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Energy Research and Development Division

FINAL PROJECT REPORT

Reciprocating Reactor to Produce Low-Cost Renewable Natural Gas

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Reciprocating Reactor to Produce Low-Cost Renewable Natural Gas is the final report for the Renewable Natural Gas Transportation Fuel Production Systems with Value Added Co-Products/Benefits (Contract Number PIR-12-021) conducted by Interra Energy, Inc. The information from this project contributes to Energy Research and Development Division's Natural Gas Transportation Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

The goal of the Interra project was to develop a low-cost, pyrolysis-based biomass conversion technology, known as the Reciprocating Reactor, to produce renewable natural gas and biochar. The Reciprocating Reactor is designed to convert biomass into renewable natural gas at higher efficiencies compared to other thermal conversion technologies. However, the project encountered major technical challenges including in maintaining the required operating pressure in the first prototype version of the technology and the effect of significant nitrogen dilution on pyrolysis producer gas. While mechanical testing confirmed that, under ambient conditions, the material handling system was able to push the maximum designed rate of biomass through the reactor, operational testing revealed significant issues with multiple systems, including the auger design, biomass intake system, and combustion flare. The design failures detected during operation testing drove the need for iterative experimental testing and ongoing repairs to address the technological challenges of effectively operating at the desired system temperature and throughput rate. Further research, component development and refinement, and small-scale testing is needed to validate full performance and stability of the system prior to pilot-scale testing and renewable natural gas production.

Keywords: Biofuel, biomass, biochar, bioenergy, distributed energy, gasification, greenhouse gases, organic waste, pyrolysis, sustainability, producer gas, low-energy gas, waste-to-energy

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EXECUTIVE SUMMARY

Introduction

California faces ongoing concerns over the effects of climate change – including catastrophic wildfires – and the need for economical low-carbon fuel source. For decades, the state has used biomass – organic waste materials from forests, agriculture, food processing, water treatment facilities, and landfills – to produce clean energy, or bioenergy. Bioenergy includes renewable bio-based electricity, low carbon transportation fuels, and pipeline gas. Unfortunately, bioenergy still faces many challenges, including the lack of available technology options for biofuel and bioenergy production that can economically process certain sources of biomass, such as forest tree die-off and urban green waste.

Interra designed a system that aimed to produce both a low-emission renewable gas and a valuable biochar co-product using a thermochemical process called pyrolysis. Pyrolysis is a promising technology that converts biomass and produces low-carbon fuels by heating the biomass in the absence of oxygen to produce combustible gases, liquids, and solid residues. Producing low emission renewable gas and biochar can improve the economics of the technology to allow increased deployment and contribute to achieving California's policy goals to decrease carbon emissions, increase renewable energy and biofuels, and reduce forest fire risk.

This project sought to demonstrate a unique pressurized pyrolysis biomass reactor to address a major technical problem – the low heat of reaction and the resulting inability to create a thermally self-sufficient continuous reaction. To address the technological problem, Interra's technology aimed to modify the traditional conversion process by removing a methanation step and convert biomass at higher efficiencies compared to other thermochemical conversion technologies. To increase the economic viability of the technology, research focused on producing both a transportation-quality renewable natural gas (RNG) and a valuable biochar co-product.

Project Purpose

This project aimed to develop a low-cost, pyrolysis-based biomass conversion technology, the Reciprocating Reactor, to produce renewable natural gas and a biochar product. The project's primary performance goal is to produce a gas with sufficient amounts of methane and carbon dioxide so that only enhanced carbon dioxide scrubbing and tar removal would be needed to meet California Air Resources Board's specifications for transportation-quality renewable natural gas. The project included biochar co-production for two reasons: (1) biochar's value can improve the technology's economic viability; (2) agricultural soils incorporate biochar as a carbon sequestration strategy, which could make the biofuel production net carbon negative.

Project Approach

The project was divided into three phases: 1) pre-construction; 2) construction; and 3) system testing. System testing was further divided into two subcategories, mechanical tests and operational performance tests. The mechanical tests were intended to validate the mechanical performance of the reactor's unique conveyance method, while operational performance tests were used to determine the effect on the quantity and quality of product output from varying reactor conditions.

Construction began in August 2013 with structural scaffolding and procurement of components. By October 2013, Interra had received most of the system's reactor components, piping, and flanges and begun construction of the reactor. After the auger components arrived, mechanical testing confirmed that under ambient conditions, the augers could push the maximum designed rate of biomass through the reactor. During this time, testing also took place for most of the facility's sub-systems. Results revealed several problems in multiple systems that would require upgrading or modification. The most extensive changes necessary involved redesigning the feed and reciprocating augers to sustain the higher temperature.

Project Results and Lessons Learned

Interra was able to test and validate the core design and gather valuable data on its ability to generate both producer gas (the gas produced through pyrolysis) and biochar. Work was completed at a scale much larger than the traditional bench scale, and the resulting solutions to problems identified during the project can help address issues in future pilot-size projects using similar technology; however, Interra's system inefficiencies revealed that additional component testing should have been completed at a smaller scale. There is still a substantial amount of research, prototype design and development, and testing that will need to be completed before the technology is ready for commercial rollout; however, the core lessons learned under this project can improve the likelihood of success for future projects by providing information on design issues, and highlighting the value in laboratory-scale system testing.

The most critical and valuable lesson learned from this project for future developers of thermochemical biomass conversion technologies relates to the design of the augers that will be used to move biomass through a feed tube. Shaftless augers are typically used to move a diverse mix of biomass sources but the biomass has tendencies to wind around the augers and bind. Project demonstration showed that shaftless augurs designed to push rather than pull material through the feed tube are more likely to bind and seize. This is due to an increase in the outer diameter of the auger under the pressure of pushing, unlike a pulling augur, which will shrink under tension, affecting the turning of the augur.

Because Interra's reactor design requires a pushing augur, future designs that use such a reactor will need to account for potential seizing, as experienced during Interra's reactor hot testing. Methods to address seizing and other augur related issues include:

- Devices to measure torque on auger drive shafts could detect biomass material obstruction and allow fast and automatic shutoff to reduce the risk of component damage. Also, an automatic "reverse then resume" function would be useful so that when the control system detects a spike in torque it can stop the motor, reverse the augur to release the obstructed material, then resume forward operation without the operator needing to intervene.
- Recommend increasing the horsepower in the motor that moves the biomass material by 50-100 percent and controlling the speed with a variable-frequency drive. Models to determine the necessary horsepower for biomass conveyance using shaftless augurs often prescribe undersized motors.
- Designing auger with increased strength to not yield at the highest potential reactor temperatures, after considering the maximum torque that the drive motor and assembly can produce under fully seized jam conditions. This calculation should be done with at

least a 1.5x factor of safety, and as much as 2.5x if a more powerful motor will eventually be used.

- When calculating augur strength, factor in temperatures well above the maximum desired reactor temperature to account for "hot spots" that can develop that can affect internal materials; the assumed peak temperature used in calculating material strengths should be 200°F -300°F degrees hotter than those read on the outside of an auger-based reactor.

Not all project experiments are completed due to the ongoing issues with the auger design and inability to complete verification testing of the system. The prototype unit that Interra began constructing under this project identified critical components for future research and demonstration of similar systems, including:

- The mechanical feasibility of reactor's unique concentric and opposing auger design.
- Auger-based reactor designs used in thermochemical biomass conversion systems.

Renewable natural gas production through thermochemical biomass conversion presents several challenges because pipeline quality gas requires a minimum of 80 percent methane, but the gas produced through pyrolysis is composed of hydrogen, carbon monoxide, carbon dioxide, methane, nitrogen, and tars. The most established thermochemical biomass pathway to produce renewable natural gas involves multiple steps to remove or convert the non-methane portions of the gas and should be the focus in the future development of advanced RNG production systems. This project attempted to improve that pathway in several ways, including eliminating one of the steps to convert carbon dioxide into methane, called methanation. Existing literature suggested that high enough reaction pressures could take the place of the traditional catalyst used in the methanation process and provide an additional benefit of increased thermal efficiency and reduced tar and tar molecule size.

The project development process identified several design factors that could limit the ability of the first reactor prototype to achieve the shift to high methane concentrations needed for the necessary level of gas purity. These factors included difficulty maintaining the required pressure in the reactor and possible nitrogen dilution in the product gas due to using air as the oxidant. Ultimately, the ability to build a system capable of maintaining the pressures required to produce the methane-dominated gas needed for renewable natural gas proved unattainable within the budget and time available under the grant.

Benefits to California

If the project had been successful in designing a workable system and demonstrating RNG production, it could have demonstrated potential to provide the following benefits for California ratepayers and for the advancement of the technology:

- Lower cost renewable energy due to the biochar co-product subsidizing the production of fuel gas: As California's electricity system moves toward the higher percentage of renewables under state mandates, reducing the costs of renewable resources becomes increasingly important to keeping the cost of electricity affordable to ratepayers.
- New option for distributed renewable energy in rural areas: Many rural areas have abundant biomass from agricultural or forest wastes. However, transporting these wastes to processing centers can be cost prohibitive because they are typically moved

by large diesel trucks that are subject to increasing fuel costs. Locating biomass generation facilities closer to the fuel source reduces costs while providing other benefits to rural communities, such as improved air quality and reduced fire danger.

- Reduced carbon intensity of the bioenergy sector due to the biochar co-product, carbon sequestering potential, and the renewable fuel product: Removing carbon from the atmosphere, through storage or the use of low carbon fuels, is an essential step toward reducing the social and environmental costs of climate change, and will benefit ratepayers and others.
- Proven mechanical performance of an innovative renewable energy technology and validation of the production of usable renewable fuel gas: The renewable energy sector continues to expand, driven by state clean energy and climate change mandates. New technologies and energy sources are essential to continued growth and improvement in the industry.

CHAPTER 1: Introduction

Overview

Interra designed the Reciprocating Reactor system to help address the lack of available technology options for biofuel and bioenergy that can economically process biomass sources such as forest and urban green waste at distributed scales. The system is designed to produce both a low-emission renewable gas and a biochar co-product, which can increase deployment of the technology and contribute to California's policy goals to decrease carbon emissions, increase the use of renewable energy and biofuels, and reduce the risk of forest fires.

Figure 1: Interra Impacts

Source: Interra

The reactor aimed to surpass a thermal efficiency threshold in biomass pyrolysis (previously thought impossible in practice) and achieve a continuous and self-sustaining biomass pyrolysis reaction without requiring combustion or oxidization reactions internally or externally. The Interra technology design modifies the traditional conversion process by removing the methanation step and convert biomass at higher efficiencies compared to other thermochemical conversion technologies. This level of thermal efficiency in biomass has been described as the "ideal carbonizing process."

The technology sought to advance thermochemical production systems through two main advantages over existing bioenergy technologies:

- Interra's technology sought to increase tons-per-day throughput, gas quality output, and biochar yield while decreasing the capital cost compared to existing technologies.
- The technology would have two saleable products that should not require expensive equipment to upgrade them prior to their use. Revenues from the co-products of biochar, bioenergy, and biofuel are therefore diversified and can subsidize each other.

The technology and integrated business plan could help bring down the cost of distributed biofuel facilities and renewable electricity rates. In addition, the ability to cost-effectively process wood waste material using distributed-scale installations can help California reduce wildfire threats from tree death due to the bark beetle and drought.

Pyrolysis Overview

Biomass is a renewable energy source derived from plant-based material. Wood is the most common biomass used for power generation and is comprised mainly of cellulose (~50 percent), lignin (~25 percent), and hemicellulose (~25 percent).[1] Because cellulose is the largest constituent of woody biomass, it is usually used to approximate most pyrolysis processes. Cellulose is a polysaccharide consisting of several thousand linear chain D-glucose units. Cellulose is composed mostly of carbon (C), hydrogen (H), and oxygen (O) in the following atomic ratio:[2]

$$Cellulose: (C_6\, H_{10}O_5)_n$$

At temperatures above 500°F, the linked glucose chains will irreversibly break into smaller molecular weight components.[3] This process of thermal decomposition is referred to as pyrolysis. Pyrolysis produces volatile gases, carbon dioxide (CO_2), and char. Char is made up of residual carbon and ash, which remains solid through pyrolysis. The char produced from the pyrolysis of biomass is referred to as biochar.

At temperatures above 1,000°F, the volatile gases produced during pyrolysis are mainly carbon monoxide (CO), hydrogen (H_2), and methane (CH_4) with lesser amounts of heavier hydrocarbons.[3] At temperatures above 1,300°F, gasification reactions, such as the conversion of char to additional gas, take place at higher rates:

$$C(char) + H_2O \rightarrow H_2 + CO$$

Gasification reactions decrease the char content but increase the volume of producer gas (the gas produced through pyrolysis). Producer gas from pyrolysis has a usable heating value. Producer gas can be burned in an engine to create electricity, used in to generate heat in thermal processes, or used as a chemical feedstock. The exact quantity and composition of the producer gas produced during pyrolysis depends upon reaction variables such as temperature, pressure, feedstock particle size, moisture levels, oxygen concentration, and gas mixing rate.[4]

The original scope of work for the project (PIR-12-021) included determining the impact of pressure, temperature, and feedstock particle size on the pyrolysis reaction, as well as the

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[1] Roberts, A.F. 1970. *A Review Of Kinetics Data For The Pyrolysis Of Wood And Related Substances*. Combustion and Flame 14 (2): 261-272. doi:10.1016/s0010-2180(70)80037-2

[2] Vassilev, Baxter, Andersen, and Vassileva. 2010. *An overview of the chemical composition of biomass*. Fuel 89:913-933.

[3] Banyasz, Li, Lyons-Hart, and Shafer. 2001. *Cellulose pyrolysis: the kinetics of hydroxyacetaldehyde evolution*. Journal of Analytical and Applied Pyrolysis, 57:223-248.

[4] Banyasz, S. Li, J. Lyons-Hart, and K. H. Shafer. 2001. *Gas evolution and the mechanism of cellulose pyrolysis*. Fuel, 80:1757-1763.

effect of these variables on the producer gas heating value and conversion efficiency. Below is a review of the three major pyrolysis variables that were investigated.

Impact of Pressure

Higher reactor pressure has several effects on the pyrolysis reaction of cellulosic biomass. At elevated pressures, pyrolysis begins at lower temperatures,[5] so more biomass will break down into producer gas at a given reaction temperature at a fixed residence time.[6] This concept is confirmed by Okekunle et. al. (2014), which states that increased reaction pressure increases producer gas production rates.[7] Increasing reaction pressure has also been shown to reduce tar production.[8] These factors suggest that the efficiency of producer gas production will increase with higher reactor pressure.

Impact of Temperature

Temperature influences the production of producer gas and biochar during pyrolysis,[9] causing wide variations in decomposition and combustion reaction rates during the process. Most reaction rates increase at higher temperatures, which is favorable because it also increases the thermal efficiency of conversion.

Temperature also affects product yields. At higher temperatures, gas yields increase exponentially, while char and tar production decrease (Figure 2). [10]

The composition of the producer gas is also affected by temperature. At an equivalent pressure, the CO_2 content of the gas decreases and the H_2 content increases with elevated temperature (Figure 3). This allows for less CO_2 scrubbing and gas upgrading post-reactor for higher temperatures.

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[5] Antal Jr, Michael and Gronli, Morten. 2003. *The Art, Science, and Technology of Charcoal Production*. Ind. Eng. Chem. Res. 42, 1619-1640, at 1630.

[6] For material flowing through a volume, residence time is a measure of how much time the material spends in the reservoir.

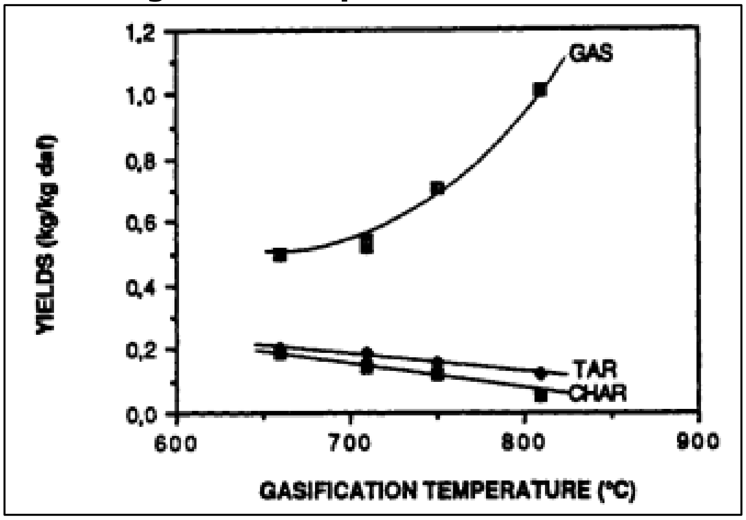
[7] Okekunle and Osowade. 2014. Numerical Investigation of the Effects of Reactor Pressure on Biomass Pyrolysis in Thermally Thin Regime. Chemical and Process Engineering Research, ISSN 2224-7467 (Paper), ISSN 2225-0913 (Online), Vol.27, at 19, Figure 5 Gas release rate at different reactor pressures.

[8] *Id*. at 19.

[9] Emami Taba, Leila, Muhammad Faisal Irfan, Wan Ashri Mohd Wan Daud, and Mohammed Harun Chakrabarti. 2012. *The Effect Of Temperature On Various Parameters In Coal, Biomass And CO-Gasification: A Review*. Renewable And Sustainable Energy Reviews 16 (8): 5584-5596. doi:10.1016/j.rser.2012.06.015

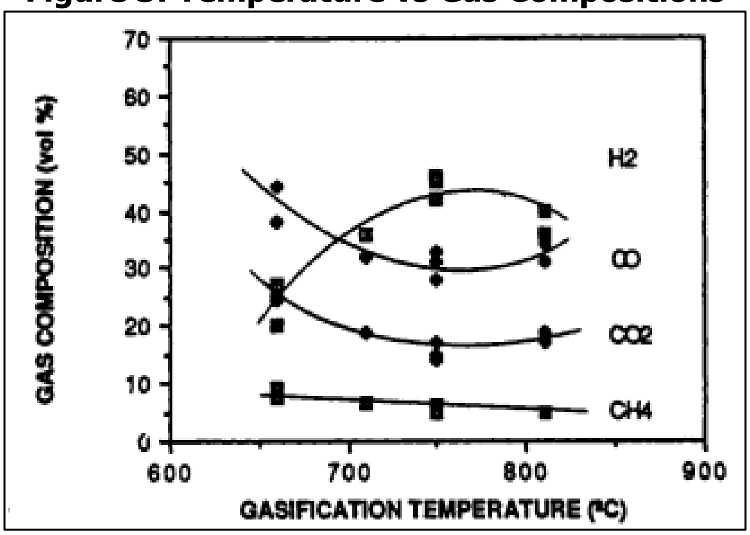
[10] Corella, Jose, Maria P. Aznar, Jesiis Delgado, and Elena Aldea. 1991. *Steam Gasification of Cellulosic Wastes in a Fluidized Bed with Downstream Vessels*. Chemical and Environmental Engineering Department, University of Saragossa, 50009 Saragossa, Spain.

Figure 2: Temperature vs Yields



Source: Interra

Figure 3: Temperature vs Gas Compositions



Source: Interra

Impact of Feedstock Particle Size

The combination of pressure and temperature variations is expected to allow the system operator to adjust the producer gas composition and produce an energy dense gas at a favorable yield rate from the chosen biomass particle size. The size of feedstock particles has a considerable effect on the pyrolysis reaction.[11] Larger feedstock particles have a lower surface area to volume ratio, with molecules in the center of large particles having a heating lag compared to surface molecules. This temperature difference can affect the gas produced during pyrolysis.

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[11] Valenzuela-Calahorro, C., A. Bernalte-Garcia, V. Gómez-Serrano, and Ma.J. Bernalte-García. 1987. *Influence Of ParticleParticle Size And Pyrolysis Conditions On Yield, Density And Some Textural Parameters of Chars Prepared From Holm-Oak Wood*. Journal of Analytical and Applied Pyrolysis 12 (1): 61-70. doi:10.1016/0165-2370(87)80015-3.

CHAPTER 2: Pre-Construction Facility Design

The first step in designing the Reciprocating Reactor facility was to create a process diagram (see full schematic provided in Appendix A). The process diagram shows material flow pathways, major pieces of equipment, piping connections, and instrumentation. Once the system's flow pathways were finalized, the scale of the facility was set.

During the early design stages, it was determined that at the traditional "bench-scale" the unique aspects of the Reciprocating Reactor's technology would be impossible to demonstrate or measure. The most important factor contributing to this limitation was that to scale down the system, one must also scale down the feedstock size. However, the size of biomass particles can be reduced only so far before their bulk flow characteristics change drastically and they start to behave like a powder instead of a bulk material. It was therefore decided that the design scale chosen was the smallest that could conservatively be used without introducing new risk variables that would not exist in a future commercial-scale design.

Before construction began, Interra modeled the facility using three-dimensional Computer Aided Design (CAD). This was necessary to determine the facility footprint, piping sizes and lengths, and create drawings from which vendors would fabricate parts.

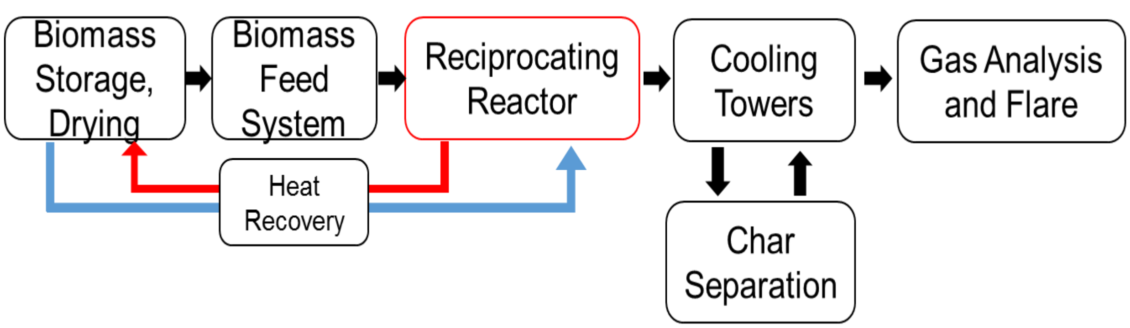
This chapter provides a brief facility overview along with process diagrams and images for all the major sub-systems that make up the facility.

Facility Overview

To better understand the operation of the Reciprocating Reactor facility, it can be separated into six fundamental sub-systems: biomass storage and drying, biomass feeding, the reciprocating reactor, cooling towers, char separation, and gas handling. Figure 4 shows a schematic of the fundamental stages of the facility.

Biomass is dried in the integrated dryer bin and then injected into the Reciprocating Reactor, the heart of the facility. Biomass is pyrolyzed in the reactor at up to 1,300°F, resulting in producer gas and biochar. The hot producer gas and biochar are separated in the cooling towers.

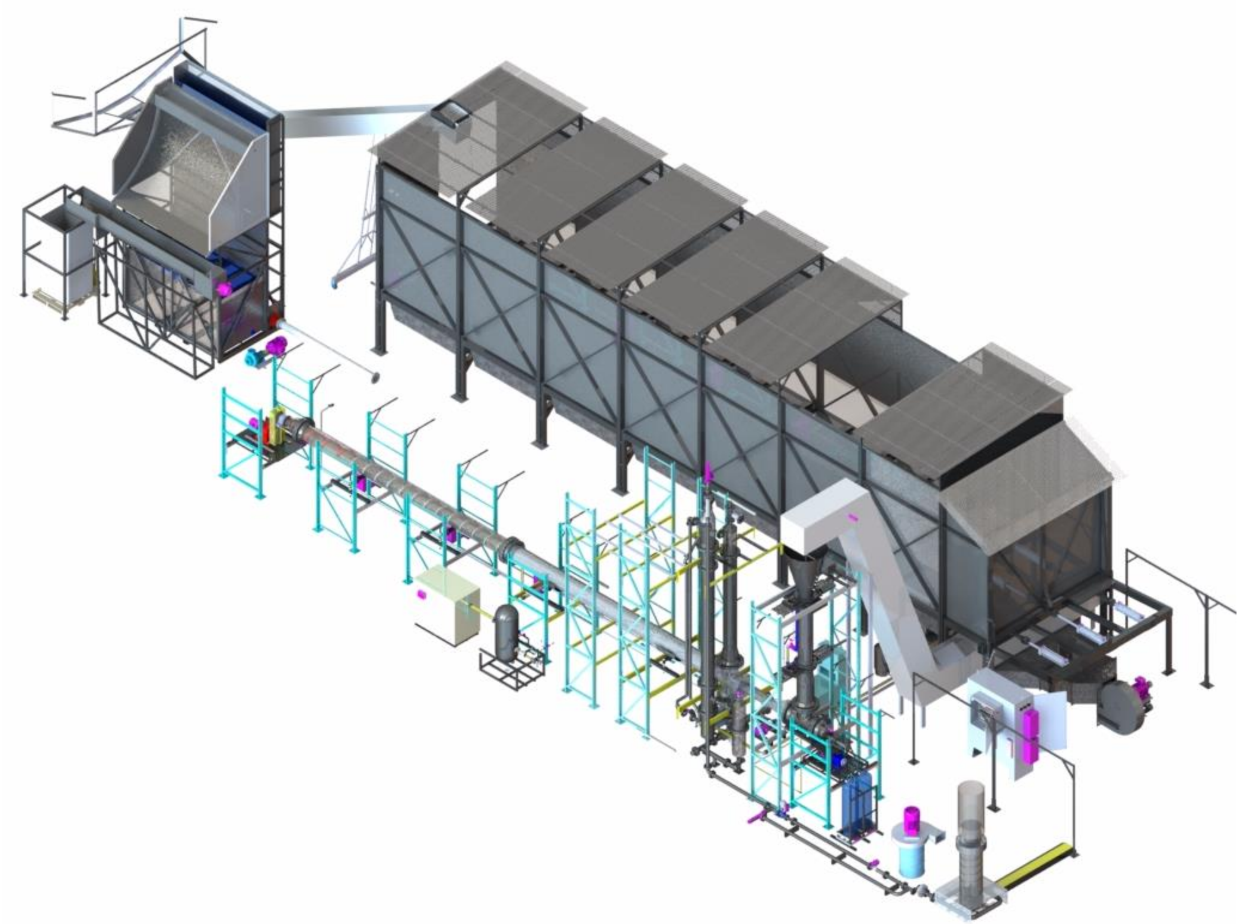
Figure 4: Facility Schematic



Source: Interra

The producer gas is measured before being burned in a research flare. Biochar produced in the reactor is separated from the water and collected for analysis. A CAD image of the entire facility is shown in Figure 5.

Figure 5: Reciprocating Reactor Facility

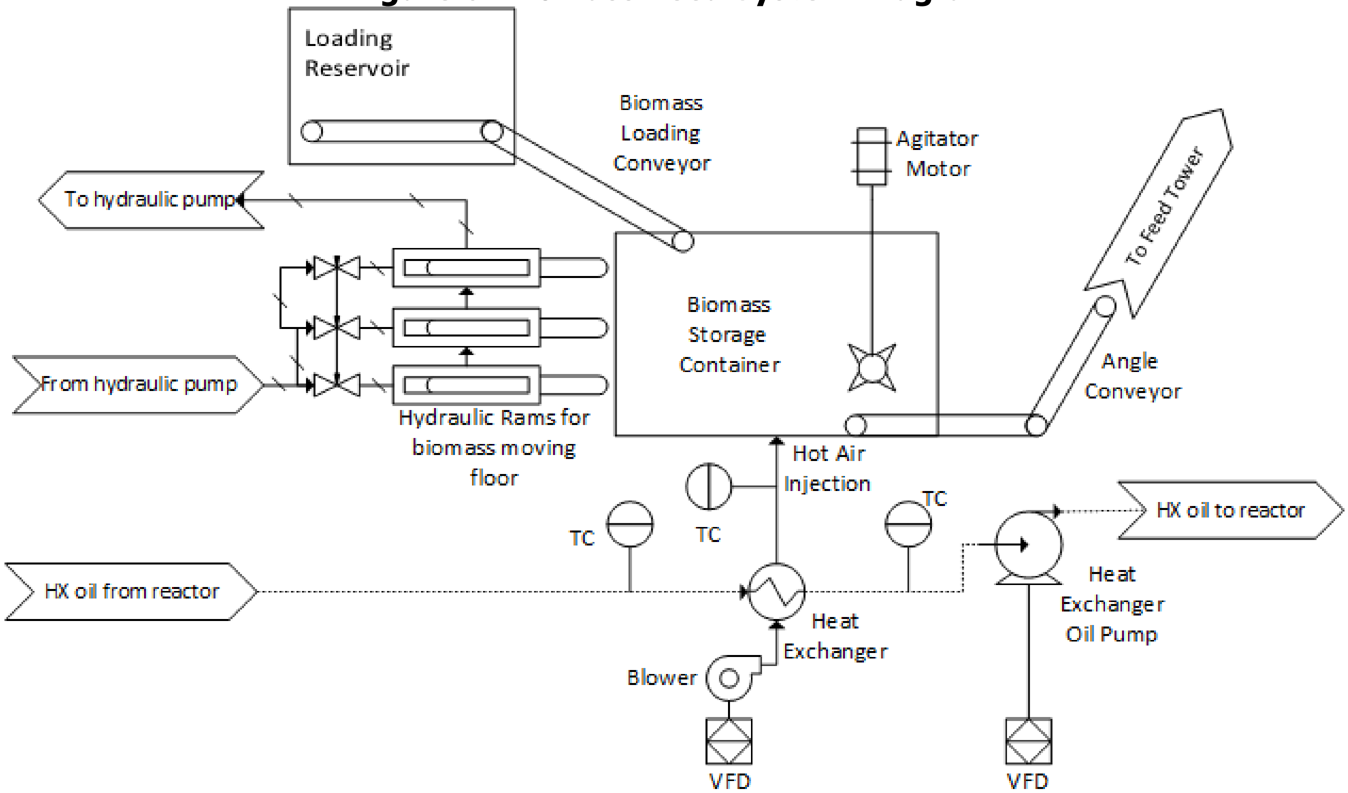


Source: Interra

Biomass Handling and Feeding

Facility operation begins with the biomass storage and drying (Figure 6). Biomass is delivered by truck to the loading reservoir. A conveyor moves the biomass into the storage container, which can hold 20-30 tons of feedstock. Three hydraulic actuators attached to three sets of puller floor rails move the contents of the storage container to the exit chute to extract biomass when desired.

Figure 6: Biomass Feed System Diagram



Source: Interra

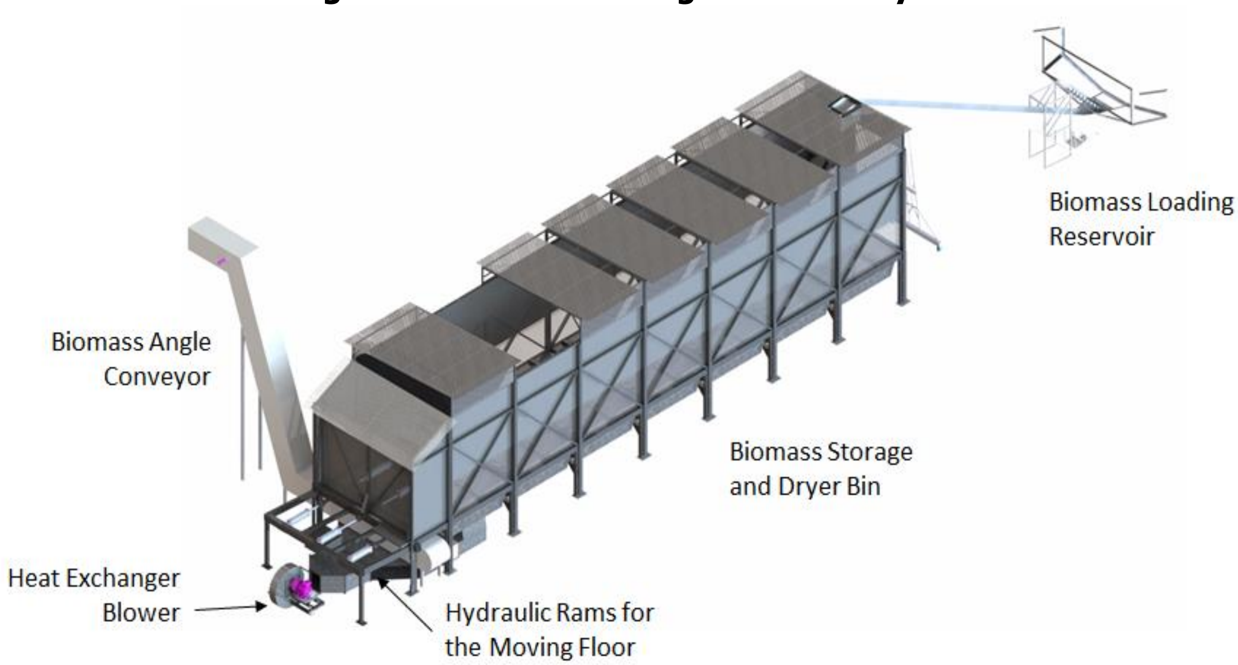
An agitator above the angle conveyor's belt breaks up large clumps and evenly distributes the material on the belt. An angled conveyor belt moves the biomass from the storage container up to the intake funnel of the feed tower, an important step in pyrolysis which is further discussed in Chapter 3. Biomass drying is considered highly useful in pyrolysis applications because moisture reduces flame temperatures and the efficiency of combustion,[12] and raw biomass feedstock can have a moisture content between 30-50 weight-percent.[13] For pyrolysis, this means that more air must be injected to maintain similar reactor temperatures, increasing the amount of nitrogen dilution in the producer gas.

To reduce moisture levels in the feedstock to below 15 percent, heated air is blown through the porous floor of the biomass storage container. Oil is cooled in the heat exchanger then pumped back to the reactor to absorb more heat (Figure 7). Collecting leftover heat from the reactor reduces the burden on the cooling towers and recycles energy back into the system. Figure 8 shows the position of the blower that pushes ambient air through a heat exchanger located under the biomass storage container.

[12] Amos, Wade A. 1998. *Report on Biomass Drying Technology*. National Renewable Energy Laboratory. NREL/TP-570-25885.

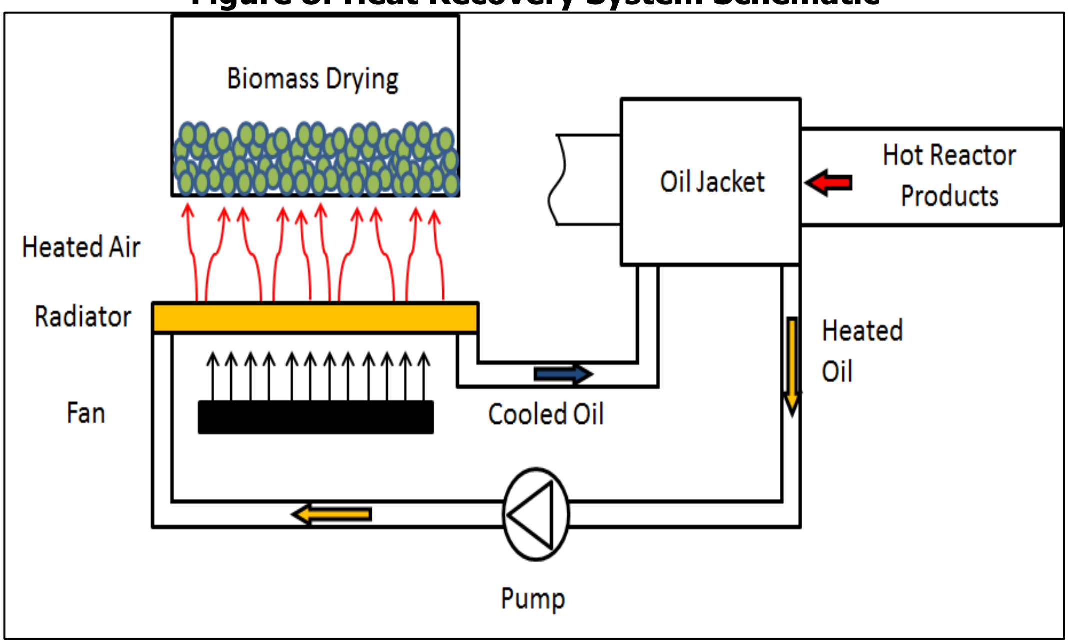
[13] Roos, Carolyn J. 2008. *Biomass Drying and Dewatering for Clean Heat & Power*. Northwest CHP Application Center. Olympia, WA.

Figure 7: Biomass Storage Bin and Dryer



Source: Interra

Figure 8: Heat Recovery System Schematic

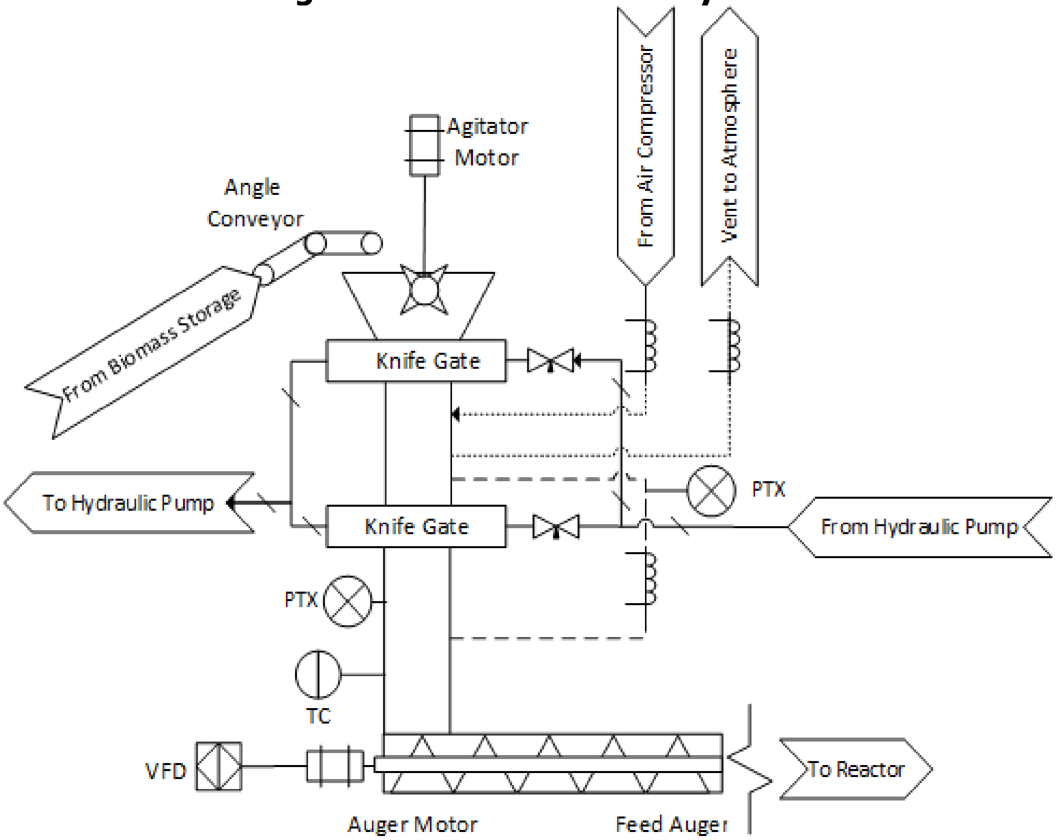


Source: Interra

Biomass Intake System

Figure 9 shows a process diagram of the biomass intake system. A lock hopper system is used to ensure that the reactor remains pressurized when adding feedstock.

Figure 9: Biomass Intake System



Source: Interra

The angle conveyor moves biomass from the storage container to an intake funnel. To add material to the pressurized reactor, the top knife gate is opened, and biomass is gravity-fed into the 5-cubic-foot pressure lock volume between the two knife gates. After the top gate is closed, the lock is pressurized to the same pressure as the reactor environment. The bottom knife gate is then opened, and the material falls onto the feed auger conveyor. The feed auger then moves the material into the reactor where the pyrolysis reactions occur.

Figure 10 shows a CAD model of the biomass intake tower.

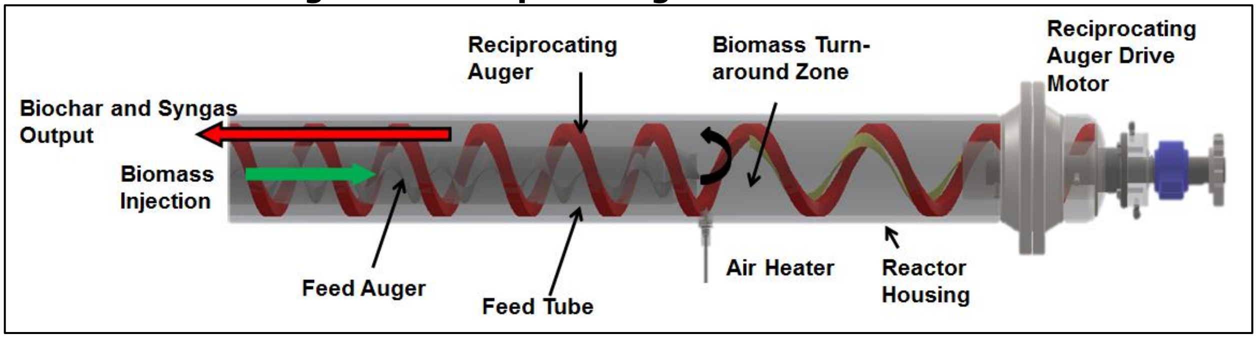
Figure 10: Biomass Intake Dryer

Source: Interra

Reciprocating Reactor and Cooling Towers

The Reciprocating Reactor (Figure 11) is the heart of the plant. The feed auger pushes biomass through the inner reactor tube into the turn-around zone. The temperature of the reactor reaches its maximum at the end of the inner reactor tube, also referred to as the turn-around zone. The Reciprocating Reactor is heated to up to ~1,300°F through the partial combustion of the biomass feedstock. Air can be added either through the feed tube or through the air heater to assist in partial combustion.

Figure 11: Reciprocating Reactor Schematic



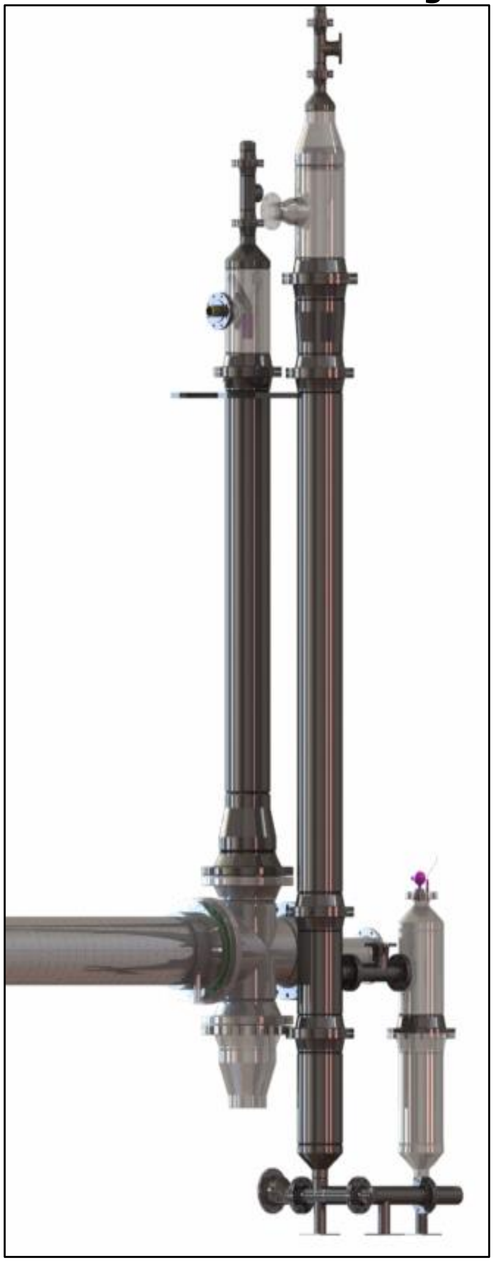
Source: Interra

The air heater uses a 6 kilowatt electrical heating element that can provide air to the reactor at temperatures up to 800°F. The air heater is used during the startup procedure to ignite the biomass feedstock.

The biomass/biochar mixture in the turn-around zone is moved slowly out of the reactor by the reciprocating auger, which pushes material in the opposite direction of the feed auger. The biomass/biochar mixture is forced into the annulus space between the feed tube and the reactor housing. This material mixing encourages heat transfer between the biochar and the feed tube, pre-heating the incoming biomass. The patented counter-current heat exchanger design maximizes heat recovery and increases the efficiency of pyrolysis.

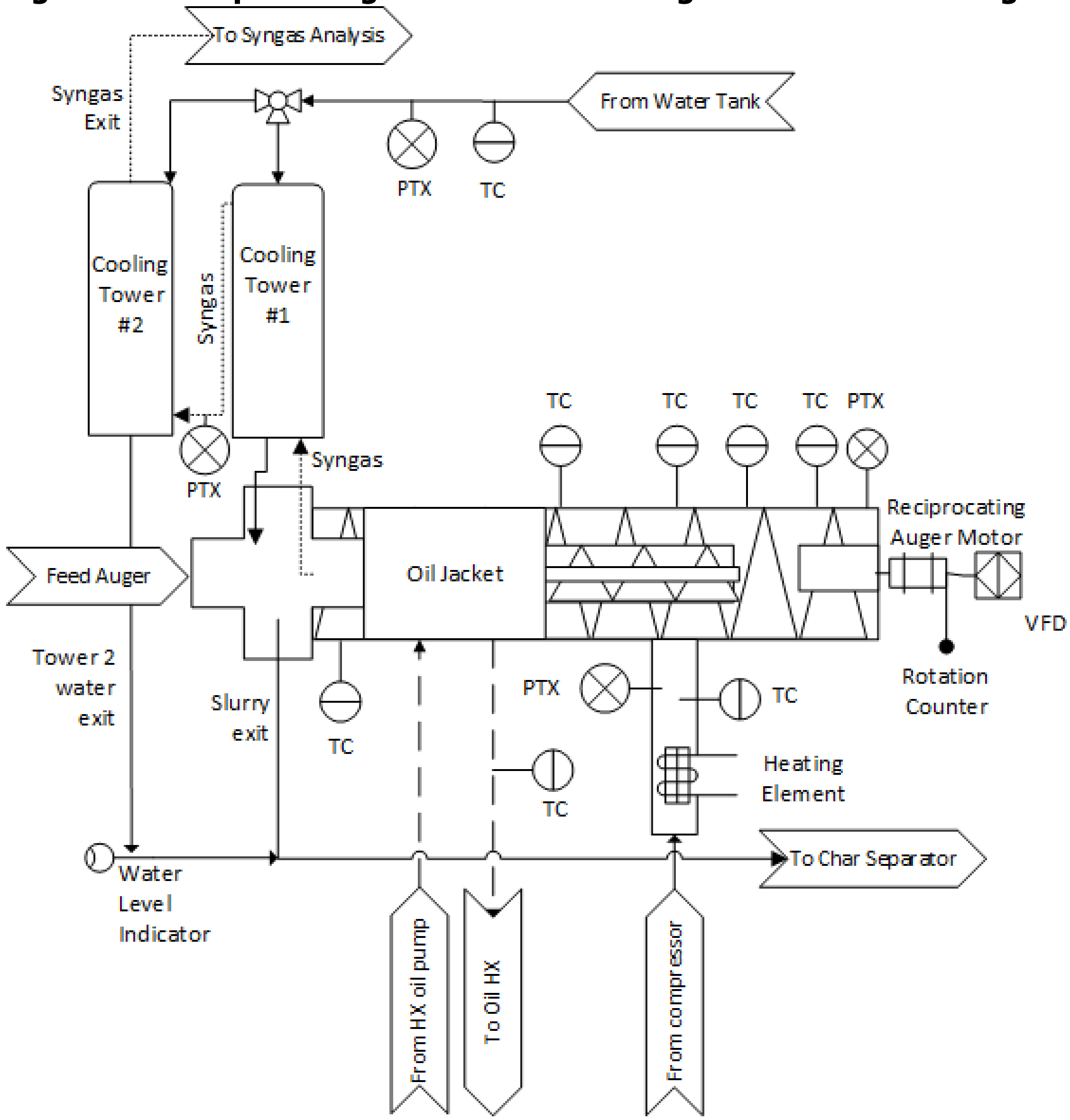
After leaving the reactor, the producer gas/char mixture empties into the first cooling tower. Cooling water and biochar form a slurry that exits through the bottom of the tower. The producer gas travels up the cooling tower while being cooled and filtered by the water from above. When the producer gas cools, tars condense and are captured by the water. Smoke or solid particles entrained in the gas are filtered out. The producer gas must pass through a second cooling tower before it is clean enough to be measured. Figure 12 shows a CAD model of the cooling towers and Figure 13 shows the process diagram for the Reciprocating Reactor and cooling towers.

Figure 12: CAD Model of Cooling Towers



Source: Interra

Figure 13: Reciprocating Reactor and Cooling Towers Process Diagram

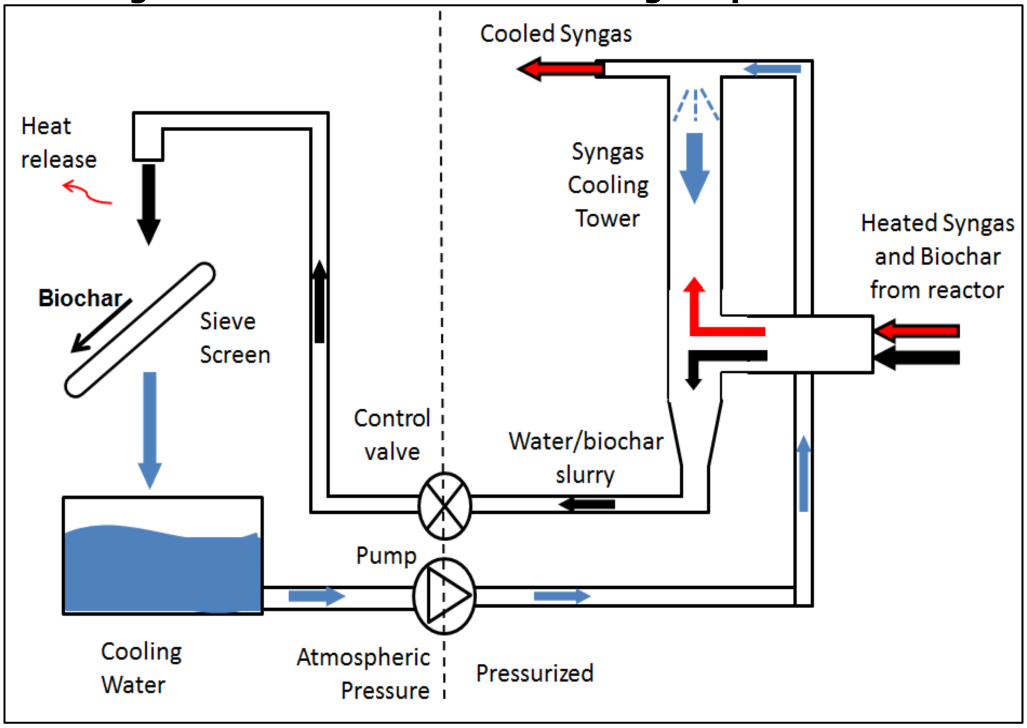


Source: Interra

Char Separation

Hot biochar exiting the reactor and cooling water form a slurry that is washed out of the system to the separator sieve screen. The slurry empties onto the screen, allowing water to pass through while the biochar solids remain on top. The separated biochar is then pushed by an auger to a collection bin for drying and storage. Figure 14 shows a schematic of the reactor product cooling loop.

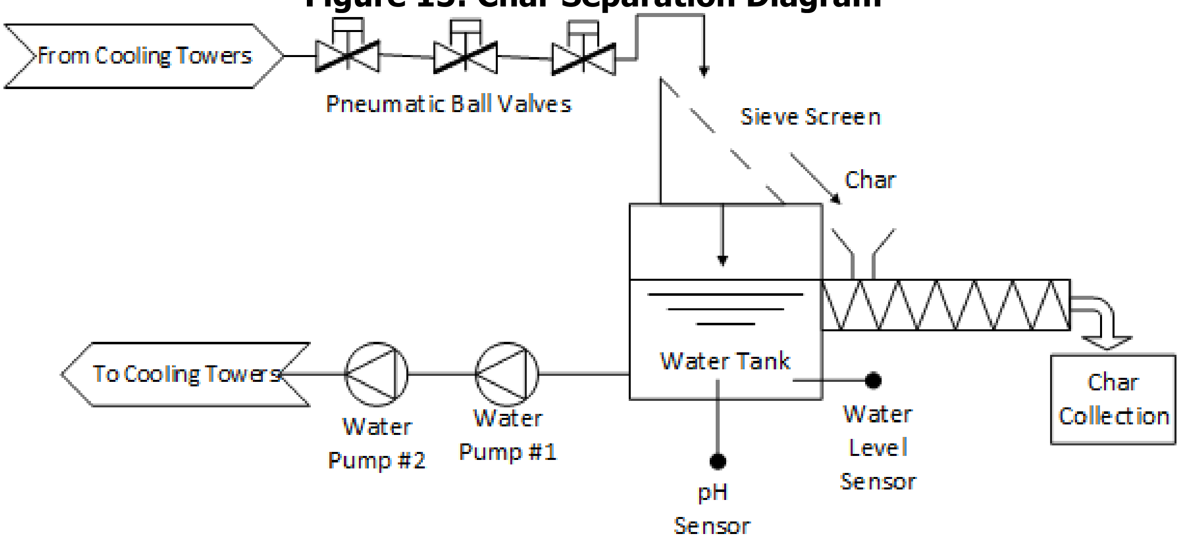
Figure 14: Reactor Product Cooling Loop Schematic



Source: Interra

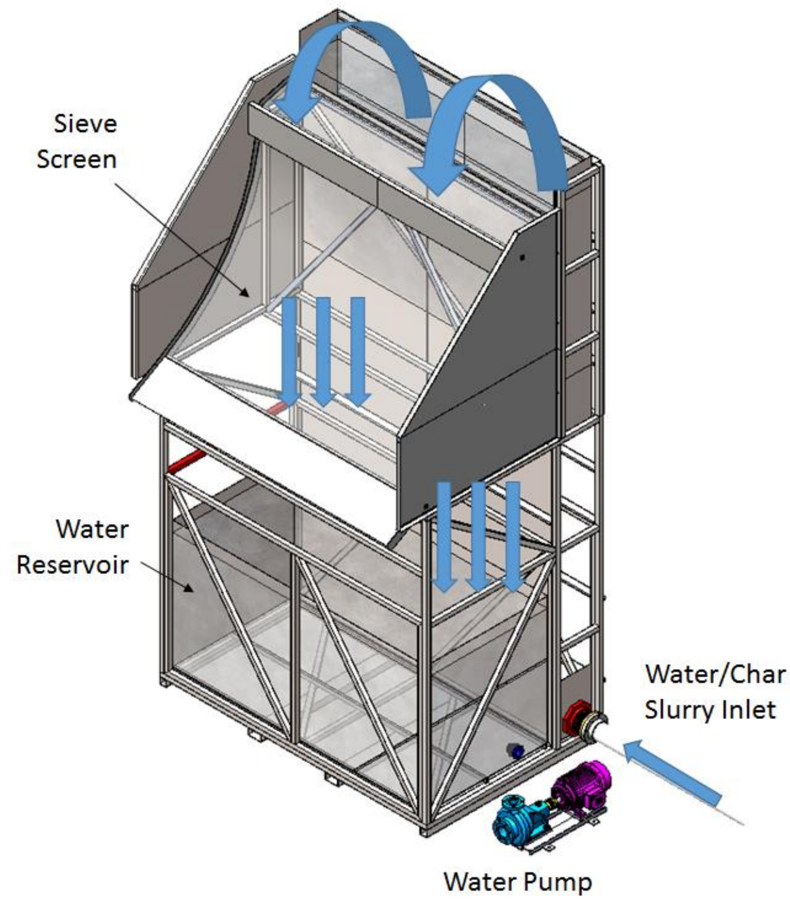
The cooling water is heated by the producer gas/biochar mixture exiting the reactor. Heat is released during its interaction with ambient air as it passes through the sieve screen. Additional cooling of the water loop may be included in the future. The screened and cooled water is finally collected and pumped back to the cooling towers once again.

Figure 15: Char Separation Diagram



Source: Interra

Figure 16: Char Separation Tower

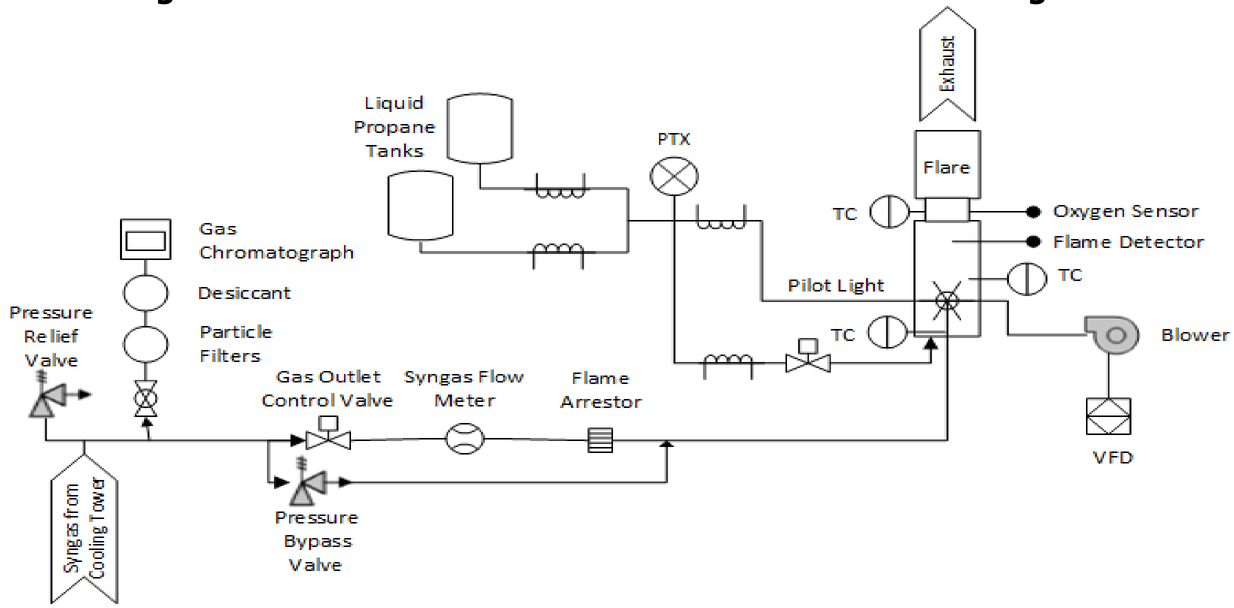


Source: Interra

Producer Gas Measurement and Flare

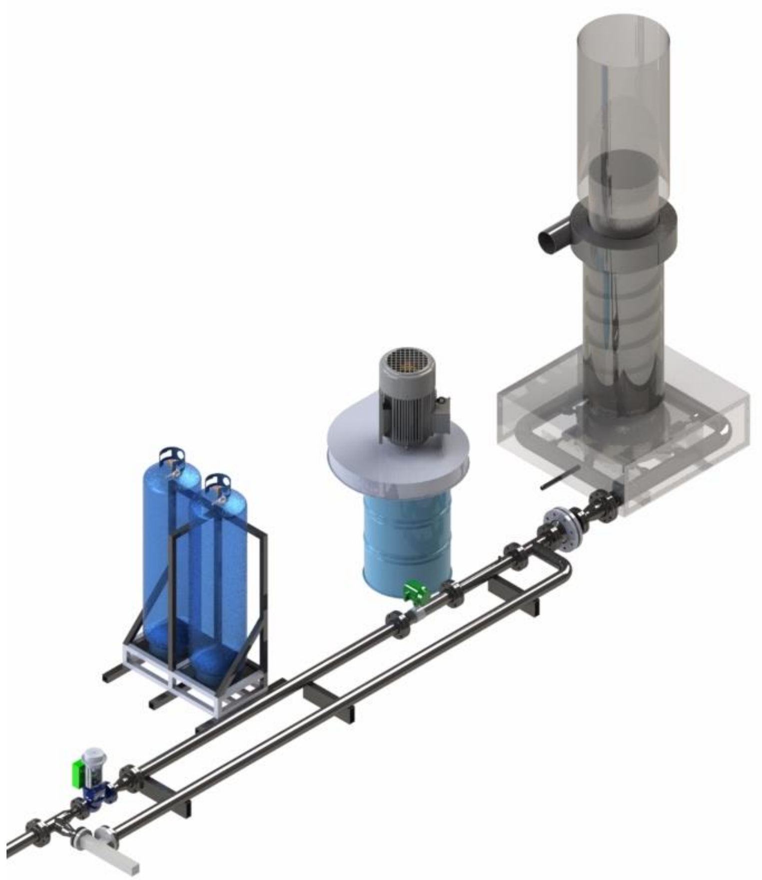
After the producer gas produced in the reactor is cooled and cleaned by the water scrubbing towers, its quantity and composition is measured (for details on data acquisition, see Chapter 4). The most responsible way to dispose of the gas during research and development is to burn it in a flare to allow flare products to be safely exhausted. Figure 17 shows the process diagram for the producer gas measurement and flare sections, and Figure 18 shows the CAD model.

Figure 17: Producer Gas Measurement Flare Process Diagram



Source: Interra

Figure 18: Gas Measurement and Flare

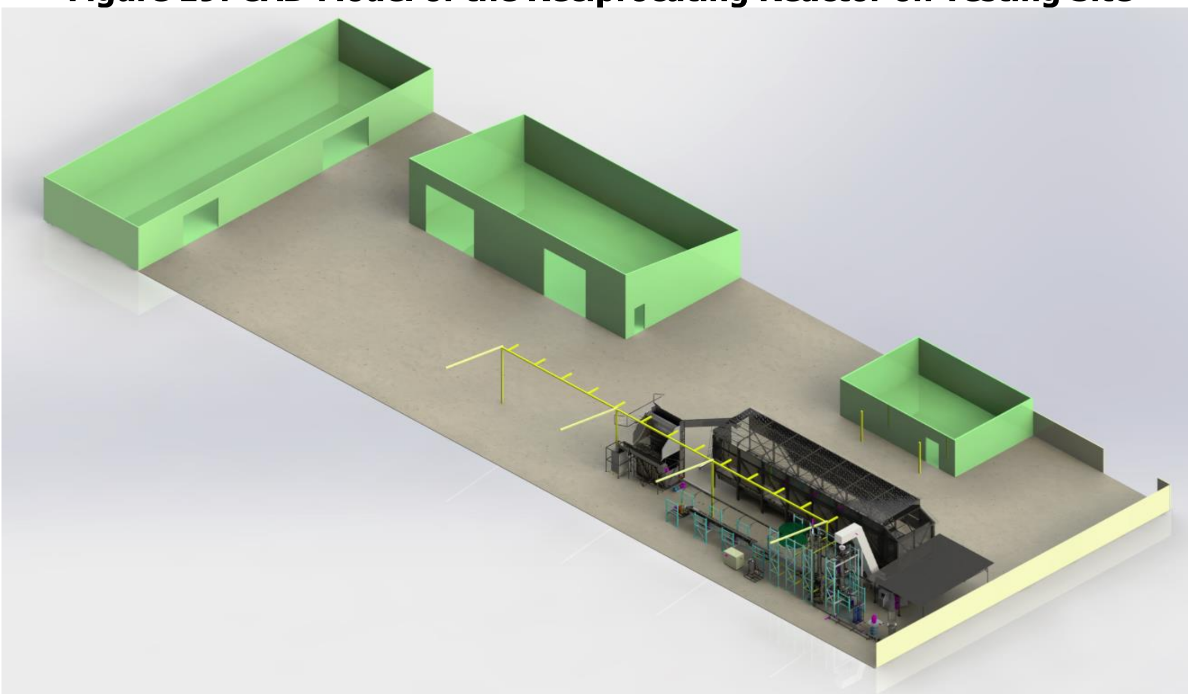


Source: Interra

Site Plan

Interra reached an agreement in July of 2013 to build its Reciprocating Reactor on the property of Adept Process Services, Inc. in National City, California. Adept Process Services provides fabrication services for various industries. They have a wide variety of tools, which were used in fabricating the facility. Figure 19 shows the CAD model of the Reciprocating Reactor facility on the testing site.

Figure 19: CAD Model of the Reciprocating Reactor on Testing Site



Source: Interra

CHAPTER 3: Construction

To fully study the Reciprocating Reactor technology, it had to be built, tested, and operated. As discussed in the previous chapter, a small bench-scale unit was not capable of providing insight into the core reactor configuration of the unit. To successfully operate the unit at the chosen scale, Interra also had to design, fabricate, and construct suitably scaled subsystems to feed the reactor and handle its outputs. In many ways, the prototype and its supporting subsystems had to be built much closer in size to a full-scale unit than a typical bench-scale prototype. Though doing so substantially front-loaded difficulties in the technology development timeline, it should shorten the path to full commercial operation once the prototype system is demonstrated and validated. This chapter describes the construction process from procurement to fabrication and installation.

Procurement

Interra procured various parts and equipment to fabricate and construct the Reciprocating Reactor. Because this grant was for the first prototype of this technology, all components and materials had to be procured to build a working prototype from the ground up. Component procurement began in July 2018, shortly after the Energy Commission Project Kick-Off Meeting, starting with the reactor and other piping structures (Figure 20 and Figure 21).

Interra spent $480,916 on equipment and used 108 different vendors, although most of the transactions were for high volume of low-cost items. Only 14 vendors received more than $10,000. These included those related to the main welding and fabrication partner (Adept Process Services), vendors who supplied core reactor parts such as the augers, valves, and pipes, and vendors related to the control system.

Figure 20: Steel for Supports and Scaffolding

Source: Interra

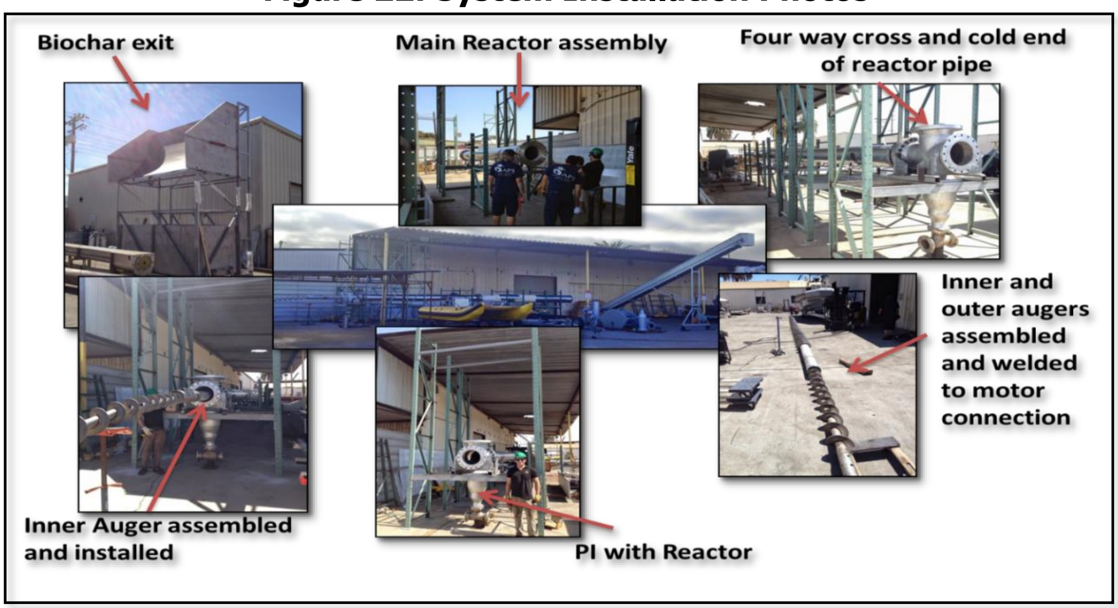
Figure 21: Reactor and Water Loop Tubing

Source: Interra

Fabrication and Installation

Fabrication and installation were done primarily on a subsystem-by-subsystem basis, with an emphasis on starting with the reactor components and working outward. Figure 22 shows images of the reactor and several of the subsystems being assembled.

Figure 22: System Installation Photos



Source: Interra

Figure 23 is an image taken during the erection of the angled conveyor that conveys the feed biomass from the system's biomass handling system to the biomass intake system. An angled conveyor system was required, rather than other conveyance technologies, due to space constraints at the build site.

Figure 23: Installation of Angled Conveyor Belt

Source: Interra

Figure 24 and Figure 25 illustrate the auger fabrication process. The original augers were fabricated from stainless rectangular tubing. An outside vendor coiled the tubing into 8 foot sections called "flights".

Figure 24: Pre-Fabrication Outer Auger Flights

Source: Interra

Figure 25: Post Fabrication Outer Auger

Source: Interra

Figure 26 shows the coiled section after being welded together. In order to connect to a drive shaft, drive shaft couplers were fabricated, as shown in Figure 27.

Figure 26: Feed Auger Drive Coupling

Source: Interra

Figure 27: Outer Auger Drive Coupling

Source: Interra

Once fabricated, the completed augers were loaded into the reactor. Figure 28 illustrates how the augers and inner reactor pipe (inner auger is inside the inner reactor pipe) were installed.

Figure 28: Augers and Inner Pipe Being Loaded Into Reactor

Source: Interra

Chain and sprocket drive assemblies with reducing gears were designed and fabricated to rotate the augers. The assemblies had to be designed with the flexibility to extend somewhat to accommodate the linear growth of the reactor once it is heated up. The reducing gearboxes (Figure 29 and Figure 30) were attached to a slide plate that was held top and bottom with PTFE (Teflon®) guide plates.

Figure 29: Outer Auger Drive Assembly

Source: Interra

Figure 30: Inner Auger Drive Assembly

Source: Interra

Figure 31: Dryer Bin and Biomass Storage Container

Source: Interra

Figure 31 is an outer view of the completed dry bin used to hold and dry the feedstock prior to loading into the reactor. Figure 32 shows some of the construction of the dryer bin. Figure 33 and Figure 34 illustrate the loading of the dryer bin system with biomass ready to feed into the main reactor.

Figure 32: Loaded Biomass

Source: Interra

Figure 33: Biomass Delivery

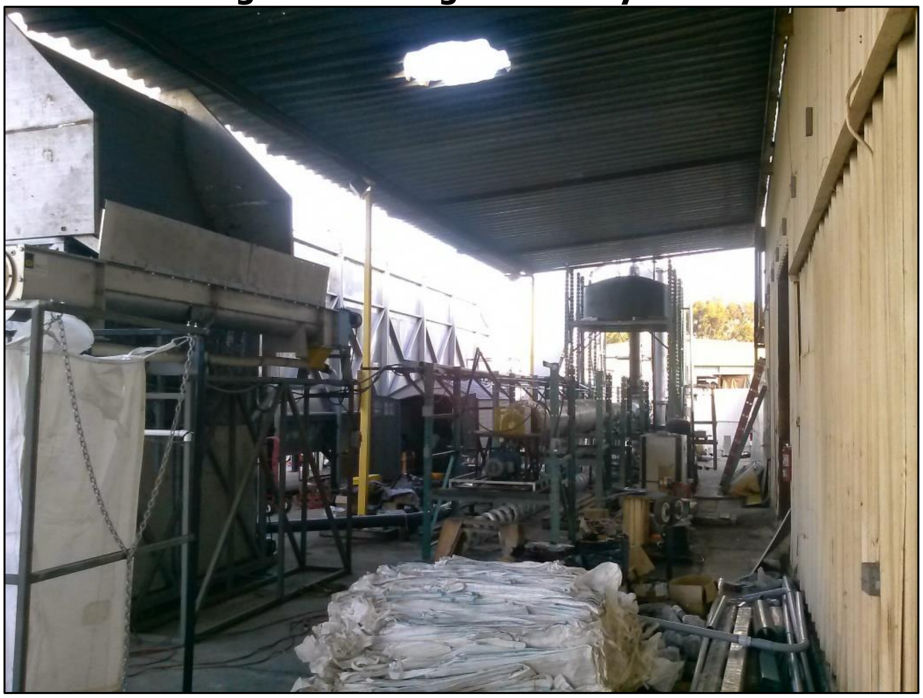
Source: Interra

Figure 34: Dryer Bin "Wedged Walking Floor" Under Construction

Source: Interra

Below are two long-view images of the completed Reciprocating Reactor. Figure 35 is a closer view on the reactor section. Figure 36 is a longer view where the layout in relation to the dryer bin and the water/biochar separation screen can be seen.

Figure 35: Long View of System



Source: Interra

Figure 36: Reactor View of Reciprocating Reactor

Source: Interra

CHAPTER 4: Data Acquisition and System Control

The two categories of system instrumentation in this project are data acquisition and control hardware. Both categories were interfaced with National Instruments® (NI) modules to provide high-resolution data collection and real-time control over each reactor subsystem.

Each reactor system was fitted with the sensor package necessary to perform its individual role along with any additional sensors or control instrumentation that were needed to integrate the system with the reactor's full operation.

Data acquisition uses sensors that measure temperature, pressure, gas composition, fluid flow rates, auger revolutions per minute (RPMs), and motor amperage in real time. Proximity sensors throughout the reactor identify auger RPMs, knife gate opening and closing, dryer floor movement, and so on.

Data Acquisition Hardware

A suite of sensors interfaced with the NI data acquisition modules measures the operational variables (Table 1) at various points throughout the reactor. Examples of hardware are shown in Table 2.

Table 1: Control Mechanisms Used to Vary Desired Operational Variables

Operational Variable	Control Mechanism
Solids residence time	Feed auger speed, return auger speed
Gas residence time	Pressure, temperature, air injection rate, solids residence time, gas off-take rate
Gas densities	Pressure, temperature
Pressure	Air injection rate, producer gas exit rate
Temperature	Feedstock input rate, throughput rate, air injection rate

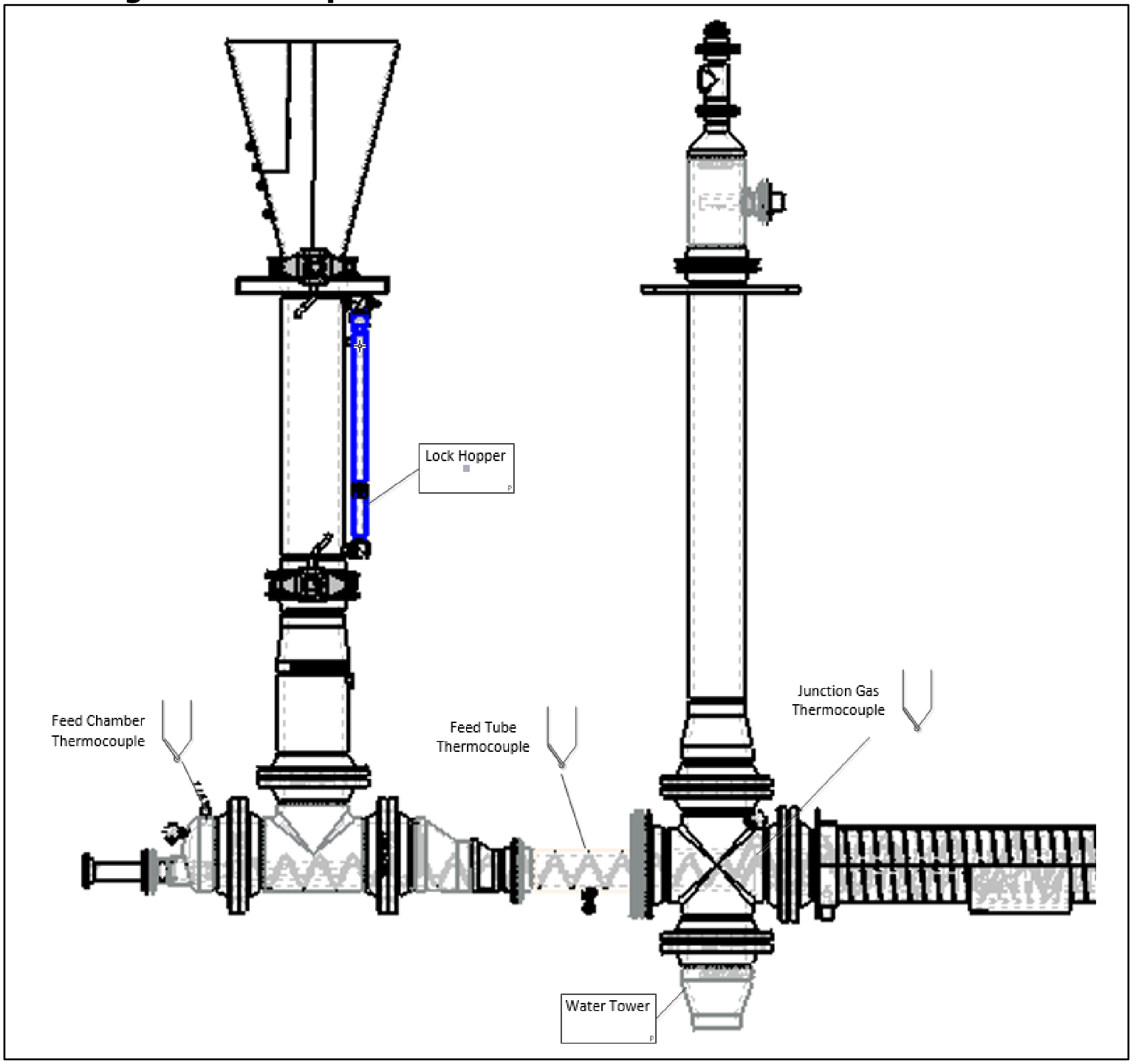
Source: Interra

Table 2: Data Acquisition Hardware Examples

Measurement	Sensor	Technology
Temperature	K-type thermocouple	Chromel-alumel thermocouple
Pressure	Pressure transducer	Steel diaphragm pressure transducer
Proximity	Proximity Sensor	Capacitive and inductive proximity sensors
Flow Rates	Yokogawa YF10x*E	Shredder bar pulse flow measurement
Gas Composition	Wuhan Cubic 3100	Continuous infrared chromatography

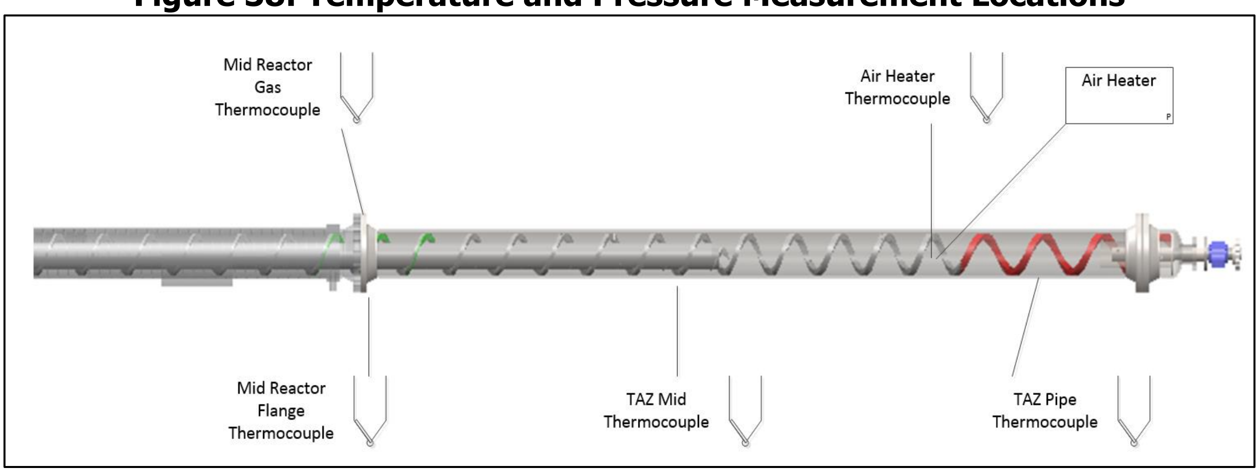
Source: Interra

Figure 37: Temperature and Pressure Measurement Locations



Source: Interra

Figure 38: Temperature and Pressure Measurement Locations



Source: Interra

Control Hardware

System control is performed by a National Instruments cRIO-9022 embedded controller, with a cRIO-9114 eight slot expansion chassis. The cRIO hardware is equipped with a number of NI data acquisition modules to enable for real-time data capture from analog and digital sources. Real-time control of the system has been developed using LabView real-time code across a transmission control protocol/Internet protocol network interface using embedded code on the cRIO real-time controller and a Human Machine interface on a networked computer. Software revision control and management has been conducted using TortiseSVN subversion client.

Figure 39: NI Embedded Controller and Data Acquisition Hardware

Source: Interra

Minimal control parameters are needed for the core technology along with controls on the pressurized lock hopper, the heat recovery and oil loop, the water injection and slurry circuit, and the flare.

Figure 40: Variable Frequency Drive Cabinet

Source: Interra

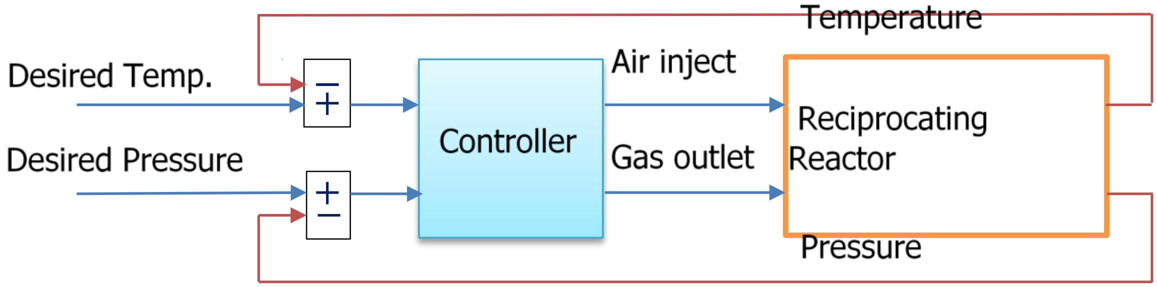
Variable Frequency Drives (VFD) are used for all key motors and pumps in the operation of the reactor and its subsystems. Each VFD is controlled by a 0-10 Volt output from a cRIO module, allowing for precise control of each motor pump as necessary.

Pressure and Temperature Control

To monitor the temperature of the reactor, thermocouples were installed in several locations (Figure 41). The temperature of the system is controlled by injecting air and controlled release of produced gases. Injecting more air into the system helps increase the temperature by accelerating the oxidization process.

Automatic pressure and temperature regulations were implemented early in the process. Both loops use proportional integral derivative feedback control to stabilize the values in the reactor based on the changing values of the thermocouples and pressure sensors. During operation of the reactor there are large variations in pressure and temperature, so these control loops have been tuned and are robust, even in harsh conditions.

Figure 41: Pressure and Temperature Control Loops



Source: Interra

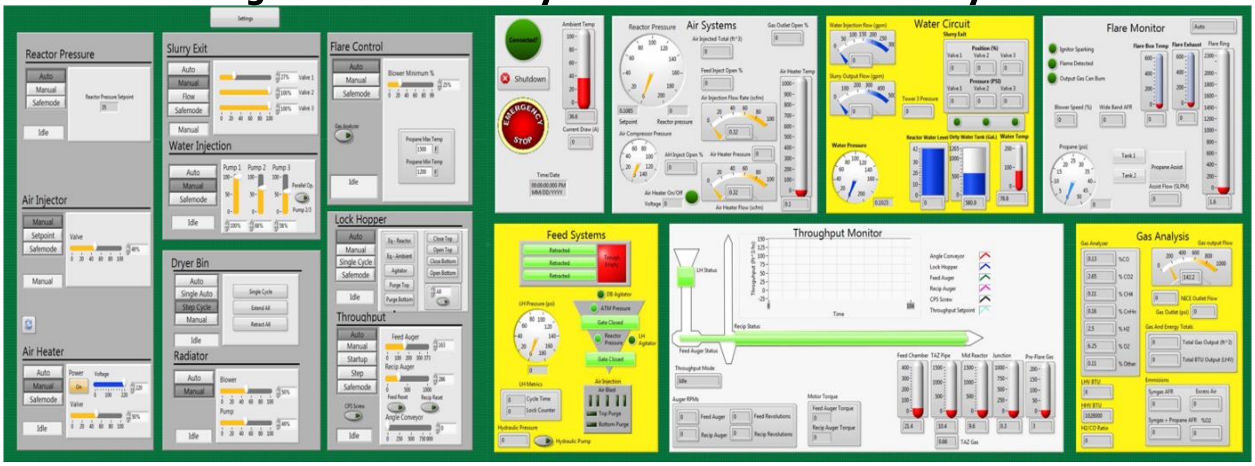
In addition to the main air injection and pressure loops, there is also an electric air heater that requires control during startup of the reactor. This air heater is in line with an air injection site and is controlled by varying the amount of air injected across electrically heated coils. A layer of safety triggers were implemented for the heater to turn off, should the temperature exceed a safe operating range at any point during the operation of the reactor.

The system is equipped with an Aivyter SGV30A screw compressor that uses a 30 horsepower (HP) motor to compress air up to 170 pounds per square inch. This air compressor drives all air injection to the reactor.

Control Software

Figure 42 is a display of the Human Interface Layout used to control the reactor. The layout uses two monitors to distribute all of the important indicators and reactor controls. Each panel on the left of the screen represents a set of subsystems that work together. From these panels, it is possible to change the modes of each subsystem from fully manual, discrete control, to automatic operation. Where possible, most subsystems are set to automatic.

Figure 42: Control System Human Interface Layout



The operational indicators for the reactor are on the right. These are also divided into panels that group relevant information. The panels show pressure, temperature, flow, and gas readings collected by the sensor suite, along with any calculated measurements necessary for real-time operation of the system.

The data produced from each test run is sorted and stored by subsystem and is available in .tdms file format (a proprietary National Instruments/LabView format) for export to Microsoft Excel, or a similar spreadsheet tool. The data, which includes all raw signals and calculated values from the reactor, are recorded and available in real time, but are also useful for post-processing and run-time analysis.

CHAPTER 5: System Mechanical Testing

Mechanical testing was used to determine the nominal operational conditions of each auger and the mechanical forces associated with moving biomass and char through the reactor. This section describes the configurations of both the feed and reciprocating auger drive.

Mechanical tests offer valuable insight into the overall design and operation of the system. Because the augers are one of the key components of the system, the forces acting upon them must be understood prior to moving on to further testing. These tests allow the use of accurate indicators of operational stresses to define safe operating parameters of the machine and inform control methods. Finally, by understanding the rates at which the augers turn, the material flow rate through the system can be modeled. This model will determine the residence time of material in the reactor and will be used to control throughput.

Drivetrain Losses

To understand the forces acting on each auger, the absolute motor torque is determined from the motor power draw measured at the Variable Frequency Drive (VFD), referred to as the lossless torque at the motor. Additionally, to determine the torque seen by the drive shaft, the power transmission losses between the VFD and the shaft must be understood. While there are additional losses, they are negligible in size compared to the power losses caused by the 3-phase National Electrical Manufacturers Association (NEMA) motor, the worm gear speed reducer, and the chain and sprocket assembly. These major losses are shown in the chart below:

Table 3: Drive Train Mechanical Losses

Mechanical Interface	Power transfer
NEMA Motor	89%
Worm gear reducer	94%
Chain and Sprocket	93%
Effective Power Conversion	78%

Source: Interra

The combination of these three major components of power loss can be expressed as a single percentage and used to determine the effective torque at the drive shaft, which is 78 percent of the lossless torque. This value will be used for both augers as they conform to the same electromechanical power transmission interfaces.

Feed Auger

The feed auger geometry and motor profile is shown in Table 5. In this report, the nominal torque for the feed auger is defined as the torque experienced at the maximum supply voltage (480 Volt) and 60 Hertz (Hz). The frequency of the power input can be raised to a maximum of 120 Hz. although above 60Hz the RPMs increase as power remains effectively constant, correlating to a decrease in torque.

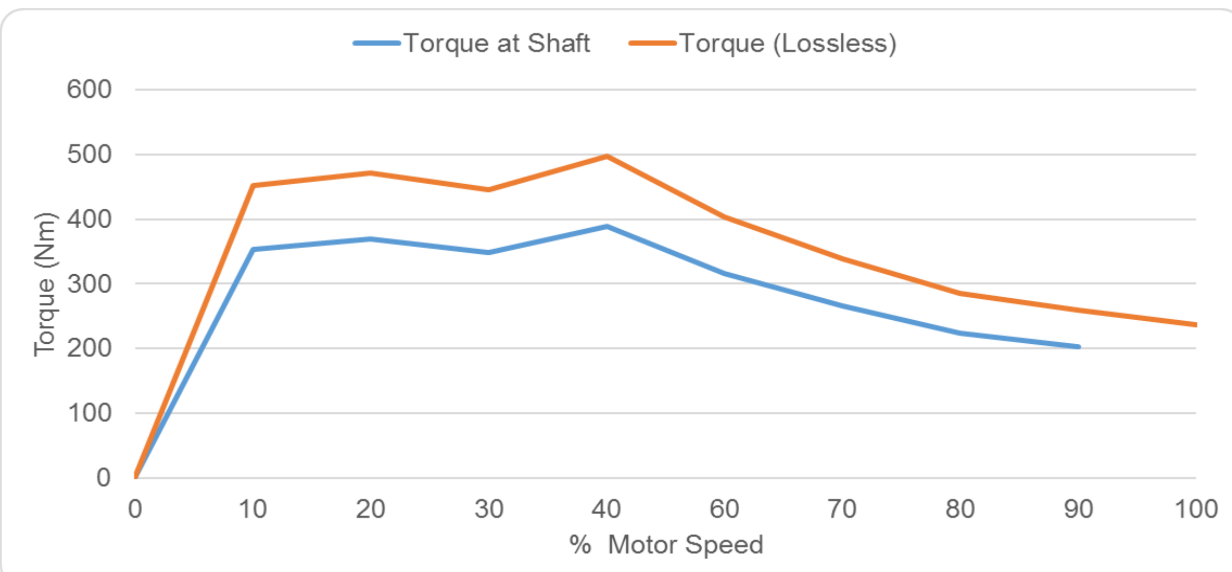
Table 4: Feed Auger Specifications

Item	Spec.
Pitch (in.)	8
Coil OD (in.)	7.625
Biomass Moved per Rotation (ft^3)	0.14
Motor Power (horsepower)	5
Maximum Motor Frequency (Hz)	120
Gear Ratio (Teeth Driven/Drive)	19/17

Source: Interra

To test for nominal torque and torque across the full range of motor operation, VFD current draw data was collected across a range of motor speeds. The auger was spun at different rates from 0 percent to 100 percent speed (0Hz-120Hz) while full of biomass, allowing data to be collected, reflecting operational torque outputs. Figure 43 shows both the lossless torque calculated at the VFD and the mechanically transferred torque at the shaft of the auger across this range of motor speeds.

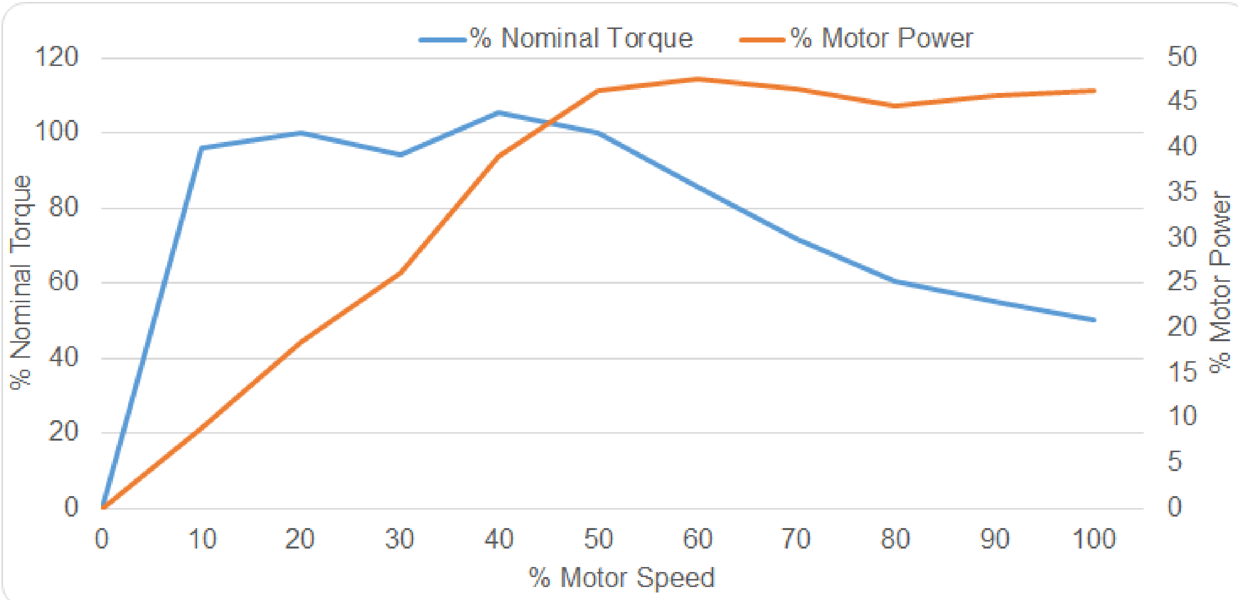
Figure 43: Feed Auger Lossless Toque and Toque at Shaft



Source: Interra

Figure 44 shows the relationship between the feed auger motor speed, motor torque, and required horsepower, and the relationship between VFD frequency output and torque, displaying what that means in terms of motor horsepower required to turn the auger.

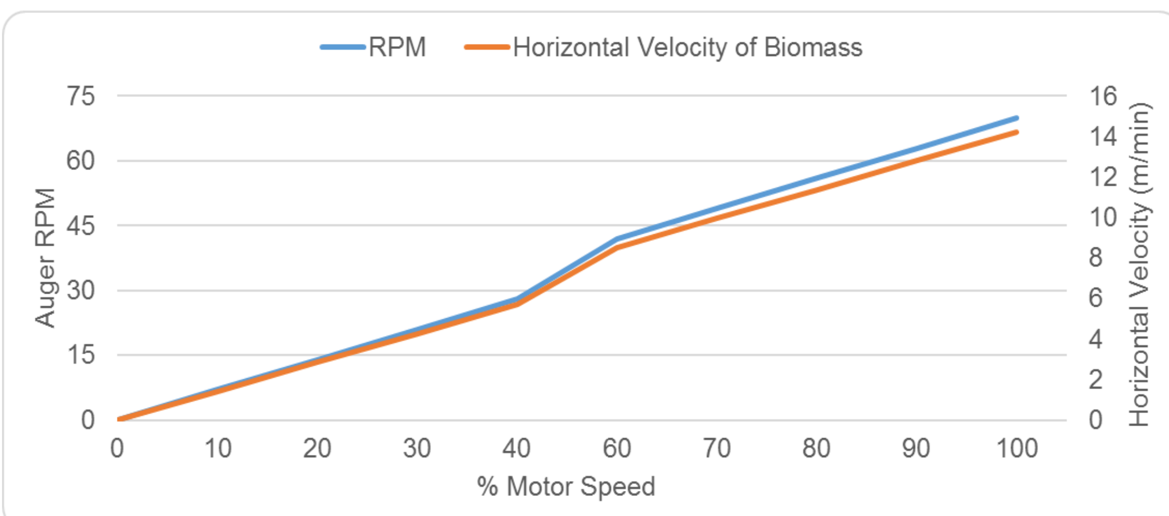
Figure 44: Feed Auger Motor Speed vs % Nominal Toque (Nm) and % Power (HP)



Source: Interra

Nominal torque occurs in this graph at 60Hz, or 50 percent of motor speed. At 50 percent motor speed, horsepower (HP) reaches its maximum at 46 percent of available power, or 2.34 HP. The feed motor has roughly double the capacity necessary to push biomass with the auger used, which allows the feed motor room to push harder in the case of jams.

Figure 45: Feed Auger Motor Speed vs RPM and Horizontal Material Velocity



The rotational speed of the auger across the full range of motor operation is another important metric of these mechanical tests. This value is used to determine the movement of material from the feed chamber into the feed tube, and through the feed tube into the turn-around zone. The relationship between motor speed and RPM is shown in Figure 45.

As expected, motor RPM increases proportionally to motor speed. The horizontal speed of biomass can be estimated by using the geometry of the auger to determine how far material moves per rotation. This value was tested and verified by moving a known quantity of material through the reactor feed chamber and measuring the time to empty. The real world values showed that an extrapolated horizontal velocity is appropriate to use in further calculations based upon motor speed.

Reciprocating Auger

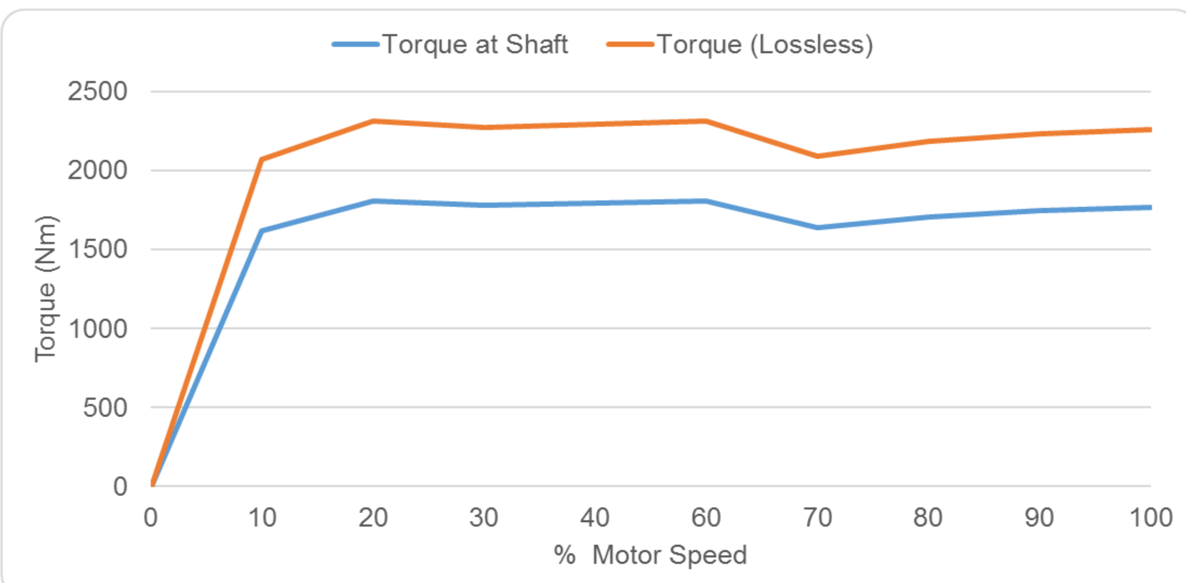
The reciprocating auger geometry and motor profile is shown in Table 6.

Table 5: Reciprocating Auger System Specifications

Item	Spec.
Pitch (in.)	15
Coil OD (in.)	13.25
Biomass Moved per Rotation (Ft^3)	1.504
Motor Power (HP)	3
Maximum Motor Frequency (Hz)	60
Gear Ratio (Teeth Driven/Drive)	19/16

Source: Interra

Figure 46: Reciprocating Auger Lossless Toque and Toque at Shaft

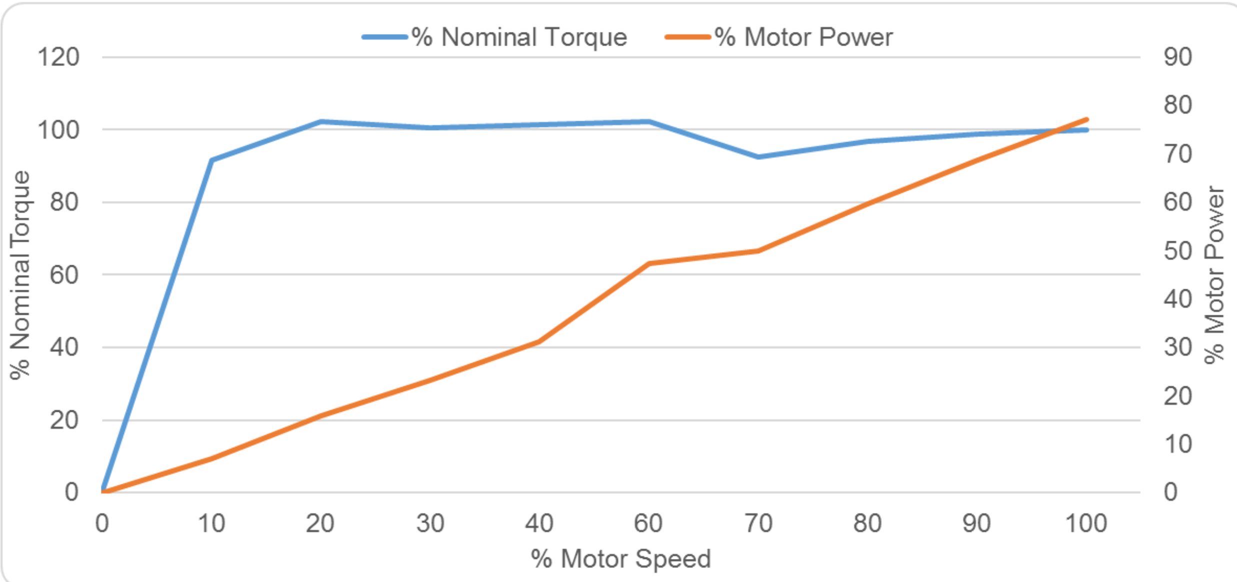


The same testing methods used for the feed auger were used to determine the lossless torque, and torque at the reciprocating auger drive shaft (Figure 46).

Unlike the feed auger, the reciprocating auger motor operates only up to 60Hz. Because of the VFD voltage scaling, the torque across the reciprocating auger motor speed range is effectively constant, with no drop off at high-end motor speed. This is important, as the reciprocating auger requires more power to turn than the feed auger and at higher RPM the motor will still provide adequate torque using this configuration. This relationship is demonstrated in Figure

47. Figure 47 also shows that the maximum motor power is 78 percent at 100 percent motor speed, or 2.4 HP.

Figure 47: Reciprocating Auger Motor Speed vs % Nominal Toque (Nm) and % Power (HP)

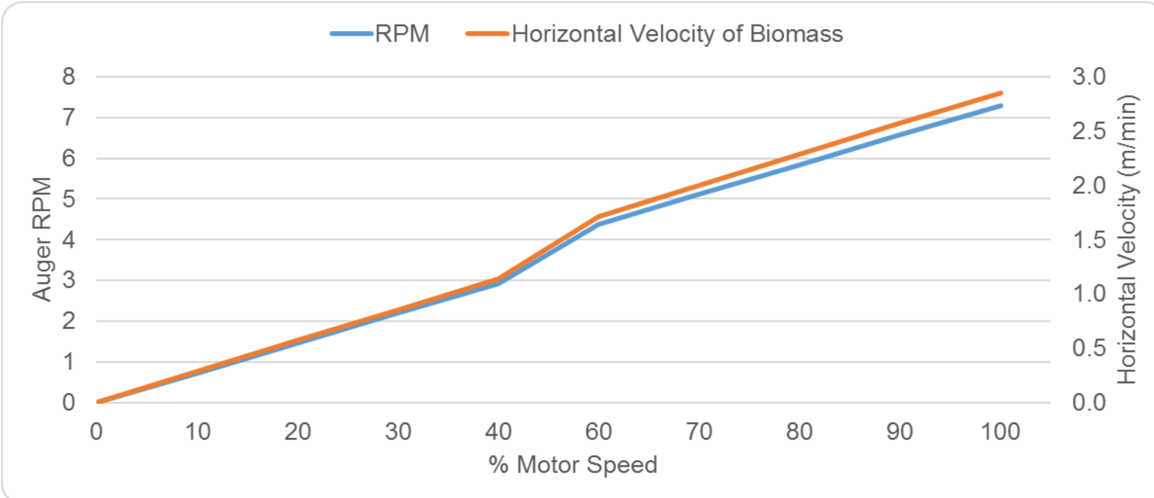


Source: Interra

While this is within the capabilities of the 3HP motor installed, in the future this motor could be upgraded to a 5HP motor. A larger motor power capacity would allow great room for increased variations in torque during operation at the expense of an increased chance of an over-torque scenario, which could cause damage to the system at high temperatures. Because there are two layers of motor over-torque prevention, both at the software level, and at the VFD level, these high torque spikes can be avoided.

Figure 48 shows the motor speed vs RPM graph for the reciprocating auger. Because the reciprocating auger moves more than 9 times the biomass by volume as the feed auger, the RPM at top speed is much lower. A larger worm gear reducer was used to achieve the low RPMs from a 1,750 RPM motor. This relationship between feed and reciprocating auger RPM is important to ensure maximum efficiency in moving material smoothly through the reactor, starting from the feed chamber and ending in the slurry exit. If the peak RPMs are compared, the same ratio, ~9x, will be found of the Feed/Reciprocating rotations. This allows the system to be run at any motor speed that is driven by the feed auger, while maintaining a steady flow of material by manipulating the reciprocating motor's speed.

Figure 48: Reciprocating Auger Motor Speed vs RPM and Horizontal Material Velocity



Source: Interra

CHAPTER 6: Operational Testing

This chapter discusses problems encountered during initial operating performance testing of the Reciprocating Reactor. Multiple repairs were needed after design failures were detected during testing at operational temperatures. Due to the untried nature of the reactor geometry, iterative experimental testing was required to solve many of the technological challenges. Lessons learned during testing are summarized in Chapter 9: Conclusions.

Feed Tube Geometry Issues

The original design of the feed tube had a reducing cone at its opening to the turn-around zone. The 8” nominal tube was subsequently reduced to 6” to align the feed tube tip with the outer auger in the event that the outer tube was not perfectly linear, as well as to force pyrolysis gases to pass through charring biomass at the end of the feed tube.

However, a problem was immediately detected with this geometry. Before the reactor could heat up to working temperatures, uncharred biomass would form a restriction strong enough to halt feed auger operation. The biomass clog, along with an inadequate feed auger tip design, caused large torque spikes from the feed drive motor.

To solve the problem, the area where the clog occurred was widened from 6” to 7”. Additionally, the feed auger pitch was lengthened at the feed tube exit from 8” to 10”. Widening the auger pitch increases the distance that particles travel during each rotation. This made up for the 25 percent reduction in tube area due to the restriction, allowing material to continuously flow without clogging.

Air Heater Issues

The 6 kilowatt in-line heater used to warm up the system uses electric resistance to heat a small heating element. When air is forced over the element, heat is transferred to the air. During initial testing, the heating element was powered without air flowing over it, causing the element to overheat and break.

Figure 49: Upgraded Air Heater configuration at feed tube

Source: Interra

To address this issue, additional control methods were implemented to protect the heating coils. Low flow power cutoffs were added along with additional software safety checks. A hardware temperature cutoff switch was also added as a redundancy. The upgraded air heater installation is shown in Figure 49.

Auger Failure

To heat the reactor up to operational temperatures (1,000-1,250°F), the air heater injects air into the feed tube at up to 800 °F. The air heater ignites the biomass injected into the feed tube. Biomass is continuously injected and fully combusted until the entire reactor reaches the desired operating temperature. While undergoing full combustion, the feed tube experienced temperatures of up to 1,500°F.

Figure 50: Feed AUger Failure at Original Air Heater Zone (1)

Source: Interra

The yield strength of the 321-grade stainless steel decreased when heated by the combustion of biomass to a point where the normal operating torque from the motor was enough to deform it. Images of the failed feed auger are shown in Figure 50, Figure 51, and Figure 21.

Figure 51: Feed Auger failure at Original Air Heater Zone (2)

Source: Interra

Figure 52: Feed Auger Failure in Feed Tube

Source: Interra

CHAPTER 7: Technology Transfer Activities

Technology Transfer Plan

Sharing Data

Interra has followed Energy Commission policies concerning the sharing of research data, as outlined by the Energy Commission, and has presented in this report the research data gathered using the support of the Energy Commission under PIR-12-021.

Sharing Research Materials

Interra will also comply with the Energy Commission requirements governing technology transfer and adhere to the policies and guidelines addressing technology transfer and the distribution of Energy Commission funded research materials. If Interra is in possession of materials generated during the Energy Commission contract PIR-12-021 it will strive to make the unique research resources readily available for research purposes to members of the Energy Commission under contract PIR-12-021, and to non-profit organizations and commercial collaborators in accordance with Energy Commission guidelines. Interra will not be expected to share internally held intellectual property.

Licensing of Intellectual Property

Interra will license intellectual property developed as it sees fit. Shared information will be treated as confidential by participating institutions and commercial collaborators as is necessary. When ownership of the Energy Commission contract PIR-12-021 technology involves multiple institutions, the participating institutions will form agreements involving the consolidation and central management of intellectual property rights. Similarly, Interra may collaborate to package technologies under contract PIR-12-021 for licensing as necessary to commercially develop such technologies in a timely fashion.

Interra will make adaptations of its technologies available for licensing at its discretion. Commercial collaborators interested in licensing technologies used under the Energy Commission contract PIR-12-021 shall notify Interra. Licenses will be executed when appropriate, and milestones may be used to ensure that the licensing leads to timely commercial development. In such licenses, Interra will strive to limit the exclusive license to the commercial field of use, retaining rights regarding use and distribution of any technology that is a research tool.

CHAPTER 8: Production Readiness Plan

Production Readiness Plan

Because full-system testing was not completed under this project, Interra was unable to generate a full production readiness plan. Until the system has been fully tested and operationally validated for at least 500 operational hours, it would not be prudent to finalize manufacturing plans. Once the core reactor system and its subsystems have been tested and validated, Interra will determine the necessary steps to begin manufacturing Reciprocating Reactor units for operation throughout California.

Manufacturing of the first commercial units will require more testing prior to any type of scale-up work. The construction efforts funded under the project allowed Interra to identify most of the required parts and all the required vendors for future manufacturing efforts. The next step will be to continue research and development to address issues associated with the auger, feed tube and air heating issues, followed by potentially operating the technology at a pilot-facility to validate the research hypothesis. This will ensure there is enough operational data to satisfy investors and financial institutions needed to commercialize the technology.

Because Interra was not successful in completing testing of the system a solid understanding of the costs of a commercial facility including equipment, pre-development work, and permitting will require additional efforts. In addition, once validation of the technology is complete, it will be possible to access government loan guarantee programs from the United States Department of Agriculture and Department of Energy. Moreover, companies looking to further advance this technology based on lessons learned from this project could look to raise funds for commercialization efforts from private investors. Interra encourages the Energy Commission to continue to help fund projects in the early stages of technology development and demonstration, since private funding is still very difficult with the level of risk and uncertainty surrounding such projects.

CHAPTER 9: Conclusions

The goal of this project was to develop a low-cost, pyrolysis-based biomass conversion technology, called the Reciprocating Reactor, to produce renewable natural gas (RNG). Due to uncertainties in the quality of RNG that could be produced, alternative goals were also included in the original proposal to increase the project viability. The production of biochar was included for its value in soil enhancement, water retention, and carbon sequestration. The performance goals of this project were to produce RNG quality gas and a high yield of biochar co-product.

Mechanical testing performed in September 2014 confirmed that under ambient conditions the augers could handle the maximum stress of pushing the maximum designed rate of biomass through the reactor. Results of the hot testing revealed that multiple systems including the augers, biomass intake system, and flare needed upgrading to properly operate at the desired system temperature and throughput rate. Despite working several months beyond the original project timeline, not all of the proposed experiments could be completed and Interra was unsuccessful in demonstrating the system as mentioned in Chapter 6.

Nonetheless, California benefited by funding of this project through the knowledge gained on the technical barriers and limitations identified, which will support efforts to continue to advance thermochemical production technologies in distributed biofuel and biochar sectors. The technical challenges uncovered during this project can potentially provide insight into how to make improvements to similar low-cost renewable fuel production systems in the future. The prototype that was designed, constructed, and tested under this project has served as a platform for continued development of the technology under post-grant development. When sufficiently refined and scaled up to approximately 3-4 dry tons of biomass input per hour, this technology can potentially demonstrate its anticipated cost and environmental benefits for California ratepayers, however additional research and testing will be required.

Critical lessons learned during this research effort relate to the auger design and are likely the most valuable lessons for future thermochemical biomass conversion technology development.

Auger Design

Heterogeneous waste biomass can present many difficulties for augers. Shaftless augers are typically used with heterogeneous biomass because this material tends to stick, wind around, or bind. One important lesson learned during this research was that shaftless augers configured to push material through a tube are more likely to jam than those configured to pull. When a pushing shaftless auger experiences resistance, the outer diameter of the auger grows. This growth can increase resistance to turning and result in a full jam of the auger.

A pulling auger will shrink under tension, making it much more likely to disengage with obstructions, avoiding jams. Interra's reactor design requires a pushing shaftless auger so the increased potential for jamming must be accounted for in the design. Methods to address this and related difficulties with auger design include:

- Use of a high-fidelity torque-measuring device on auger drive shafts. Measuring the torque experienced by the drive shaft is effective in detecting auger jams and allows for fast, and automatic, shutoff response to reduce the risk of damaging components. An automatic "reverse then resume" function is useful when jamming is common, such as with pushing shaftless auger applications inside a tube. That is, when a torque spike is detected, the control system can stop the motor prior to risk of potential damage, reverse the auger for 1-2 rotations to release the jammed material, then resume forward conveyance without operator intervention.

- Use of a motor sized 2-3 times larger than what is calculated as required to move the material, then control the speed with a Variable Frequency Drive. Models to determine the horsepower needed for biomass conveyance for shaftless augers leave much to be desired because they often prescribe for undersized motors and under-strength augers. Starting with available motor horsepower models but upping the motor horsepower by 50-100% is prudent given the modeling's predictive weaknesses.
- Increase the strength of the auger. Design the shaftless auger to not yield at the highest potential reactor temperatures factoring in the maximum torque that the drive motor and assembly is capable of producing under full jam conditions. This calculation should be done with at least a 1.5x factor of safety. If there is the potential that a more powerful motor may ever be desired, using a factor of safety of greater than 2.5x is wise.
- The auger material strength assumptions should use strength figures factoring in temperatures well above the maximum desired reactor temperature. The temperatures inside auger-based reactors are difficult to measure with precision and "hot spots" often develop that can subject internal materials to significantly higher temperatures than those being measured on the outside walls of the reactor. For this reason, the assumed peak temperature used in calculating material strengths should be 200-300 degrees hotter than those read on the outside of an auger-based reactor.

These lessons learned, if applied from the beginning of the project, would have avoided substantial delays and budget difficulties in Interra's reactor development. Future developers of auger-based thermochemical reactor designs will also benefit from considering the lessons offered above.

GLOSSARY

Term	Definition
Auger	A drilling device, or drill bit, that usually includes a rotating helical screw blade called a "flighting" to act as a screw conveyor to remove the drilled-out material. The rotation of the blade causes the material to move out of the hole being drilled.
Bark beetle	Beetles that bore through the protective bark of a tree to lay eggs in the living inner bark; beetles and larvae feed on the living tissue, cutting off the tree's ability to transport nutrients, and cause high levels of tree death in California.
Bench-scale	Testing of materials, methods, or chemical processes on a small scale, such as a laboratory worktable.
Biochar	A form of charcoal produced by exposing organic waste such as wood chips, crop residue, or manure to heat in a low-oxygen environment; used especially as a soil amendment.
Biomass	Plant material, animal waste, and other organic waste materials that can be used to produce energy.
Carbon intensity	The amount of carbon by weight emitted per unit of energy consumed.
Cellulose	An insoluble substance that is the main constituent of plant cell walls and vegetable fibers; a polysaccharide consisting of chains of D-glucose (dextrose) units.
Distributed energy	Small, modular energy generation and storage technologies that can provide electric capacity or energy where it is needed; may be connected to the local power grid or isolated from the grid in stand-alone applications, and can include wind turbines, photovoltaics, fuel cells, microturbines, reciprocating engines, combustion turbines, cogeneration, and energy storage systems.
Feedstock	Raw material to supply or fuel a machine or industrial process.
Hemicellulose	A polysaccharide related to cellulose that comprises about 20 percent of plant biomass; different from cellulose in that it is derived from several sugars in addition to glucose.
Hydrocarbons	A compound of hydrogen carbon, such as those that are the chief components of petroleum and natural gas.
Lignin	A complex organic polymer deposited in the cell walls of many plants, making them rigid and woody.
Lock hopper system	A feeding device that incorporates a double pressure seal that enables solids to be fed into a system with a higher pressure than the pressure existing in the solid's storage area; also a letdown device that similarly allows solids to be withdrawn from a system with higher pressure than that existing downstream of the lock hopper.
Methanation	Conversion (usually of carbon monoxide and hydrogen) into methane.

Term	Definition
Net carbon negative	The result of capturing carbon released from biomass conversion for energy and sequestering it so that it is removed from the atmosphere.
Oxidant	A substance that can oxidize (remove electrons from) other substances in their proximity as part of a chemical reaction.
Polysaccharide	A carbohydrate (for example, starch, cellulose, or glycogen) whose molecules consist of a number of sugar molecules bonded together.
Producer gas	Fuel gas that is a mixture of nitrogen, carbon monoxide, and hydrogen, made through a process that supplies less oxygen than is needed for complete combustion of the fuel.
Pyrolysis	The chemical decomposition of organic materials using heat in the absence or near absence of oxygen; without oxygen, the material does not burn but instead the chemical compounds (cellulose, hemicellulose, and lignin) decompose into combustible gases and charcoal.
Renewable natural gas	Natural gas derived from organic waste material that is processed to purity standards to be pipeline quality and fully interchangeable with conventional natural gas; can be used as a transportation fuel or to generate electricity and heat.
Slurry	A semi-liquid mixture of fine particles suspended in water, such as manure or concrete.
Syngas	Abbreviation for synthesis gas, a mixture of carbon monoxide, carbon dioxide, and hydrogen produced by gasification of a carbon-containing fuel into a gaseous fuel.
Thermochemical conversion	Application of heat and chemical processes in the production of energy products from biomass.
Torque	A measure of how much a force acting on an object causes that object to rotate about an axis.

LIST OF ACRONYMS

Term	Definition
CAD	Computer Assisted Design
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water
°F	Degrees Fahrenheit
HP	Horsepower
Hz	Hertz
NEMA	National Electrical Manufacturers Association
NI	National Instruments®
RNG	Renewable Natural Gas
V	Volt
VFD	Variable Frequency Drive

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APPENDIX A:
Process Diagram for Reciprocating Reactor Facility