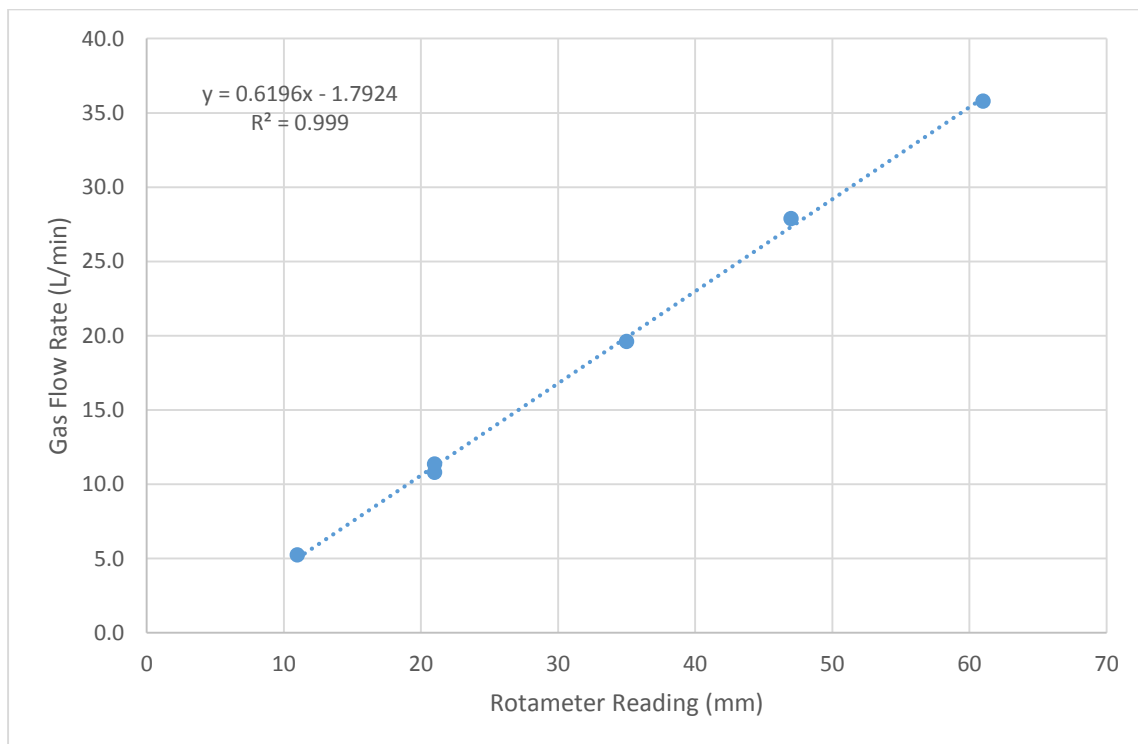


Figure 2-20 Steam Rotameter Calibration

2.16.2 Temperature

The temperature inside the reactor was measured using high temperature thermocouples inserted into the probe tubes. The specific model of thermocouple was selected after speaking with a representative from OMEGA (www.omega.com) and asking for advice on which model would best fulfill the project requirements. The team chose a combination of two types of thermocouples. First, a XCIB Series K-Type High Temperature Inconel Overbraided Ceramic Fiber Insulated Thermocouple with Style 5 probe was chosen because it met the temperature requirements and had a flexible design. This thermocouple could be moved up and down in the reactor so that temperature was measured at different heights. The downside to this design is that the end of the probe is grounded, which makes it susceptible to electrical interference and can therefore result in less accurate temperature readings. Additionally, since this thermocouple would be moveable, it would not be able to be directly affixed to the wall of the probe tube and thus there would be some temperature difference due to heat transfer through the air in the probe tube. Therefore, the team also purchased a ¼" TJ36 Series Rugged Heavy Duty Transition Joint Thermocouple Probe with an ungrounded probe. This thermocouple was to be attached to the wall of the probe tube using heat transfer cement to give a very accurate temperature reading at the upper combustion zone. This is the hottest area of the reactor. Inserting the thermocouple at this location would ensure that the temperature there never exceeded the maximum operating temperature. Additionally, it would allow a comparison between measurements from the XCIB Thermocouple to give a sense for the difference in accuracy between the two thermocouple types. The team did not get a chance to install the TJ36 thermocouple before the end of the semester.

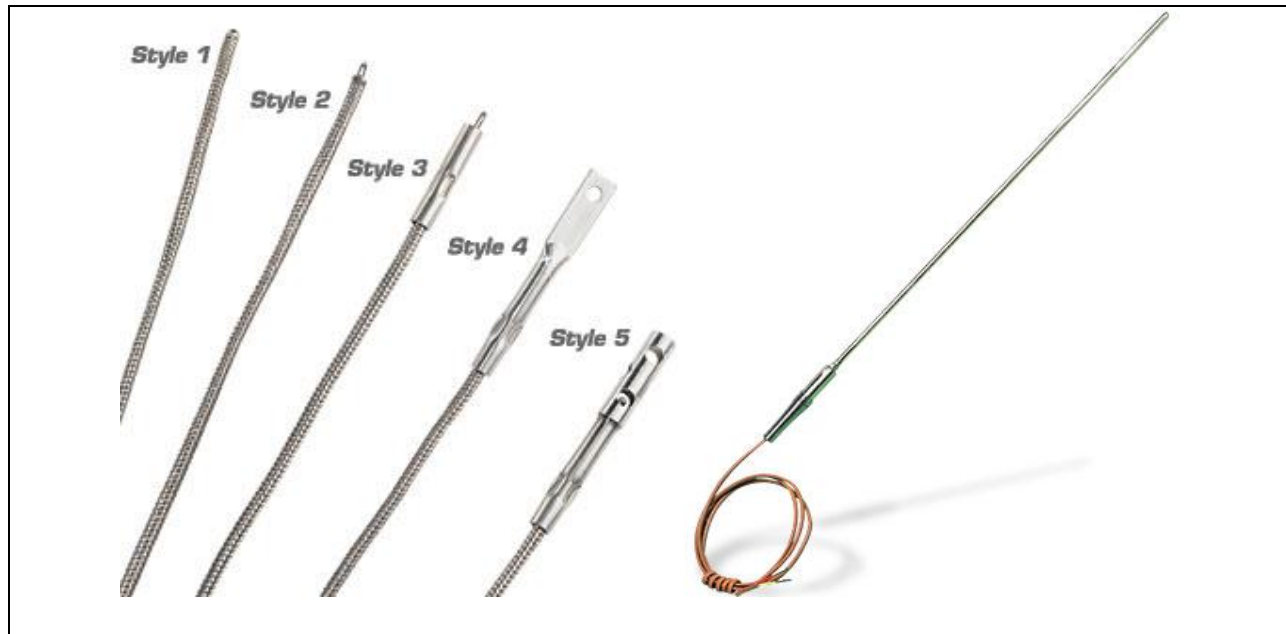


Figure 2-21 XCIB Series Thermocouple (left) and TJ36 Series Thermocouple (right)
<http://www.omega.com/pptst/XCIB.html>, <http://www.omega.com/pptst/TJ36-ICIN.html>

Once the team received the thermocouples, they obtained a calibration for K-type thermocouples. However, the team wanted to ensure that the calibration was accurate for their specific thermocouples so they created an independent calibration for comparison. Using the small oven in the Thermodynamics Lab they were able to measure temperatures up to 800°C and create a calibration curve. The data for each of the two thermocouples is compared to the manufacturer supplied calibration in Figure 2-22. Based on the results of this test the team felt confident using the literature calibration since they agreed with their experimental results and included data for temperatures above 800°C.

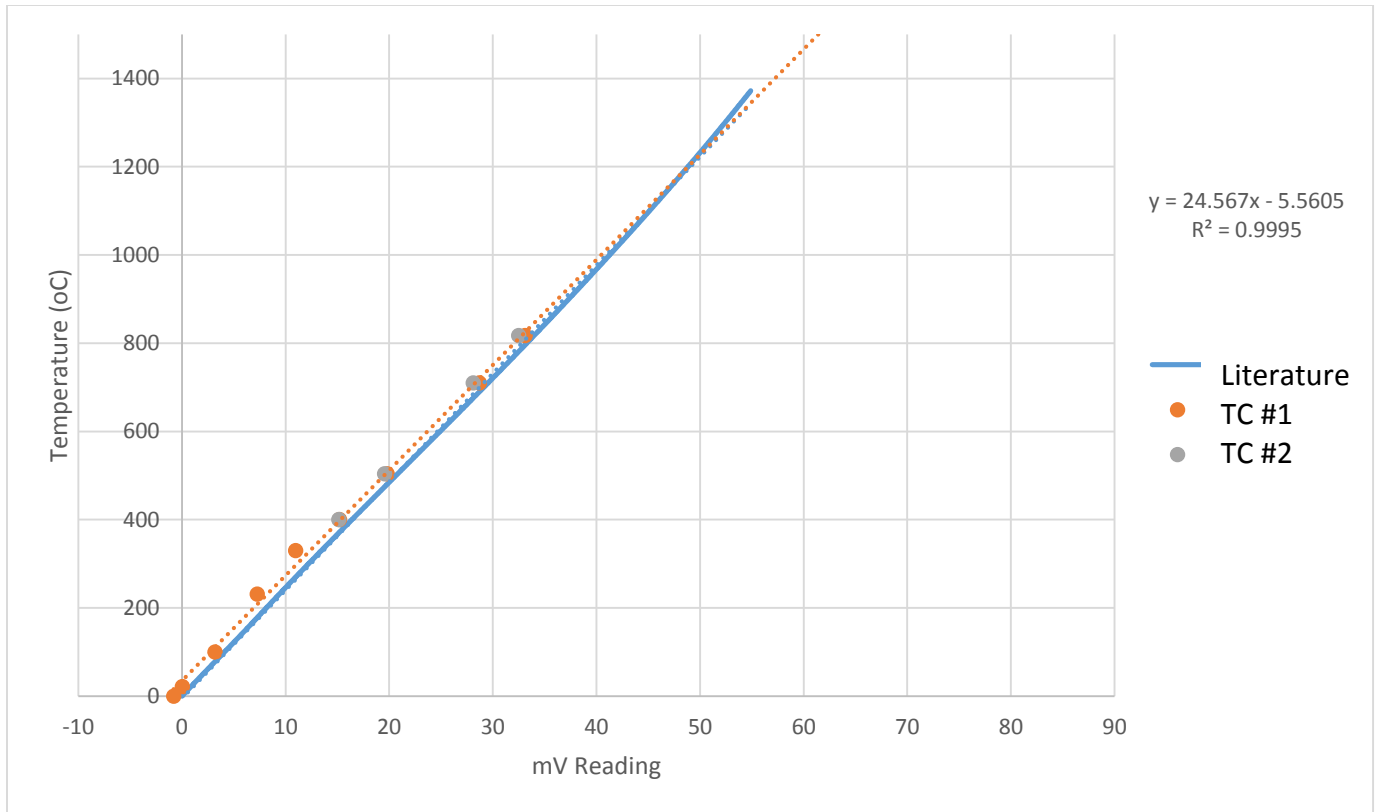


Figure 2-22 K-Type Thermocouple Calibration Data Compared to Literature Data

2.16.3 Pressures

The pressure in the reactor and in the pilot plant is measured by installing water manometers made of flexible plastic tubing. This tubing is connected to the reactor using a length of steel pipe with a barbed end. The pressure is measured in inches of water. The team did not have time to install the manometers before the end of the semester.

2.17 Pallet

All portions of the design, including the reactor, heat exchanger, sampling apparatus, and flare, operate most effectively in close proximity to each other. Keeping the pilot plant in a small area also is beneficial when considering how the gasifier might be used in a residential setting to power a home. For the purposes of the pilot plant, the design must also be easily transported in and out of the engineering building between testing periods. In order to satisfy these requirements, the team decided

to design the system to fit on a wood pallet 48 inches on each side. Other spatial requirement possibilities certainly exist and might be better for a final product permanently installed outside of a home. However, for use in this project, BIOburners was able to obtain a wooden pallet from Calvin College physical plant. This pallet was suitable for the purposes of this project and provided the advantage of being easily moved between testing and storage locations with the aid of a pallet jack.

2.18 Physical Layout

How the reactor, heat exchanger, sampling apparatus, flare, and other portions of the pilot plant were arranged on the pallet was another consideration for BIOburners. In order to ensure that the gasifier was as safe to operate as possible, the team decided to try to keep all the high-temperature portions of the pilot plant on one side of the pallet and the remaining, cooler portions of the gasifier, with which they were more likely to interact, on the other side. A photograph of the pilot plant is shown in Figure 2-24 below. The reactor (along with its support system) and 55-gallon drum heat exchanger take up the majority of the space on the pallet. On one side of these two portions of the design is the flare, which will be operating at high temperatures. The pipe containing hot synthesis gas enters the heat exchanger on this side of the pallet as well. The sampling apparatus, door to the ash removal system, and hinged door of the heat exchanger are located on the opposite side of the pallet. Rotameter and thermocouple readings can also be obtained from this side of the unit. Designing the physical layout of the pilot plant on the pallet in this way decreases the likelihood that team members are burned while operating the gasifier since they will be recording data, obtaining samples, and emptying ash in areas that are farther from high-temperature areas. Details regarding the specific pipe lengths required to assemble the gasifier are described in Section 12.3.1 in the Appendix.

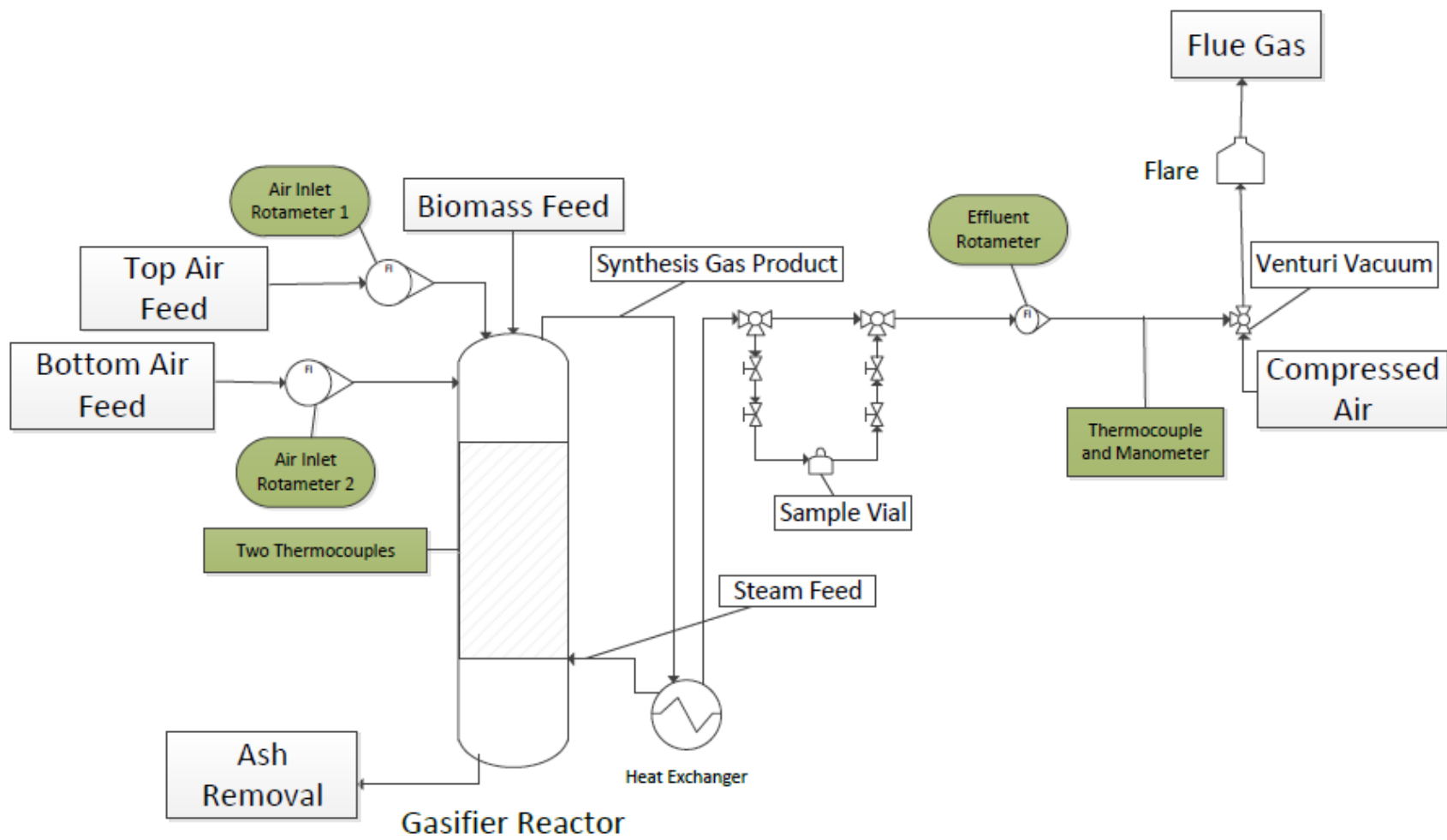


Figure 2-23 Initial Pilot Plant Design Process Flow Diagram



Figure 2-24 Assembled Pilot Plant

3 Pilot Plant Operation

The pilot plant was operated on six occasions for a total of approximately five hours. Several changes in the pilot plant took place over the course of testing in an attempt to improve the operation of the pilot plant. The first three times the pilot plant was started up without insulation installed around the reactor because the team wanted to see how the heat distributed around the reactor. Furthermore, BIOburners knew that the reactor would cool down much more quickly without insulation should any problems be encountered. The team was very careful to not get too close to the reactor body while the insulation was not installed. In addition, the heat exchanger was removed after the third operation of the gasifier when the team discovered it was not functioning to produce steam. The method of sealing the ash door changed several times as the team searched for the best method. The runs occurred between March 29 and April 11, and the events of each test are described below.

3.1 Operation 1: March 29

As this was the first operation of the gasifier, the primary goal for this test was to try to get the gasifier up and running. This included proving that air was being pulled into the gasifier, that the combustion zones were reaching the desired temperatures, and that the product gas could be combusted.

Operators: Matt Lomasney and Nate Myton

Experimental Conditions:

1. No insulation
2. No hopper (after filling reactor with pellets, biomass feed pipe sealed with duct tape during operation)
3. Tar traps not installed
4. Heat exchanger installed
5. Ash door sealed with hinged door and foam gasket
6. Air fed to both combustion zones
7. Both combustion zones lit with butane torch
8. Operated for approximately 30 minutes

Observations:

1. The top combustion zone peaked at 500°C.
2. The bottoms combustion zone heated up very quickly, achieving a temperature of 1300°C.
3. Smoke was produced and exited from the flare.
4. The flare could not be lit.
5. Steam was not produced.

From these observations, we concluded that the venturi was successfully pulling air into the reactor and allowing for gasification of the biomass and was very pleased with this. However, the flare was unable to be lit. Due to the short operating period, we wanted to run more tests before making further conclusions. Additionally, we were not too concerned with the lack of steam production because of the short period of operation and because the synthesis gas was exciting the reactor at a much cooler temperature than desired due to the lack of insulation.

3.2 Operation 2: March 31

Due to the fact that the gasifier was run for such a brief period of time during the first operation and that Eric and Nicole were not present, no operational modifications were made for this test run.

Operators: Eric Sager, Matt Lomasney, Nate Myton, and Nicole Michmerhuizen

Experimental Conditions:

1. No insulation
2. No hopper
3. Tar traps not installed
4. Heat exchanger installed
5. Ash door sealed with hinged door and foam gasket
6. Air fed to both combustion zones
7. Both combustion zones lit with butane torch
8. Operated for approximately 30 minutes

Observations:

1. The top combustion zone peaked at 500°C.
2. The bottoms combustion zone heated up rapidly to 1000°C.
3. During shutdown, the temperature continued to increase because the ash door was open.
4. Smoke was produced and exited from the flare.
5. The flare could not be lit.
6. Steam was not produced.
7. Ash was not exiting through the grate.

The bottom combustion zone heated up much more quickly than we anticipated. Furthermore, we only planned on operating the bottoms combustion zone around 800 or 900°C, but the temperature was 1000°C. Because of this, BIOburners shut off the bottoms air feed during operation, but the bottom combustion zone temperature continued to increase, albeit at a decreased rate. The reactor was shut down by disconnecting the compressed air feed from the venturi. The bottoms temperature then began to decrease. After some time, the ash door was opened to determine how much ash had dropped through the grate. To BIOburners' surprise, the ash duct contained almost no ash, suggesting that the grate was not allowing ash to drop through. Additionally, we had been monitoring the bottoms temperature closely to ensure that it cooled to an acceptable level. However, we noticed that the bottoms temperature increased when the ash door was left open, even when the venturi was not running. Looking into the gasifier through the port hole, we saw that the bottoms combustion zone was still glowing red hot. BIOburners hypothesized that enough air entered through the ash door to sustain the combustion of the biomass even without the venturi vacuum. The ash door was immediately sealed with duct tape and the bottoms temperature began dropping once again.

This operation prompted several changes in the pilot plant. First, the team was convinced that a substantial amount of air was leaking into the bottom of the gasifier through the ash door. The hinged door and gasket material were removed and replaced with duct tape, sealing the opening. Furthermore, BIOburners decided that the gasifier should not be left unattended with the ash door open, as this could sustain biomass combustion while no one was present to supervise the gasifier.

3.3 Operation 3: April 1

The goal of this operation was to test the improved ash door seal. Only the top combustion zone was lit, and the team hypothesized that the bottoms combustion zone would not get hot during operation if the seal quality had been improved as desired.

Operators: Eric Sager, Matt Lomasney, Nate Myton, and Nicole Michmerhuizen; Nate's parents present

Experimental Conditions:

1. No insulation
2. No hopper
3. Tar traps not installed
4. Heat exchanger installed
5. Ash door replaced with duct tape
6. Air fed only to top combustion zone
7. Top combustion zone lit with butane torch; bottom remained unlit
8. Operated for approximately 60 minutes

Observations:

1. The top combustion zone peaked at 500°C.
2. The bottom combustion zone did not exceed 150°C.
3. Smoke was produced and exited from the flare.
4. The flare could not be lit.
5. Steam was not produced.

From this run, BIOburners determined that air leaks were likely still present in the ash duct. However, we were confident that the duct tape was sealing the door adequately. Nate's mother suggested a method to test for air leaks in the system called the "soapy water" test. This method involved duct taping over the flare while the gasifier was cool and then cracking the compressed air feed. This resulted in a slight pressurization of the system. Soapy water was administered to the suspect leaky areas of the gasifier and bubbles appeared if a leak was present. This method was first used following the fifth operation.

3.4 Operation 4: April 3

On April 2, BIOburners installed insulation around the reactor and installed the biomass feed hopper. Nate and Eric attempted to start up the gasifier, but were unsuccessful because water had leaked into the heat exchange pipes. When they turned on the compressed air feed, water shot out of the flare because the pipes were completely filled with water. The pilot plant piping and heat exchanger were completely disassembled and the tar was cleaned out of the pipes. The pipes were then reassembled without the heat exchanger to prevent water from leaking into the pipes. Although the temperature control method had been removed, this was not considered a deterrent to the project because the synthesis gas was not exiting the reactor at high enough temperatures to require significant

cooling. Furthermore, the team was not successful in producing steam in any of the previous trials, so the functionality of the heat exchanger was not sacrificed. The pilot plant was started up later that night, with a goal of seeing how the reactor operated differently with the insulation and feed hopper installed.

Operators: Eric Sager, Matt Lomasney, Nate Myton, Nicole Michmerhuizen, and JP Speyart van Woerden

Experimental Conditions:

1. Insulation installed
2. Hopper installed
3. Tar traps installed
4. Heat exchanger removed
5. Ash door sealed with duct tape
6. Air fed only to top combustion zone
7. Top combustion zone lit with butane torch; bottom combustion zone remained unlit
8. Operated for approximately 90 minutes

Observations:

1. More tar was produced than expected.
2. The flare could sustain a flame with low vacuum and thus low air feed.
3. The top combustion zone peaked at 600°C.
4. Bottom combustion zone started out near room temperature, then suddenly spiked above 500°C.

Since the bottom combustion zone temperature increased quickly and reached nearly 500 °C the team concluded that there must still be air leaks in the ash duct. BIOburners determined that duct tape did not provide an air tight seal to the ash duct, especially when the gasifier was run for extended periods of time. The excessive tar production observed was likely the result of a number of factors. For one, the pipes had just been washed out and were therefore quite wet. Since the water vapor in the pipes condensed in the tar traps, the tar production appeared to be significantly more than expected. Moreover, because this was the first run with insulation the tars that had been building up in the reactor were vaporized as higher temperatures were attained. These vaporized tars were then condensed in the tar traps.

3.5 Operation 5: April 6

Instead of duct taping around the edges of the flimsy swinging door of the ash duct, BIOburners fabricated a flat metal plate of the appropriate size to completely cover the ash duct opening. This plate was sealed to the opening with duct tape to better prevent air leaks that originally resulted from the rivets in the swinging door. The goal of this test was to both evaluate this method of sealing the ash grate and also to determine if steady state operation could be reached.

Operators: Eric Sager, Matt Lomasney, and Nicole Michmerhuizen

Experimental Conditions:

1. Insulation installed
2. Hopper installed
3. Tar traps installed
4. Heat exchanger removed
5. Metal plate taped over ash door
6. Air fed only to top combustion zone
7. Top combustion zone lit with butane torch; bottom combustion zone remained unlit
8. Operated for approximately 30 minutes

Observations:

1. Minimal tar
2. The top combustion zone peaked at 600°C.
3. Bottom combustion zone remained near room temperature.
4. Smoke leaked out of the manifolds and pipe fittings in the synthesis gas exit pipe after banging on reactor to eliminate possible bridging.
5. Detailed observations and temperature data found in Section 12.9 in the Appendix.

During operation, the reactor's temperature appeared to be rising steadily. It appeared as though the product gas pipe was especially hot. Operation seemed to be going smoothly for a period of time until suddenly the upper combustion zone temperature stopped increasing at around 700 °C. It was suspected that bridging was causing the problem. To break up the bridging biomass bed, Matt struck the synthesis gas exit pipe with a pipe wrench several times. Within seconds, both the synthesis gas manifold and some of the fittings on the synthesis gas exit pipe began leaking smoke. As a result of the inexplicable smoke leaks, the reactor was shut down before reaching steady state.

One possible explanation for the smoke was that once the pipe was struck, air began to leak into the manifold which caused biomass in the pyrolysis zone to burn. Air leaks could also explain why the temperature in the upper combustion zone stopped rising. Another possible reason that the temperature stopped rising was that the caps had fallen off the air feed and synthesis gas tubes below the grate. The team used the soapy water test to determine if air leaks were present and found several significant leaks at the manifold, the ash duct, and the tar traps. BIOburners attempted to fix this problem by putting more high-temperature caulk on the ash duct and applying other sealing agents to the manifolds. These sealing agents included Xtreme Liquid Steel and Gorilla Tape.

3.6 Operation 6: April 11

The purpose of this experiment was to evaluate the performance of the new seals. BIOburners was hoping to reach the desired top combustion zone temperature of 1200°C.

Operators: Eric Sager, Matthew Lomasney, Nate Myton, and Nicole Michmerhuizen

Experimental Conditions:

1. Insulation installed
2. Hopper installed
3. Tar traps installed
4. Heat exchanger removed
5. Metal plate taped over ash door
6. Air fed only to top combustion zone
7. Top combustion zone lit with butane torch; bottom combustion zone remained unlit
8. Operated for approximately 30 minutes.
9. Ignition port opened after 30 minutes to fix bridging.

Observations:

1. The flare could sustain a flame with the port hole open, but not when it was closed.
2. The top combustion zone peaked at 690°C.
3. The bottom combustion zone remained cool during operation.
4. Minimal tar in the tar traps.
5. Flare ceased to be self-sustaining after closing the ignition port.
6. After opening the ignition port during operation a flame shot out.
7. Detailed observations and temperature data found in Section 12.9 in the Appendix.

During operation the gasifier appeared to be performing well. However, after about 30 minutes the reactor had not reached 1000°C so the team suspected that bridging may be occurring. They

opened the ignition port investigate the problem, but while the port was open a flame shot out of the ignition port, burned Matt, and ignited the outside of the gasifier. The gasifier was shut down immediately. The full details of the safety incident are reported in Section 12.10 in the Appendix. Due to this event no further testing was performed.

It was extremely surprising that a flame would exit the ignition port because the gasifier is operated under a vacuum. This means that when the ignition port is open air will be drawn into the reactor instead of pushed out of the reactor. The best explanation for the flame was that some of the bridged biomass suddenly dropped, compressing synthesis gas which flowed out of the opening and caught fire. However, because the team could not guarantee that this event would not happen again without significant redesign. In light of this, Professor Wentzheimer recommended that the experimental plan be suspended and that the team focus on redesigning the pilot plant so that such an incident not happen again.

4 Pilot Plant Redesign

Based on the problems the team experienced during operation of their initial pilot plant design, this gasification process was redesigned to operate more effectively, efficiently, and safely. The team focused the design changes on the manifold system (particularly related to the inlet air flow), steam feed, feed hopper, and ash removal system. The design criteria highlighted in Section 2.1 above were still of the greatest importance in their design decisions.

The HAZOP and operating procedures for the original design were updated for the redesigned gasifier and can be found in Sections 4.8 and 4.9 below.

4.1 Disassembly

After BIOburners completed the testing of there were many questions that could not be answered without disassembling the reactor. One of the chief questions was whether or not bridging was occurring. There had been discussion of bridging as a potential explanation for why the reactor was not reaching the desired temperature. Therefore the team looked for areas of the biomass bed that appeared to be bridging. Additionally, BIOburners feared that ash was not falling through the ash grate. This was suspected due to minimal ash found in the collecting duct. The reactor was disassembled and the result is shown below in Figure 4-1, Figure 4-2, and Figure 4-3. Finally the team was very concerned with the amount of tar production. As mentioned in Section 1, tar production is a key design criteria, therefore minimizing the amount of tar in the system was crucial. Therefore in disassembly BIOburners carefully inspected the entire pilot plant for signs of tar.

Figure 4-1 shows the biomass bed within the tube shell during gasifier disassembly. It is clear from this picture that there are several empty spaces where biomass had burned away adjacent to areas of uncharred biomass. This is conclusive evidence that there was massive bridging occurring in the gasifier.



Figure 4-1 Evidence of Bridging in Gasifier Disassembly

Figure 4-2 and Figure 4-3 are related to problems with ash discovered during gasifier disassembly. Figure 4-2 displays that the ash grate was plugged with biomass so that the ash could not fall through into the ash duct to be removed. Figure 4-3 shows mixed charred pellets and a large quantity of ash that had not fallen through the grate and instead built up in the reactor bed. Due to the problems with ash removal, the grate was an area of redesign.



Figure 4-2 Plugged Ash Grate Observed in Gasifier Disassembly



Figure 4-3 Charred Pellets and Ash Observed in Gasifier Disassembly

Figure 4-4 clearly shows that there were large tar deposits in the synthesis gas manifold. The tar traps downstream of the manifold also contained large quantities of tar. Therefore in the redesign it was necessary to account for this tar production problem. The likely reason for the high tar production was the low operating temperature of the gasifier. At low temperatures tars are not cracked and therefore large quantities of tars are able to build up.



Figure 4-4 Synthesis Gas Manifold with Tar Deposits

The final concern was that the pipes would deform under the high temperature conditions of the combustion zone. Figure 4-5 below shows that there was very little deformation of the pipes. Therefore no changes were made in the material used in the stainless steel tubes.



Figure 4-5 Pipes in Disassembled Gasifier

4.2 Manifold

The portion of the gasifier that required the most significant modifications was the manifold system. Changes were made to both air and synthesis gas manifolds; the most significant changes, however, took place for the air feed. There were three primary problems with the pilot plant manifold system. First, the constriction through the pilot plant manifold system to deliver the feed pellets to the reactor was about 1.5 inches in diameter and presented many opportunities for bridging. Second, the manifold did not deliver enough air to the top combustion zone, which prevented the temperature in this region from reaching the desired level. The lower combustion zone has a much lower temperature than the top combustion zone, so the insufficient air feed was not as problematic in this region. Because the temperature was not as hot as desired in the top combustion zone, however, large amounts of tar built up in the reactor. Third, the original manifold design required metal-to-metal junctions that could not be welded and which were sealed with caulk and tape. These seals made it difficult to keep air from leaking into the system, which reduced the effect of the vacuum created by the venturi and thereby contributed to the problem of insufficient air feed.

In the redesign, three alternatives to the original manifold design were evaluated. The first alternative used tubes on the outside of the reactor body rather than in the biomass bed; the second employed feeds directly into each combustion zone; the last alternative was a modified version of the original design with fewer tubes of larger diameter.

These designs were considered according to the original criteria for the manifold system (flexibility, seal quality, and ease of manufacturing). Potential for bridging and heat exchange were additional criteria considered in the redesign of the manifold. Flexibility was weighted somewhat less highly than in the original decision matrix because BIOburners did not anticipate constructing, operating, disassembling, modifying, and reassembling the redesigned gasifier as they did when making design decisions for the initial pilot plant.

Design Alternative 1: External Tubes

Advantages:

- Fairly easy to construct
- Good seal quality
- Very flexible
- Little potential for bridging

Disadvantages:

- Minimal heat exchange between entering air and biomass

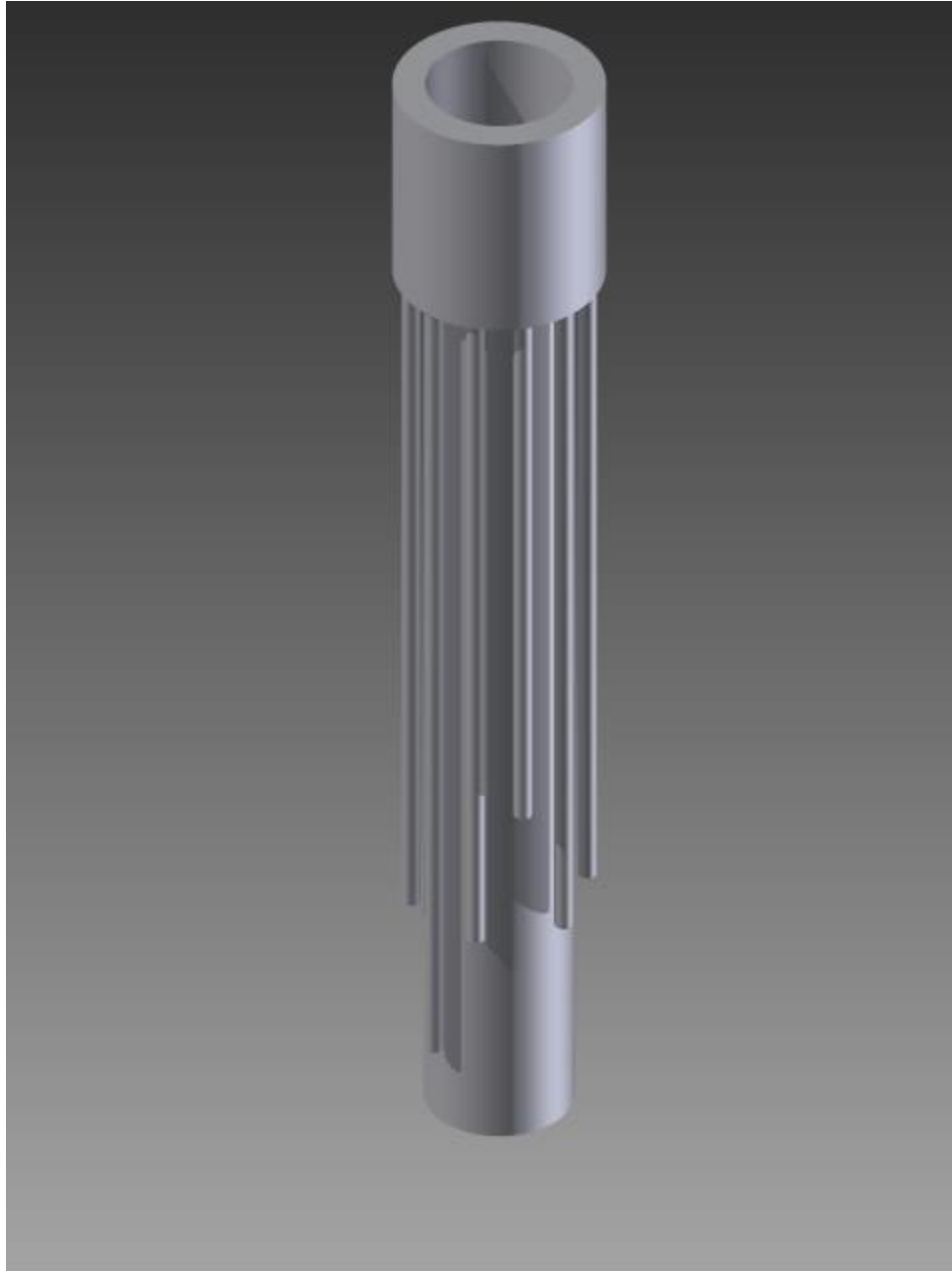


Figure 4-6 External Tubes Manifold Design Alternative

Design Alternative 2: Air Feed Directly to Each Combustion Zone

Advantages:

- Fairly easy to construct
- Good seal quality
- Very flexible

- Little potential for bridging

Disadvantages:

- No heat exchange between entering air and biomass

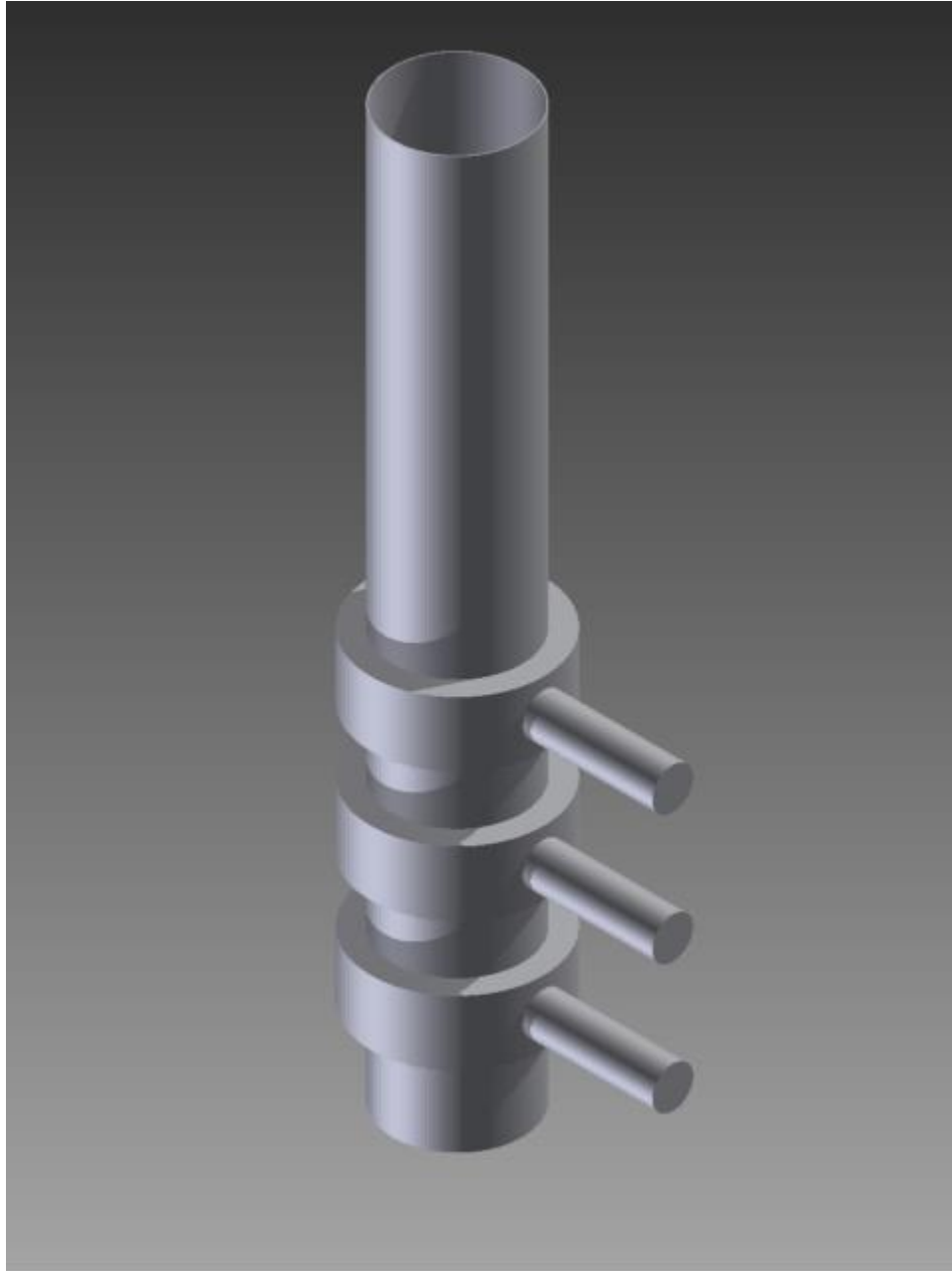


Figure 4-7 Air Feed Directly to Each Tube Design Alternative

Design Alternative 3: Modified Original Design

Advantages:

- Easier to construct than original manifold design
- Improved seal quality due to use of welding rather than tape and caulk
- More flexible than original manifold design due to decreased number of pipes
- Little potential for bridging due to increased diameter of biomass feed pipe
- Maintains spirit of original design
- Allows heat exchange between entering air and biomass

Disadvantages:

- Less flexibility than other redesign alternatives
- More difficult to construct than other redesign alternatives

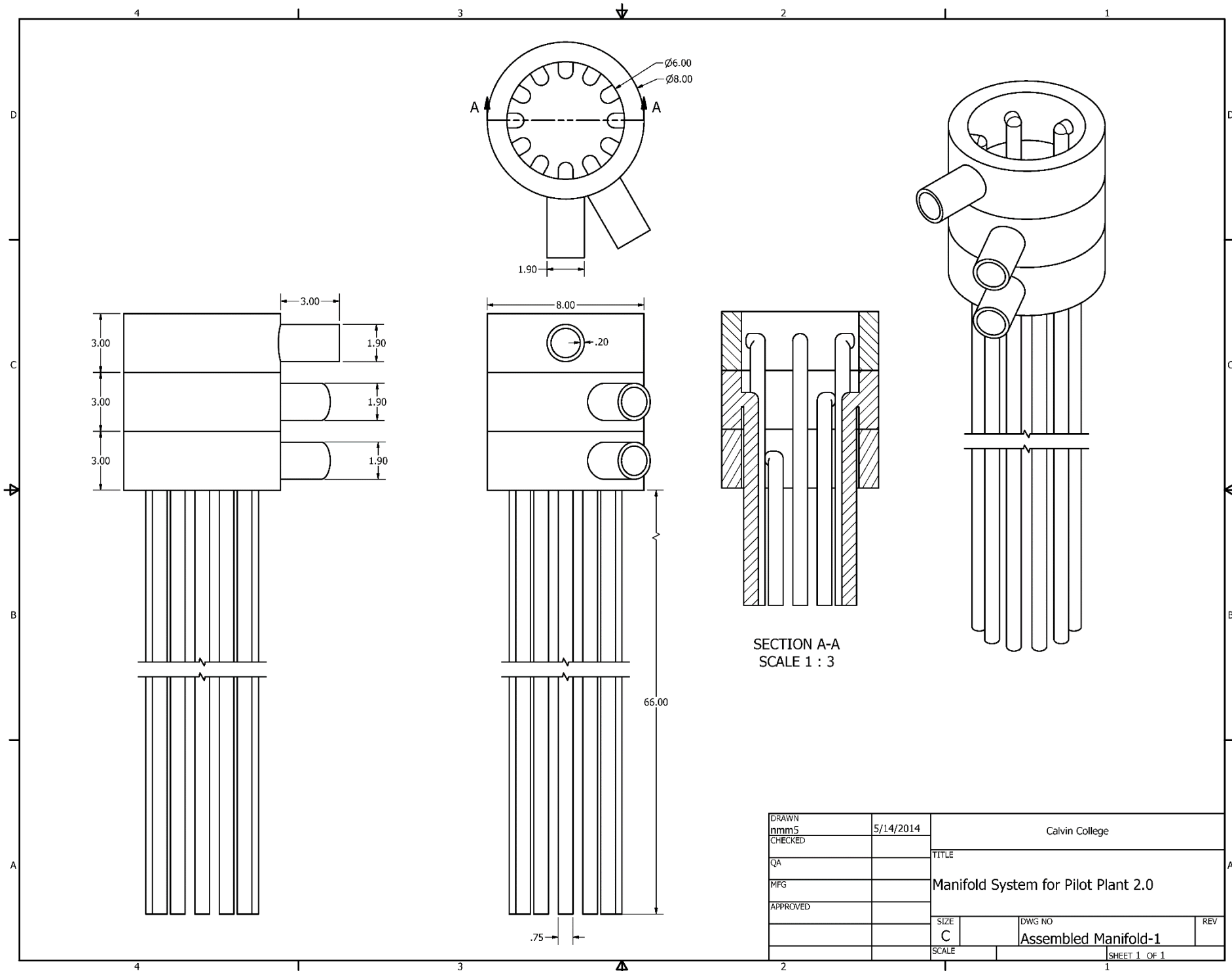
Table 4-1 Redesigned Manifold Decision Matrix

	Flexibility	Seal Quality	Ease of Manufacturing	Potential for Bridging	Heat Exchange	Total
Category Weight	x2	x2	x1	x2	x3	
Original Manifold Design	2	2	1	1	3	17
External Tubes	3	3	3	3	1	24
Feed to Each Zone	3	3	3	3	1	24
Modified Original Design	2	3	2	3	3	28

Selected Design Alternative: Modified Original Design

Based on a comparison of the design criteria using a decision matrix shown in Section 2.5.2, the modified version of the original manifold system was chosen for the redesign of the pilot plant. This design is shown in Figure 4-8 and Figure 4-9. This manifold will use 12 tubes with 3/4 inch outer diameter rather than 27 tubes with 1/2 inch outer diameter. Seven of these tubes will be used to remove the synthesis gas product while five will be used for the air feed. This will result in a reduced

pressure drop in the tubes while maintaining the same area for synthesis gas to travel out of the system and allowing more air to be fed to the reactor. Two of the air feed tubes will deliver to the bottom combustion zone and will be 180° relative to each other. These tubes enter below the grate. An elbow diverts flow to a horizontal section of pipe that is perforated to allow the air flow to diffuse equally. The final three tubes will provide air to the top combustion zone and will be placed at 120° of each other. These three air feeds will provide sufficient distribution of air, so a diffuser system is not needed. Based on calculations for this design found in section 12.5 in the Appendix, this results in 40% more air feed to the top combustion zone at constant vacuum. This will allow the reactor to reach a higher temperature at this level. The air feed will allow 25% of the oxygen required for complete combustion to be fed, which is the equivalence ratio cited in the literature for gasification at temperatures exceeding 1000°C (see Figure 1-4). Reaching a higher temperature will reduce the tar production of the process by thermally cracking the tars. The biomass feed through the manifold will also be much larger than in the original design. By increasing the diameter of the constriction from 1.5 inches to about six inches, the potential for bridging will be greatly reduced. The manifolds will also be constructed with welded seals rather than caulk to eliminate air leaks.



DRAWN	5/14/2014	Calvin College		
CHECKED		TITLE		
QA		Manifold System for Pilot Plant 2.0		
MFG		SIZE	DWG NO	REV
APPROVED		C	Assembled Manifold-1	
		SCALE	SHEET 1 OF 1	

Figure 4-8 Manifold Design

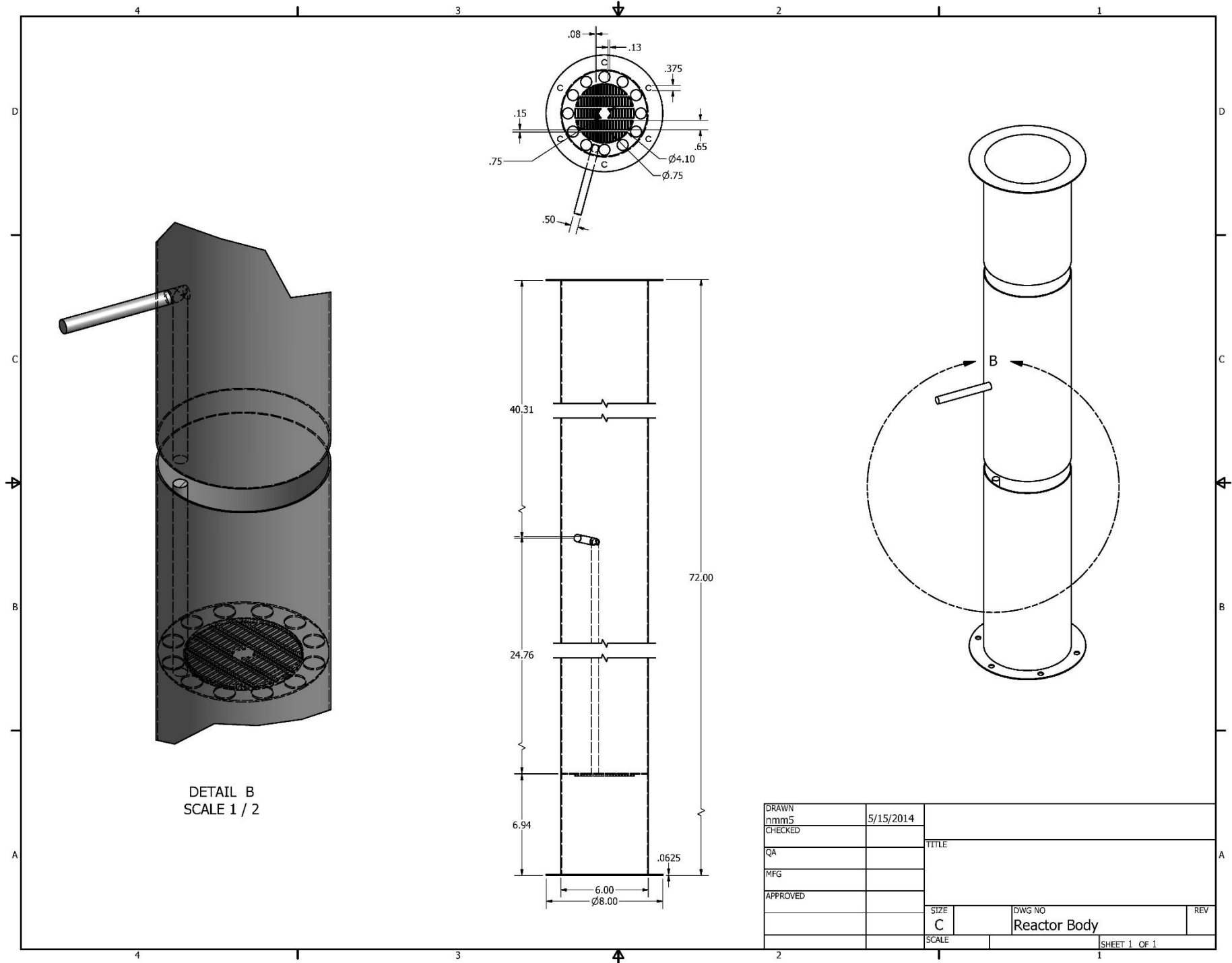
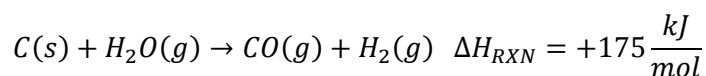


Figure 4-9 Reactor Body and Grate Design

4.3 Steam Feed

The steam feed to the reactor was not operational in the original pilot plant design, in part due to the lower than expected synthesis gas exit temperature. In order to be able to use the steam feed to carry out the water gas shift reaction, a new design was proposed. This design removes the heat exchange function of the original steam feed and thereby simplifies the process. It uses a heating element to bring the water to its boiling point. This design does not cool the synthesis gas, however, this is not a major problem because a metal orifice plate will replace the original design's plastic synthesis gas rotameter.

The steam feed provides a means of consuming the char that builds up in the lower half of the reactor as well as cooling down the reactor. The heating element was sized based on the amount of steam that must be fed in order to consume the lower 10 cm of char in 30 minutes. The char is consumed using the following endothermic reaction.



The calculations detailed in Section 12.3.4 showed that a 1.4 kW heating element would vaporize the required 2L of water per hour. This flow rate of steam would not be used continually during normal operation. Instead, this would be done periodically to purge the lower combustion zone of built-up char and it would be used to cool the reactor when it is shut down. The cooling rate in the combustion zone for a steam feed rate of 2L per hour was calculated assuming the reaction shown above. These calculations are detailed in Section 12.6 in the Appendix. A steam feed rate of 2L water per hour will provide a cooling duty of about 6 kW. This will cool the combustion zone at about 1 °C/s. For example, to cool the combustion zone from 1000°C to 400°C will take about 11 minutes.

This design is slightly less efficient because heat is no longer being recovered from the synthesis gas to produce the steam. This is especially true when the heating element is operating at a full 1.4 kW as this would equate to about half of the total electrical production, reducing efficiency by 50%.

However, this would only occur during shutdown. Additionally, this thermal efficiency is not important in the pilot plant because the pilot plant is only being used for testing and optimizing the design. For this application the heating element will provide highly consistent results which is a higher priority. The steam production for the final design is discussed in Section 7.1.2.

4.4 Feed Hopper

The feed hopper used in the original pilot plant design was effective in housing sufficient biomass for sustained periods of operation, but air leaks in the feed hopper due to poor seals at joints contributed to bridging. Additionally, the small constriction between the feed hopper and gasifier added to this problem. In order to correct these issues, as explained above, the redesigned feed hopper has a much larger constriction of about six inches rather than 1.5 inches, feeding into almost the entire area within the circle enclosed by the air feed and syngas exit tubes. The hopper would also be constructed so as to have greater structural integrity. Welds, rather than rivets and caulk, would be used to ensure there were no air leaks into the system. The body of the hopper would be made of a commercially available 20 gallon steel drum. This drum would already have a lid with a reliable seal and would be modified on the bottom to attach to the reactor. The redesigned feed hopper is shown in Figure 4-10 below.

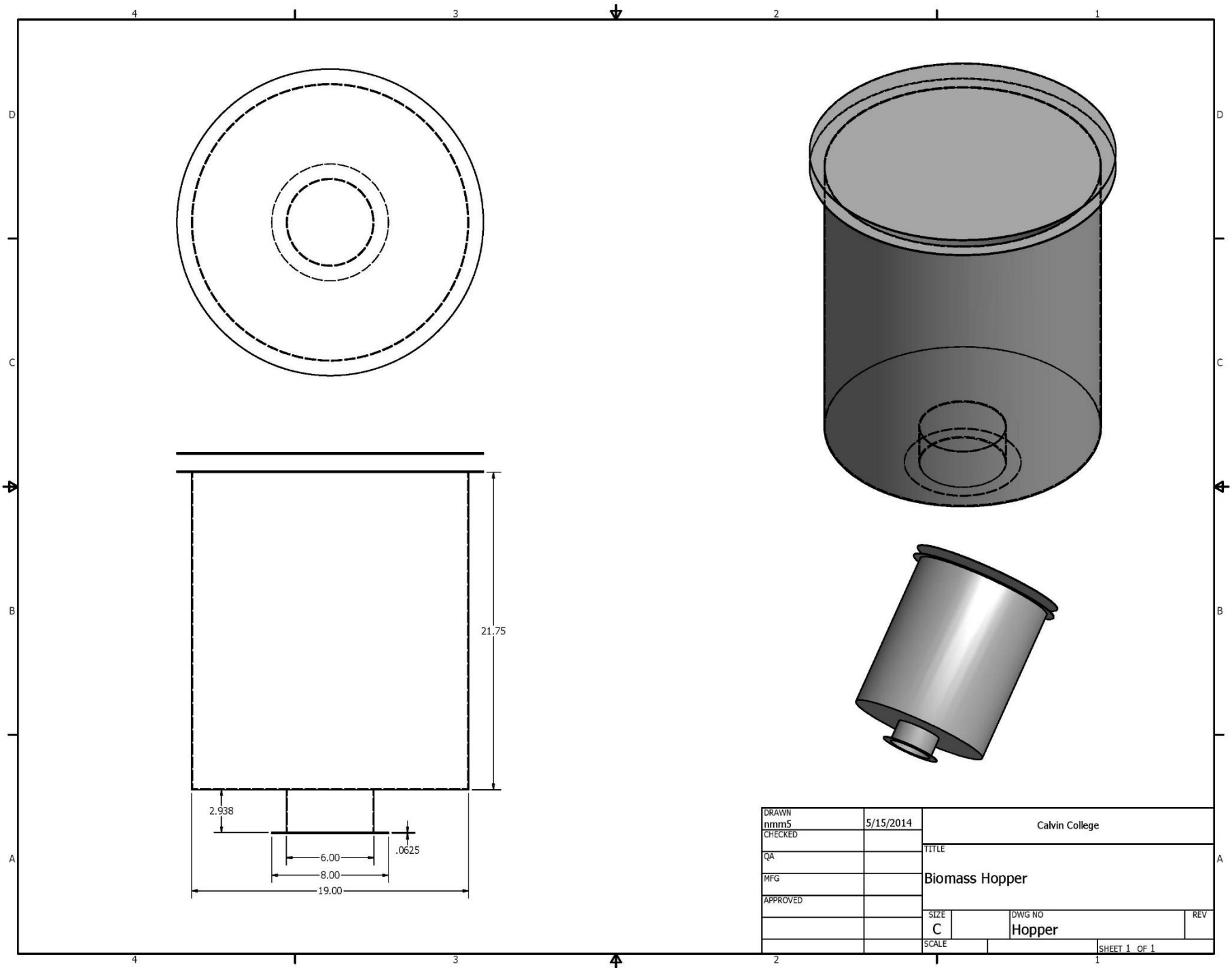


Figure 4-10 Feed Hopper Design

4.5 Ash Removal

The original pilot plant design used a steel plate perforated with 3/8" holes to support the biomass and allow ash to fall through into a duct below the reactor; BIOburners referred to this perforated plate as the "grate." The installed position of the grate in the reactor can be seen in Figure 4-9. While the original design supported the weight of the biomass, it did not allow ash to pass through the perforations. In order to remove the ash and keep it from building up in the reactor, larger holes are needed in the grate. Instead of using a perforated plate, an expanded metal sheet will be used for ash removal in the second pilot plant design. The expanded metal sheet gauge thickness and diamond size need to be determined experimentally, as the properties of the ash change greatly at elevated temperatures and with different amounts of tar and these variables cannot be modeled. Because of this, the expanded metal sheet will rest on top of a sheet metal donut so that the expanded metal can be easily removed and replaced if need be. Moving forward, BIOburners has selected an 18 gauge expanded metal sheet with a 0.5" nominal diamond size. This sheet size will be modified if necessary during the experimental program outlined in Section 6.

4.6 Connections and Fittings

During pilot plant construction, BIOburners learned the importance of the seals used throughout the pilot plant. Poor seal quality resulted in air leaks that introduced many problems during operation. Figure 4-11 shows numbered labels for the fittings and connections in the pilot plant and Table 4-2 details how each junction will be appropriately sealed in the redesigned pilot plant.

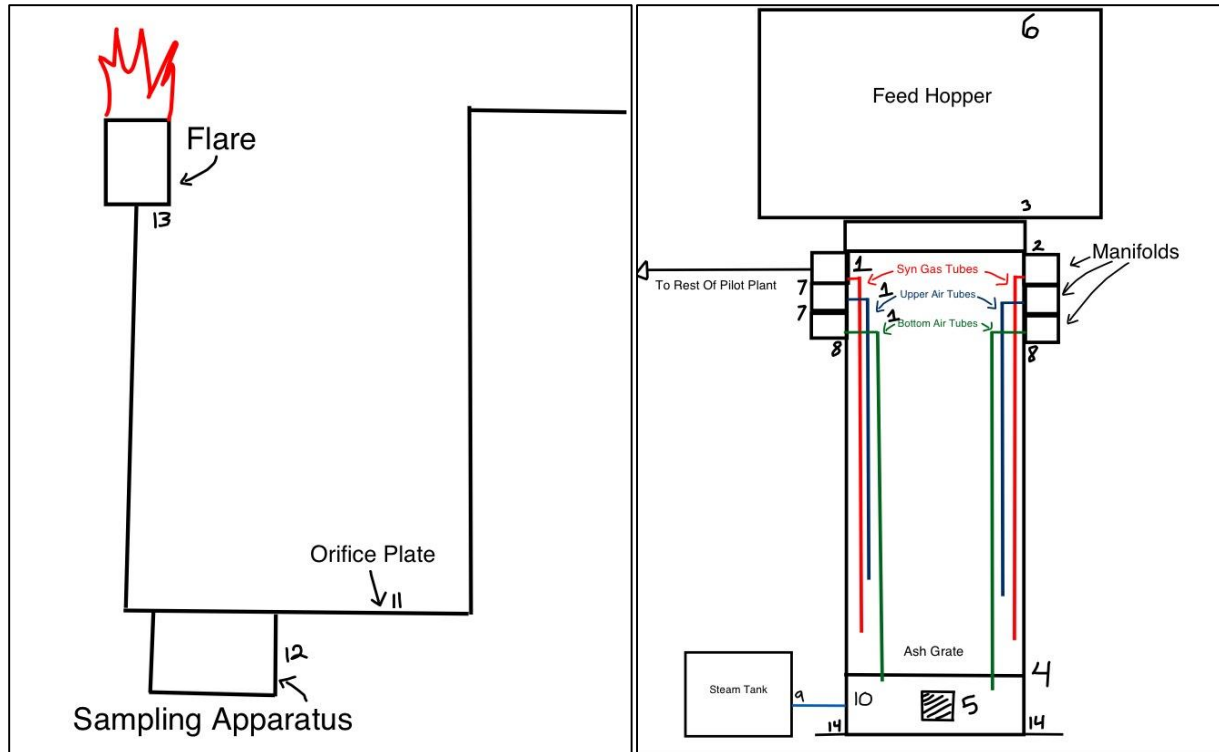


Figure 4-11 Schematic of Pilot Plant Fittings and Connections

Table 4-2 Description and Type of Seals in Pilot Plant

Location	Description	Seal Type
1	The tubes into each manifold. For each tube there is a connection to the manifold and another connection between an elbow and another pipe feeding into the desired location.	Each pipe will be welded into the manifold using TIG welding. Each pipe will be threaded into the elbow.
2	At the top of the reactor there is a 1" flange that will be connected to a 6" diameter pipe with a 1" flange.	Ceramic rope will be used in this connection.
3	The base of the feed hopper will be connected to the top of the 6" diameter pipe.	The feed hopper will be bolted to the flange on the 6" pipe and a ceramic rope gasket will be used to form the seal.
4	The ash grate is supporting the weight of the biomass and must be held in place. All of the tubes pass through the ash grate.	The grate will be held to the reactor using a small welded knob below the grate on the reactor. Additionally the tolerance between the grate holes and the air pipes is very small and thus will provide support.
5	The ash door is made of a flat steel plate that is pressed against the surface of the reactor.	The ash door will be sealed by bolting the flat plate on to the surface of the reactor and using a ceramic rope gasket.
6	The top of the feed hopper must be easily opened to feed biomass while still maintaining an air tight seal when closed.	The 20 gallon drum contains a plug that can be threaded into the top. This threaded plug provides an air tight seal while remaining easy to open and close.

7	The manifolds have 1" of overlap between each manifold. The top manifold overlaps with the 1" flange on the top of the reactor pipe.	The seals will all contain ceramic rope gaskets. The top flange will be held to the bottom manifold using a winch that will hold the manifolds tightly together to provide the air tight seal.
8	The bottom manifold (lower air feed) will be in connection with both the middle manifold (upper air feed) and a 1" flange connected onto the reactor.	Both of these seals will be sealed using ceramic rope gaskets and bolted to the top manifold using a winch to tightly hold the manifold to the flange.
9	The steam tank will be connected to the reactor below the ash grate using a copper pipe.	The copper pipe will be sealed to the steam tank by sending the pipe into a rotameter and bolting that rotameter to the steam tank.
10	The copper pipe will be connected to the reactor beneath the ash grate to feed steam in to the bottom combustion zone.	The pipe will be threaded into a ball valve welded onto the bottom of the reactor to control the flow rate of steam into the reactor.
11	The orifice plate is used to measure the flow rate of product gas. It is constructed in the 1.5" pipe out of the reactor. When using an orifice plate it is also necessary to use a manometer to measure pressure difference.	The orifice plate will be welded into the 1.5" pipe. The manometer will also be welded into the 1.5" pipe.
12	The sampling vial must be attached to the system to take quantitative measurements of both product gas composition and tar content.	The sampling apparatus will be connected using two tees that will be followed by 2 valves. Next there will be 2 unions that will allow the apparatus to be easily removed. Finally the sample will be taken in a 500 mL round-bottom flask. (See Figure 2-15)
13	The flare is used to oxidize the toxic product gas to carbon dioxide.	The flare will be welded on to the vacuum pump.
14	The reactor is 6" wide and 6' tall. Therefore it must be firmly rooted to ensure that there is no risk of falling over, especially at high temperatures.	The bottom of the reactor contains a 1" flange that will be bolted to the docking station. Ceramic rope will be placed between the flange and the docking station to provide a better seal.

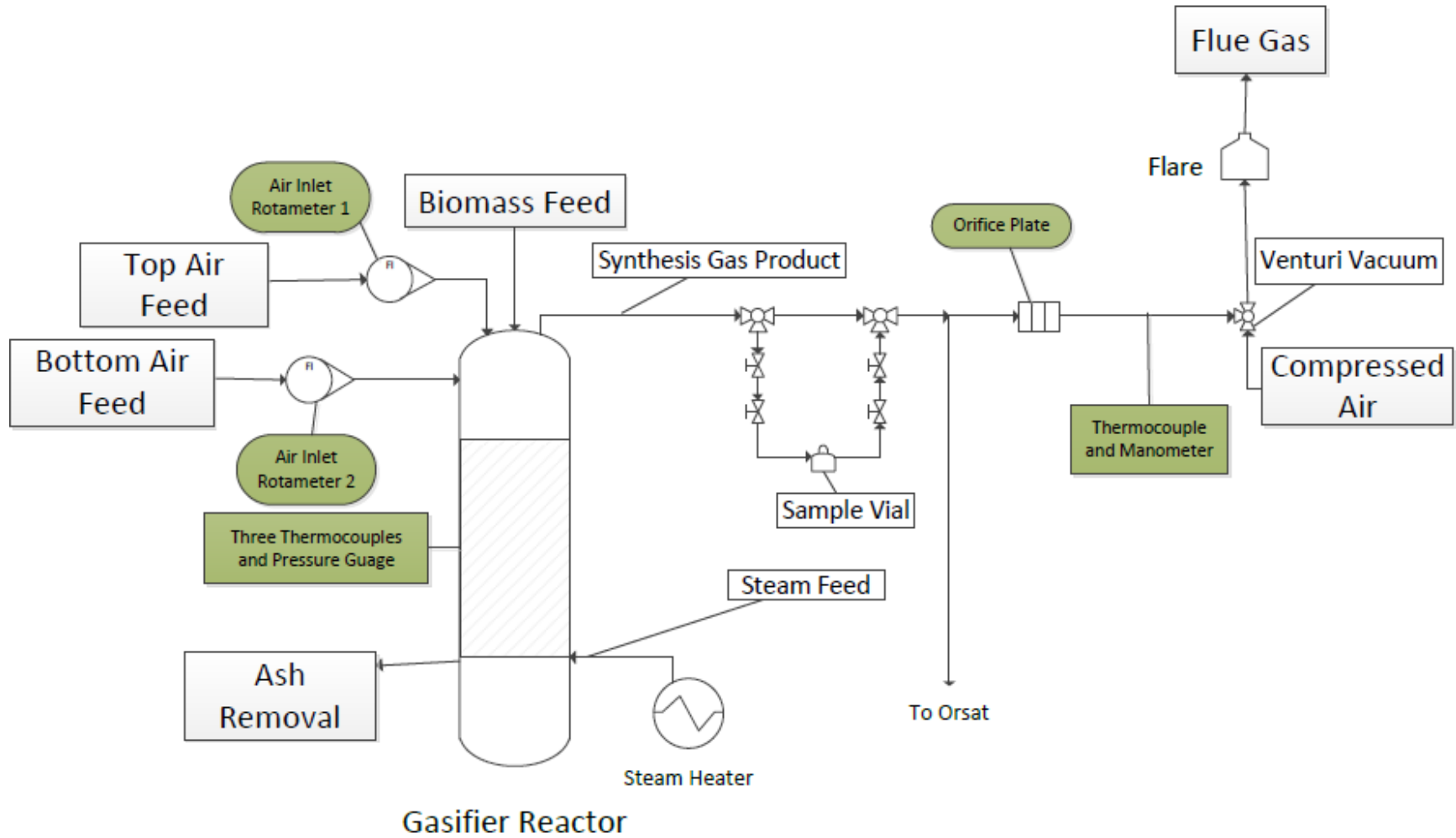


Figure 4-12 Pilot Plant Redesign Process Flow Diagram

4.7 Instrumentation

4.7.1 Flow Rates

During the initial design of the pilot plant the team determined that it is difficult and expensive to purchase rotameters that appropriate for use at high temperatures. The team avoided this problem by cooling the product gas in the steam feed heat exchanger. In the redesigned piloted plant this heat exchanger has been removed and thus the product gas will still be hot during measurement. Therefore, the flow rate of the product gas will be measured using an orifice plate installed in the pilot plant piping. The orifice plate will be carbon steel and therefore has no significant concerns related to temperature. The steam feed flow rate will also be measured using an orifice plate to avoid concerns related to temperature.

4.7.2 Temperatures

The redesigned pilot plant no longer has probe tubes in which to insert the thermocouples, so they will be placed directly in the reactor body in contact with the biomass. As a result, the two thermocouples, one at the upper and one at the lower combustion zone, will provide a more accurate temperature reading. The TJ36 Series thermocouple will be ideal for this application.

4.7.3 Pressures

Operating the pilot plant taught the team of the importance of having a variety of measurements in order to understand what is happening inside the reactor and in the rest of the pilot plant. Therefore, accurate pressure readings throughout the system will be an integral part of the redesigned pilot plant. There are two methods that are commonly used to measure pressure: gauges and manometers. Manometers are ideal to measure the pressure difference. A water manometer will be used to determine the pressure difference across the orifice plate. A small pressure gauge will measure the pressure of the reactor. The specific locations of these instruments are shown in the PFD of the redesigned pilot plant.

4.8 Hazards and Operability Study (HAZOP) for Redesign

Hazard Definitions: Low (no risk to human life or damage to equipment)

Medium (no risk to human life, but damage to equipment)

High (risk to human life and damage to equipment)

Changes to the HAZOP created for the initial pilot plant are in red.

Storage and Transport

Question 1: Where will the gasifier be stored?

Answer: The gasifier will be outside the engineering building near the south bay garage door. It will be covered with a tarp once it has cooled.

Question 2: Where will the gasifier be operated?

Answer: The gasifier will be operated outside of the garage door at the back of the engineering building. The team will ensure that there are no people or cars within a 10 meter radius of the operating area.

Question 3: What if the gasifier falls over?

Likelihood: Low

Hazard: Low-Medium

Safeguards: Gasifier is bolted to the pallet. The gasifier is most likely to fall during transport. In order to balance the significant amount of time required for cooling (more than two hours in some cases) with safety risks at increased temperatures, an internal temperature of 400°C and an external temperature of 50°C are required before moving the gasifier. To most safely transport the gasifier, one person will be operating the pallet jack and another will be responsible for stabilizing the unit.

Start-Up

Question 1: What if the blow torch ignites the insulation or other material besides the biomass?

Likelihood: Low

Hazard: Medium

Safeguards: Two people will always be present during gasifier operation. For start-up specifically, one person will observe and ensure that the blow torch is being operated with necessary caution. A fire extinguisher will also be nearby.

Question 2: What if the flame travels down the flare tube?

Likelihood: Low

Hazard: Medium

Safeguards: A flame arrestor is installed just prior to the flare. This acts as a heat sink, which prevents ignition upstream of this device.

Question 3: What if the reactor gets too hot before steam is produced?

Likelihood: Medium

Hazard: High

Safeguards: Temperature will be closely monitored during start-up. During the initial start-up and subsequent runs if necessary, the water will be pre-heated using a heating element to produce steam more quickly. If the temperature exceeds 800°C before the water is boiling, we will choke the reaction by decreasing the air feed to the gasifier.

Question 4: What if flare ignition causes a burst of flame?

Likelihood: Medium

Hazard: Low

Safeguards: A propane torch will be used to provide a pilot light during startup and if at any time the flame goes out. If it is difficult to maintain a flame, small pieces of steel wool will be used as tinder.

Question 5: What if combustible gases from previous operations build up inside the reactor and ignite when the blow torch is used to start the reaction?

Likelihood: Medium

Hazard: High

Safeguards: The venturi will be turned on and air will be flushed through the reactor for two space times (about 2.5 minutes at 50 scfh) before the reaction is started.

Question 6: What if the flame travels out the port hole while it is open for start-up?

Likelihood: Low

Hazard: High

Safeguards: The port hole will be open only for a few moments during start-up. Combustible gases will not be present at appreciable levels during this time, so the flame is extremely unlikely to travel out of the reactor. Operators will wear personal protective equipment and stay out of the line of the port hole. The insulation will also be covered with material sprayed with flame retardant. In addition, a check valve will be installed in the port hole to ensure that the flame does not travel out.

Feeding Biomass

Question 1: What if the flame front travels quickly up the reactor?

Likelihood: Low

Hazard: Low

Safeguards: We will ensure that the entrance to the hopper is tightly sealed. The lid will only be opened for short periods of time (less than 30 seconds) while feeding biomass to the reactor. If the flame front does begin to travel upward, the lid will be immediately placed on the hopper and sealed.

Question 2: What if the flame reaches the biomass hopper?

Likelihood: Very low

Hazard: Low

Safeguards: The lid will be placed on the hopper as soon as possible. In any case, the gasifier will be shut down until the biomass is finished combusting and has cooled.

Gasifier Operation

Question 1: What if the reactor gets too hot?

Thermocouple Reading Above 1100 °C (Maximum Expected Temperature, at which Tar Cracking Occurs)

Likelihood: Medium

Hazard: Low

Safeguards: We will choke the reaction by lowering the air feed rate via the venturi vacuum system. More steam produced using the heating element will also be admitted to the reactor to decrease temperature.

Thermocouple Reading Above 1300 °C (Integrity of Stainless Steel Compromised)

Likelihood: Low

Hazard: Medium-High

Safeguards: The venturi vacuum will be inactivated, preventing air from being fed, effectively cooling the combustion zone of the reactor. The steam valve will be fully opened. We will move away from the area. This event is unlikely because prior measures will be taken if the temperature exceeds 1100 °C.

Question 2: What if the entire reactor bursts into flames?

Likelihood: Very Low

Hazard: High

Safeguards: The venturi vacuum will be immediately inactivated. The compressed air valve for this

will be located at least 10 feet away from the reactor so that it can be shut down despite the fire. A fire extinguisher will also be kept near the reactor during operation to douse the flames.

Question 3: What if a dangerous amount of carbon monoxide or hydrogen gas leaks out of the reactor?

Likelihood: Low

Hazard: High

Safeguards: The reactor will be welded to prevent leaks and will be operated under a vacuum, so gas cannot leak out. If the reactor does leak, air will leak in, rather than synthesis gas leaking out. Additionally, a carbon monoxide detector will be kept nearby to monitor atmospheric carbon monoxide levels. If the alarm goes off, the team will shut the reactor down by turning off the vacuum. The team will then exit the area and allow the carbon monoxide to dissipate before re-entering. Operating the gasifier outdoors will also allow higher levels of carbon monoxide without danger to operators or others nearby.

Question 4: What if the gasifier explodes?

Likelihood: Low

Hazard: High

Safeguards: The gasifier might explode if liquid water is fed to the reactor. In order to avoid this, a hole has been placed in the heater in order to leak any liquid water before it enters the reactor and avoid the possibility of explosion.

Question 5: What if the synthesis gas is unable to exit the reactor?

Likelihood: Low

Hazard: None

Safeguards: Because the vacuum is generated on the back-end of the pilot plant, closing a valve after the reactor will cut off the vacuum to the reactor, effectively shutting down the reactor.

Question 6: What if insulation is touched?

Likelihood: High

Hazard: None

Safeguards: According to our calculations, due to its low thermal conductivity, the outside of the gasifier's insulation should be less than 150 °C and therefore will be safe to touch for short periods of time.

Question 7: What if another portion of the reactor is touched?

Likelihood: Low

Hazard: High

Safeguards: The manifold system, the synthesis gas exit pipe, and the flare will be too hot to touch. All hot surfaces, including manifold system, synthesis gas exit pipe and flare, will be painted red and labeled appropriately. The high temperature of the manifold system could present dangers only while feeding biomass. Anyone loading the feed hopper will wear gloves.

Question 8: What if the flare is extinguished?

Likelihood: High

Hazard: Low

Safeguards: A carbon monoxide detector will be placed near the reactor. Some carbon monoxide might be leaked to the atmosphere. Synthesis gas typically contains approximately 18% carbon monoxide, but this will be diluted using compressed air from the venturi vacuum system. The carbon monoxide output should not be dangerous if the flare is extinguished, especially given that the gasifier will be under supervision at all times while it is running.

Question 9: What if the synthesis gas produced is outside the flammability range?

Likelihood: Low

Hazard: Low

Safeguards: The synthesis gas will never be near the UFL value because the reactor uses an air feed, so it is diluted with nitrogen gas. The team is aware of the LFL value and will monitor this closely until a better understanding of the reactor's operation is obtained. In a worst case scenario, the gas will be too dilute to ignite at the flare and the air dilution valve on the venturi vacuum will be closed to reduce the vacuum.

Source LFL and UFL:

[https://qspace.library.queensu.ca/bitstream/1974/7221/3/Spaeth Christopher T 201205 MASC.pdf](https://qspace.library.queensu.ca/bitstream/1974/7221/3/Spaeth_Christopher_T_201205_MASC.pdf)

$$\text{Calculating LFL: } LFL_{\text{mix}} = \left(\frac{C_i}{LFL_i} + \frac{C_j}{LFL_j} + \dots + \frac{C_k}{LFL_k} \right)^{-1}$$

Using this equation and the desired synthesis gas composition found in Table 1-2, the lower flammability limit of the mixture was calculated as 14.2% as shown in below.

Table 4-3 Synthesis Gas Lower Flammability Limit Calculations (Matheson Gas Products, 2001)

Compound	LFL	Composition	C/LFL
Carbon monoxide (CO)	12.5%	24.0%	1.92
Hydrogen (H ₂)	4.0%	18.0%	4.50
Methane (CH ₄)	5.0%	3.0%	0.60
Mixture LFL	14.2%		

Question 10: What if the flame travels out the port hole?

Likelihood: Low

Hazard: High

Safeguards: The port hole will be never be open except during start-up. A check valve will also be installed. See also Question 6 above in the Start-up section.

Question 11: What if there is a significant air leak that causes the reactor temperature to increase and cannot be located and/or fixed to cool the reactor?

Likelihood: Low

Hazard: High

Safeguards: The soapy water test will be performed periodically. A significant mechanical failure might not allow the reactor to be salvaged. If the temperature cannot be decreased, all operators will move away from the reactor and it will run using only air provided via leaks until all the biomass has combusted.

Sampling

Question 1: What hazards are present when collecting a sample?

Likelihood: High

Hazard: Medium-High

Safeguards: To avoid potential burns while collecting a sample, heat-resistant gloves will be worn during this process along with usual PPE. The sampling station will be a few feet from the reactor, but the unit will be insulated and hot pipes will be labeled.

Question 2: What if the sample leaks?

Likelihood: Medium

Hazard: Low

Safeguards: Air must leak in to dilute the sample before any hazardous gas is released to the atmosphere. If air did leak in to equilibrate the pressure between the sample and the atmosphere, the sample might leak. However, in the event that gases did leak to the atmosphere, it would be a small amount. A carbon monoxide detector will be near the gasifier to ensure that hazardous levels are not reached.

Question 3: What if the chemicals used to operate the Orsat are spilled?

Likelihood: Low

Hazard: High

Safeguards: Gloves and goggles will be worn at all times when operating the Orsat. Operators also will not have any exposed skin. The Orsat will be operated in the hood so as to ventilate any toxic

gases. Also see the safety guidelines in Section 4.9.

Ash Removal

Question 1: What if toxic gases build up in the reactor before ash is removed?

Likelihood: Low

Hazard: High

Safeguards: Ash will be removed only after the gasifier has cooled and been flushed with air for two space times to prevent build-up of combustible or toxic gases.

Shutdown

Question 1: How will the gasifier be shutdown?

Air feed will be closed, the compressor hose will be disconnected, and the reactor will be allowed to cool to 150 °C outside the engineering building before it is transported inside and stored.

Question 2: After shutdown, when can the gasifier be operated again without the danger of explosion due to build-up of combustible gases?

The gasifier can be flushed with air for two space times (about 2.5 minutes at 50 scfh) and operated again once the temperature is below 250 °C, which is the auto-ignition temperature.

4.9 Operating Procedures for Redesign

4.9.1 Startup

4.9.1.1 *Transport*

Two people should work together to move the gasifier. The gasifier sits on a pallet and should be moved using a pallet jack. One person should operate the pallet jack and the other should make sure the path is clear and be ready to stabilize the gasifier. Should the gasifier begin to fall over it is important to move away and allow it fall to prevent injury. The gasifier should be located outside the southwest Engineering Building (EB) garage door. The gasifier should be at least 10 feet from any building or car and there should not be any overhanging objects or branches.

4.9.1.2 *Supplies*

Make sure that the following objects are easily accessible before start up.

- Gasifier
- Fire extinguisher
- Propane torch
- Leather gloves (two pairs)
- Compressed air hose
- Charcoal (3 bags, only for first startup)
- Wood pellets
- Extension cord
- Wrench for ignition port caps
- Steel wool (3+ pieces)
- Carbon monoxide detector

4.9.1.3 *Preparation*

Make sure that all of the following are completed before beginning the startup procedure. Have a second team member check through this list before proceeding to start up.

- Close compressed air valve
- Connect compressed air line from Engineering Building to venturi flare
- Close generator valve
- Open flare valve
- Close steam valve
- Turn off water heater
- Connect extension cord from EB to water heater
- Fill gasifier to about 3 feet with charcoal (only for first startup)

- Top off gasifier with wood pellets
- Close hopper securely
- Empty ashtray and close securely
- Fill water barrel to fill line
- Close sample lines
- Open valves on air feed rotameters

4.9.1.4 *Startup*

Startup is time sensitive. Once this list of steps is begun, it is important to act quickly and efficiently and complete the steps below within 15 minutes if possible. Make sure that you completely understand and are able to complete each step before beginning start up. Unnecessary delay between startup steps could lead to overheating in the reactor. One person should be watching the temperature reading in the combustion zone and be ready to control the temperature as described in the operating section.

The gasifier should only be started up with two or more team members present. The first member should be responsible for closely monitoring the temperature of the reactor and actively watching for any potential dangers. This operator should also operate all valves and controls. The second member should be responsible for ensuring that the flare remains lit and for recording the reactor temperature, synthesis gas temperature, reactor pressure, flow rates, valve positions (100% open, 50% open, etc), and flare status (not burning, burning yellow, burning white) every 2 minutes.

- Turn on water heater
- Wait for water to begin boiling (up to 30 minutes)
- Open compressed air valve fully
- Watch the flare, waiting for a continuous flow of smoke and a temperature in the combustion zone of 400°C

- Using the butane torch try to light the flare for a duration of 3 seconds every 3 minutes until it maintains a self-sustained flame
- Set the air feed rotameters according to the experimental plan
- Throttle the compressed air valve to achieve 4-6" water vacuum exiting the reactor (this is the expected value as cited in the literature (ALL Power Labs, 2014))
- Adjust the steam valve following the temperature control guidelines in the operating section

4.9.2 Operation

Once the gasifier has been started up, reduce the oxygen feed to the desired operating level (~0.25 equivalence) so that the combustion zone temperature does not become excessively high. During operation, monitor the combustion zone temperatures. If this temperature ever exceeds 1100°C, the compressed air feed to the venturi vacuum should be reduced using the venturi needle valve. If the temperature continues to climb or does not begin to decrease, steam should be added using the heating element. The steam causes an endothermic reaction, which will drop the reactor temperature. If the temperature ever exceeds 1300°C, the compressed air feed to the venturi vacuum should be completely closed (venturi needle valve) and the steam feed valve should be opened completely (steam valve) until the temperature drops below 1100°C. The first thermocouple should give an accurate approximation of the combustion zone temperature because it is inserted directly in the biomass bed. A second thermocouple can be moved to other regions of the reactor to obtain a temperature gradient. It will typically be used to measure the temperature of the bottom combustion zone.

4.9.2.1 *Cautionary Notes*

While the gasifier is operating, the outside of the insulation will be near 150°C. According to our calculations, you can safely touch this surface for one second without feeling pain. With that being said, this surface should never be intentionally touched without an insulated glove, but if it is touched momentarily, no harm will come to the individual.

The synthesis gas pipe exiting the reactor is extremely hot (up to 800°C) and should never be touched during operation. This pipe has been painted red with cautionary words inscribed on the surface to warn users. The pipe cannot be insulated because the synthesis gas should be cooled by the surrounding air. The high temperature portions of the pilot plant have purposely been positioned on the opposite side as the sampling valves, rotameters, and digital temperature readout so that the team will not be near the hottest parts of the system during operation.

4.9.2.2 Adjusting the Air Feed Rate

Air is pulled into the reactor by a venturi vacuum pump located near the flare. The total air feed rate should be adjusted primarily by opening or closing the venturi needle valve near the flare, which modifies the vacuum on the system. The air distribution to the top and bottom combustion zones can be modified by adjusting the air feed valves located on the rotameters connected to the bottom two manifolds. One valve controls the air feed to the top combustion zone, while the other controls the air feed to the bottom combustion zone. The rotameters near these valves should be used to measure how much air is being fed to each region. Under normal operating conditions, more air will be fed to the top combustion zone than the bottom to thermally crack the tars at higher temperatures. It is important to understand the relationship between air feed and reactor temperature. Combustion is an exothermic reaction that generates a lot of heat. The more air fed to the reactor, the hotter the reactor will get. However, this is a tradeoff because too much air will cause complete combustion of the biomass and less synthesis gas will be produced. Gasifier literature states that air should be fed at approximately 25% of the amount required for complete combustion of the biomass to obtain the best quality synthesis gas. A material balance should be calculated to determine the total air feed based on a 25% equivalence ratio.

4.9.2.3 *Adjusting the Steam Feed Rate*

Steam is fed to the bottom of the reactor by cracking the steam valve. The steam rotameter near this valve will be used to measure the steam flow rate. As was stated earlier, steam causes an endothermic reaction (water shift reaction) that cools the reactor. This will be one of the primary means of controlling the reactor temperature, along with the air feed rate.

4.9.3 Sampling

In order to take continuous samples, the valves on either side of the sampling apparatus should both be open. The synthesis gas product should be allowed to flow through the sampling apparatus shown in Figure 2-15 for a few minutes to ensure that the previous sample is evacuated and that the current sample is representative. After the sample is obtained, the valves will be closed to divert the flow back through its normal exit path. The unions will be unscrewed to remove the sampling vial. The sample will be cooled using an ice bath. The tar content will then be assessed as described in Section 5.1. Then the apparatus will be reattached to the unions and operation will continue as described above until a sample is again obtained. The sample for the Orsat should be collected through the metal pipe, fed to the instrument, and analyzed as described in Section 5.2.2.2.

4.9.4 Shutdown

There are two different scenarios in which the gasifier will be shut down. Either the team will be shutting down the gasifier because they finished their experiment, or they will be shutting it down because something has broken and then the reactor has become unsafe to operate. Both scenarios will follow the same general procedure described below.

4.9.4.1 *Preparing for Shutdown*

During shutdown there must be two people present. The team will ensure that they have excess flare material on hand as it is likely that the flare will extinguish multiple times while shutting down the reactor.

4.9.4.2 *Shutdown*

To shut down the gasifier the next step will be to close the valve on the venturi. This will choke the reactor and prevent air from feeding into the reactor. At this time there will be carbon monoxide and other gasification byproducts coming out of the manifold system and therefore the team must not be within 10 feet of the reactor. During this time the team will carefully monitor the temperature for the upper combustion zone. The steam valve will also be opened to promote cooling in the reactor. The team will wait until the core combustion zone temperature of the reactor is below 400 °C. When the temperature reaches this level, it will be safe for the reactor to be lifted on the pallet jack.

4.9.4.3 *Moving the Reactor*

To move the reactor the pallet jack in the engineering building will be used. The reactor's outer temperature will still be approximately 150 °C and therefore must not be touched. The reactor must be well-balanced before moving and will be placed in the storage area in the engineering building. Because the reactor will still be cooling down, caution tape will be used to ensure that people do not hurt themselves by touching the reactor.

5 Analytical Methods

5.1 Tar Analysis

The tar produced by the gasifier must be reduced to under 50 mg of tar per m³ of synthesis gas in order to operate effectively in an internal combustion engine. Tar production is one of the primary metrics by which the team planned to critique the synthesis gas quality. To measure the amount of tar in the product, the team planned to use a method proposed by Professor David Benson. Using this approach, BIOburners would collect a gas sample and quickly cool it to condense the tars. Then, the remaining gases would be evacuated before weighing the sample. Using the mass of the container before the sample was obtained, the mass of the tars can be determined. In a 500 mL sample, less than 0.025 mg of tar is the target value. Using the analytical balance available in the Calvin College chemistry & biochemistry stockroom, this level of precision can be attained.

GC could also have been used to determine the tar content of the synthesis gas produced. This method accurately measures the amount of a number of hydrocarbons in the sample, which could then be summed to obtain the total amount of tar. GC would provide much more detailed information than the method described above as it could be used to determine the identity of a number of hydrocarbons and their relative amounts as well as the total level of tar production. However, neither the correct type of GC nor the appropriate column for the tars (which are aromatic hydrocarbons with molecular weights of approximately 80-300 g/mol) are available at Calvin College to perform this detailed analysis. Purchasing this equipment would cost several thousand dollars. Even if the equipment and columns were available, extreme care would also have to be taken in order to avoid destroying the columns with samples containing high levels of tar.

5.2 Gas Composition Analysis

5.2.1 Selection of an Analytical Method

The product gas exiting the reactor will be primarily composed of inert nitrogen from the air feed as well as significant amounts of hydrogen and carbon monoxide in synthesis gas. Carbon dioxide, oxygen, methane, and hydrocarbon tars will also be present in the product. The composition of various components of the gas could be determined using a number of methods including gas chromatography (GC), mass spectroscopy (MS), and Orsat gas analysis.

These three techniques analyze the sample based on three distinct characteristics. A gas chromatograph consists of a column with an inert solid support used to attach a thin layer of liquid or polymer. This microscopic layer of particles is termed the stationary phase. Interactions between the gas being analyzed, which is called the mobile phase, cause the different components to separate based on differences in polarity. This allows a determination to be made for the composition of the gas. MS determines composition based on the mass-to-charge ratios observed in an ionized sample since these ratios are correlated to specific fragmentation patterns. Orsat gas analysis is a technique that has been replaced by more modern instrumentation for many applications, but it remains a simple and reliable technique for analyzing combustion products. 100 mL of sample gas are fed to a series of surfaces, which individually absorb carbon dioxide, oxygen, and carbon monoxide gases. The residual gas volume is measured after contact with each surface, which allows the composition of each of the three components to be calculated accurately by difference as long as concentrations are high enough.

These three design alternatives were evaluated using the criteria of accuracy, training required, cost, and availability.

Design Alternative 1: Orsat Gas Analyzer

Advantages:

- Little training required
- Costs about \$1500, which is at least ten times less expensive than GC instrument and column
- Can be repurposed for other engineering projects

Disadvantages:

- Less accurate than GC
- Only gives composition of CO, CO₂, and O₂ (not N₂, H₂O, H₂)

Design Alternative 2: Gas Chromatography (GC)

Advantages:

- Accuracy
- Provides composition of each component
- Equipment already available at Calvin in chemistry department

Disadvantages:

- Columns sensitive to tar
- Some training required

Design Alternative 3: Mass Spectroscopy (MS)

Advantages:

- Accuracy
- Provides composition of each component

Disadvantages:

- No access to equipment
- Training required

Selected Design Alternative: Orsat Gas Analyzer

Orsat was the analytical method selected to determine the composition of synthesis gas samples. While other more rigorous methods of synthesis gas analysis could certainly be adopted, Orsat will be sufficient for the purpose of this design project and is the simplest and most practical alternative. This piece of equipment is available on Calvin's campus (unlike MS) and can be operated more easily than both MS and GC. A diagram of this equipment is in Figure 5-1 below. Orsat can be used to determine the composition of only three of the six gases of interest in the synthesis gas product stream. However, the amount of nitrogen can be determined by material balance as it should be equal to the amount in the air feed to the reactor. Low quantities of water vapor are expected in this stream and will also condense as the sample is cooled. Therefore, the amount of hydrogen can be approximated by total material balance. The ratio of carbon monoxide and hydrogen in a typical synthesis gas is also approximated in the literature as 0.78 (Chopra & Jain, 2007), which can be used as a check on these assumptions.

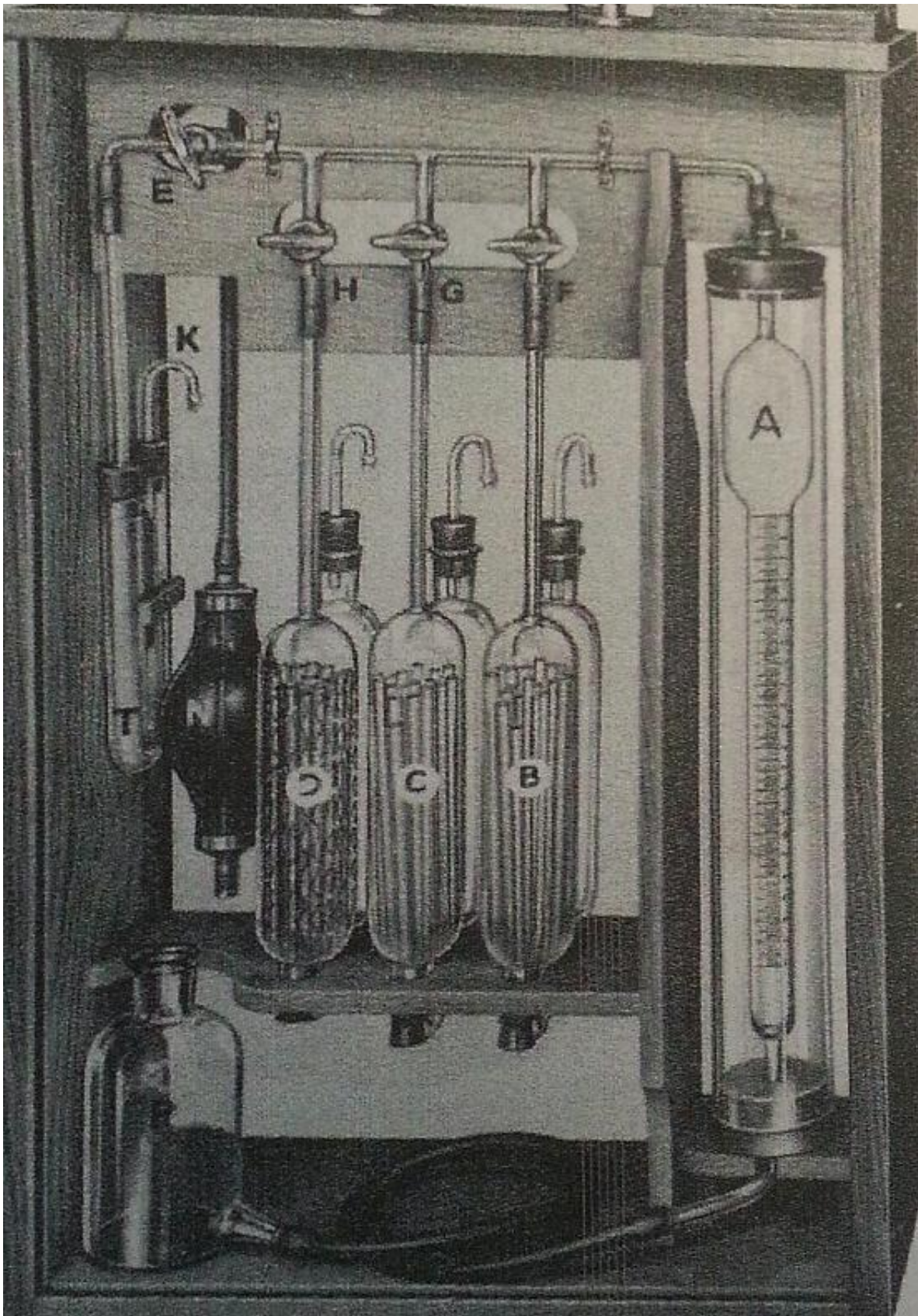


Figure 5-1 Schematic of Orsat Gas Analyzer

5.2.2 Orsat Operating Procedures

The operating procedures detailed below reference labels in Figure 5-1.

5.2.2.1 *Filling Pipettes*

1. Remove the stoppers from the pipettes and fill with respective reagents until pipette is half full (approximately 100 millileters).
2. Open stopcock E to position 1 and ensure F, G, and H are closed. Raise the pressure bottle to fill the burette with 100 mL of water.
3. Close stopcock E to position 2 and open F. Lower the pressure bottle until the solution is drawn up to the mark on the capillary. Close stopcock F.
4. Fill each pipette in a similar manner using stopcocks G and H.

5.2.2.2 *Analyzing Samples*

1. With stopcock E open (position 1), fill the Orsat with the gas to be analyzed using suction pump N. Then close stopcock E to position 3.
2. Lower the pressure bottle so that the water level falls below the bottom of the scale. Then close stopcock E to position 2. The water level in the pressure bottle and burette should be the same.
3. Raise the pressure bottle to fill the burette with 100 mL of water.
4. Open stopcock F and raise the bottle until the water level in the burette reaches the 100 mL mark.
5. Lower the pressure bottle.
6. Raise and lower the pressure bottle several more times to ensure complete absorption.
7. After lowering the pressure bottle for the final time, the water level in the burette should be read. Ensure that the pressure bottle is in its original position. This gives the amount of gas absorbed in the pipette.
8. Repeat steps 3-7 using stopcocks G and H.

Pyrogallol and cuprous chloride are toxic and carcinogenic and must be handled with care. Materials safety data sheets for these chemicals can be found at <http://www.msds-online.com/msds-search/>.

5.2.3 Standard Sample Testing

While the Orsat was not able to be used to test the composition of the synthesis gas product due to the safety incident detailed in Section 12.10 in the Appendix, several standard samples were analyzed to allow the team to become familiar with the operation of the instrument and to analyze the instrument accuracy. Atmospheric air (79% nitrogen and 21% oxygen), pure carbon dioxide, and a mixture of 93% nitrogen, 5% carbon dioxide, and 2% oxygen were tested.

The team created the necessary reagents for the gas analysis and attempted to learn how to operate the unit. However, the team could not figure out how to equalize the pressures within the Orsat, so the testing of the samples was postponed two days. During this time, the reagents absorbed atmospheric oxygen and carbon dioxide, expending some of their potency, which is a source of error in the subsequent gas analyses. The next time the Orsat was run, we figured out how to equalize the pressure within the Orsat (see Section 5.2.2 for details). First, three air samples were run. Each sample showed 0% carbon dioxide absorption, which is expected because atmospheric air contains parts per million (ppm) levels of carbon dioxide, which is below the detection limit of the Orsat. The oxygen absorbance of the air samples was determined to be 19%, 19%, and 18.5%. See Section 12.10 in the Appendix for the complete operating data. The team was pleased that the results were repeatable. The drop in composition of the third sample was attributed to the absorbent being expended during the two days between when the team made the reagents and when the samples were actually tested. Next, a pure CO₂ sample was tested. This sample was obtained from an in-line tap in the biology lab at Calvin College. However, we quickly realized that this sample could not be evaluated using the Orsat because the gradations used to measure the 100 mL gas sample only extend 40 mL up the burette. Therefore, the team learned that the Orsat can only be used to analyze gas mixtures that have a total CO₂, CO, and

O₂ composition of less than 40 mol%. A typical synthesis gas composition is provided in Section 1.2. The combined composition of CO₂, CO, and O₂ in a typical synthesis gas is near 30% in the literature. Therefore, the team believes that Orsat analysis is a legitimate method for testing the synthesis gas composition.

Because the team suspected that the absorbents had been depleted, we wanted to prepare fresh absorbents and retest several samples. Fresh absorbents were made and air was retested; the composition was determined to be 19.3 mol% O₂. Furthermore, the oxygen in the air sample absorbed much more quickly, confirming the team's hypothesis that the absorbents had been depleted (see Section 12.10 in the appendix for the complete data set). Figure 5-2 illustrates the impact of absorbent depletion for three different air samples run on the Orsat. This shows that the fresh absorbent solutions absorb more oxygen with fewer washes.

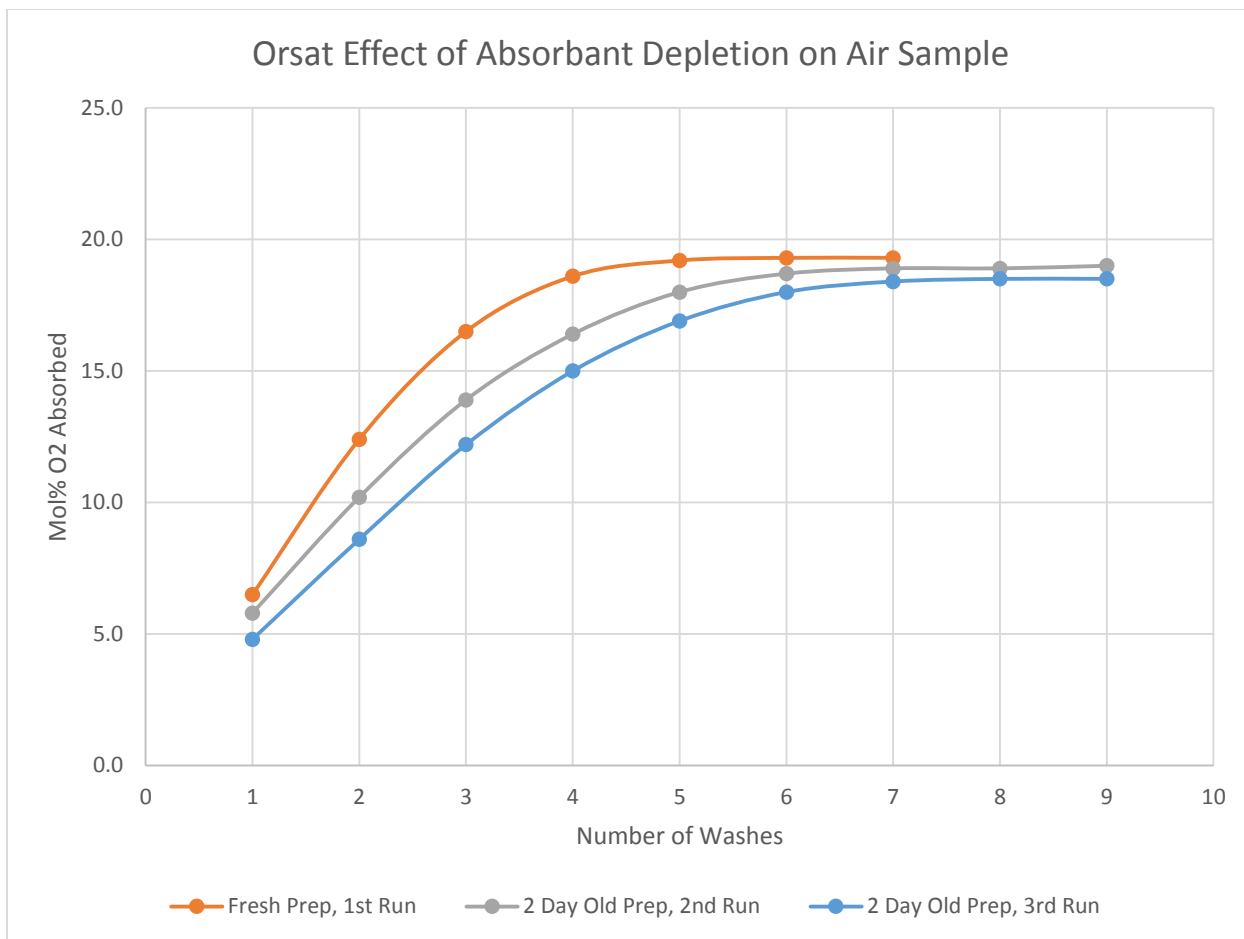


Figure 5-2 Orsat Gas Analysis: Impact of Absorbant Age

This test showed the team that it is important to make fresh absorbent solutions each day the Orsat is run to ensure that accurate results are being obtained from the instrument. The next gas sample that was tested was a mixture of 93 mol% N₂, 5 mol% CO₂, and 2 mol% O₂. A compressed gas cylinder containing this gas mixture was conveniently hooked up to a glove box in one of the biology labs. To obtain the gas sample, a one liter flask was placed in the glove box and was allowed to equilibrate for two hours. The flask was removed from the glove box, attached to the Orsat using rubber hosing, and was tested. The results were very far from accurate for this sample: 0.9 mol% CO₂ and 11.2 mol% O₂ (see Section 12.10 for the complete data set). We have attributed this error to be due to air dilution, which is consistent with the results because the measurements show an increased amount of oxygen and a decreased amount of CO₂. From this experiment, the team learned that batch samples do not work well

with the Orsat because the air must be flushed from the instrument before the new sample is loaded, otherwise significant dilution with air will occur. To counter this problem, we recommend that the Orsat be connected directly into the product gas stream. The pressure bottle can be used to pull the gas into and out of the Orsat multiple times, effectively flushing the instrument with any residual gases.

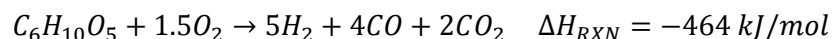
5.3 Material Balance

Material balances were planned for this system while the gasifier was operating at steady-state. With the feed rate of biomass equal to the rate at which the biomass is combusted, the sum of the air flow rates to each of the combustion zones and the biomass feed rate should be equal to the product gas flow. The ideal gas law will be used to determine the number of moles of gas, which will then be used to find the mass flow rate. The ideal gas law is a good assumption since the gasifier operates at high temperature and low pressure. The molecular weight of the gas is calculated based on the composition determined as described above. These two pieces of information allow the mass flow rate of both the air feeds and biomass feed rate to be compared to the product flow rate. Some error will be introduced to the material balance due to the mass of the ash collecting in the grate. The amount of ash collected will be measured once an appreciable amount builds up. This will allow an estimate of the amount of ash produced over a known operating period. Only about 1% of the biomass is expected to be converted to ash (Wood Pellets FAQ, 2011), so this estimate will not introduce significant error into the overall material balance.

It is difficult to anticipate the expected error in material balances for this process. While errors might be significant due to the assumptions required and due to the potential for air leaks, computing the percent error during testing will allow comparison between experiments. Significant deviation in the percent error between trials will encourage further consideration of potential issues with the pilot plant.

5.4 Energy Balance

An energy balance is another good way to check for the consistency of measurements taken during operation of the gasifier. Four key energy flows were identified. First, the gasification which was modeled by the following reaction.



Second, the steam cooling which was modeled as discussed in Section 4.3. Third, the heat loss from the insulation which was based on the calculations described in Section 0 of the Appendix. Finally, the heat leaving from the effluent was calculated using an estimated specific heat for the synthesis gas and assuming that the air feed enters at 25°C. These calculations were performed for estimated values of the flow rates into and out of the reactor and are detailed in Section 12.7 of the Appendix. During operation the team hopes to have less than 20% deviation in the energy balance.

6 Proposed Experimental Plan

The following variables were scheduled to be tested in the spring 2014 semester. BIOburners planned to critique the variables based on the quality of synthesis gas produced, as determined by the Orsat analytical technique and the tar content analysis (see Section 5 for details regarding these analytical techniques). Since the purpose of the gasifier is to provide power using this gas, the quality of the synthesis gas is the primary dependent variable. The primary considerations for the pilot plant independent variable study were equivalence ratio, air feed distribution to the two combustions zones, and use of steam in the air feed. If time allowed, the team also hoped to optimize the reactor height and to implement and test the throat design. The planned variable study was terminated, however, due to an incident that occurred while troubleshooting the pilot plant startup (see Section 12.10 in the Appendix for a complete incident report). Thankfully, no one was seriously injured due to this incident. Instead of discussing test results, the following subsections will outline an experimental plan for testing the gasifier, discuss the results that BIOburners anticipates and how these results would affect the redesign of the pilot plant. In some cases the results do not affect the pilot plant design, but rather determine the optimal operating conditions for the gasifier.

According to the literature, the combustion zone temperature has a profound effect on the tar thermal cracking rate. Temperatures exceeding 1100°C have been shown to nearly eliminate tars from the synthesis gas product (Basu, 2010). A temperature of 1000-1100°C was used as a target to eliminate a sufficient amount of tar from the synthesis gas. The combustion temperature is controlled by the air and steam feed rates, which are linked to other variables such as equivalence ratio. With that being said, monitoring the reactor temperature allows for quick feedback regarding the reactor operation. It is also necessary to monitor the temperature to ensure that the integrity of reactor is maintained. In a final design, a controls system may be implemented to maintain a specified temperature using solenoid valves to adjust the air flow. Because of these factors, the combustion zone temperature should be

monitored closely during testing. The temperature will serve as a dependent variable, which will help to easily fix the gasifier at optimum operating conditions.

6.1 Steady State Calculations

BIOburners was unable to test the time required to attain steady state during operation because the desired temperature was never obtained. However, the team made some calculations to estimate the time to steady state. The calculations assumed a biomass combustion rate of 2 kg/hr, which is consistent with the literature for similarly sized gasifiers. The volume between the top air feed and the synthesis gas exit pipes is 3.7 liters. Assuming a constant wood pellet bulk density of 700 kg/m³, the space time for biomass through this gasification region is 1.3 hours. Therefore, a conservative estimate of 3 hours to steady state is suggested, allowing for 2 space times of the biomass. Two space times were used because this is sufficient to reach steady state in a PFR and the biomass flows similarly to the reactants in this piece of equipment. These calculations should be verified while establishing the range of operation as outlined in Section 6.3.

6.2 Experimental Plan Schedule

An experimental plan was developed to test the effect of the following independent variables on the synthesis gas composition and production rate: equivalence ratio, air feed distribution to the two combustions zones, use of steam in the air feed, the reactor height, and the presence of a throat. The proposed experimental schedule will require two people working full time (8 hours/day, 5 days/week) for a month. See the proposed Gantt chart below in Figure 6-1 for more details.

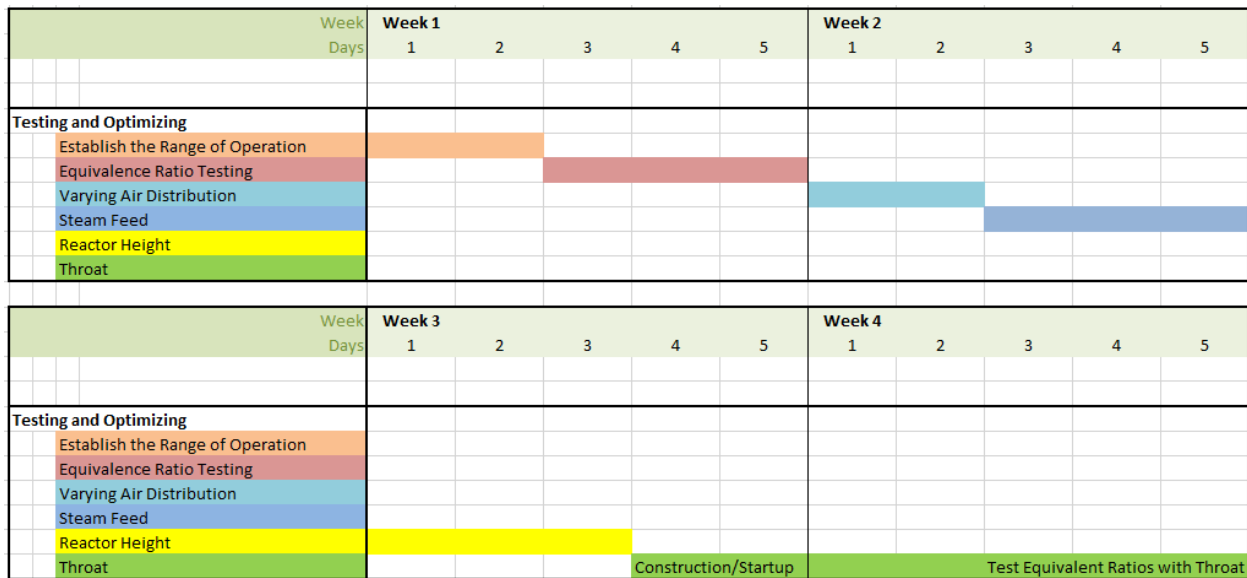


Figure 6-1 Gantt Chart for Proposed Experimental Plan

6.3 Establish the Range of Operation

As mentioned in section 6.1, a conservative estimate of the time to steady state is 3 hours. To experimentally determine the time to steady state, synthesis gas samples should be analyzed every fifteen minutes of operation until the composition and flow rate remain nearly constant. In addition, the system temperatures and flow rates should be monitored to ensure proper material balance agreement and further prove steady state. Even after a more precise determination of steady state, BIOburners recommends that a safety factor of fifteen minutes be added and that duplicate samples should be taken five minutes apart from one another to prove that steady state has been obtained. Orsat analysis does not take more than 10 minutes to complete for a single sample; however, this analysis does not need to be performed immediately after obtaining synthesis gas from the pilot plant to be accurate.

Once the time to steady state has been determined, the operators (in theory, members of BIOburners or others interested in biomass gasifier operation under various conditions) can move on to determining the operating range of the gasifier. BIOburners has defined the range of operation as the region between the minimum and maximum air flow rates that allow the flare to light in a sustainable manner. This will ensure that the synthesis gas is within the flammability limits and will function

properly in a generator or engine. To simplify this process and allow time to optimize other more critical variables, only the top air feed will be operated in this test. All other variables, including compressed air feed in the venturi vacuum and steam feed rate, will be constant.

To determine the minimum air feed that still allows flare sustainability, first allow steady state to be reached with the flare successfully lit, then decrease the air feed by several standard cubic feet per hour and wait about five minutes. Continue to decrease the air feed by this manner until the flare cannot sustain a flame. Now increase the air feed by one standard cubic foot per hour and wait fifteen minutes, checking to see if the flare will ignite during this time period. Repeat this process until the flare can sustain a flame. The same procedure should be used to determine the maximum air feed that still allows flare sustainability, but the air flow rate will be increased instead of decreased. When the flare is no longer self-sustaining, the product gas is below the lower flammability limit. An estimate for the lower flammability limit is 14.2% based on compositions in the literature and calculations in Table 4-3. Once the actual operating range of the gasifier is known, the ranges of independent variables suggested for testing should be modified accordingly.

The following dependent variables should be measured at both the minimum and maximum reactor conditions: biomass combustion rate, process temperatures, synthesis gas flow rate, and average ash production rate.

6.4 Equivalence Ratio

The equivalence ratio is defined as the amount of air fed compared to the air required for complete combustion. For example, 100% equivalence means that enough air is present to achieve complete combustion, while 50% equivalence means that only half the air required for complete combustion was fed to the gasifier. During the troubleshooting process, BIOburners discovered that this variable is difficult to fix independently because two control variables are simultaneously in play: the air feed rate and the biomass combustion rate. Obviously, the combustion rate cannot be directly fixed, it

can only be approximately measured. To determine the combustion rate, the team planned to measure the rate at which the biomass level dropped in the reactor by inserting a metal rod until it reaches the biomass. Assuming a constant bulk density of the biomass, an approximate combustion rate could be determined. The air feed rate is obtained from the rotameter reading and is quite easily controlled. With both the biomass combustion rate and the air feed rate known, the equivalence ratio can be calculated. From researching the gasifier literature, the team discovered that the optimum equivalence ratio for most biomass feed stocks was near 25% equivalence (Basu, 2010). BIOburners expects similar results for the combustion of wood pellets in their gasifier. To limit variability in this procedure, only the top air feed should be operated. Feeding to the top combustion zone reduces tar production while also eliminating additional variables from affecting these experimental results.

The synthesis gas higher heating value can be calculated from the composition of the gas. BIOburners suggests that a trend be developed for the higher heating value versus the equivalence ratio. Because the anticipated maximum heating value should be near 25% equivalence, this value should be set as the median independent variable. Therefore, BIOburners suggests testing equivalence ratios near 15%, 20%, 25%, 30%, and 35%. These values should be modified if they fall outside of the temperature operating range of the reactor, as determined in Section 6.3. The equivalence ratio cannot be set exactly since it is affected by the biomass combustion rate, which cannot be tightly controlled, as well as the air feed rate. As a result, BIOburners recommends that the technicians use the biomass combustion rate determined in the previous study (described in Section 6.3) to approximate the air feed necessary to obtain the desired equivalence ratio. In addition to measuring the composition and flow rate of the product gas, the tar content and process temperatures should also be measured.

6.5 Air Feed Distribution

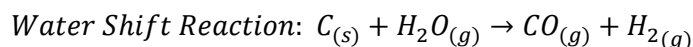
BIOburners' double fire gasifier design affords great flexibility with the air feed. By operating only the top air feed, the gasifier can be operated as a downdraft gasifier. Similarly, by operating only the bottom air feed, the gasifier can be operated as an updraft gasifier. Additionally, the double fire design allows these two gasifier types to be run simultaneously by feeding air to both locations, affording the benefits of both updraft and downdraft gasifiers while diminishing the drawbacks of each. To confirm that the advantages of both updraft and downdraft gasification were gained using the double-fire design, the team planned to test various ratios of top air feed to bottom air feed. Because the biomass at the bottom's combustion zone has already been mostly combusted in the top combustion zone, the team expects that less air will be required at the bottom zone. Therefore, we expect an air distribution ratio (the air flow rate to the top combustion zone divided by the air flow rate to the bottom combustion zone) that is greater than one. BIOburners believes that the test results could possibly show that the bottom air feed does not have an appreciable effect on the quality of synthesis gas produced. If these results are obtained, the pilot plant design would be modified to be a downdraft gasifier by removing the bottom air feed tubes. However, during troubleshooting of the pilot plant the team realized that ash often builds up on the grate without passing through the grate holes. The bottom air feed could allow higher temperatures for combustion of material that would otherwise fall through the grate as ash. This would improve the convenience of operation, although it may not improve the amount of energy provided using the synthesis gas produced. The effect on synthesis gas quality as well as practical effects will be considered in the testing and redesign of the pilot plant.

For the experimental plan, BIOburners suggests that six air feed ratios should be tested at the optimum equivalence ratio as determined in Section 6.4. The air feed distribution has been defined as the percentage of air fed to the top combustion zone compared with the total air feed (100% being all air to top and 0% being all air to bottom). Therefore, only five unique data points remain to be tested

because 100% air distribution was already tested in section 6.3. For the remaining tests, BIOburners suggests that air feed distributions of 80%, 60%, 40%, 20%, and 0% be tested. This will test operation of the gasifier as a downdraft gasifier, updraft gasifier, and several gradients in between. The dependent variables that should be monitored are synthesis gas composition and flow rate, tar content, process temperatures, and biomass combustion rate.

6.6 Use of Steam in Bottoms Air Feed

The presence of steam in the reactor promotes the water shift reaction, which converts charcoal (carbon) and water to carbon monoxide and hydrogen as shown in the reaction below:



This reaction has two key effects on the gasification process. First, the addition of water increases the synthesis gas yield by driving the reaction toward the products, carbon monoxide and hydrogen. Secondly, the water shift reaction helps to lower the combustion zone temperature because it is slightly endothermic. Therefore, this reaction can be used to control the temperature of the combustion zone if it is getting too hot. However, if the temperature is decreased too much, the rate of synthesis gas production and product quality will take a severe hit. This behavior suggests a tradeoff. The steam feed rate should therefore be optimized to achieve the best synthesis gas production rate and product quality. During this optimization, the equivalence ratio and air feed distribution will be constant at the optimum values determined from earlier tests.

BIOburners sized the steam feed system by calculating the steam needed to consume the charcoal in the lower gasification region within a half-hour of operation. The steam reservoir is capable of delivering a maximum of 2.2 L/hr of steam at 1 atm and 100°C. See Section 12.4.1 in the Appendix for the steam heater calculations. Therefore, BIOburners suggests that five steam feed rates be tested between no steam feed and the maximum steam feed. The data point for zero steam feed should have been collected while testing the air feed distribution, so a total of six data points can be portrayed while

only testing five steam feed rates. The same dependent variables should be monitored as in previous studies: synthesis gas composition and flow rate, tar content, process temperatures, and biomass combustion rate.

6.7 Reactor Dimensions

Increasing the height and diameter of the reactor will provide a higher fuel credit by producing more synthesis gas. The feed rate of biomass and air will not be increased significantly when reactor dimensions are changed. Therefore, an increased reactor height should theoretically increase the amount of synthesis gas produced due to an increased residence time in the pyrolysis zone. This increased residence time should also theoretically decrease the tar content because the tars have longer to reach the temperatures at which they are broken down before exiting the reactor. The reactor diameter will increase the synthesis gas production by allowing for higher air flow rates and more surface area contact between the air and the biomass. However, the reactor diameter will be excluded from the scope of this study due to budget constraints as this would require a complete rebuild of the gasifier. While increasing the reactor height seems quite favorable, at some point the increase in height will have a minimal effect on the synthesis gas and tar production and will no longer be economically favorable. This behavior suggests that there is an optimal (most cost effective) reactor height.

The synthesis gas composition and quality (tar content) will be considered for five artificial reactor heights. The effective height of the reactor will be modified by varying the level of biomass in the reactor and maintaining the level at that height. At this point in the testing phase, the technicians should have a good idea of the biomass combustion rate. By adding biomass every ten or fifteen minutes at a rate equal to the combustion rate, the biomass height can be maintained within the reactor. Since the reactor will not be reconstructed before testing this variable, only shorter reactors can be considered—it is not possible to increase the height of the bed as it is currently maximized at the top of the gasifier. The biomass height should be double-checked by inserting a metal rod into the reactor

and measuring the level of the pellets. The reactor of the current pilot plant design is six feet tall, with the upper four feet of the reactor allocated to biomass pyrolysis. Based on the knowledge that BIOburners has gained throughout this project, we believe that at least one foot of pyrolysis is necessary. Therefore, pyrolysis zone heights between one foot and four feet should be studied in 6" increments. This will result in five additional data points, as the four foot pyrolysis zone has been proposed for testing in Section 0. This gasifier should be operated at the optimum equivalence ratio, air feed distribution, and steam feed rate as determined from prior testing. Further studies could include determining the optimal height of reactors with varying diameters, thus establishing a heuristic for the height and diameter of a gasifier. While this in-depth study is not recommended at this point due to the large amount of time which would be required for fabrication, such a heuristic would be invaluable in scaling gasifiers should this technology become more prevalent in the United States.

6.8 Throat Design

The use of a throat (diameter restriction) at the level of the combustion zone increases the temperature in the region according to the literature. This also reduces the amount of tar produced. However, throats also increase the chance of bridging, especially when a small diameter throat is implemented. Bridging occurs when the biomass sticks together and spans the reactor diameter, effectively plugging the reactor and creating a void space underneath the bridge. A throat will be implemented at the level of the top combustion zone with similar dimensions as what has been reported as being successful in the literature (4 inches). The throat should be installed directly below the top air feed, in accordance with the literature (ALL Power Labs, 2014). The effect on synthesis gas production rate and purity will be analyzed following the addition of the throat, and the change in combustion zone temperature will also be quantified.

7 Consumer Product

In addition to the two pilot plant designs, BIOburners has also designed a final product for the market. The gasifier reactor is quite similar to the redesigned pilot plant, however, some modifications may be necessary based on the results from the proposed experimental plan from Section 6 (eg. reactor height and steam feed rate). Additionally, the synthesis gas does not require cooling anymore because the product gas does not need to be sampled and tested, so this greatly reduces the amount of additional piping required outside of the reactor. A controls system will also be implemented to produce a safer, more reliable product that does not require supervision.

In addition to the gasifier reactor and venturi vacuum/flare unit, the product requires a source of compressed air to run the venturi vacuum, a propane torch or heating element to light the biomass, and a generator to burn the product gas and produce electricity. BIOburners recognizes that many customers may already own air compressors and generators, so in an attempt to reduce product cost and increase customizability for the consumer, BIOburners proposes to have these items available a-la-carte. These add-on items will be outlined in greater detail later on.

We have identified two main customer uses for our gasifier product. The first target group will operate the gasifier completely off-the-grid, allowing for use in disaster relief situations or at a cabin where grid electricity is not available. The second target group will use the gasifier as a source of sustainable energy at home to limit their environmental impact and to reduce energy costs at home. The recommended add-on items for each target customer group are outlined in detail in Section 7.1.4. The following subsection details the design decisions for the consumer product.

7.1 Design Decisions

7.1.1 Port Holes

As with the pilot plant designs, the final product will employ a port hole at each combustion zone. These port holes will function in gasifier startup and will be equipped with check valves to improve the safety of the system. The check valves will prevent the potential for a blow back like was experienced in the safety incident. Optional heating elements may be installed to eliminate the need for propane torch startup, however, the product will still have portholes so that the gasifier can still be started in the event of a power outage or burnt out heating coil. Heating elements have the added benefit of allowing for an auto-startup at a set time of day. See Section 7.1.3 for details on the auto-startup feature and other control system implementations.

7.1.2 Steam Generator

In the final product, steam will be generated using a method different from the 55-gallon drum heat exchanger used in the first pilot plant and the heating element used in the redesigned pilot plant. This change will improve the marketability of the design and allow it to operate off-the-grid. Four heat exchanger types were considered for the steam generator: a shell and tube heat exchanger, double pipe heat exchanger, a water bath similar to the one used in the first pilot plant, and a custom design where water is fed parallel with the air feed and synthesis gas pipes within the reactor (see Figure 4-9).

Design Alternative 1: Shell and Tube Heat Exchanger

Advantages:

- Small size
- Integrated with control system easily

Disadvantages:

- Most complex
- Most expensive

Design Alternative 2: Double Pipe Heat Exchanger

Advantages:

- Less expensive than shell and tube heat exchanger
- Integrated with control system easily
- Simple

Disadvantages:

- More expensive than custom design
- Large size required to achieve desired steam production rate

Design Alternative 3: Water Bath Heat Exchanger

Advantages:

- Less expensive than shell and tube heat exchanger
- Integrated with control system easily
- Simple
- Smaller than double pipe heat exchanger

Disadvantages:

- More expensive than custom design

Design Alternative 4: Custom Design

Advantages:

- Inexpensive
- Simple
- Integrated with control system easily

Disadvantages:

- More difficult to fabricate and modify

Assuming that each alternative would be designed in such a way as to provide the necessary steam feed, the following criteria were considered: size, price, and ability to be integrated with the control system described in Section 7.1.3 below. Size and price were the most important criteria and were weighted twice as much as the ability to integrate the steam generator with the control system in the analysis. This weighting for the criteria was selected because the product could not support a bulky heat exchanger addition and the final price point would suffer greatly if a complex heat exchanger were selected. Additionally, the team anticipated that each alternative had an equal ability to be integrated with controls systems, so that criterion was weighted the lowest.

Table 7-1 Decision Matrix for Final Product Steam Generator

	Size	Price	Integration with Control System	Total
Category Weight	x2	x2	x1	
Shell and Tube Heat Exchanger	3	1	3	11
Double Tube Heat Exchanger	1	2	3	9
Water Bath Heat Exchanger	2	2	3	11
Custom Design	3	3	3	14

Selected Design Alternative: Custom Design

Based on the decision matrix results in Table 7-1 above, the custom design for the steam generator was selected. This is the least expensive design. It is also fairly compact with a large part of the design integrated into the reactor body rather than external to the gasifier. Each of the alternatives could be integrated into the control system equally well, so the custom design did not pose any disadvantages in this area.

7.1.3 Control Systems

A variety of control systems were implemented in the consumer product design to improve the product safety, reliability, and to allow for unsupervised operation. The first system controls the air feed to the top combustion zone via a solenoid valve controlled by the top combustion zone temperature. If the top combustion zone temperature is less than the desired temperature of 1200°C, the solenoid valve

will be opened more widely, allowing more air to be fed to this region of the gasifier. The top combustion zone temperature will be measured using a thermocouple and a PID controller will direct the solenoid valve appropriately. A control loop schematic of this process can be seen in Figure 7-1 below.

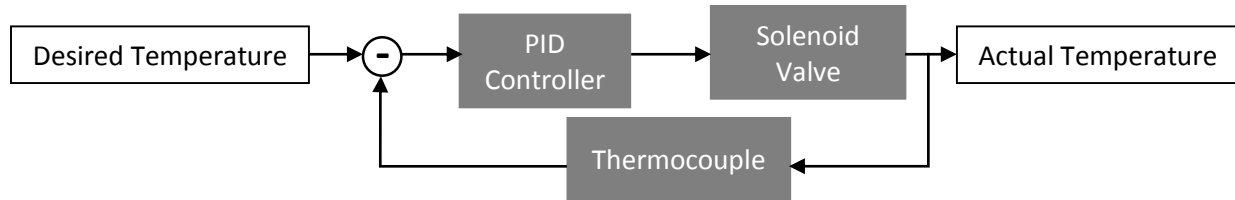


Figure 7-1 Top Combustion Zone Air Feed Control Loop

The air feed to the bottom combustion zone will be determined using the optimum ratio of the top and bottom combustion zone air feeds determined from the proposed experimental plan in Section 6. A solenoid valve will be used to fix the bottom air feed at the desired ratio to the top air feed. Using these air feed rates, the bottom combustion zone temperature will be controlled using an additional PID controller for steam feed. Recall that steam forces an endothermic reaction, which will decrease the temperature of the bottom combustion zone. If the temperature of the bottom combustion zone is greater than the desired value of 900°C, the solenoid valve on the water hopper will be opened more widely to feed more steam to the gasifier. The control loop for this process is identical to Figure 7-1, except that the solenoid valve now controls the steam feed rather than the top air feed.

For the consumer who wants a more hands-off gasifier unit, BIOburners has developed a “Gasifier Plus Package,” which offers two additional control features. These control features are optional and increase the user friendliness of the product, but are not critical to the operation of the gasifier. As was mentioned in Section 7.1.1, every gasifier will have port holes to light the biomass, but the customer has the option of using heating elements to ignite the biomass. If heating coils are used to ignite the biomass, the gasifier system can be programmed to startup and shut down automatically at a specified time of day using a PLC controller. The PLC coordinates the PID controllers, which turn on the

gasifier system by opening the air feed valves, turning on the air compressor, and turning on the generator. Secondly, the consumer may choose to add a level alarm to the biomass feed hopper. An indicator light and beeping alarm will be installed in the consumer's household so that they are notified when the hopper contains two hours' worth of biomass. This relay system is achieved using a PLC controller. Additionally, when the hopper runs out of biomass the PLC will direct the gasifier to automatically shutdown by closing the appropriate solenoid valves and turning off the generator. The addition of these two controls systems makes the product much more user friendly for the consumer and only add approximately \$600 to the final product price. See the economic analysis in Section 8.1 for details.

7.1.4 Additional Items

In addition to the optional controls systems, the user may opt to purchase some remaining equipment to customize the gasifier for their intended use. Every user of our gasifier product will require a generator to provide power from the synthesis gas exiting the unit. This generator can be purchased with the final product if desired. The 5500 W generator shown below in Figure 7-2 would be appropriate for this system and costs about \$800.



Figure 7-2 5500 Watt Generator

<http://www.electricgeneratorsdirect.com/Honda-EM6500-Portable-Generator/p6562.html>

The user will also require an AC air compressor to power the venturi vacuum pump during startup. Once the gasifier is producing enough synthesis gas to power the generator, the air compressor is no longer required and can be shut down because the vacuum is then supplied by the generator. An AC air compressor can be obtained for approximately \$150 (<http://www.sears.com/craftsman-7-gallon-portable-horizontal-air-compressor-with/p-00915364000P?sid=IDx01192011x000001&kpid=00915364000&kispla=00915364000P>).

If the user wishes to operate completely off-the-grid, they need to purchase a DC air compressor and a deep-cycle 12 volt car battery to provide power until the gasifier startup phase is complete and the generator is running off the synthesis gas. Once startup is complete, the generator will recharge the battery for the next startup. The battery can be added to the final product for approximately \$100 (http://www.amazon.com/UB12500-Wheelchair-Medical-Mobility-Rechargeable/dp/B009LLAQ94/ref=sr_1_2?ie=UTF8&qid=1400125784&sr=8-2&keywords=12v+battery+deep+cycle+50+ah), while the 12 V DC air compressor will cost about \$220 (<http://www.powerequipmentdirect.com/VIAIR-45040-Air-Compressor/p5060.html#reviews>). Thus, to outfit the gasifier to operate completely off-the-grid will only require \$320 in addition to the generator.

For customers desiring a hands-off gasifier, heating elements are available for purchase that allow for startup without manually lighting the biomass through the port hole. Pellet stove igniters are available for about \$60 each (<http://www.ebay.com/itm/Whitfield-Lennox-Pellet-Stove-Standard-Igniter-XP3500-H8127-12150213-/161195375929>).

7.1.5 Consumer Product Schematics

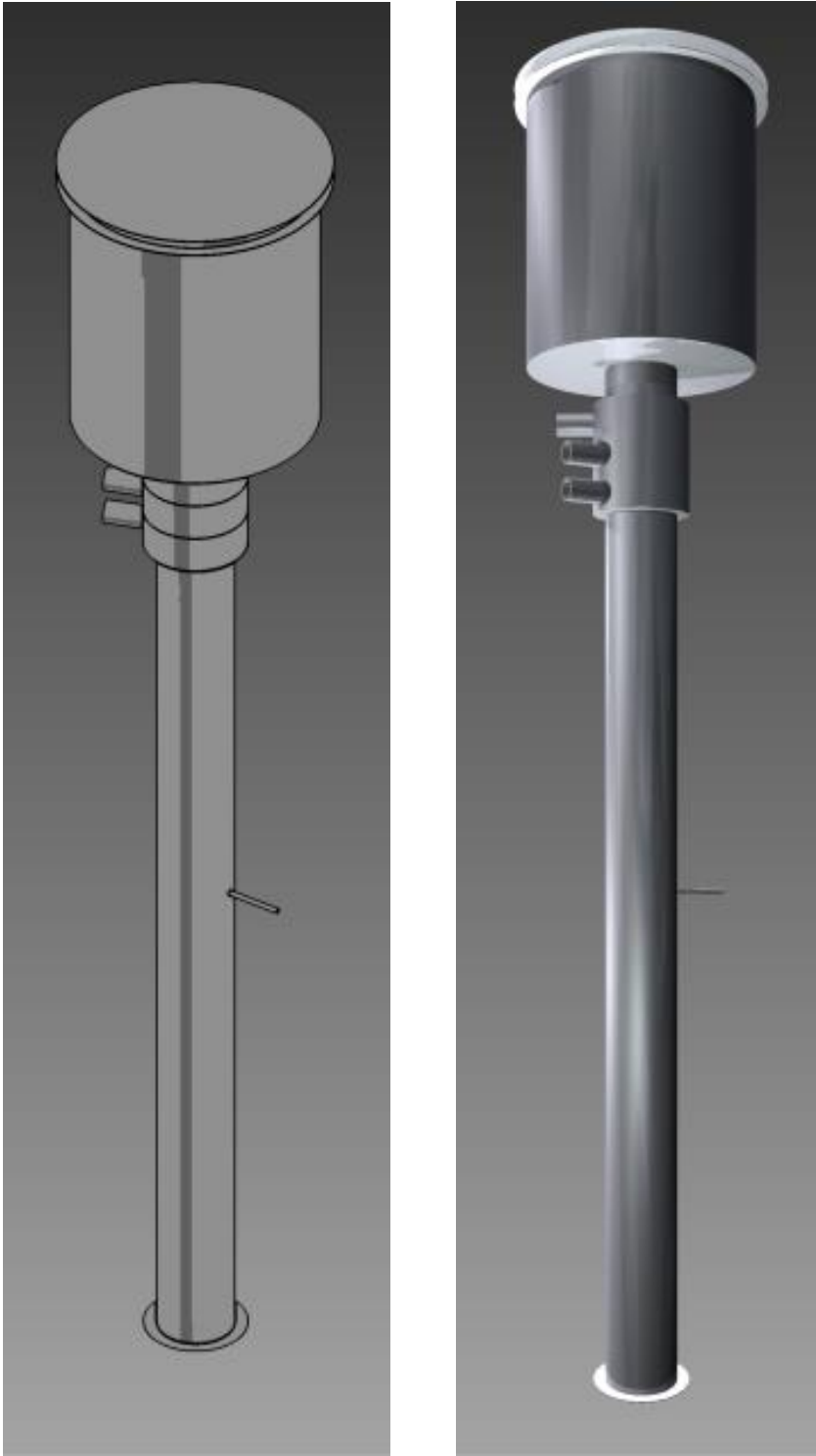
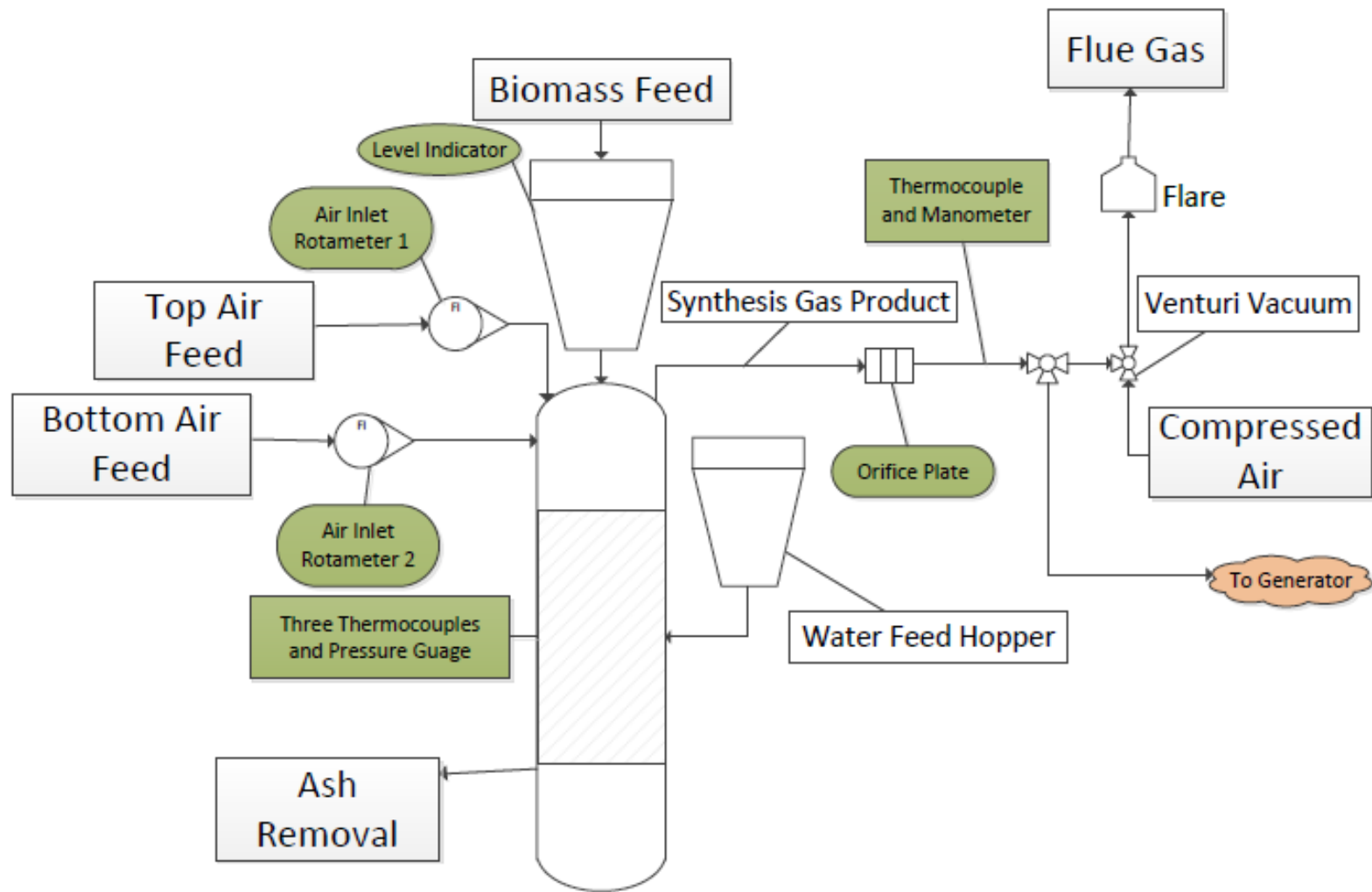


Figure 7-3 AutoCAD of Final Consumer Product



Gasifier Reactor

Figure 7-4 Final Consumer Product Process Flow Diagram

8 Economic Analysis

Clean energy is of growing importance in today's society. Biomass gasifiers provide an environmentally sustainable means of generating clean fuel. Because of this, BIOburners believes that this gasifier outlined in Section 7 is a viable and marketable product.

8.1 Cost Estimate

Table 8-1 and Table 8-2 below detail the fixed and variable costs associated with the production of the consumer product outlined in Section 7. The fixed costs were calculated based on a production volume of 100 units per year and a very streamlined business model. The details of this business plan are explained in *BIOburners Business Plan* (Lomasney, Michmerhuizen, Myton, & Sager, 2013), a report compiled last semester by the design team. The business would begin operations from the garage of one of the team members and would employ one person full-time for management and accounting. Two machinists would be hired at \$35,000 per year. Both management and the machinists will be offered benefits valuing \$15,000 per employee. Based on the fixed and variable cost estimates, the base gasifier product should be sold for \$6,500, while the gasifier plus package should be sold for \$7,500. These values include a 50% markup to maintain a sustainable business. Recall from Section 7 that the user of this gasifier would require at a minimum two additional items for operation: a 5 kW generator and an air compressor, which adds approximately \$1000 to the cost of the unit if the consumer does not already own these items. If free biomass is available from the user's own property, then the operating costs for the gasifier are nearly zero. However, if free biomass is not available, wood pellets can be purchased for approximately \$200/ton. Producing 5 kW of energy requires a feed rate of about 8 lb/hr of biomass, which equates to an operating cost of \$0.80/hr or an energy cost of \$0.30/kWh.

Table 8-1 Variable Costs for Gasifier Production

Item	Quantity	Cost	Total
Stainless Steel Reactor Pipe	1	\$ 200	\$ 200
3/4"x6' SS Tube (Air Feeds)	12	\$ 20	\$ 240
Air Rotameters	2	\$ 50	\$ 100
Thermocouples	3	\$ 40	\$ 120
Insulation	1	\$ 220	\$ 220
3/4" elbows (Manifolds)	12	\$ 7.50	\$ 90
Steel Sheet Metal (2'x4'x1/8")	1	\$ 50	\$ 50
Expanded SS Sheet	1	\$ 20	\$ 20
12' of 1" Ceramic Rope (Gasket)	1	\$ 10	\$ 10
Pilot Plant Piping and Fittings	1	\$ 250	\$ 250
6" Steel Pipe for Manifolds (9"/gasifier)	1	\$ 10	\$ 10
8" Steel Pipe for Manifolds (9"/gasifier)	1	\$ 25	\$ 25
Misc. Bolts/Nuts Etc.	1	\$ 30	\$ 30
Metal Pallet	1	\$ 30	\$ 30
Docking Plate (2'x2'x0.135")	1	\$ 30	\$ 30
Hopper Drum (20 gal - 20"x20")	1	\$ 70	\$ 70
Flanged (6"x4") pipe - Hopper Feed	1	\$ 20	\$ 20
High Temp. Electrical Element	1	\$ 100	\$ 100
PID Controllers	2	\$ 100	\$ 200
Solenoid Valves	3	\$ 150	\$ 450
PLC Module*	1	\$200	\$ 200*
Solenoid Valves*	2	\$ 150	\$ 300*
Auto Igniter*	1	\$ 10	\$ 10*
Level Sensor*	1	\$ 100	\$ 100*
Total			\$ 2,265
Total* (Gasifier Plus Package)			\$ 2,875*

Table 8-2 Fixed Costs for Gasifier Production

Item	Cost	Cost/Unit
Management (1 Employee)	\$ 60,000	\$ 600
Liability Insurance	\$ 6,000	\$ 60
Marketing (3 rd Party)	\$ 20,000	\$ 200
Machinist (2 employees)	\$ 35,000 x 2	\$ 700
Employee Benefits	\$ 15,000 x 3	\$ 450
Total	\$ 201,000	\$ 2010

8.2 Economic Comparison

The average Michigan home uses about 680 kWh per month at a price of \$0.14/kWh (U.S. Energy Information Administration, 2014). This equates to an average annual electric bill of \$1,200. If biomass is available for free then the annual savings are \$1,200. Assuming a combined cost of the gasifier, generator, and air compressor of \$7,500 (\$8,500 for gasifier plus package), the payback time is around 6 years (7 years for gasifier plus package).

A payback period of six years would be very attractive for a consumer with access to free biomass. By comparison, transitioning to solar energy in Michigan costs almost \$18,000 and the payback period is 17 years (One Block Off the Grid, 2014).

If biomass is not available for free, one ton of wood pellets costs \$200-\$300 depending on the location. At \$200/ton, the annual operating cost will be \$2,500/year, which is \$1,300/year higher than average Michigan electrical costs. Customers who need to purchase biomass would not be able to pay off the capital costs for the gasifier by operating the gasifier for day to day energy needs. Nonetheless, this product can still be valuable. People who live in areas prone to power outages could keep a supply of biomass available for use in an emergency. Additionally, this product could be used in remote areas where there is no access to a centralized electrical grid, such as a cabin in the woods. Biomass is a more reliable energy source than solar or wind power, since it can provide energy regardless of the weather conditions.

Energy costs continue to rise as fossil fuels become more limited and as people become more environmentally conscious. Out gasifier offers a solution to these problems that will only become more attractive as time goes on.

9 Conclusions

9.1 Challenges Overcome and Lessons Learned

- Team Dynamics: staying on schedule and finalizing the design
 - The team addressed the scheduling hurdle by assigning team roles. Nicole Michmerhuizen was assigned to be the scheduling manager. She held the team accountable to meet project deadlines. By mid-November, the team had developed a functional design for the initial pilot plant, but for two weeks continued to debate details that could not be finalized without a working pilot plant. The team manager, Nate Myton, finally stated that it was necessary to finalize the design and order materials for construction.
 - The team learned the importance of delegation and assigning positions to each team member. Additionally, BIOburners learned that there is a time when research and changing design details is no longer productive and it is necessary to build a working pilot plant.
- Preliminary Design
 - This obstacle was overcome through an iterative process of research and model development. Some preliminary feasibility testing was performed to determine burn patterns and biomass behavior as shown in Figure 9-1.



Figure 9-1 Iteratively Testing Designs for Both Constructability and Feasibility

- Through the process described above, the team learned the value of developing a physical model at each stage in the design process. This was best displayed when the team attempted to build a recyclable model of the internal manifold system discussed in Section 2.5 and shown in Figure 9-1. The design seemed reasonable on paper; however, it became clear that the manufacturing complexity was beyond the team's capabilities. Additionally, after completing the burn pattern analysis, the team learned that the flame front would remain in the desired location as long as air only enters at the desired combustion zones.
- Pilot Plant Construction
 - This was a major hurdle because none of the team members possess experience with metalworking of any sort. Before anything could be manufactured, the team had to first practice with the equipment until the metal shop manager, Phil Jasperse, deemed that we could proceed to actual fabrication. This greatly slowed the construction process.
 - Calvin's metal shop has limited hours (7 am to 4 pm) that conflicted with our class schedules, making it difficult to find time to work on construction.
 - The amount of time to manufacture the pilot plant was grossly underestimated. Initially, BIOburners estimated it would take around 200 man hours to build the pilot plant. However, the actual time spent was around 600 man hours.
- Pilot Plant Operation and Redesign
 - The reactor itself started up quite easily; it only took about ten seconds with a butane torch in the ignition port to begin the combustion process. However, many other problems were soon encountered that severely limited the operational ability of the pilot plant. For example, several air leaks were discovered that fed air to undesirable locations in the reactor, bridging of the biomass occurred in the biomass feed pipe when the manifolds got very hot, and the desired temperature in the top combustion zone of the reactor was not

achieved. These problems initiated a troubleshooting process that is detailed below. The problems encountered led to a complete redesign of the pilot plant. See section 4 for details regarding the pilot plant redesign.

- Air leaks were located by implementing the "soapy water test," during which the reactor was slightly pressurized with compressed air and soapy water was applied to the suspect leaky areas of the reactor. If the soap bubbles foamed up, we determined that there was a leak at that location. Leaks were located in the manifolds, bottom ash ductwork, several of the pipe fittings in the pilot plant, and the tar traps. These leaks were fixed by welding, taping, and caulking the various fittings and holes. However, the team came to discover that the "high temperature" tape and caulk were really temporary fixes that will not hold up for years of operation. The redesign allows for more welding and better gasket seals with larger flanges, which will result in fewer air leaks in the reactor.
- Bridging occurs when there is enough friction between the biomass particles and the walls of the enclosure to suspend the biomass in the reactor, thereby creating a vacant space underneath the bridged biomass. This problem was encountered primarily in the small biomass feed pipe through the manifolds (1.5 inch diameter). Besides the small diameter of the feed pipe, air leaked into this pipe due to insufficient welding and poor gasket materials, thereby charring the biomass and increasing the bridging. Some bridging also occurred just under the manifolds in the reactor body, but this was not as severe and the team believes this problem will be solved by eliminating air leaks in the manifolds. The pilot plant redesign addressed these problems by widening the biomass feed pipe to six inches and by increasing

the surface area contact between the manifolds eight-fold to create a better gasket seal.

- BIOburners hoped to achieve 1000°C at the top combustion zone; however, a temperature of only 600°C could be reached during operation. This problem was attributed to limited air flow due to a high pressure drop in the air feed tubes and insufficient air flow rate. Additionally, the low temperature caused large amounts of tar production, which coated the synthesis gas exit pipes, further increasing the pressure drop. To combat these problems, BIOburners exchanged the twenty seven, half inch diameter air feed and synthesis gas tubes for twelve, three quarter inch diameter tubes. This modification increased the cross-sectional pipe area for air feed by 40%, while maintaining approximately equivalent synthesis gas cross-sectional pipe area. See Section 12.5 in the Appendix for calculations supporting this claim.
- In addition to the troubleshooting process, the team learned how challenging it is to complete a thorough safety and HAZOP analysis. Although we had completed what we thought to be an all-inclusive, fool-proof safety analysis and operating procedures (critiqued by Calvin's safety inspector), we experienced a safety incident in which Matthew Lomasney suffered some minor burns (See Section 12.11 in the Appendix for the complete incident report). The incident occurred because a troubleshooting procedure was developed by Matthew Lomasney and Nate Myton on-the-fly when the bridging problem was encountered. A major lesson that the team took away from this experience was that any new operational procedure should be developed and reviewed off-line, rather than trying to fix the problem at hand immediately. Since we were not able to complete testing, an

experimental plan was proposed to test equivalence ratio, air feed distribution, use of steam feed, reactor dimensions, and the presence of a throat (see Section 6).

- Synthesis Gas Analysis

- BIOburners identified methods to analyze both the synthesis gas composition and tar content. See Section 5 for details behind these analytical methods.

- Professor Benson suggested a method for tar analysis where the tar content of a sample is measured in terms of mg tar per m³ synthesis gas.

- The Orsat was identified as a means of measuring the mol% composition of O₂, CO₂, CO, and remaining gas. Because N₂ from the air does not react, this composition is also known by material balance from the measured air feed. The Orsat method was tested with samples of known O₂ and CO₂ composition to check for accuracy.

Therefore, the team has deemed this analytical technique to be accurate at least for O₂ and CO₂ gas analysis.

- Consumer Product

- There were two main areas of the redesigned pilot plant that were altered in the design of the consumer product. The first is the method of steam generation. Instead of a heating element, the steam will be produced using the heat of the biomass bed in a tube passing through the reactor parallel with the air feed and synthesis gas removal tubes. Control systems will also be used to control the temperatures at the combustion zones by adjusting the air feed and steam feed rates. Heating elements will be used to ignite the biomass, and a PLC will automate start-up and shut down. A level alarm is also located in the feed hopper to indicate when more biomass feed is required.

- The base package for the consumer product will be marketed for \$6,500. An additional \$1,000 will provide the features of automation in the gasifier plus package. This will result

in a six-year payback time if biomass is available. If biomass must be purchased, the gasifier will not pay itself off due to the cost of the biomass feedstock.

9.2 Objectives and Requirements Analysis

The following section is an analysis on how BIOburners carried through with the objectives and requirements initially established for the project. While the project evolved throughout the year by necessity and some objectives and requirements became irrelevant, the team believes it is still worthwhile to compare our initial thoughts about the project with the actual project deliverables.

Objectives:

1. Equipment cost of under \$2,500
 - As stated in the budget (Section 1.3.3), BIOburners spent almost \$3,000 on the project; however, \$1,400 of this was used to purchase the Orsat gas analyzer unit, which was purchased by Calvin for use in the engineering department. Therefore, only \$1,600 was technically spent on this project. Additionally, the economic analysis (Section 7) of the redesigned pilot plant shows a final equipment cost of just under \$2,000, including a 20% contingency factor. Therefore, BIOburners met this objective.
2. Able to operate for 24 hours without direct supervision
 - BIOburners was not able to test this objective because the gasifier was not operating long enough for the team to feel comfortable leaving it unattended.
3. Produce under 50 mg tar/ Nm³ synthesis gas while running
 - Because the operation of the pilot plant was terminated, BIOburners never reached the point of analyzing the product gas for tar content. However, the team is certain that the product gas was above this threshold based on the amount of tar collected in the tar traps during operation. Therefore, we did not meet this objective.
4. Start-up time of under 15 minutes

- BIOburners determined that the biomass in the reactor could be lit to a sustainable flame within ten seconds and the product gas flare could be lit within five minutes. Therefore, BIOburners achieved this objective.
5. Operate using a wide variety of biomass fuel sources
- This objective was removed from the scope of the project due to the difficulty and cost associated with acquiring a diverse assortment of biomass feeds. Initially, we tried to acquire stocks such as *Miscanthus giganteus* for testing. In the end, we determined that the amount of time required for this portion of the project was better spent in other areas including design and construction of the pilot plant. Wood pellets were purchased locally and were primarily used in this project. Charcoal was also used for start-up.

Requirements:

1. Produce between 3-5 kW of synthesis gas
 - This metric could not be evaluated because of the termination of gasifier operation.
2. Fit on a standard 48" x 48" pallet
 - This requirement was met, as evidenced by the pilot plant pictures in Section 2.18.
3. Able to be operated by a single person with minimal training
 - This was not tested, however, the operational procedures that BIOburners developed are quite thorough. If not for the safety incident, the team is convinced that a person with a high school degree could operate the gasifier with the assistance of the operating manual.
4. Hopper capable of holding three days of fuel
 - This initial requirement was modified to hold 12 hours' worth of biomass. The team realized that three days of biomass requires a lot of floor space. The design was altered

so that hopper was located above the gasifier, thereby reducing the amount of floor space required while still providing sufficient biomass feed.

5. Handle synthesis gas and other products in a safe and environmentally friendly way
 - BIOburners designed the gasifier to operate under a vacuum to prevent any buildup of flammable gas within the pilot plant. Additionally, the team was successful in achieving a self-sustaining flare, so we knew that the toxic gases were being converted to carbon dioxide and water.
6. Include safety measures to prevent injury due to hazardous gases or high temperatures
 - Although the team went to great lengths to develop thorough HAZOP and operating procedures for the pilot plant, including collaboration with safety officer Jennifer Ambrose, a safety incident occurred, which resulted in early termination of the project. However, this was a result of a failure to follow operating procedures appropriately and necessary safety measures are in place for the redesigned pilot plant and consumer product.

9.3 Summary

The results from this project can be divided into three primary sections. First, a preliminary pilot plant was designed, constructed, and operated. Secondly, the pilot plant was redesigned based on problems encountered during operation, and an experimental plan was developed to optimize the gasifier based on key variables. Finally, a consumer product was designed, and the economic viability of this product was considered. The final product will cost \$6,500 and will break even after 6 years of operation provided that free biomass is available to the consumer. Additionally, the team developed thorough operating procedures and a HAZOP for the gasifier. We also developed operating procedures for the Orsat gas analyzer and tested several standard samples for accuracy.

10 Acknowledgements

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We would also like to thank our family and friends for the encouragement and support they have offered throughout the year.

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12 Appendices

12.1 Metal Properties

The team considered several materials when selecting materials of construction for the gasifier.

The decision making process is outlined in Section 2.12. The material properties information below was used with this decision making process (Teadit, 2013).

CARBON STEEL

Material frequently used in manufacturing jacketed gaskets and Ring Joints. Due to its low resistance to corrosion it should not be used in water, diluted acids or saline solutions. It may be used in some alkalis and in some concentrated acids. Temperature limit 900°F (500°C).

Approximate Hardness: 90 to 120 HB.

STAINLESS STEEL AISI 304

Alloy with 18% Cr and 8% Ni is the material most used in the manufacturing of industrial gaskets due to its excellent resistance to corrosion, low cost and availability in the market. Its maximum operating temperature is 1400°F (760°C). Due to Stress and Intergranular Corrosion, its continuous service temperature is limited to 790°F (420°C).

Approximate Hardness: 160 HB.

STAINLESS STEEL AISI 316

This alloy with 18% Ni, 13% Cr and 2% Mo, offers excellent resistance to corrosion. It can have carbonate precipitation at temperatures between 860°F (460°C) and 1650°F (900°C), under severe corrosion conditions. Maximum recommended temperature for continuous service is 1400°F (760°C).

Approximate Hardness: 160 HB.

ALUMINUM

Due to its excellent resistance to corrosion and easy handling it is very often used in manufacturing gaskets. Maximum service temperature: 860°F (460°C).

Approximate Hardness: 35 HB.

TITANIUM

Metal with excellent corrosion properties in elevated temperatures, oxidant service, Nitric acid and caustic solutions. Temperature limit: 2000°F (1100°C).

Approximate Hardness: 215 HB.

12.2 Gasifier Sizing Calculations

Sizing of a gasifier is discussed in Section 1.2.6. Table 12-1 shows the conversion rules of thumb that were used in this process. The feed rate of 3.5 kg/hr was the feed rate selected for the design of the pilot plant, and therefore these values were used as estimates of the gas production and power output of the gasifier. These calculations were performed by Nate Myton and checked by Eric Sager.

Table 12-1 Gasifier Sizing

Wood Feed	3.50	kg/hr
SynGas Flow	7.65	m ³ /hr
Heat from Combustion of Gas	11.1	kW
Shaft Work	2.93	kW
Shaft Work	3.92	HP
Electrical Power	2.64	kW

Specific Gas Production Rate	420	m ³ gas/hr m ²
Throat Area	0.0182	m ² throat
Throat Diameter	0.152	m
Throat Diameter	5.99	in

12.3 Pilot Plant Component Sizing

12.3.1 Piping Lengths

Table 12-2 below shows the pipe lengths used to connect the components of the pilot plant. In many cases, the tolerance of the pipe length was up to several inches, as the primary purpose of the piping was to connect two components fixed in an approximate location. Table 12-2 describes the different pipes needed to construct the pilot plant and Figure 12-1 shows the location of each pipe in the completed pilot plant.

Table 12-2 Pilot Plant Piping Lengths

Name of Pipe	Pipe Number	Diameter (in)	Quantity	Length (in)
Reactor to syngas downpipe	1	3/4	1	18
Syngas downpipe	2	1 1/2	1	72.5
Heat Exchanger Pipes	3	1 1/2	4	26
Up out of Heat Exchanger	4	1 1/2	1	~20
Sampling Pipe	5	1 1/2	1	38
Sampling to Syngas Rotameter	6	1 1/2	1	~9
Rotameter Stand-In	7	1 1/2	1	14

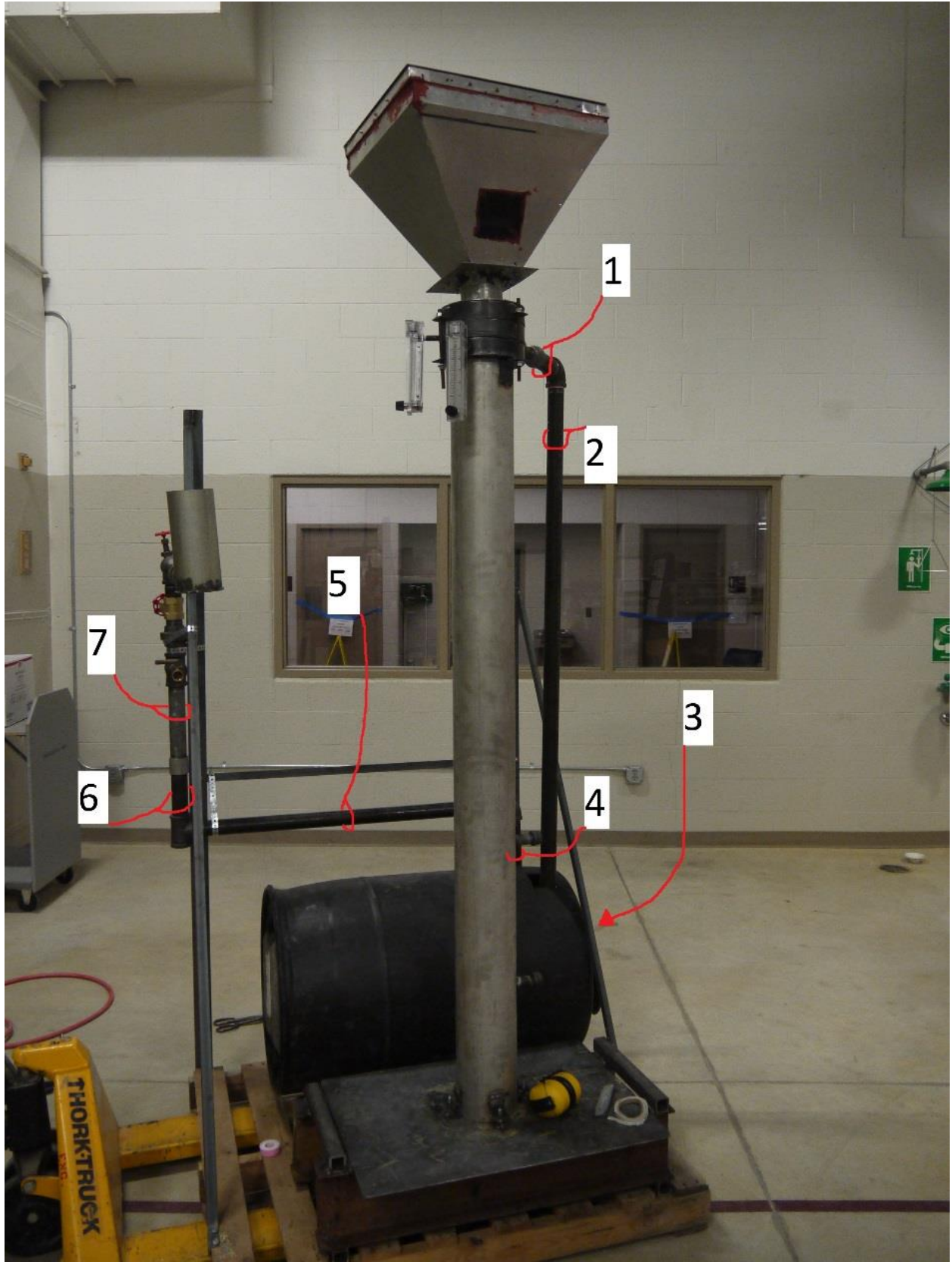


Figure 12-1 Labeled Pilot Plant Piping

12.3.2 Ash Containment

Table 12-3 below presents the initial calculations for the ash containment section of the gasifier. These calculations were made prior to the addition of the ash duct, which provided significantly more space. Regardless, the initial calculations were intended to provide adequate space in the bottom of the reactor to hold the ash generated from 120 hours of operation. Key assumptions behind these calculations include 1% ash content in the wood pellets, a conservative estimate based on the literature (*Wood Pellets FAQ, 2011*), an ash bulk density of 609 kg/m³, and a biomass combustion rate of 2 kg/hr. These calculations were performed by Nate Myton and checked by Matthew Lomasney.

Table 12-3 Ash Containment Sizing

Ash Containment Sizing			
		Note	Ref
Ash Content	1%	High estimate, most pellets 0.2-1.0 %	1
kg/hr	2		
kW/kg	3.165		2
kW/hr	6.33	Direct Heat Produced	
Ash ρ (kg/m ³)	609	Dry loose ash	3
Op. Time (hrs)	120		
Volume Buildup (m ³)	0.0039		
Reactor D (in)	6		
Ash Collect Height (in)	8		
Volume (m ³)	0.0037		
Reference			
1	http://woodpellets4me.com/pdf/2011-2012-PelletReview.pdf		
2	http://wiki.gekgasifier.com/w/page/6123680/Biomass%20to%20Woodgas%20to%20BTU%20to%20HP%20to%20KW%20to%20MPG%20conversion		
3	http://www.anval.net/downloads/bulk%20density%20chart.pdf		

12.3.3 Biomass Hopper

Figure 4-10 displays an AutoCAD drawing of the biomass feed hopper for the final product design. While we expect our final product to be able to run for a more extending period without refilling (~12 hrs), we designed our pilot plant with a smaller hopper for convenience of loading and construction. We designed the hopper to contain biomass for about 6 hours on continuous operation between reloading. The sizing calculations are shown in Table 12-4 and were performed by Nicole Michmerhuizen and checked by Nate Myton. The top was covered with a sheet of steel and sealed with duct tape. This allowed for an airtight seal while the device was operating (slight vacuum in the reactor will help). An appropriately sized aluminum hopper was found in the Engineering Building parts room and was used for this purpose. The hopper was bolted to the top plate of the manifold system to provide structural rigidity. We expect the temperature in the hopper to be < 200°C. The temperature in the hopper will be much lower than the temperature of the pyrolysis zone because, unlike in the pyrolysis zone, there is not heat exchange with the hot synthesis gas passing. 200°C is well below the auto-ignition temperature of wood (300°C) (Fuels and Chemicals - Autoignition Temperatures, n.d.). Furthermore, the hopper will be anoxic because of the vacuum in the gasifier, so combustion of the biomass in the hopper is not possible.

Table 12-4 Pilot Plant Hopper Sizing Calculations

Required Volume		
Storage Time	6	hrs
Mass Flow	2	kg/hr
Density Wood	700	kg/m ³
Volume of Hopper	17.1	L
Volume of Cone		
Diameter	12	in
Height	8	in
Volume	4.95	L
Volume of Cylinder		
Diameter	12	in
Height	6.58	in
Volume	12.20	L
Total Volume	17.14	L
Pressure Relief		
Plate Thickness	0.25	in
Density Steel	8000	kg/m ³
Steel Density	0.289	lb/in ³
Pressure to Relieve	0.0723	psig

The final product was designed to run for approximately 36 hours without refilling. The final product will use a simple steel drum as the hopper to ensure an air-tight seal. The calculations in Table 12-5 present the sizing for the hopper. These dimensions correspond closely to those of a commercially available 20 gallon drum.

Table 12-5 Final Product Sizing Calculations

Required Volume		
Storage Time	36	hrs
Mass Flow	2	kg/hr
Density Wood	700	kg/m ³
Volume of Hopper	102.9	L
Volume of Cylinder		
Diameter	21	in
Height	19.00	in
Volume	107.93	L

12.3.4 Steam Heating Element

Table 12-6 below was used to determine the necessary size for the heating element used to provide steam to the redesigned gasifier. Steam feed promotes the water shift reaction, which produces carbon monoxide and hydrogen from carbonaceous charcoal and water. In order to completely react the char between the bottom combustion zone and the synthesis gas effluent pipes (a distance of 10 centimeters), a feed of 2 L/hr of steam is required. Using the heat of vaporization of water, the power required to provide this steam feed is 1.4 kW. These calculations were performed by Nate Myton and checked by Matthew Lomasney for accuracy.

Table 12-6 Steam Heating Element Sizing Calculations

Height	10	cm
Diameter	15.2	cm
Volume	1820	cm ³
Density Char	0.4	g/cc
Mass Char	728	g
MW Char	12.0	g/mol
Mol Char	60.7	mol
Time	0.5	hr
Feed Rate	121	mol/hr
Feed Rate	2180	g/hr
Feed rate	2	L/hr
$\Delta H_{vap} H_2O$	40.7	kJ/mol
Heat Input	1.4	kW

12.4 Heat Transfer Calculations

12.4.1 Heat Exchanger

The heat transfer calculations for the heat exchanger required determining three heat transfer coefficients: the first for the convective heat transfer through the synthesis gas inside the pipes, the second for the conductive heat transfer through the metal pipes, and the third for the film-boiling effect in the water due to the large temperature difference between the synthesis gas and the water. The equations used for these calculations were found in a textbook written by Geankoplis (Christie J, 2003). The equations used for the convective heat transfer coefficient appears as follows:

$$\text{Laminar Flow: } N_{Nu} = \frac{h_i D}{k} = 1.86 \left(N_{Re} N_{Pr} \frac{D}{L} \right)^{\frac{1}{3}} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \quad \text{Equation 12-1}$$

$$\text{Turbulent Flow: } N_{Nu} = \frac{h_i D}{k} = 0.027 N_{Re}^{0.8} N_{Pr}^{1/3} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \quad \text{Equation 12-2}$$

A key assumption used to simplify Equation 12-1 and 12-2 was $\mu_b = \mu_w$. Additionally, the predicted flow pattern based on Reynolds number was in the transition region. To account for this, both laminar and turbulent calculations were made and the worst-case was assumed (which ended up being turbulent flow). The correlation used to model the film boiling coefficient of the water is presented below in Equation 12-3:

$$\text{Film Boiling: } h_o = 0.62 \left[\frac{k_v^3 \rho_v (\rho_l - \rho_v) g (h_{fg} + 0.4 c_{pv} \Delta T)}{D \mu_v \Delta T} \right]^{1/4} \quad \text{Equation 12-3}$$

Finally, these heat transfer coefficients were brought together to determine an overall heat transfer coefficient, incorporating the conductive heat transfer through the metal pipes. This correlation can be seen in Equation 12-4 below.

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{(r_o - r_i) A_i}{k_A A A_{lm}} + \frac{A_i}{A_o h_o}} \quad \text{Equation 12-4}$$

The inlet and exiting synthesis gas temperatures were specified and the overall heat transfer coefficient was used in the general heat transfer equation to determine if the length of pipe was sufficient to cool the synthesis gas. The general heat transfer equation appears as in Equation 12-5.

$$q = UA \Delta T_{lm} \quad \text{Equation 12-5}$$

The calculations were developed in excel and can be seen in Figure 12-2 below. The excel solver add-in was used to set the heat transfer required to cool the synthesis gas equal to the heat transfer achieved through the synthesis gas, metal pipes, and into the water by varying the pipe length. The specifications of the system were modified until a reasonable pipe length was obtained. The final results show that 3.2 m (10.5 ft) of 1.5" steel piping was required to cool the synthesis gas from 200°C to 120°C. The actual heat exchanger was designed with 4 passes, each with 32" length, of 1.5" steel pipe in a 55 gallon drum

of water. This design displayed a total of 12' of piping including the inlet and exit pipe from the heat exchanger, conservatively fulfilling the requirements for heat transfer. These calculations were initially done by Matthew Lomasney and were repeated using simpler correlations by Nate Myton to ensure reliability of the calculations.

Syngas Cooling, ($q=nC_p\Delta T$)	
n (mol/hr)	164
C_p (J/mol*K)	30.3
T.in (C)	200
T.out (C)	121
T.in (K)	473
T.out (K)	394
$\Delta T.lm$ (K)	50.8
Q (W)	109
Heat Transfer Calcs. ($q=UA\Delta T$)	
Water Calculations - Film Boil	
T.sat (K)	373
T.wall (K)	403
T.film (K)	388
$\rho.l$ (kg/m ³)	958
$\rho.v$ (kg/m ³)	1
$k.v$ (W/m*K)	0
hfg (J/kg)	2.44E+06
$C_p.v$ (J/kg*K)	1890
$\mu.v$ (Pa*s)	0
h.o (W/m²*K)	206

Piping - Steel	
k (W/m*K)	37
L (m)	3.20
Do (in)	1.9
Di (in)	1.6
Do (m)	0.0483
Di (m)	0.0406
Wall Thick (m)	0.004
A.i (m ²)	0.409
A.o (m ²)	0.485
A.lm (m ²)	0.446
Syngas	
T.ave (K)	434
μ (Pa*s)	2.416E-05
ρ (kg/m ³)	0.717
v (m/s)	3.305
Re	3985
k (W/m*K)	0.036
Pr	0.691

	Laminar	Turbulent
Nu	6	18
h.i (W/m ² *K)	5	16
Ui (W/m ² *K)	5.2	15.0
Uo (W/m ² *K)	4.4	12.6
Qi (W)	108.8	310.6
Qo (W)	108.8	310.7

Figure 12-2 Heat Exchanger Calculations (Christie J, 2003)

12.4.2 COMSOL Multiphysics Analysis For Heat Transfer in the Reactor

COMSOL was used to simulate heat transfer through the reactor and the air feed pipes. Key assumptions behind this analysis are listed below.

Assumptions:

- Wood Pellet Properties: 675 kg/m^3 , $1150 \text{ J/kg}\cdot\text{K}$, $0.17 \text{ W/m}\cdot\text{K}$
- Top Surface Temp = 25°C , Varied Combustion Temp between 850 and 1100°C
- Air feed pipes on each side, with top surface temp defined as 25°C .
- Outer surface fully insulated except for the top surface and the bottom wood pellet surface
- Neglected heat transfer from synthesis gas product
- 6 inch head space above the bed

Figure 12-3 shows a sample heat transfer simulation from COMSOL. Many case studies were run, but they all appeared quite similar to the one presented below.

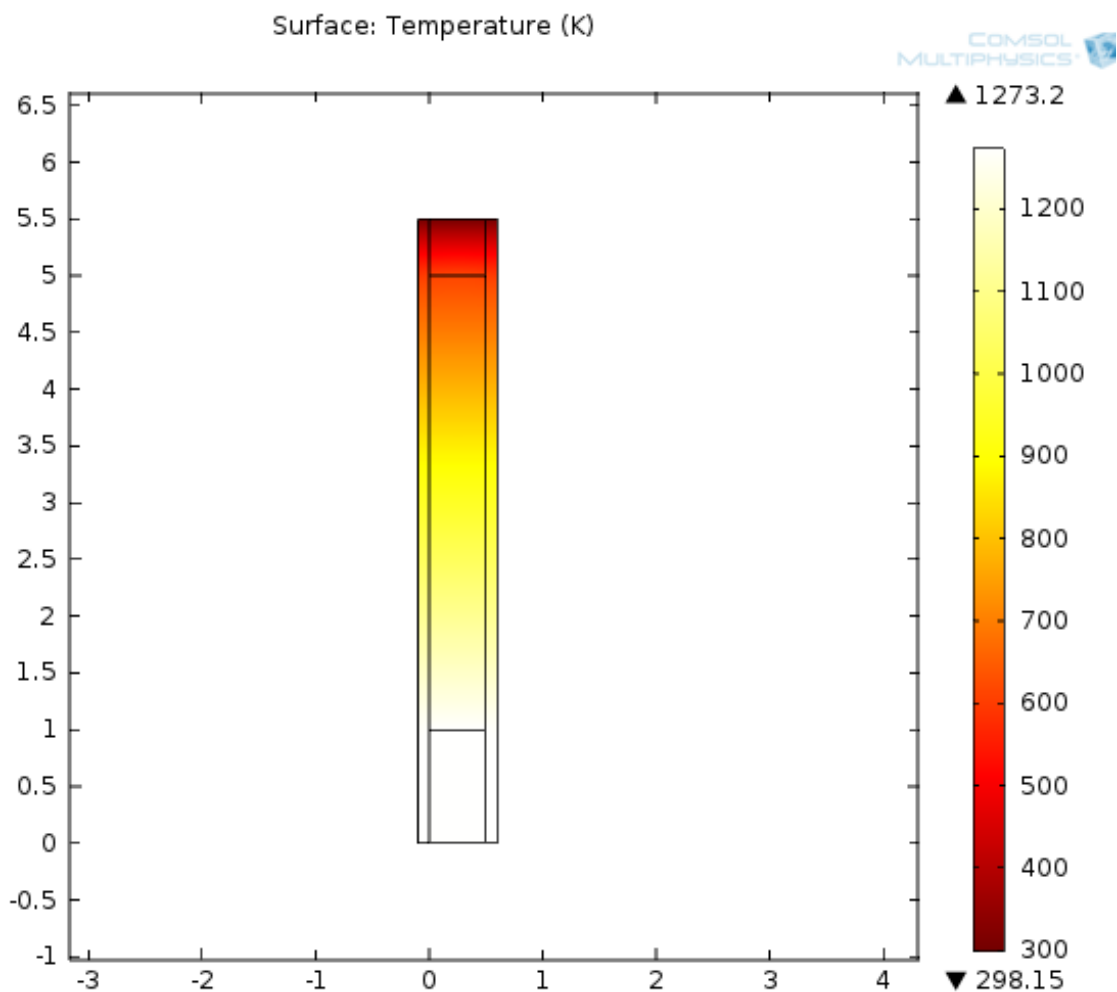


Figure 12-3 Sample Heat Transfer Diagram from COMSOL

A summary of the simulation case study can be seen in *Table 12-7* and *Table 12-8*. These tables show that a reactor height of at least five feet should be used to ensure that proper pyrolysis could occur.

Table 12-7 Summary of Heat Transfer Case Sensitivity Study

Height	Base Case (°C)	Cold Case (°C)	Hot Case (°C)
0	1000	850	1100
1	1000	850	1100
2	837	712	917
3	680	577	837
4	502	432	557
5	342	284	372
5.5	25	25	25

Table 12-8 Pyrolysis Zone Height Calculations

Pyr. Zone	400°C Height
Base Case (°C)	4.7
Cold Case (°C)	4.3
Hot Case (°C)	4.8

12.4.3 Synthesis Gas Cooling: Free Convection

These calculations were performed to ensure that the synthesis gas would be cooled down sufficiently before passing through the plastic rotameter downstream, which had a temperature requirement of 100°C. The heat transfer was modeled as free convection and the correlations were found in Geankoplis (Christie J, 2003). Equation 12-6 below was used to model the free convection heat transfer coefficient from the cylindrical pipes. This equation was the same for both horizontal and vertical pipes when $N_{Gr}N_{Pr} > 10^9$, which was the case with our system.

$$h = 1.37 \left(\frac{\Delta T}{L} \right)^{1/4} \quad \text{w/ } N_{Gr}N_{Pr} > 10^9 \quad \text{Equation 12-6}$$

Figure 12-4 shows some of the specifications and constants for the system. The length and synthesis inlet and exit temperatures were specified. Excel solver was used to set the heat loss of the synthesis gas equal to the heat transfer by natural convection, shown in

Figure 12-5.

Constants	
Pipe D (in)	1.5
Pipe D (m)	0.0381
Pipe A.x (m ²)	0.001140
L (m)	2.70
Pipe A.s (m ²)	0.324
MW.syn (g/mol)	26.86
T.Air (K)	298

Thermal Conductivity of Metals	
Copper (W/m*K)	400
Steel (W/m*K)	51

Synthesis Gas Composition			
Species	Composition	MW (g/mol)	Cp (J/mol*K)
CO	0.25	28.01	29.1
CO ₂	0.12	44.01	37.135
CH ₄	0.04	16.05	35.69
H ₂	0.10	2.02	28.836
N ₂	0.49	28.02	29.124
		Sum	30.31

*Assume the Outer Pipe Temp = Bulk Syn-gas Temp		
	T.syngas In	T.syngas Out
oC	200	100
K	473	373
n (mol/s)	0.045437	0.04544
Heat Flow (W)	275.5	137.7

Figure 12-4 Specifications and Constants

The total heat transfer ($q = UA\Delta T$) had to be calculated as a series of linear approximations. U and A remain constant throughout the cooling process, but ΔT changes dramatically over the pipe length. Therefore, the cooling curve is an exponential decay so a linear model would not work. Because

of this, linear approximations were made between each 100°C of cooling to more accurately portray the cooling curve. The results from this analysis can be seen in Figure 12-6 below. These calculations were done by Matthew Lomasney and double checked for accuracy by Nate Myton. We determined that 27 feet of piping was required to cool the synthesis gas from 1000°C to 75°C.

Natural Convection Calculations		
	Initial	Final
$g\beta\rho^2/\mu^2$	1.75E+07	5.70E+07
N.Gr	6.06E+10	8.46E+10
N.Pr	0.708	0.708
Gr*Pr	4.29E+10	6.00E+10
Vertical Cylinders		
h (W/m ² *K)	6.936	5.229
q (W)	393	127
Horizontal Cylinders		
h (W/m ² *K)	6.936	5.229
q (W)	393	127

Figure 12-5 Natural Convection Heat Transfer Coefficient Calculations

T In (oC)	1000	900	800	700	600	500	
T out (oC)	900	800	700	600	500	400	
Length (m)	0.1	0.12	0.14	0.17	0.21	0.27	
T In (oC)	400	300	200	100	75		
T out (oC)	300	200	100	75	50		Sum (m)
Length (m)	0.38	0.59	2.15	1.39	2.7		1.01
							ft
							3.3

Figure 12-6 Linear Approximations for Synthesis Gas Cooling

12.4.4 Insulation and “Safe Touch”

The heat losses due to conduction and convection were calculated to determine the outside temperature of the insulation as shown in Table 12-9. To calculate the surface temperature the heat transfer via conduction through the insulation was calculated as was the heat transfer via convection from the surface of the reactor. These heat flows must be equal to each other at steady state. The surface temperature is varied until that constraint is true. The heat transfer was calculated using the same methods outline in Section 12.4.1 in the Appendix.

Table 12-9 Reactor Temperature

Temperatures			Convection		
Reactor Temp	1200	C	Tf	85	C
	2192	F	L	1.8288	m
Outside Temp	150	C	ρ	0.988	kg/m ³
	302	F	g	9.81	m/s ²
Air Temp	20	C	β	2.79E-03	1/K
			DT	130	K
Conduction			μ	2.00E-05	kg/m s
k	0.6	BTU-in/hr/sf/F	NGr	5.32E+10	
DT	1890	F	NPr	0.71	
Thickness	5.72	in	NGr*NPr	3.77E+10	
Reactor rad	3	in	k	0.028	W/m K
Total Rad	8.72	in	a	0.13	
Length	6	ft	m	0.33	
Q	3339	BTU/hr	Nnu	436.1	
Q	979	W	h	6.68	W/m ² K
$Q = 2\pi kV \frac{(T_1 - T_2)}{\ln(r_2/r_1)}$			A	1.13	m ²
			Q	979	W

Then, using the temperature and the conductivity of the material the amount of contact time before the sensation of pain was calculated based on an article by NASA (Eugene Ungar, 2014) as shown in Table 12-10 and Figure 12-7.

Table 12-10 Safe Touch Temperature

k	0.5	BTU-in/hr/sf/°F
k	0.000172	cal/s cm °C
density	2.73	g/cm ³
specific heat	1130	J/kg °C
specific heat	0.270	cal/g °C
kpc	0.000127	cal ² /cm ⁴ °C ² s
1/(kpc)^{0.5}	88.77	
a	0.92	
b	69.97	
T_{object}	151.6	°C

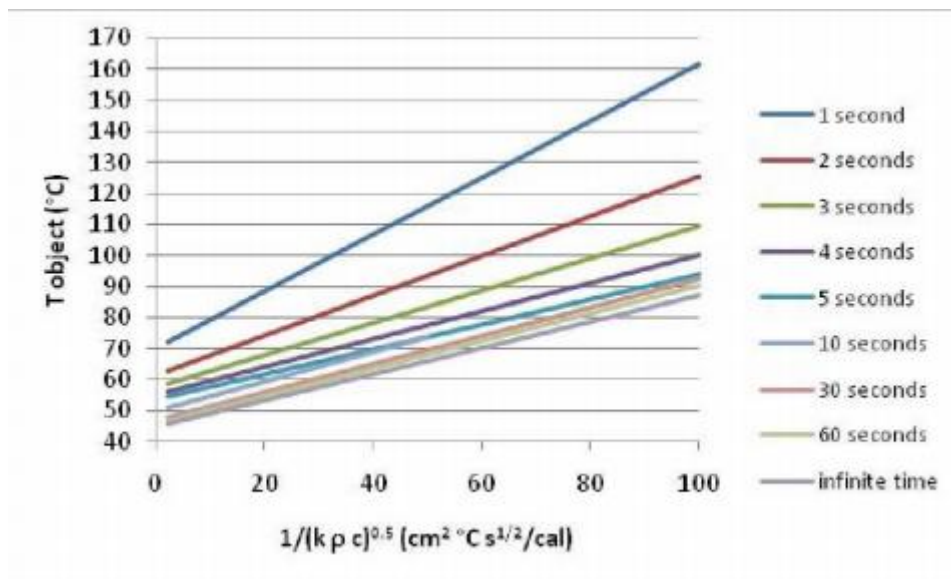


Figure 12-7 Safe Touch Temperature (Eugene Ungar, 2014)

12.5 Manifold and Air Tube Design Calculations

12.5.1 Number of Reactor Pipes

Table 12-11 shows calculations for the number of 0.5" air feed pipes that can fit in a ring inside the 6' reactor pipe. The calculations were made by first finding the circumference of the inscribed circle of the air feed pipe ring. This circumference was then divided by the air feed pipe outer diameter (0.5") to find the number of pipes that will fit in the reactor. It was determined that 33 pipes could fit. These calculations were performed by JP and were checked for accuracy by Matthew Lomasney, Nate Myton, Eric Sager, and Nicole Michmerhuizen.

Table 12-11 Number of Air Feed/Synthesis Gas Pipes that Fit in Reactor Calculations

6	OD big pipe		
0.065	skin big pipe		
5.9	ID big pipe		
0.5	OD small pipe		
5.4	diam. Circle on center of small pipes		
16.9	circumf		
33.7	pipes		
33	whole pipes		
5.5	sets		
5	whole sets		
30	primary pipes		
3	excess pipes		

The number of pipes was modified for the pilot plant redesign because the diameter of the air feed pipes were increased. The calculations for this analysis can be seen in Table 12-12 below. The same process was made for these calculations as was done previously. These calculations were performed by Matthew Lomasney and were reviewed by Nicole Michmerhuizen for accuracy.

Table 12-12 Redesign Air Feed and Synthesis Gas Calculations

Specifications			
Reactor Pipe Diameter (in)	6		
Air Tube O.D. (in)	0.75		
Clearance b/w reactor pipe and tubes (in)	0.125		
Calculations			
Inscribed Circle Diameter (in)	5		
Inscribed Circle Circumference (in)	15.7		
# of Tubes (close fit)	20.9	Space Between Tubes	
Fraction of Circ. w/ Tubes	0.57	0.559	inches
# of Tubes with spec'd void space	12.0		
Flow Rate Comparison to Old Tubes			
Old Tube O.D. (in)	0.5		
Big Ax/Small Ax	2.25		
Air Feed Flow Rate (Big/Small)	1.41	~40% more Air Flow	
Syn Gas Flow Rate (Big/Small)	0.98	~Same Syn Gas Flow	

12.5.2 Pilot Plant Piping: Flow Rates

Table 12-13 shows the calculations to determine the gas velocity through various pipes in the pilot plant. These velocities were used in the pressure drop calculations presented in Section 12.5.3. The key assumptions behind these calculations include the ideal gas law, which states that $P_1V_1/T_1 = P_2V_2/T_2$, and that 2 kg/hr of biomass combustion yields approximately 4 m³ of wood gas at standard conditions.

Table 12-13 Synthesis Gas Flow Rate Calculations

Assumptions:					
2 (kg Biomass/hr) = 4 (m ³ STP Woodgas/hr)					
IGL assuming constant moles (n ₁ =n ₂)					
P ₁ V ₁ /T ₁ = P ₂ V ₂ /T ₂					
STP Gas Values		Effluent Conditions		Velocity Down Pipe	
P1 (atm)	1	P2 (atm)	0.95	Pipe Diameter (in)	1.025
T1 (K)	298	T2 (C)	120	Pipe Diameter (m)	0.026035
V1 (m ³ /hr)	4	T2 (K)	393	Pipe Area.x (m ²)	0.000532
		V2 (m ³ /hr)	5.55	Syn-Gas Velocity (m/s)	2.90

Table 12-14 shows calculations for the required air feed to attain 25% equivalents assuming a combustion rate of 2 kg/hr. The required air feed was first determined for complete combustion using the chemical reaction equation for completely combusting cellulose, presented in Table 12-14. The mol/hr of oxygen required was calculated via material balance using the stoichiometry in the chemical equation, and the amount of air was calculated knowing that air is 21 mol% oxygen. This molar air feed was then converted to a volumetric flow rate using the ideal gas law at standard conditions (because atmospheric air was being used). The 25% equivalents ratio was then applied to determine the desired air flow rate. The velocity through the air feed pipes was also calculated so that the pressure drop could be determined. These calculations were performed by Matthew Lomasney and reviewed by Nicole Michmerhuizen.

Table 12-14 Air Feed Calculations

Cellulose Complete Combustion Equation:																
1	C₆H₁₀O₅	+	6.0	O₂	+	22.56	N₂	→	5	H₂O	+	6	CO₂	+	22.56	N₂

m.biomass (kg/hr)	2
MW.cellulose (g/mol)	162.16
n.cellulose (mol/hr)	12.33

Heat Transfer Estimate	
ΔH.rxn (kJ/mol)	-745
Q (kW)	-2.55

Air Feed Calculations	
n.O ₂ (mol/hr)	74.00
n.N ₂ (mol/hr)	278.24
n.Air (mol/hr)	352.24
ρ.Air (mol/L)	0.0409
V.Air (L/hr)	8614
V.Air (L/min)	143.56
Equivalence Ratio	0.25
V.Air (L/min)	35.89

Velocity Down Pipe	
Pipe Diameter (in)	0.5
Pipe Diameter (m)	0.0127
Pipe Area.x (m ²)	0.000127
Air Velocity (m/s)	4.72
Air Velocity/pipe (m/s)	2.36

12.5.3 Pilot Plant Piping: Pressure Drop

The venturi system is capable of pulling about 20" water vacuum. The reactor should operate with a vacuum of about 5" water. The pressure drop in the piping of the pilot plant, especially in the heat exchanger, must not lead to a pressure drop that makes it impossible to get sufficient vacuum in the reactor. A pressure drop of less than 8" water was considered acceptable. The calculations shown in Table 12-15 were used to determine the pressure drop for different pipe diameters. These calculations were performed in conjunction with the heat transfer calculations in Section 12.4.3 to ensure sufficient heat transfer area while also maintaining an appropriate pressure drop. These calculations show that if the entire system is made from 1" piping the pressure drop will be less than 1" water. If then entire system was made of 1/2" pipe the pressure drop would be nearly 20" of water, which is unacceptable. The physical properties in the calculations were from The Engineering ToolBox (The Engineering ToolBox, 2014) and equations used for these calculations are shown below and were found in Geankoplis (Christie J, 2003).

$$N_{Re} = \frac{Dv\rho}{\mu} \quad \text{Equation 12 - 7}$$

$$\psi = \left(\frac{\mu_a}{\mu_w}\right)^{0.23} \quad \text{Equation 12 - 8}$$

$$f' = f\psi \quad \text{Equation 12 - 9}$$

$$\Delta P = 4f\rho \frac{\Delta L v^2}{D} \frac{1}{2} \quad \text{Equation 12 - 10}$$

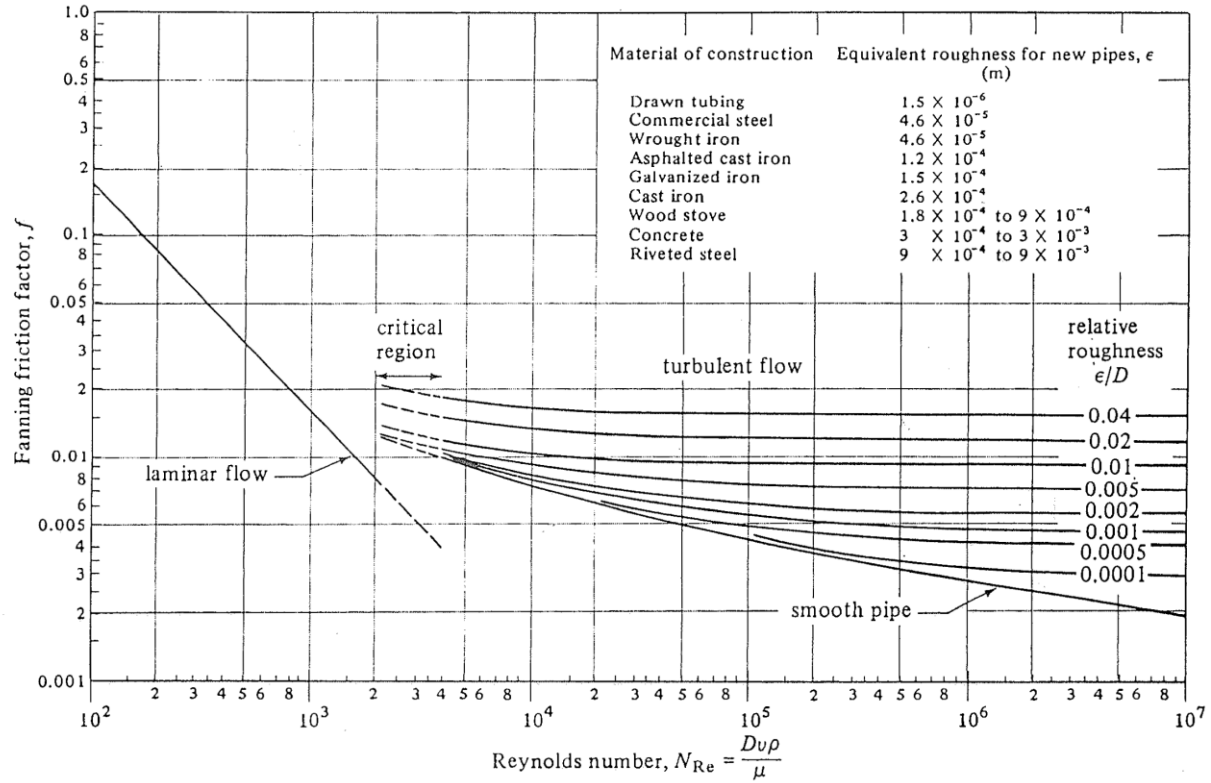


FIGURE 2.10-3. Friction factors for fluids inside pipes. [Based on L. F. Moody, *Trans. A.S.M.E.*, 66, 671, (1944); *Mech. Eng.* 69, 1005 (1947). With permission.]

Figure 12-8 Fanning Friction Factor Based on Reynolds Number and Pipe Roughness (Christie J, 2003)

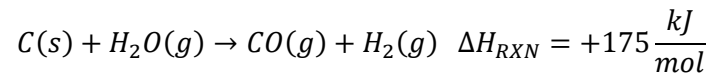
Table 12-15 Pressure Drop Calculations

			Notes
T _{in}	800	C	High estimate
T _{out}	50	C	Rotometer Max Temp
T _{avg}	425	C	
μ _{avg}	3.33E-05	Pa s	air at 700K
P	1	atm	
MW	26.86	g/mol	Matt's sheet
ρ	739.0522	g/m ³	
T _{wall}	100	C	In boiling water
μ _{wall}	2.29E-05	Pa s	air at 400K
STP Flow	4	m ³ /hr	
mass flow	4.47	kg/hr	
L	18.8	m	From Equiv Length Calculation
ID	1	in	Of cooling pipe
ID	0.0254	m	
x _A	0.000507	m ²	
G	2.45	kg/s/m ²	
Re	1869		
ε	4.60E-05	m	Pipe Roughness
ε/D	0.00181		
f	0.011		From Fig 2.10-3 Geankoplis
ψ	1.042247		Correction for non-isothermal
f corrected	0.010554		
P ₁	1.01E+05	Pa	
P ₁	406.64	in H ₂ O	
P ₂	1.01E+05	Pa	
P ₂	405.81	in H ₂ O	
ΔP	0.84	in H ₂ O	Should be <8 in

Equivalent Length			
Fitting	Number	L/D	L (m)
Return Bend	3	75	5.72
Open Gate	1	9	0.23
Coupling	10	2	0.51
Elbow	10	17	4.32
Straight			8
Total			18.8

12.6 Temperature Drop from Steam Feed

One of the mechanisms for cooling down the reactor during operation or for shutting down the reactor at the end of operations is the feed of steam into the reactor. This will cool the reactor by the following endothermic reaction.



The steam is fed into the bottom of reactor which means that most of this heat absorbed by this reaction will be absorbed from the lower portion of the reactor (the combustion zone). The cooling process is modeled using the calculations in

Table 12-16 using the following assumptions:

- Cooling takes place in the lower 36" of the reactor
- This portion of the reactor is filled with charcoal
- Water vapor is fed in at 2 L/hr, based on the flow rate delivered by the heating element sized in Section 12.3.4 in the Appendix

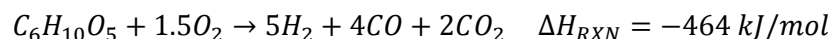
Based on these calculations the steam feed will provide a cooling duty of about 6 kW and the combustion zone will cool at about 1 °C/s. This means that the combustion zone can be cooled from 1000°C to 400°C in about 11 minutes.

Table 12-16 Steam Cooling Calculations

Steam Cooling		
Feed Rate	122	mol/hr
Feed Rate	2200	g/hr
Feed rate	2	L/hr
$\Delta H_{vap} H_2O$	40.7	kJ/mol
Boiler Heat Input	1.4	kW
Heat Reaction	175	kJ/mol
Heat Flow	-5.9	kW
Height	91	cm
Diameter	15	cm
Volume	16700	cm ³
Density Char	0.4	g/cc
Mass Char	6.7	kg
Specific Heat	1	kJ/kg K
Heat Drop	-0.9	K/s
1000°C->400°C	-11	min

12.7 Energy Balance

A simple energy balance was performed using predicted values for the flow rates into and out of the gasifier. The gasification reactions were represented by the following reaction.



The heat lost from steam feed is modeled as described in Section 12.6 of the Appendix. The heat loss from the insulation was based on the calculations described in Section 0 of the Appendix. The heat leaving from the effluent was calculated using an estimated specific heat for the synthesis gas and assuming that the air feed enters at 25°C.

Table 12-17 Energy Balance

Energy Balance		
Combustion/Gasification		
Feed Rate Wood	3.5	kg/hr
MW Glucose	180	g/mol
Moles Char	19	mol
Heat RXN	-464	kJ/mol
Heat Produced	2.51	kW
Steam Cooling		
Feed Rate	5	mol/hr
Feed Rate	90	g/hr
Feed rate	0	L/hr
$\Delta H_{\text{vap H}_2\text{O}}$	40.7	kJ/mol
Boiler Heat Input	0.1	kW
Heat Reaction	175	kJ/mol
Heat Flow	-0.2	kW
Insulative Heat Loss		
Heat Leaving	1	kW
Effluent Heat Loss		
Flow Rate	7.6	m ³ /hr
Temp	800	C
Cp	30	J/mol K
Density	22	L/mol
Flow Rate	345	mol/hr
Heat Out	-	kW
Net Heat Flow	0.0	kW

12.8 Calibration Data

The following data was obtained to calibrate the rotameters and thermocouples using the methods described in Sections 2.16.1 and 2.16.2 above.

Table 12-18 Synthesis Gas Rotameter Calibration Data

Rotameter Reading (L/min)	Measured Flowrate (L/min)
1	28
2	54
3	80
4	113
5	143

Table 12-19 Steam Rotameter Calibration Data

Rotameter Reading (mm)	Measured Flowrate (L/min)
11	5.2
21	11.4
21	10.8
35	19.6
47	27.9
61	35.8

Table 12-20 K-Type Thermocouple Calibration Data

Temp	Volt (mV)
21.8	0.05
231	7.28
330	10.96
100	3.2
0	-0.8
400	15.2
504	19.8
710	28.7
817	33.1

12.9 Pilot Plant Operation Data

Of the six times that the team operated the gasifier, they only recorded details of the operation for the final two operations. During those runs the team recorded temperature at both combustion zones and made qualitative comments every 2-5 minutes. The data from these runs is shown below. The rotameter for the top air feed maxed out at 50 scfh. Under some conditions, the ball in the rotameter was bouncing on the top of the gauge at the 50 scfh mark. This was represented as 50+. At other times, the rotameter was completely pegged out at the 50 scfh mark, which was represented as 50++.

Date	4/6/2014							
Time (min)	Top Temp	Unit	Bottom Temp	Unit	Top Air Feed (scfh)	Tar in Mason Jars	Flare Notes	Other notes
5	335	° C	25	° C	50 +	None	No smoke	
7	387	° C	25	° C	50 +	None		
9	389	° C	21	° C	50 ++	None	Opened to increase air feed	
12	397	° C	25	° C	50 ++	None		
15	17.6	mV	26	° C	50 ++	None	Smoke	
18	20.1	mV	27	° C	50++	None	Opened fully	
20	21.2	mV	31	° C	50++	None		Syngas exit tube too hot to touch
23	23	mV	29.7	° C	50++	None		
25	23.8	mV	32.5	° C	50++	None		Smoke from top of manifold
28	23.2	mV	36	° C	45	None	Turned down	

Date	4/11/2014			
Time	Top (mV)	Top (°C)	Bottom (°C)	Comments
10:10am	0.01	35.2		Started (Matt, Nicole, Eric, Nate present)
10:13am	1.3	65.9	25.3	Top ignition port open, feeding air to top
10:15am	6	177.8	40.0	Self-Sustaining flare with venturi turned down
10:17am	15	392.0	55.7	
10:19am	22	558.6	74.6	
10:21am	25.5	641.9	103.6	Eric and Nicole left
10:25am	26.9	675.2	153.4	
10:30am	27.4	687.1	200.9	Capped the top ignition port
10:36am	27.5	689.5	235.3	Flare no longer self-sustaining
10:40am				Ignition port opened to fix bridging, Matt burned
10:45am				Gasifier shut down, Went for treatment for Matt

12.10 Orsat Operation Data

Orsat Operation Data						
Test #	1		2		3	
Sample Type	Air		Air		Air	
Run After Absorbant Prep	1		2		3	
Days Old Prep	2		2		2	
Wash #	Mol% CO2	Mol% O2	Mol% CO2	Mol% O2	Mol% CO2	Mol% O2
1	0.0	19.0	0.0	5.8	0.0	4.8
2			0.0	10.2	0.0	8.6
3				13.9		12.2
4				16.4		15.0
5				18.0		16.9
6				18.7		18.0
7				18.9		18.4
8				18.9		18.5
9				19.0		18.5
Test #						
	4		5		6	
Sample Type	CO2		Air		93% N2, 5% CO2, 2%O2	
Run After Absorbant Prep	4		1		2	
Days Old Prep	2		0		0	
Wash #	Mol% CO2	Mol% O2	Mol% CO2	Mol% O2	Mol% CO2	Mol% O2
1	50.0		0.0	6.5	0.8	5.7
2	75.0		0.0	12.4	0.9	8.9
3	75.0			16.5	0.9	10.4
4	80.0			18.6		11.1
5				19.2		11.2
6				19.3		11.2
7				19.3		

12.11 Incident Report: Reported to Professors Wentzheimer and Sykes and Jenifer Ambrose

On Friday, April 11, the team met around 9am to operate the gasifier. All four members were present. Eric and Nicole were wearing safety glasses, Nate was wearing his prescription glasses, and Matt was not wearing safety glasses. After gathering all the necessary tools and connecting the compressed air to the venturi, the team was ready to start the gasifier. The top air manifold was opened all the way and the bottom was closed completely. The bottom ignition port was kept closed and the top ignition port was opened. The venturi was turned on and the propane torch was used to light the wood in the top ignition port (10:10 am). The torch was only needed for a few seconds before the wood began to glow brightly. The ignition port was left open to allow increased air flow, which allowed the gasifier to heat up more quickly. After 5 minutes of operation (10:15 am), they checked the flammability of the product gases by turning down the venturi and lighting the flare. This resulted in a self-sustaining flame, which suggested that the gasifier was producing significant amounts of flammable gases. The venturi was then turned back up to allow the gasifier to continue to heat up. Eric and Nicole left for class around 10:20 and Nate and Matt remained to operate the gasifier.

After 10 minutes (10:30 am) the gasifier had reached about 650°C at the top ignition zone and about 200°C at the bottom. While the top combustion zone had not yet reached the desired temperature of 1,000°C, Matt and Nate decided to close the ignition port. They wanted to prevent excessive channeling due to uneven air flow in the reactor. If excess air is fed to only one side of the reactor they thought that it would cause the wood on that side of the reactor be consumed much more quickly. This could form a void space where all of the wood had been consumed. The gasifier continued to run with the port closed. After about 5 minutes of operation with the ignition port closed (10:36 am), the venturi was turned down briefly to check if the flare was self-sustaining. It

could not sustain a flame, which suggested that combustible gas was not being generated in sufficient quantities.

After another 5 minutes (10:40 am), Matt and Nate decided to check the gasifier for bridging in the reactor body (as this could prevent the production of combustible gases). To test this, they decided to open the bottom ignition port and knock on the air feed tube to break up any bridging. However, the ignition port was stuck, possibly due to thermal expansion of the metal, and they could not get the cap off. Therefore, they decided to access the tubes from the top ignition port. They removed the cap and looked inside to see that the wood was glowing orange. From looking inside, it was not clear whether or not bridging was occurring.

Nate climbed the ladder to watch the level of pellets in the feed hopper. Because the level of the pellets had not changed since they started operating, they thought that bridging was a likely possibility. To test this hypothesis, they proposed that Matt should knock the pipes in the reactor to break up the bridging while Nate watch the level of pellets in the feed hopper. If their hypothesis was correct, Nate would be able to see the pellets in the hopper shift down as Matt knocked on the pipes.

Matt equipped himself with high temperature resistant gloves and used an 8" section of half inch, stainless steel pipe to reach into the ignition port. A pipe wrench was then used to tap the pipes inside the reactor and hopefully break apart bridging. After knocking for about 30 seconds, Nate had seen little impact on the level of pellets in the hopper. He told Matt that it looked like they had settled downward about half an inch. Matt then stopped to look into the ignition port. After looking for a moment, he felt an intense heat.

Matt leaped backwards and instinctively patted his face to put out any flames. Nate got down from the ladder and checked on Matt. After confirming that Matt could see and had suffered no serious injuries, Nate saw that the sheet on the outside of the gasifier had caught fire. Nate grabbed the fire extinguisher and put out the fire. At the same time, Professor Koetje, who was walking by at the time,

saw what had happened and brought Matt inside the Engineering Building to wash out his eyes. Nate stayed outside to tend to the reactor. He capped the ignition port and turned off the venturi. After checking the gasifier to make sure that nothing else was on fire and double checking to ensure the venturi was off, he joined Matt inside. Phil Jasperse found them there and gave Matt saline solution for his eyes, which relieved some of the discomfort that Matt felt.

Matt and Nate then went to Calvin Health Services (about 11:30 am). They spoke with the Calvin nurse, who advised them to schedule an appointment with an ophthalmologist to check Matt's eyes. They scheduled an appointment at 2:45 pm at Grand Rapids Ophthalmology and returned to the Engineering building. Matt put some burn ointment on his face before Eric drove him home to rest. At 2:00 pm Eric and Nate picked up Matt at his house and drove him to his appointment. There the ophthalmologist reported that he had suffered no major damage to his eyes and that his vision was still normal. She provided Matt with artificial tears to relieve any discomfort or dryness in his eyes. By that evening, Matt reported that the burn marks and swelling on his face had gone down significantly and that he was feeling much better.

The injuries that Matt sustained include 1st degree burns on his brow ridge, nose, and under his eyes, and singeing of his eyelashes, eyebrows, and hair on the front and left sides of his head.