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Project Title: **Demonstrating the Potential for Distributed Power Generation Using Converted Biomass**

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MILESTONE REPORT
Milestone 2 for Boiler/Generator System

Executive Summary:

CSR's contribution to Milestone 2 of the "Demonstrating Potential for Distributed Power Generation Using Converted Biomass" required meeting a number of institutional and design-based thresholds. The milestones CSR achieved included: 1) finalization of designs and fabrication materials; and 2) finalizing arrangements for the purchase orders for steam electric generator materials and components.

On a technical and research basis, the core of "Milestone 2 – Fabrication" focused around the final design of the boiler generator system and lining up agreements with various subcontractors to undertake fabrication of the unit. This required further refining of the conceptual designs we undertook as part of Milestone 1, to a point where the engineering could be checked and verified by the CSR Professional Engineer for certification and, ultimately, fabrication. The major portions of the design process focused on the two key components: 1) boiler design and 2) steam engine / generator design and interface. We have worked in a cooperative nature with industry collaborators to ensure that the designs are of logical scope to fabricate.

The biggest deviation taken as part of this Milestone was the shift away from a traditional piston engine design. Indeed one of the largest delays in completion of this Milestone involved engineering complications related to sizing of key steam engine components. The design process is summarized in the Technical Progress summary to follow, but in the end, the CSR Team has opted to collaborate with a

rotary steam engine OEM to provide the integrated, light weight 100 kW steam expander / alternator / control system.

Technical Progress:

Technical progress on the boiler generator unit is broken into two interrelated, but distinct portions: 1) the boiler; and 2) the engine/generator unit.

Boiler:

The boiler development team utilized an iterative process to translate the conceptual designs present in the output of Milestone 1 into a detailed 3D model from which the boiler can be fabricated, as the output of this Milestone. This included multiple meetings with the selected boiler manufacturer, Williams & Davis Boilers, as well as the development of extensive fundamental design calculations related to combustion, heat transfer, structural integrity, and steam generation.

Design Process

The CSR design team has worked extensively to refine the concepts outlined in the grant application and Milestone 1 into an innovative steam power plant. Key to its design was the simplification and refinement of the "locomotive-style" fire tube boiler. Traditionally, locomotive-style boilers featured a proportionately high steam generation rate as a function of their size. This is an important design feature of the distributed generation system, in that size, weight, and portability are key design considerations.

What enables the compact size of a locomotive-style boiler is the relationship between a stayed firebox, the combustion chamber, and the tube space. Those key features, when coupled to an efficient combustion system, results in a relatively compact boiler that can burn energy-sparse fuels and still generate sufficient steam to run a generator and create process steam.

Point in case - the most important element of CSR's boiler design process concerned the firebox, which is intended to prove out the feasibility of utilizing the torrefied biomass in conjunction with the Gas Producer Combustion System for minimized output of criteria pollutants. This engineering required taking empirical design guidelines for sizing the firebox as well as the primary and secondary air inlets and melding them with boiler component dimensions that would allow operation of the unit at design pressure according to the ASME Boiler and Pressure Vessel Code.

This required a parallel process of selecting preliminary component dimensions, verifying them with code calculations, creating a 3D component model, creating a 3D assembly model to check for fit, interferences, and manufacturability. After each iteration, a detailed assessment of the assembly model would point to design deficiencies, after which components would be modified to address the identified deficiency. Once the design reached a state of maturity whereby it was thought to be code compliant, capable of the desired performance, and manufacturable, it was submitted to the CSR Professional Engineer for review.

Finalizing Boiler Design

After a detailed review, the CSR Professional Engineer made a few recommendations which were attended to and then the design was presented to the boiler manufacturing contractor, Williams & Davis Boilers. In February, 2018, CSR undertook a review of both design features and calculations on-site at the Williams & Davis facility in Hutchins, Texas, whereby additional recommendations were made by the engineering staff of the contractor. These suggestions highlighted modifications that would make for easier fabrication given the tooling and experience of the contractor.

CSR has made those modifications, and a final review by the CSR Professional Engineer is underway. As of this writing, it is expected that fabrication of the boiler will commence in Q2 2018.

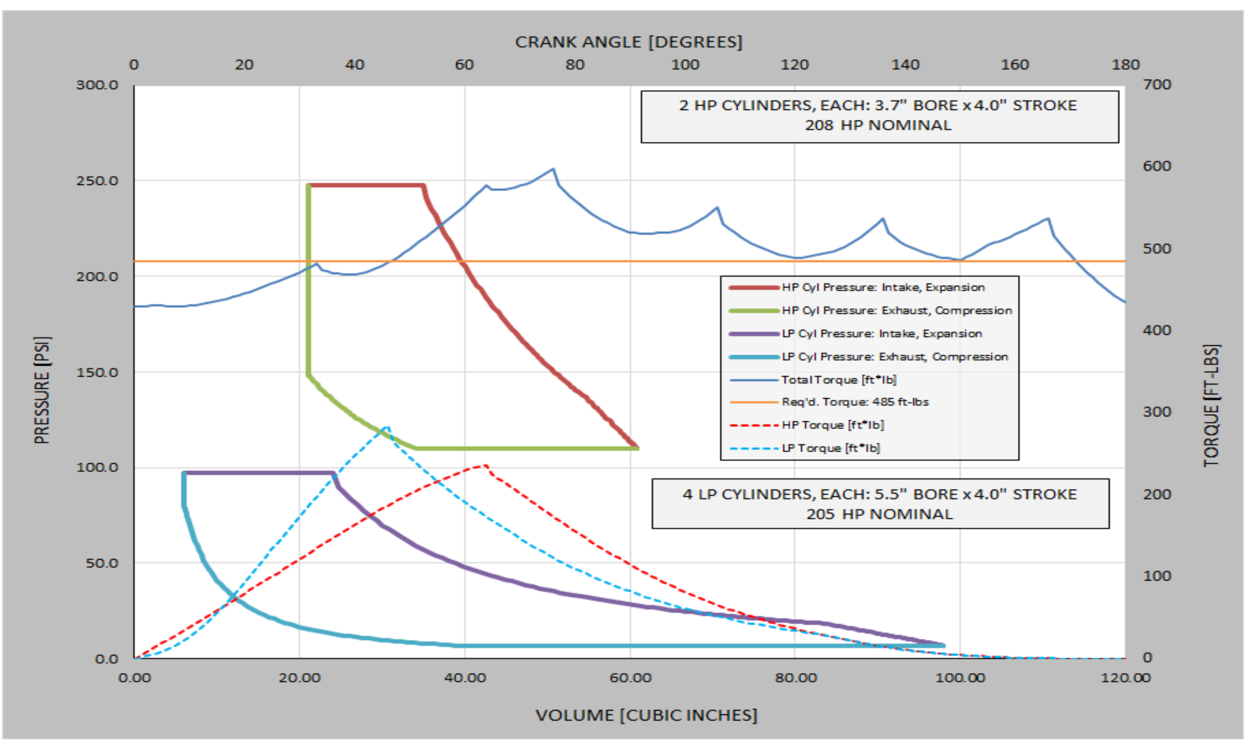
<u>Engine / Generator Unit</u>:

More so than any other portion of this engineering exercise, the design of the steam engine / generator unit proved to be the largest source of delay in the process. After multiple iterations in design, starting with a single cylinder engine, then transitioning to variations of compounding engines, then returning to a simple-expansion, multi-cylinder engine design, CSR has opted to collaborate with a rotary steam engine manufacturer to provide an OEM component. That design process and decision making process is summarized as follows.

<u>Design Process</u>

While working through Milestone 1, the CSR design team verified that the original engine concept, that of a single cylinder design, would be insufficient in size and efficiency to handle the anticipated 100kW load. As such, the team went back to the drawing board, running multiple design permutations

What the CSR Team was able to determine during the design phase was that its originally-proposed, single-cylinder steam engine would have generated enough horsepower to create 100 kW of electricity, but it did not have sufficient torque over the entirety of its stroke to spin the alternator in the steady state at that load. The initial design of engine was able to generate sufficient horsepower, but the sizing of the piston, its stroke, and the lack of power impulses across each revolution resulted in very "peaked" power performance and torque too little to spin the proposed alternator. Thus, the CSR Team began exploring multi-cylinder alternatives. The following graph shows preliminary CSR engineering of one CSR-designed multi-cylinder steam engine alternative:



In the graph above, the top X axis and the left Y axis relate to the torque of a proposed six cylinder steam engine. The instantaneous torque on the drive shaft as a function of position is represented by the peaked blue line, while the torque required to spin the 100 kW alternator is represented by the solid orange line (at 485 ft-lbs). The mean effective torque of the engine needs to be equal or in excess of that required to spin the alternator. The points where the torque dips below that required to spin the alternator, as in between 0 and 50 degrees and 170 and 180 degrees crank angle, can be counteracted in large part by an appropriately-sized flywheel. That said, the non-steady state of the torque available to spin the alternator is the key design parameter CSR had to address as part of its engineering exercise.

As the engineering project progressed and timing became ever more crucial, the CSR Team split into two working groups in October 2016, with one focusing on the boiler design and the other focusing on the engine design. While the boiler design process was completed successfully, as outlined above, the engine design process ran into a series of difficulties. The engine design team undertook multiple, additional iterations of the engine system and sought to devise a means to create a compound steam engine, which uses the exhaust steam of one cylinder to power additional cylinder(s) to add to the efficiency.

Beginning in mid-2017, it was becoming-ever-more-apparent that the engine design process was running into delays and complications, and the CSR Team decided to undertake an alternatives analysis to see if there were additional technologies on the market that might more appropriately fit the needs of the boiler generator system. In late 2017, the CSR Team began reaching out to others in the industry to identify alternative technologies currently available that could work as an integrated generator to the boiler design CSR was finalizing. The following are some of the alternatives investigated by CSR.

Alternative 1: Skinner Uniflow

One option that CSR investigated, but ultimately deemed infeasible, was a Skinner Uniflow engine generator that was for sale. The Skinner Uniflow gensets were amongst the most advanced steam piston gensets from the late 1950's, and with proper updating and specific modifications, they could be used to generate electricity with reasonable efficiency. Within short order, CSR had identified a large, 300 kW unit that was for sale (as pieces) in the Pacific Northwest. This unit was of reasonable cost and could have been overhauled, but it was a massive piece of machinery. Not only was the unit sized to generate up-to three times the power as outlined by this grant, but it also was designed for stationary (non-portable use), meaning it is meant to be mounted on a permanent foundation and is a massive machine (in excess of 20 tons). Images of the generator are below:

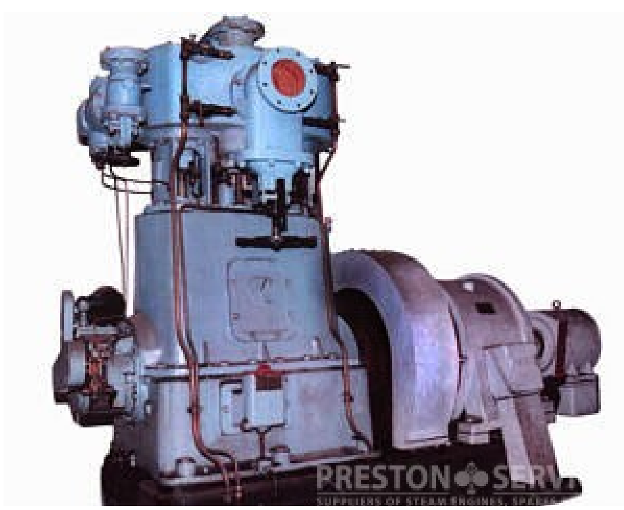
The Skinner generator set is designed with a large, multi-pole alternator, shown at LEFT above. Notice the size of the alternator in comparison with the concrete masonry unit (CMU) wall in the background (each CMU is eight inches tall).

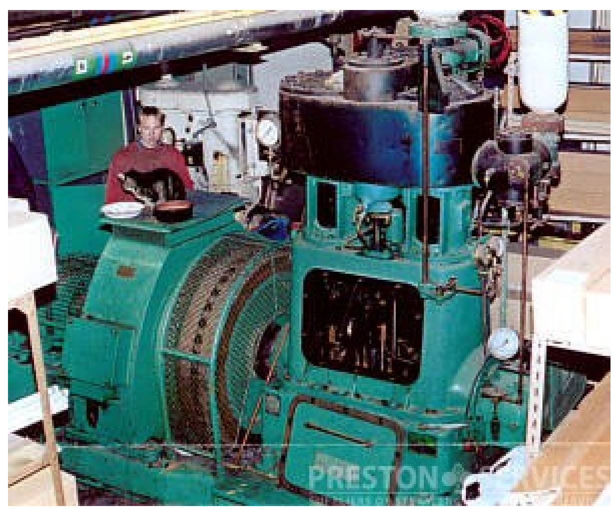
CSR's Senior Mechanical Engineer developed a preliminary modification plan to the Skinner which would have improved its efficiency and made it a more modern machine. That said, its size, the logistics associated with its move and relocation, and the fact that it was not a "mobile" unit indicated to the CSR Team that it would need to seek an additional alternative.

Alternative 2: Allen Genset

Another alternative similar to the Skinner Genset that the CSR Team investigated, but ultimately proved infeasible, were two, 125 kW "Allen" steam gensets for sale in Great Britain. These Allen Gensets were built sometime in the first half of the 20th Century for use generating electricity at factories. They are two cylinder compound steam engines designed to operate at 500 RPM, though they were built to operate on lower steam pressure than the CSR boiler is designed to produce (up-to 175 PSI vs. 295 PSI of the CSR boiler). That said, according to the broker, they are designed to consume 12-13 lbs of steam per horsepower hour, meaning an estimated steam consumption of approximately 2,175 lbs/hour at 100 kW.

Again, however, the Allen Gensets are quite large and not specifically designed for a portable system. The CSR Team again was considering a means to modify an engine to operate at higher pressures (lining the cylinders, decreasing the bore, modifying the engine), thus enabling higher efficiencies. That said, the logistics associated with transporting the large units was deemed to be both cost prohibitive, let alone the fact that the generator would have been relatively counter to the thrust of the research project at hand. The following photographs show the two Allen Gensets CSR considered. Note the size of the Genset compared with the operator / cat at RIGHT:



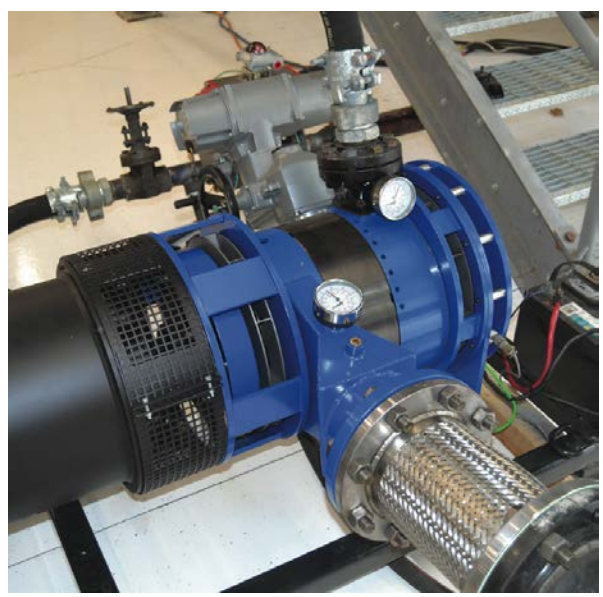


Alternative 3: Practical Steam Rotary Engine

After reviewing the other options, the most feasible option the CSR Team identified was a product manufactured by "Practical Steam," a company based in Kennesaw, Georgia. The Practical Steam Engine "PSE" is a rotary steam engine design coupled with a generator and phase harmonizing unit that is similar in purpose to that originally proposed by CSR as part of the grant application. The PSE is designed to generate electricity on the distributed basis, and the use of pistons, in this case rotary pistons, results in a design that is of higher efficiency than a turbine of similar output. In general, steam expanders (pistons) are more efficient than steam turbines below 1,000 kW of output.

A CSR Technical Advisor was able to visit with the Practical Steam engineering team and leadership at its Kennesaw facility to observe the unit in operation and to discuss the system overall.

Photographs of the PSE are included below:



In terms of design considerations, the PSE does exhibit a few constraints not otherwise present in the other alternatives CSR considered. In particular, due to the design materials of the PSE, it is not optimally suited for operations with highly superheated steam. This means is that the ultimate efficiency of the unit might be limited somewhat due to the lower maximum superheat.

Furthermore, the design of the unit, as a rotary piston engine as compared with a more traditional piston / valve engine, is a divergence from that originally outlined in the CSR grant application. That said, the size of the PSE and, thus, its portability, are directly in line with the thrust of this RDF Grant – to demonstrate distributed generation using torrefied biomass fuels and a steam electric generator.

Finalizing Engine Considerations

CSR met with NRRI PI in late March to discuss the aforementioned design process and alternatives analysis. Following that discussion, the PI and CSR decided that it would take steps to move forward into an agreement with Practical Steam regarding a PSE for use with the engine generator system. CSR has a comprehensive bid in hand for a PSE, and it is performing final vetting of the technology to gauge steam demand and verify the boiler sizing. As of this writing, it is expected that fabrication of the PSE will commence in Q2 2018.

Additional Milestones:

In concert with our work to verify the sizing and dimensioning of the key firebox components, CSR continued its torrefied biomass fuel combustion tests in conjunction with the Milwaukee County Zoo, on its 15 inch gauge railroad. The boilers on the largest of its two steam locomotives is approximately one half the size of the boiler which CSR is designing, and it served as successful testbed to test a variety of fuel sizes and compositions. In addition to the trials undertaken at the Zoo in association with Milestone 1, CSR undertook two additional trials (October 2016 and November 2017) utilizing torrefied biomass materials manufactured and densified by NRRI at its Renewable Energy Labs.

Each test provided information regarding densification techniques and the combustion of the torrefied fuels in a traditional firebox environment, in comparison with coal combustion as a control. In both cases, the torrefied fuels provided sufficient heat to generate steam with minimal smoke emissions, however the information gleaned from the former trials, in particular that related to densification techniques and methods, was beneficial in shaping the fuels research which ultimately led to that burned in the 2017 trials.

The ability to verify that torrefied fuels will burn with nearly the same characteristics as coal, as confirmed in our 2017 trials, was a key part of verifying the engineering of the GPCS firebox, mentioned in the Technical Progress portion of this milestone. Following those trials, CSR was able to finalize the firebox design and send it to the boiler manufacturer for input and refinement.

BELOW: A bed of torrefied biomass in the Milwaukee Zoo Train firebox. Note the thermocouples sticking through the firebox wall at LEFT.

BELOW: A bucket full of blended, 50/50 torrefied biomass / Powder Rriver Basin fuel briquettes used as part of the tests. Also burned were 100% torrefied oak briquettes.

BELOW: The test train climbs the steepest grade on the Zoo Train railroad. Notice the clean smokestack indicating a clean burning fire.

BELOW: The two steam locomotives of the Milwaukee County Zoo burning torrefied biomass fuel during test runs in November 2017.

Moving Bed Torrefaction System

I. Executive Summary

The information in this design report summarizes the Moving Bed Torrefaction Reactor demonstration plant equipment and controls that will be installed at Building 171 (B-171) of the NRRI facility located in Coleraine Minnesota. This building houses NRRI's Renewable Energy Center, which contains various equipment and processes to convert biomass into renewable fuels. Funding for this plant is provided through a Renewable Development Fund grant, RD4-11, which is administered by Xcel Energy and the State of Minnesota. This grant also included funds to develop, build, and operate a new, efficient steam boiler/power generator that is designed to operate on torrefied material. This effort is being conducted by the Coalition for Sustainable Rail and will also be installed at the Coleraine facility.

The design was primarily based on data obtained from operating the small moving bed torrefaction pilot plant in Gradient Technology's facility in Elk River, Minnesota over the last 18 months. In addition, input from NRRI personnel garnered from their experience operating the drier and rotary kiln torrefaction unit at Coleraine was important, especially in regards to the safety and dynamics of biomass conveyance. An internal Process Hazards Analysis (PHA) of the process and equipment, submitted separately, was conducted and resulted in some design changes. The main equipment structure will be analyzed by Krech Ojard & Associates, Inc of Minneapolis, Minnesota. Any recommendations will be implemented into the design and their report will be included in future documentation issued prior to installation at Coleraine.

The purpose of this detailed design effort is to specify the process and equipment capable of running up to 180 kg/hr of woody biomass, generating about 113 kg/hr of torrefied material. This process must interface with existing biomass handling equipment at B-171. Dried, sized, and screened wood chips will be continuously produced from their drier and pneumatically conveyed to the SynGas torrefaction unit. Torrefied product will be fed into the back end of the Coleraine process, which contains a product tank and grinding and densification equipment to produce torrefied pellets or briquettes if desired. In addition, the unit had to fit the dimensions of the existing building, B-171, particularly the maximum building height and roof slant. This restraint caused several design changes in reactor diameter, conveyor configuration, and vessel locations.

Figure 1. Coleraine B-171

This detailed design is the collaborative effort of several individuals from SynGas and NRRI with backgrounds in chemical engineering, mechanical engineering, facilities, operations, environmental health, safety, and industrial hygiene to ensure careful evaluation of all aspects of the design. The detailed design presented in this document is the embodiment of those efforts.

II. GENERAL ARRANGEMENT

The existing building this demonstration plant will be installed in, B-171, is pictured above in Figure 1. The arrangement of equipment inside B-171 is shown in various views in the figures of this section. The main structure and major equipment is located under the tallest peak of the roof, with utilities such as the boiler and air compressor against an inside wall. The cooling tower is located outside the building.

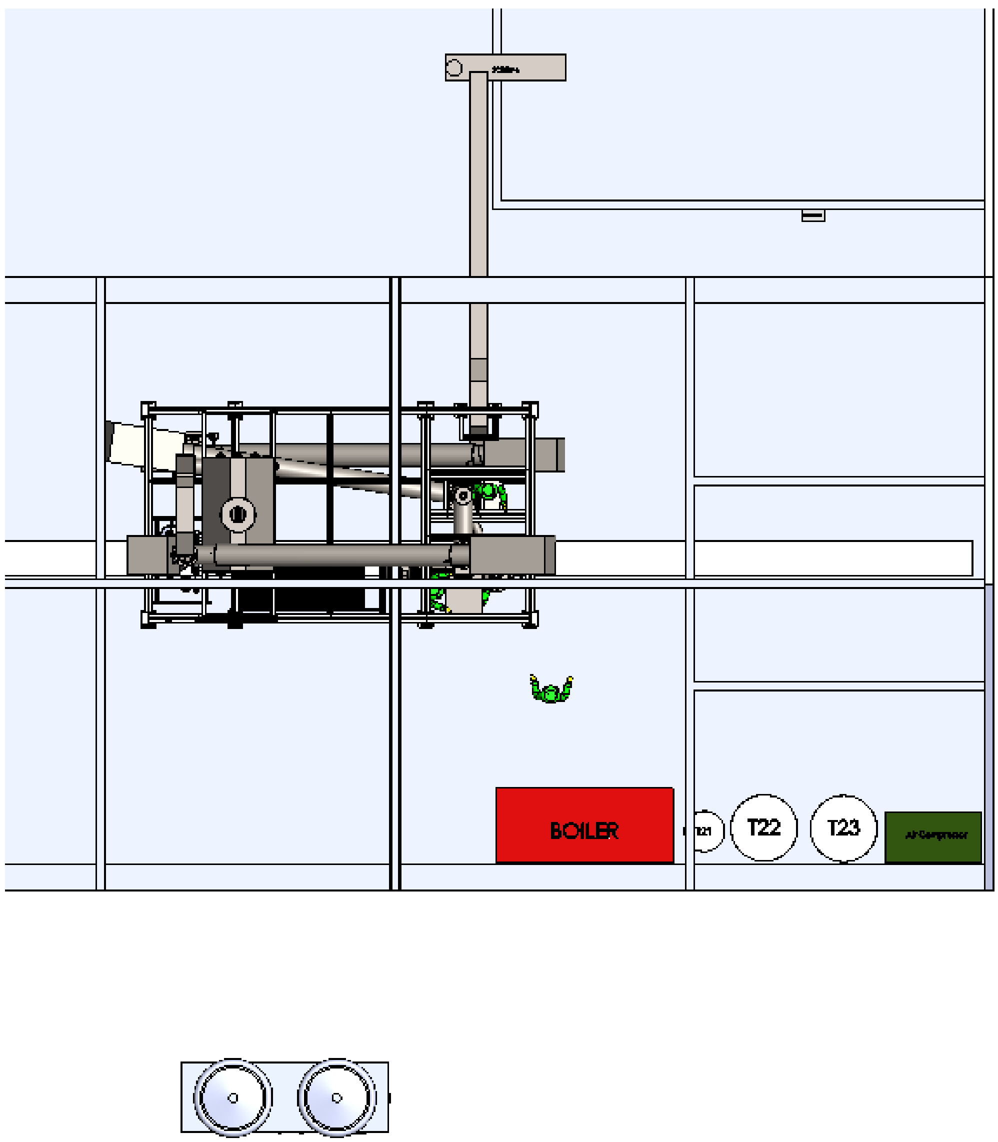


Figure 2. Xcel Plant Position in B-171 (top view)

Figure 3. Xcel Plant Position in B-171 (east view)

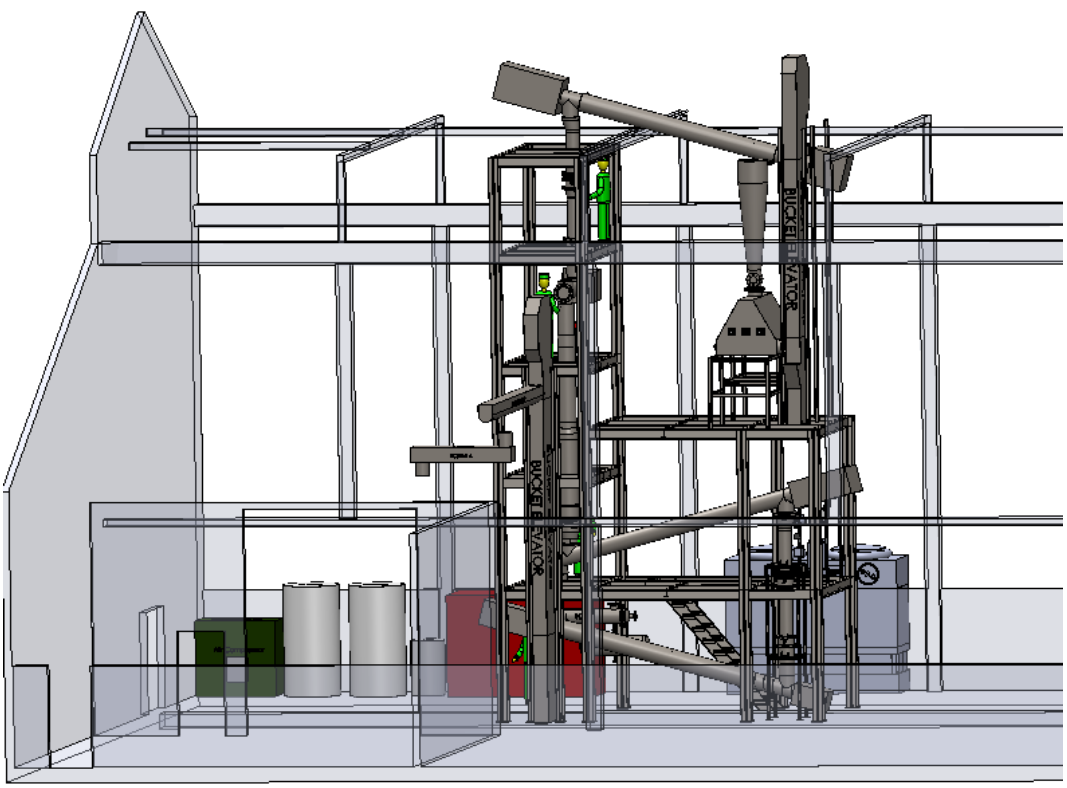


Figure 4. Xcel Plant Position in B-171 (south view)

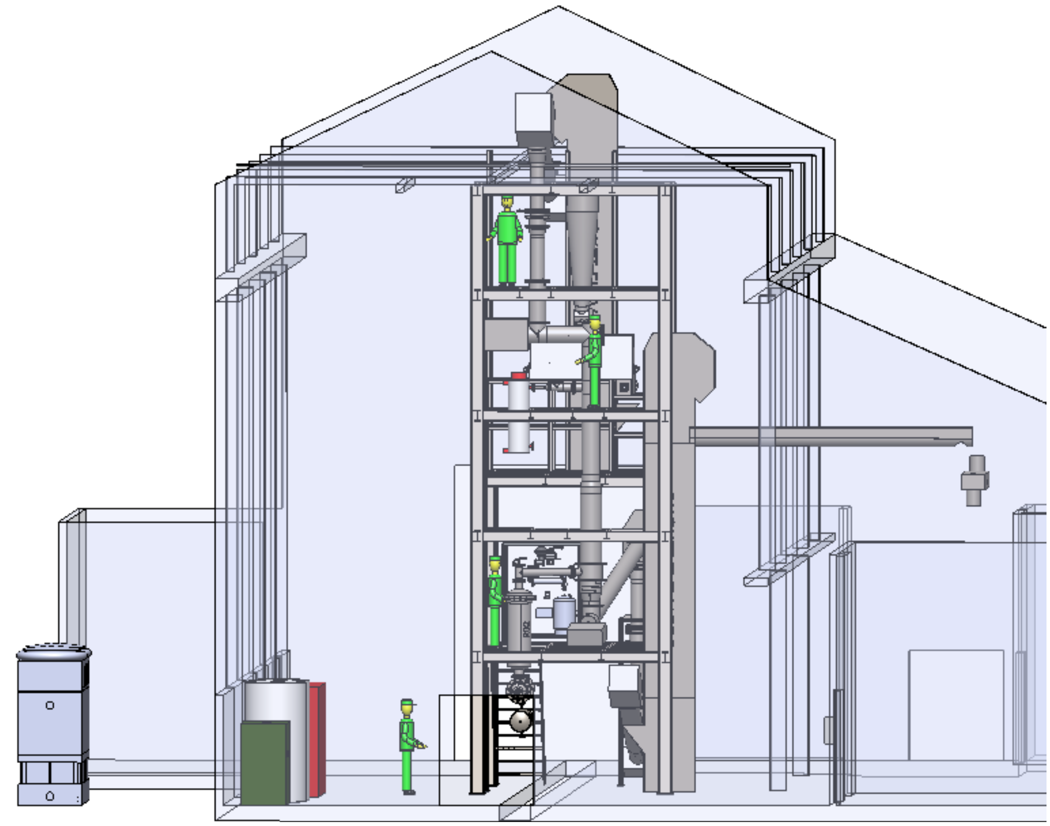


Figure 5. Xcel Plant Position in B-171 (west view)

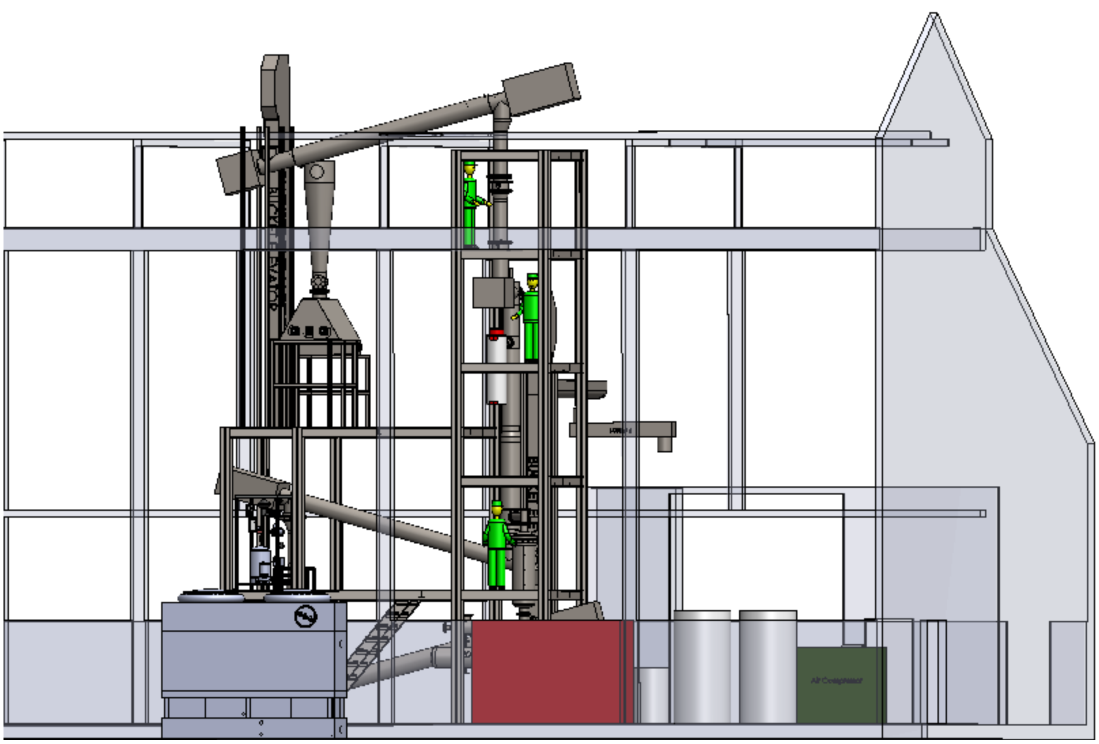


Figure 6. Xcel Plant Position in B-171 (north view)

III. DESIGN BASIS

This report provides a narrative and lists of equipment, control valves, and instrumentation submitted for the completion of milestone 2 of the project. The narrative is intended to document and give a brief description of each process stream flow and piece of equipment.

Since this plant will be connected to the existing feed and product treatment systems at Coleraine, certain building modifications need to be evaluated and/or made by NRRI. Also, some additional equipment will need to be provided by NRRI in order to make the connections to this plant. The following is a current list of these items:

1) Upgrade utilities as needed to support the SynGas design. Existing water, instrument air, and nitrogen supply are adequate. Electrical power needs to be upgraded and sewer connection needs to be installed.

2) Evaluate the load capacity of the current floor and upgrade if needed.

3) Add equipment to convey dried biomass chips to the feed bin of the SynGas unit. The curre is to pneumatically convey chips.

4) Purchase conveyance equipment to move torrefied product an additional 15 m to -allow direct tie in to the existing Screw, Surge Bin #2 and densification equipment located in the Class 2 room.

SynGas has agreed to assist in the design, sourcing, and installation of items 3) and 4) above. The items described in those points are included on the design drawings for clarity.

The design basis for the unit is predicated on producing 3 tons/day (2727 kg/day) of torrefied biomass. Assuming the following feed properties and conversion rate:

1) 10% moisture on an incoming biomass

2) 20-30% dry matter loss upon torrefaction

3) Biomass bulk density of 177 kg/m3 (typical for black ash)

the corresponding biomass feed rate is 180 kg/hr or 1.0 m3/hr. The design also will allow running at variable torrefaction temperatures, from a minimum of 232 °C to 288 °C.

Further, SynGas conducted studies on a pilot plant at the Elk River, MN facility over the past 2 years to determine additional design parameters for this unit. For example:

1) The torrefaction reactor was sized to achieve a target residence time of 20 minutes. However, the design will allow flexibility to run 10 to 30 minutes if desired.

2) Superheated steam was effective in heating the incoming biomass to torrefaction temperature and providing an inert atmosphere for biomass at torrefaction conditions. However, care had to be taken to keep all biomass and process equipment exposed to steam above the condensation temperature. This unit has been designed for a maximum pressure of 1 barg. According to the data shown (Figure 7), the minimum temperature of all biomass, equipment, and lines with this steam environment must be kept above 121 °C to avoid condensation.

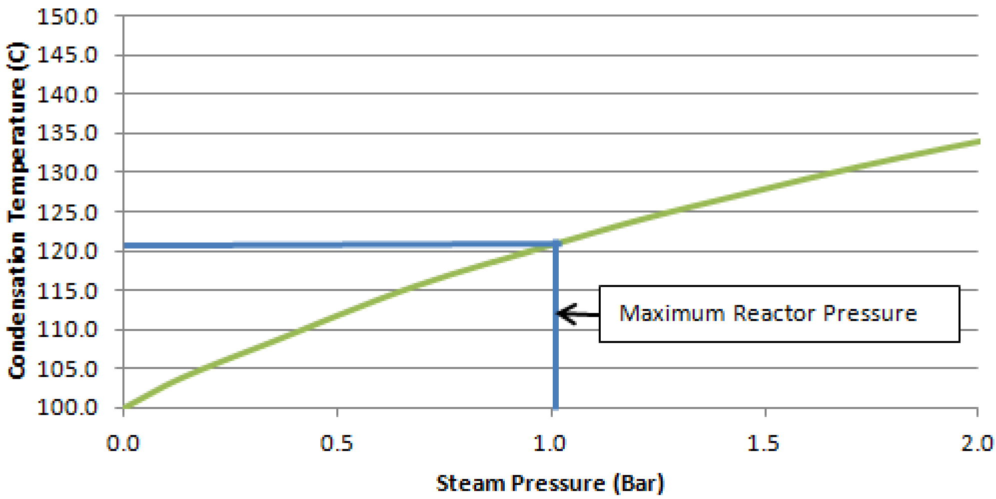


Figure 7: Steam condensation temperature versus pressure (in barg)

3) Care must be taken to maintain consistent flow of wood chips and prevent bridging. We utilized several experts in the area of biomass conveyance as well as drawing from both our and NRRI Coleraine's experience in processing biomass chips in creating this design.

4) The biomass conveyance equipment was designed for a nominal wood chip size of 16 mm (typically labeled +13 mm) and with a maximum 50 mm. Our previous studies showed better flow consistency with a larger average chip size. Smaller particle sizes and microchips could be studied as well to determine if these flow issues repeat on the larger equipment.

The SynGas torrefaction unit had to fit within the existing empty space in B-171. The building height created the biggest design challenge for a vertical reactor design such as ours. In addition, the unit had to be positioned so that the Coleraine bucket lift could drive around at least 3 sides for personnel access.

A plethora of various instruments are positioned throughout the process, most of which will transmit to a programmable logic controller (PLC), although a few will only have local read-outs. There will also be a human machine interface (HMI) station for operators to see the process conditions and make set point changes as needed. This station will be located in the existing B-171 control room.

A Process Hazard Analysis (PHA) was conducted, with the results contained in a separate report. All hazards identified through this process will be addressed through design changes and/or personnel training. In addition, we will review this PHA with Coleraine operators and hold a design review with the University of Minnesota safety department. The main equipment structure will be analyzed by Krech Ojard & Associates, Inc of Minneapolis, Minnesota. Any recommendations will be implemented into the design and their report will be included in future documentation issued prior to installation at Coleraine.

IV. BIOMASS HANDLING AND TORREFACTION EQUIPMENT

Although the torrefaction reactor is undeniably the most important piece of equipment, it is also heavily intertwined with the biomass handling equipment. Solids handling is challenging on its own, and the additional issues of overall height, temperature changes, and interfacing with existing equipment make biomass handling a close second in importance. This also explains why biomass handling equipment outnumbers any other equipment type.

The solids handling equipment comprises eight conveyors, a cyclone, rotary valve, and live bottom feeder, and two temperature-controlled pressure locks each made up of two dump valves, three accumulation chambers, and a knife gate valve. In contrast, although the reactor stack is made up of only a few pieces, each piece is a specific and complex design. In a way, all this equipment forms a single unit, solids snaking a path through the whole stack, where changes to dimensions or positions affect each piece in the group.

A. BIOMASS FEED SYSTEM

The biomass feed for the SynGas unit will be supplied from the existing Coleraine biomass prep system, which includes a live bottom trailer feeding both undersize and oversize screeners and a drier. The flow will be controlled to the target feed rate desired for the SynGas plant. The dried chips (target 10% moisture) will be pneumatically conveyed to the top of SynGas unit where a cyclone separates the solids from the conveying gas stream. The gas stream is vented while the solids drop into the feed bin via a rotary valve, which also acts as a pressure seal.

The bin is designed to hold a maximum of 2.5 m^3 which equals 2 hours of operation at the design flow rate. The level in the bin will be measured with a laser gauge, which allows the rate of material from the drier to be matched to the feed rate out of the bin controlled by the live bottom feeder. The live bottom feeder consists of several parallel screws which span the entire length and nearly the width of the bin. The design utilizes 4 screws. In addition to covering much of the width of the bin, the screws incorporate a variable pitch which allows for even unloading of the bin along its length as well. The rate of solids flow to the unit is controlled by the speed of these screws and controlled by a variable frequency drive (VFD).

The chips are dumped into the collection screw. This unit is a horizontal screw conveyor designed to move material to the bucket elevator . The bucket elevator brings the wood chips up to the top of the unit, nearly 14 m above the floor and dumps into the biomass heating conveyor.

The primary function is to heat the wood chips from essentially ambient conditions to approximately 121 °C. As previously noted in the Design Basis, this temperature is necessary to prevent

steam condensation once the chips enter the reactor section. The heating is driven by high pressure steam obtained from the steam boiler at a maximum temperature of 186 °C (saturated steam at 10.3 barg) and sent through the outer conveyor jacket as well as through the conveyor screw shaft. A steam trap located on the steam discharge allows only condensate out of the system, ensuring the efficient use of steam.

The conveyor is inclined at 15 degrees to allow drainage of the steam condensate out of the jacket and shaft as well as gaining vertical distance for the remaining equipment in the unit.

A pressure lock must be created to prevent backflow of gases from the reactor into the feed system. To maintain both material flow and a pressure lock, a double dump system will be used. The heated biomass will discharge and drop into the pressure lock stack consisting of the top accumulation chamber, knife gate valve, top Roto-Disc valve, middle accumulation chamber, bottom Roto-Disc valve, and bottom accumulation chamber. After passing through the stack, the biomass will drop into the horizontal screw conveyor. The accumulation chambers will be jacketed and/or steam traced to keep the heated biomass at temperature as it passes through the upper lock stack.

The overall cycle was set to 2 minutes to balance the stack height versus frequency of valves opening and closing. The accumulation chambers were sized to hold 120% of the maximum design biomass flow obtained in 2 minutes. The nitrogen is heated in a small heat exchanger using high pressure steam. The nitrogen purge rate is set by rotameter at a rate to achieve twice the volume of the middle accumulation chamber in 1 minute, about 0.11 Nm^3/min.

Roto-Discs were chosen as the primary valve due to their ability to maintain a pressure lock even with a difficult material like wood chips. The Roto-Disc rotates axially with the dome surface sliding across the valve's seal, pushing away any particles to prevent jamming and minimizing seal wear. To further protect the seal, a valve was added above to stop the flow of biomass chips.

In general, the cycle consists of isolating the biomass between the two closed Roto-Disc valves purging out any air in the middle chamber with heated nitrogen, and pressuring up the middle chamber to reactor pressure using back pressure regulator. Once the pressure above and below is equalized, the valve is opened, dropping the solids from the middle chamber into the bottom chamber. The valve is then closed and the other valves are opened, dropping biomass into the middle chamber again

An infrared temperature probe will measure the temperature of the biomass to ensure proper heating to the required temperature. A laser level probe will monitor the biomass volume to confirm that consistent flow is occurring. Both probes are non-contact instruments and will be installed out of the biomass flow path to avoid bridging issues.

C. REACTOR SYSTEM

A short (1.2 m) horizontal screw conveyor will move the hot biomass discharged from the upper lock into the top of the moving bed reactor. This conveyor will be designed with a higher capacity than the raw material feed rate and steam traced to ensure the biomass temperature is maintained as it passes through the conveyor. In addition, a cantilevered screw design is incorporated, which has an open discharge for direct mounting to the reactor. Thus, all support for the screw is located on the drive end.

The moving bed torrefaction reactor will be vertically oriented with co-current solids and gas flow. The reactor is designed for a maximum pressure of 1 barg and protected from exceeding this pressure by a safety relief valve. The reactor assembly consists of 3 sections of pipe, increasing in diameter down the length of the reactor in the direction the biomass moves The reactor has a central rotating shaft with small nubs at various points that acts as a solids agitator and prevents bridges, dubbed the ABNR for reasons historical to the program. The bottom of the ABNR also has flights that control the discharge rate of solids from the reactor.

The reactor top chamber is sized similarly to the accumulation chambers of the upper pressure lock to allow for the cyclic variation of flow. The superheated steam comes into the reactor through an annulus, and at the same point the reactor diameter increases. The temperature and flow rate of the steam is adjusted to control the final torrefaction temperature of the biomass.

Biomass Solids Flow

The reactor diameter increase again halfway down the remaining reactor length. The strategy of increasing diameter as the solids flow down through the bed was strongly recommended by consultants and the NRRI Coleraine staff, and also supported by experience from operating the smaller pilot unit. Expanding the volume of the reactor down the bed will reduce the packing of the wood chips in the bed, which helps reduce the tendency for the material to bridge.

The overall reactor volume was sized to achieve a solids residence time of 20 minutes at the designed flow rate of 180 kg/hr. This residence time was determined through the pilot plant studies conducted at Elk River over the past year.

Pressure and temperature are monitored at various points in the reactor. Pressure transducers monitor the pressure at the top and bottom of the reactor while thermocouples measure the top, middle and bottom reactor temperature. The thermocouples will be mounted flush to the reactor to eliminate the opportunity for solids bridging due to intrusion into the flow path. This was a major issue encountered in pilot studies. Since the reactor exterior is not heated, the wall must be well insulated to minimize heat loss and maintain the desired torrefaction temperature.

The bottom of the reactor includes the Torgas Extraction Unit (TGEU) and the ABNR flights and bearing. The TGEU allows for the separation of the torrefied solids and the torgas vapor. The TGEU, a sintered metal filter, has an inner diameter designed to match the reactor wall inner diameter to minimize the potential for solids hang up and bridging.

The ABNR auger consists of two sectional screw flights, 38.1 cm in diameter with a 7.6 cm pitch, that are attached to the ABNR shaft just below the TGEU. The material flow rate leaving the reactor is variably controlled to match the feed rate of biomass entering by monitoring the level of solids at the top of the reactor by a laser level probe and changing the ABNR shaft rotational speed accordingly.

The drive motor and gearbox are located at the top of the reactor and designed to achieve 4 rpm at 50% of the maximum motor frequency. Another feature of the ABNR is the mixing “nubs” or blades located every 61 cm along the vertical shaft. These nubs are horizontal blades, approximately 17 cm wide which can eliminate bridging if it occurs in this vertical section. The ABNR shaft is kept centered with the high temperature bearing located just above the inlet flange. Since the mounting brackets for this bearing could cause solids bridging, a sweep blade is installed just above this area.

Finally, the ABNR shaft assembly is designed for easy removal to test different configurations, such as auger flight dimensions, nub designs, or nub placement. This design flexibility was invaluable in the pilot unit. The housing below the TGEU is then removed, exposing the ABNR shaft and auger flights. The top of the shaft is then accessed through the 30.5 cm port, where the two bolts holding the ABNR shaft to the drive shaft can be removed allowing the entire shaft assembly to drop down for modification or replacement as required. The unit is then reassembled in reverse order.

The solids material discharged from the reactor and ABNR will feed directly into the primary cooling conveyor. The conveyor is designed as a horizontal, inclined mixing conveyor, and will be operated at a flow rate greater than that of the discharge of the ABNR. The conveyor is required to cool the solids to below 200 °C to stop the torrefaction reaction, but above the steam condensation temperature (121 °C).

D. REACTOR LOWER PRESSURE LOCK

The solids discharge will feed directly into the reactor lower pressure lock. The lower lock operates using the same procedure as the upper lock with the following changes:

The inert purge gas is used to evacuate any entrained steam, to prevent the steam from condensing on the solids in the secondary cooling conveyor.

The lock is depressurized before the solids are unloaded and re-pressurized after, instead of the reverse.

It also maintains a gas-tight pressure seal in the reactor while still allowing for solids flow. The same instrumentation will be installed as in the top lock.

E. TORREFIED PRODUCT CONVEYANCE

The Coleraine facility requires that the processed materials be cooled to a maximum temperature of 82 °C. To accomplish this, a secondary cooling conveyor will be used to cool the material discharged from the lower lock. The conveyor will be inclined to gain vertical height and cooled by passing water through the outer conveyor jacket as well as through the conveyor screw shaft.

This conveyor will also transport the product to a bucket elevator, which will elevate the product above the B-171 Class 2 room, approximately 8 meters above the ground. A final horizontal screw conveyor will move the material about 5.5 meters horizontally and drop into existing Coleraine Screw. From here, the material moves into the Class 2 room where it can be further processed (grinding, densification) or loaded into supersacks. All conveyors in this subsection will be blanketed with nitrogen to eliminate any possibility of a combustion event.

F. SAFETY PURGE SYSTEM

A nitrogen gas purge system is included as a safety measure in the event of material ignition in the reactor system. The entire reactor system between the upper and lower pressure locks can be quickly inerted, stopping any combustion event. This can be done manually or automatically via a high temperature alarm in any of the reactor thermocouples.

V. TORGAS HANDLING EQUIPMENT

The torgas, or offgas generated from the torrefaction, contains highly oxygenated molecules broken off from the larger wood chemical structures. The major components generated are small inorganic gases, including a large percentage of water, some carbon dioxide, and to a lesser extent, carbon monoxide. The remainder are small organic molecules, include light alcohols like methanol, acids like acetic and formic acids, and to a lesser extent, aldehydes like furfural.

A very minor component of wood chips is sulfur, which may be released into the torgas in varying degrees in the torrefaction process. Although any sulfur release would be relatively low in the torgas – in the ppm range, well below that of the organic compounds – low levels of sulfur can still pose a problem, especially in the catalyst and for downstream processing. Therefore, the potential for sulfur in the torgas has been included in the design.

Because the wood is heated by direct contact with hot gas, the torgas also includes large amounts of added steam in addition to the water generated. This makes the torgas well over 90% water. However, because some of the minor components are hazardous, the torgas must be processed before it can be vented, which is what the equipment in this section is designed for.

All equipment and piping in this section are stainless steel unless specifically noted. Torgas is a corrosive gas due to the presence of organic acids. In addition, the gas may still be acidic after combustion if there is sulfur present due to the formation of sulfuric acid. Therefore, stainless steel and plastic are the only appropriate materials of construction until the liquid is neutralized.

A. COMBUSTOR

The combustible material present in the torgas exiting the reactor will be processed in a combustor.

Although the majority of the gas is incombustible (water, carbon dioxide), VOC and automotive catalysts can be used to catalyze combustion even at ppm levels of combustibles. However, oxygen must be added to complete the combustion to carbon dioxide and water, and the gas must be sufficiently hot to get the catalyst to light off and stay lit.

In this system, torgas is mixed with hot air just prior to entering. It then passes through a catalyst monolith, which catalyzes the conversion of any combustible materials to carbon dioxide and water. Heat is released in this process, so the exiting combustion gas is hotter than the incoming torgas / air mixture. The outlet temperature limit has been set to 650 °C, to avoid approaching the upper limits of the catalyst (700 °C) and the stainless steel housing (760 °C).

Both the inlet and outlet temperatures will be monitored in order to keep within this limit and ensure performance adequately. Air flow rate and temperature are used to control both of these parameters.

Catalysts are notoriously sensitive to sulfur, so catalyst life and effectiveness may be reduced over time if sulfur is present. Combustion of any sulfur compounds will also generate SO_2 and SO_3, which form the strong acids sulfurous and sulfuric acids when in contact with liquid water.

B. COMBUSTION AIR EQUIPMENT

The air required for combustion is provided by an air compressor. The compressor is electric and has a capacity of 7.11 Nm^3/min. Because the air is being heated and mixed with the wet, dirty torgas afterwards, a post-cooler and dryer are not necessary. However, a coalescer is used to separate liquid water and oil at temperature, to avoid spending energy vaporizing water unnecessarily.

The compressor is designed to run at full capacity all the time, instead of turning on and off as needed. Since the full capacity will not be used consistently, the excess capacity needs to be vented to prevent issues. For that reason, a back-pressure regulator set to roughly 0.5 barg below shutdown pressure is installed on a vent line teed off the main air compressor outlet line. The regulator will open when the pressure builds to near the shutdown pressure and vent the appropriate amount of excess gas to keep the pressure at or below that limit.

The air is then heated by an electric air heater. Preheating is necessary to prevent condensation and provide the heat required for catalyst light-off and in some cases also to maintain steady combustion. Both the heated and bypass flows can be controlled independently via control valves, so the air temperature can be controlled closely by mixing the two streams in various ratios.

The air flow rate and temperature are used to control the combustion. If the outlet temperature approaches the upper limit, the air temperature must be decreased and/or the flow rate increased to cool the effluent by dilution. If the outlet temperature is not higher than the inlet, the torgas is not combusting and the air temperature and/or flow rate must be increased to reignite the catalyst. In some cases, the torgas will not be hot enough to sustain combustion, so the air will have to be heated to some degree even after catalyst light-off, while in other cases, the combustion will produce enough heat that the air must be put in cold to keep the outlet temperature below the upper limit.

C. PROCESS CONDENSATE COLLECTION EQUIPMENT

Despite the addition of air, the combustion gas will still be over 50% steam. Since venting this amount of steam at these temperatures is inadvisable, the combustion gas is first cooled in a horizontal shell-and-tube heat exchanger, which acts as a partial condenser. Cooling water is passed through 100 x 1.5 m tubes to cool the gases. The combustion gas is passed through the baffled shell side, where the gases are cooled to below 100 °C and a substantial portion of the steam is condensed. The heat exchanger is sized to cool the gas to 35 °C with 100% excess area.

The shell-side also acts as a vapor-liquid separator, with liquid naturally condensing on and dripping down from the tubes to collect in the bottom of the shell, separate from the gas flow. In addition, because shell-and-tube heat exchangers are designed to force shell-side flow in a tortuous path around the tubes, entrained liquid droplets are also collected as they smash into the tubes just before the gas exits, creating an excellent final vapor-liquid separation.

The hot combustion gas enters the top right side of the shell and zig-zags through the shell across the tube bundle multiple times. The cooled uncondensed combustion gas exits from the top left side of the shell and is finally routed to a vent outside the building. Allowing the process condensate to collect in the heat exchanger is not advisable, as it would either decrease heat transfer area by covering tubes or necessitate and much larger shell, so it drains out the bottom left side into the process condensate tank.

The condensate tank and its associated process condensate pump act as a small surge tank, keeping the level in the tank at 50% by adjusting speed via VFD to remove condensate at the same rate it enters. The tank and pump are sized for ±10 minutes of liquid residence time at maximum flow rate to allow for process upsets. The liquid is pumped continuously to one of two hold-and-neutralization tanks.

D. PROCESS CONDENSATE NEUTRALIZATION

Even after combustion, the process condensate from torrefaction can still be acidic. If the combustor is not operating efficiently, the most likely acidic component is acetic acid, which is one of the most common organic components of torgas. However, it is more likely that any acidity is from sulfur-based acids, formed as noted prviously. Even low sulfur concentrations in the torgas can generate pH as low as 1.5 in process condensate. Both can be neutralized using sodium hydroxide.

The two plastic tanks are each sized for 4 hours of process condensate at maximum flow rate. Each tank has a continuous level, and flow can be switched from one tank to the other remotely or automatically using actuated valves. In addition, they are connected at the top by a pipe, so that a full tank will spill over into an empty one instead of overfilling and spilling on the floor.

These tanks have a variety of functions. They can be used as hold-and-test tanks should a process upset send dirty water to them, and they can be used as excess surge capacity before discharge. However, their main function is to collect and neutralize acidic condensate. Each tank has its own mixer and pH probe, so that neutralization can proceed directly in the tank. Sodium hydroxide solution will be added to neutralize any acidic condensate to a pH of 5-9.

Both tanks drain to the same pump, although actuated valves allow the possibility to drain each tank separately. The neutralized condensate will be pumped to the building drain, the location of which has not yet been definitively identified, but will likely involve piping to and through the drainage trough in the center of the building.

E. SODIUM HYDROXIDE SOLUTION EQUIPMENT

The sodium hydroxide needed for condensate neutralization is held in a tank and dispensed by pump and is designed to create sodium hydroxide solution from pellets and water, although purchased pre-mixed solution can be added to the tank instead, if desired.

Since mixing sodium hydroxide solutions is fairly simple, the tank design is also simple. building water is added to the tank before adding solid sodium hydroxide slowly from a trough attached to a large fill port. The level is monitored with a continuous level instrument to prevent overfilling. The solution is mixed during and after the addition to ensure dissolution.

It takes only 10.5 gallons of 20 wt% solution to neutralize one condensate tank full of pH 1 liquid. The tank is sized to hold enough solution for ten such neutralizations, so that the solution only needs to be made or refilled at most every two days. The pump is sized to deliver neutralization solution over 10 minutes. Dispensing over a shorter period of time would likely lead to over-neutralization, as the pH readings in tanks will likely lag behind the solution addition due to mixing effects and continue to creep up for a short while after solution addition is complete.

VI. UTILITY FLUIDS

In addition to the process equipment described above, a number of utility fluids will be used to heat and cool various pieces of equipment. The utilities include cooling water, hot oil, and steam. Each is essentially a subsystem separate from the main process.

A. COOLING WATER

Cooling water is designed to be used in 3 different areas of the unit. The combined cooling water requirements total over 180 gal/min. This level of water use necessitated designing a closed-loop cooling water system with an induced draft countercurrent cooling tower to maintain the temperature of the system.

It measures 1.2 m deep x 3.7 m wide x 3.1 m high. The unit will be installed just outside the south wall but far enough away from the building to avoid damage from falling snow and ice from the roof. As typical for cooling towers, the water will be treated to prevent freezing and organic buildup per manufacturer's instructions.

B. HOT OIL

The primary cooling conveyor is the sole user of hot oil in the system. Due the strict temperature requirements, hot oil was chosen in order to give a wider range of fluid temperatures than cooling water could provide. Duratherm 450 will be used as the cooling medium due to its appropriate temperature range and relatively low viscosity. The hot oil skid will have the capability to both heat the oil during startup and cool the oil during operations. The skid also includes an expansion tank, pump and several temperature, pressure, and flow instruments to monitor this operation.

C. STEAM EQUIPMENT

A high-pressure boiler system (7-10 barg) is required to generate the high-temperature steam necessary for the torrefaction process. Both natural gas and electric boilers were evaluated with the electric version being selected, mainly due to its flexibility of output and ease of use. Coleraine is upgrading the B-171 electric service to accommodate the boiler power requirements.

Due to the hardness of the Coleraine water supply (typically 12-16 grains), the first step is to treat the fresh water using a dual tank automatic regenerating water softener. Water softener salt must be added periodically to the brine tank. The softened water is stored in the feedwater storage tank and pumped into the high pressure boiler chamber. A series of electric heater elements heat the water to the boiling temperature at 10 barg, 186 °C. The boiler is sized to achieve 630 kg/hr, which exceeds the combined requirements of process steam, heating jackets, heat exchangers, and steam tracing. A blowdown tank is located on the skid which will be manually utilized during shutdown and start-up. The blowdown process helps to reduce sediment buildup in the boiler chamber and increase its service life.

The boiler sends 10 barg saturated steam to the steam header line, which distributes steam to the various process and utility steam lines. The majority of the steam is for a single process steam line, which eventually goes to the main torrefaction reactor. It first passes through a forward pressure regulator, flow meter, and control valve. The forward pressure regulator reduces the pressure from 10 barg to about 1.7 barg to create slightly superheated steam and reduce the pressure drop across the control valve. The control valve maintains the steam flow rate at the desired set point with the flowmeter measuring the actual rate obtained.

It then passes through an electric superheater, which is required to obtain the inlet steam temperature required by the process, currently estimated at a maximum of 482 °C. Due to the nature of highly superheated steam, heat losses are minimized by positioning the superheater outlet less than 1 meter from the steam injection point on the reactor.

A small slip stream from the steam header, less than 10 kg/hr, can be injected into the discharge end, flow countercurrent to the biomass flow, and out through the TGEU with the torgas stream. As with the main process steam, this flow stream includes a forward pressure regulator to reduce pressure to 1.7 barg, a control valve to vary the steam flow, and a flow meter to measure the resultant rate. The purpose of this stream is to completely strip off any remaining volatile organic compounds from the torrefied product. Densification studies have indicated improved properties with “cleaner” product. This design will allow further testing of this phenomenon if desired.

The remaining steam requirements are utility lines for external heating of steam jackets, heat exchangers, and line tracing. These provide steam for heating wood chips, nitrogen purge gas, and hot oil, and steam tracing process lines for both preheat and to minimize heat loss. All these lines will have steam traps at low points and the resulting condensate will be either be returned to the feedwater tank or sent to drain.

VII. STRUCTURE

The biomass feed system, solids conveyance, reactor system, and reactor upper and lower locks are all supported by one main structure. The structure was carefully designed to hold the reactor as well as fit within B-171. The main constraint on the structure is height and accessibility both around and within the structure. It is critical to have sufficient space around the structure for the bucket lift that is located on site. Due to the overhead crane and trusses in the building, the overall height of the structure was critical. The structure could not be greater than 11.8 m tall.

The structure is built using A-36 I beams and will be analyzed by Krech Ojard & Associates, Inc (KOA). A conservative approach will be considered during the third party analysis. The weight of the plant will be an overestimate. The plant will be considered full of raw material as well as the jackets being full of water or oil. The structure is also able to hold six operators on any single level of the structure. There are two main methods to access the structure. The first is a combination of staircases and caged ladders, and the second is the bucket lift on site via gates on the structure. The beams on the structure are coped so each level of the structure lies on the same plane. This will allow safe maneuverability when on the structure by reducing trip hazards, as well as keep all the stresses in one plane by reducing bending moments on the levels of the structure. All railings, ladders, and staircases are all designed to meet OSHA standards. Railings, although not shown, are included on all levels of the structure as well around any open areas below a raised level. All joints are bolted connections using 19.05mm A325 structural bolts with lock washers and nuts.

To help reduce swaying of such a tall structure, both horizontal and vertical trusses are used on each level. All bracing consists of steel angle, for ease of manufacturability as well as good strength to weight ratio. Supporting equipment such as the hot oil skid will be mounted on the structure. The live bottom feeder and feed bucket elevator are also mounted on skids that attach to the main structure. The product bucket elevator and product conveyor rest on the floor. The product bucket elevator attaches to the structure to secure it in place vertically.

IX. CONTROLS EQUIPMENT

This demonstration plant requires an extensive electrical and controls system to facilitate operation and data acquisition. The primary use of electrical power is for motors, electric boiler, electric steam superheater, electric air heater, and the control system. The electric boiler draws a large amount of power and is powered from an independent power source on site. All other equipment power emanates from a single power distribution/motor control panel that is powered from another independent power source on site.

The control system is driven by a Siemens SIMATIC S7-1500 PLC with associated distributed I/O to control motor starters, frequency drives, actuated valves, control valves, and acquire data from instrumentation. All of this equipment is housed in a single PLC control panel and powered from a transformer that provides 120 VAC single-phase power. Lastly, a single HMI is located in the control room and allow for complete control of the demonstration plant; the HMI will communicate with the PLC via Profinet.

A. ELECTRICAL SYSTEM

Approximately 915 Amps of 480 VAC, three-phase, 60 Hz power is required for the demonstration plant.

The electric boiler is powered from an independent power source on site. A large conduit is run to the boiler skid. The rest of the demonstration plant is powered from a large power distribution/motor control panel. A single conduit is routed to this panel from another power source on site. This panel subsequently delivers power to the superheater, air heater, air compressor, motors, and a transformer that provides all 120 VAC single-phase power to the PLC control panel.

The power distribution/motor control panel contains a 400 Amp main fused disconnect. The incoming 480 VAC three-phase power is distributed to motor starters, line reactors, frequency drives, overload protection devices, the air heater controls, superheater, air compressor, and an external transformer for generating the required 120 VAC single-phase power to the PLC control panel. EMT conduit is used to subsequently deliver power to the motors and other equipment in the field.

All motors in the field have a local E-stop that is integrated into a safety relay for rapidly stopping and de-energizing each motor circuit. The motor starters are controlled via distributed I/O associated with the PLC. Hence, all motors are controlled via an operator in the control room. Currently, there are 19 motors for pumps, conveyors, mixers, and a rotary valve.

B. CONTROL SYSTEM

A single PLC control panel houses the main PLC, distributed I/O, 24 VDC power supplies, and other ancillary equipment required by specific instrumentation. A Siemens SIMATIC S7-1500 PLC with associated distributed I/O comprises the heart of the control system. The I/O required includes digital inputs (24 VDC) for point-level instruments and auxiliary contacts on the motors starters, digital outputs (24 VDC) for actuated valves and motor starter coils, analog inputs (4-20 mA) for analog instruments, and analog outputs (4-20 mA) for frequency drive and control valve set points. All instrumentation is wired to the PLC control panel via instrumentation cable. Instrumentation used includes 17 temperature transmitters, 5 pressure transmitters, 2 pH transmitters, 5 flow meters, and 8 level transmitters.

A single HMI located in the control room controls the demonstration plant. The HMI consists of a computer and monitor. The computer is connected to the PLC via a Profinet (industrial Ethernet) line run from the computer to the PLC control panel. All hardware configuration, control programming, HMI configuration, and data acquisition utilizes Siemens' TIA Portal software. If the control system requires interface with equipment already controlled by the existing Allen-Bradley control system at the site, hardware can be implemented to facilitate this communication and control.