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

Contract Number: RDF 4-11  Milestone Number: 1  Report Date: 3/20/2017  Principal Investigator: Donald Fosnacht

Contract Contact: Donald Fosnacht  Phone 218-788-2682
Congressional District: (Corporate office) 8
Congressional District: (Project location) 8

Milestone 1 Report (Prefeasibility)

Executive Summary
This submittal will complete the required tasks for Milestone 1 (prefeasibility for both the boiler/generator system and for the moving bed torrefaction demonstration facility). The project consists of three parts: Development and demonstration of the 100 kW Boiler/Generator system under the direction by the Coalition for Sustainable Rail and development and demonstration of a moving bed torrefaction system under the direction of Syngas Technology. The final part of the project is integration of the two components at the University of MN’s Natural Resources Research Laboratory Coleraine Site. Once integration has taken place, electrical production will ensue and the produced electricity will be connected through a grid connection at the Coleraine Laboratory of the University. Both Syngas Technology and the Coalition for Sustainable Rail will now enter into the detailed engineering for their systems. This report summarizes the prefeasibility work for the two components mentioned above. The project will now move into detailed engineering for each piece of equipment.

“Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund.”
Prefeasibility Summary for the Boiler/Generator System

CSR’s contribution to Milestone 1 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) registering CSR’s Mechanical Engineering Professional Engineer (PE) with the appropriate authority in Minnesota; 2) securing site control for the manufacture of the steam electric generator; and 3) completing the appropriate system model (aka Piping and Instrumentation Diagram) of the boiler generator system.

On a technical and research basis, the core of “Milestone 1 – Design” focused around the design of the boiler generator system. A balance was drawn between the conceptual engineering associated with the design phase of the project and the detailed engineering required as part of Milestone 2, resulting in substantial overlap between the two tasks. The P&ID diagram reviewed and certified by CSR’s PE outlines the general arrangement of the boiler generator system, including all aspects of boiler piping and engine transmission. The main difference in design between the initial Team proposal and the resultant design in the P&ID diagram is the inclusion of a compounding (multiple-cylinder steam engine). It was determined during this phase that the engine would be more efficient in generating the 100kWe of power using multiple pistons in a compound fashion rather than one large piston. Our work in Milestone 2 is focusing on the optimization of the exact number and size of pistons in the compound steam engine. Likewise, the work pivoting from the product of Milestone 1 is also focused on the sizing and proportions of the boiler itself.

Overall, the layout of the boiler generator system adheres to that proposed in the grant proposal and we are excited to see how the detailed design of the various sub-systems will impact overall sizing and efficiency of the system.

Technical Progress:
Aside from the important institutional issues addressed as part of Milestone 1 (e.g. Professional Engineer certification), the design of the boiler generator system proceeded as planned. The single largest breakthrough in the research relates to the size and number of cylinders required to efficiently generate 100 kW of electricity. The original grant application outlines a simple (using steam only once), single cylinder steam engine coupled to the alternator.

Design and calculations undertaken in completion of the P&ID diagram indicated that at least a two cylinder, “compounding” design would be required to generate...
an even enough torque curve across each revolution to rotate the 100 kW alternator. A “compound” steam engine uses high pressure steam directly from the boiler in a smaller diameter cylinder to push a piston, which is then exhausted into a larger, low pressure cylinder prior to being exhausted up the stack. Since the exhaust of the high pressure cylinder still has pressure (generally about 30% of the original boiler pressure), that steam can be used to accomplish work prior to being exhausted.

Not only does using multiple cylinders improve the efficiency of the design, but it also allows the torque to be more evenly distributed across each rotation of the drive shaft. This is important in that even torque at the alternator is required to generate an even frequency of power. Traditionally, the alternators used in standby, diesel-powered distributed generation units are coupled to six or eight cylinder internal combustion engines, whose power outputs include three or four power impulses per revolution respectively (on four stroke engines). The steam engine CSR proposed originally would have resulted in two very peaky torque power impulses per revolution (it is a double-acting steam engine, meaning each time the piston changes direction, it is doing work in a power stroke).

A two or three cylinder steam engine design will result in four or six power strokes per revolution, helping to smooth out the torque pulses. The P&ID diagram has included the stipulation that the engine a double expansion design (compounding), and detailed engineering undertaken in association with Milestone 2 will further verify the design of the engine.

On the boiler design side of the project, CSR has not deviated significantly from the design originally stipulated in the proposal, but it has begun to investigate methods to ease fabrication, operation, and maintenance of the boiler. These, too, will be further outlined in Milestone 2.

Delays to the project have stemmed primarily from institutional constraints associated with subcontracting. CSR is working to accelerate the process of its portion the project following those delays.

Additional Milestones:
As mentioned, CSR began work on Milestone 2 concurrent with aspects of Milestone 1. Beginning in February 2016, CSR began work on Milestone 2. The iterative nature of conceptual and detailed design warranted a two-pronged approach to the task, and it resulted in, for example, the determination that a single cylinder steam engine would not be the optimal solution for the task at hand.
As of the drafting of this report summary, Milestone 2 is well underway. Research has included multiple rounds of biofuel testing in a locomotive-type boiler at the Milwaukee County Zoo as well as detailed engineering on the boiler and generator side of the project.

The fuel testing is progressing well, with densification identified as a core area requiring attention and future research. Uniform densification of the fuel will be required to aid in transportation and proper combustion.

Regarding the boiler generator research, proportioning of the boiler components, design of the boiler, number and sizing of the cylinders, and the overall thermodynamic model are taking shape. It is anticipated that detailed design will be completed within Q1 of 2017 and that fabrication on the various components will begin shortly thereafter.

Project Status:
The project is delayed but on budget. The subcontracting of CSR to the University of Minnesota was not completed until March 2016, approximately six months after it received NTP from Xcel Energy. The technical aspects of Milestone 1 were completed by July of 2016 and detailed work associated with Milestone 2 are underway but behind schedule. We are working to address these delays as expeditiously as feasible.

Appendix (Boiler/Generator System)
I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the State of Minnesota.

Signature: [signature]

Type or Printed Name: Willard Hugh Odom

Date: 2/20/2017 License Number: 53294

PROPERTY OF CSR. Drawings are supplied to assist in construction, installation, and maintenance of CSR equipment. Do not show, distribute or provide to any third party unless for these purposes.

PROJECT: XCEL NRG FLOW 1
TITLE: MATERIAL AND ENERGY FLOW DIAGRAM OF BOILER GENERATOR SYSTEM

SCALE: 1:1
PROJECT No. DWG No. NRG FLOW 1

COALITION for SUSTAINABLE RAIL

Exhaust:
- Air: 3,039 lb/hr
- Steam: 1,498 lb/hr

Steam to Create Draft (1,498 lb/hr)

Total Engine Power Output (121 kW)

Alternator 800 RPM

Total Power Take Off (3 kW)

Saturated Steam

Secondary Combustion Air (2,857 lb/hr)

Stoker (265 lb/hr)

Stoker Motor (-2 kW)

Feedwater Pump (-1 kW)

Water Input to System 180 Gal/hr (1,498 lbs/hr)

Ash Removal Screw (26 lbs/hr)

First Stage Feedwater Heater

SECOND STAGE FEEDWATER HEATER EXHAUST DRAIN (936 lb/hr)

Steam to Second Stage FW Heater (936 lb/hr)

Secondary Combustion Air (182 lb/hr)

Primary Combustion Air (2,857 lb/hr)

Torrefied Biomass from Reactor 9,500 BTU/LB

Saturated Steam

Second Stage Feedwater Heater

Steam to First Stage FW Heater (166 lb/hr)

Saturated Steam to Aid in Combustion

Secondary Combustion Air (2,857 lb/hr)

Secondary Combustion Air (2,857 lb/hr)

Superheated Steam

Steam to High Pressure Cylinder (VIA HEAT HEAT EXCHANGER)

Steam to Superheated Steam to High Pressure Cylinder

Steam to Low Pressure Cylinder (1,664 lb/hr)

Low Pressure Cylinder (2,600 lb/hr)

High Pressure Cylinder (2,600 lb/hr)

Steam to Second Stage FW Heater (936 lb/hr)

Steam to High Pressure Cylinder (VIA HEAT HEAT EXCHANGER)

Steam to Second Stage FW Heater (936 lb/hr)

Steam to First Stage FW Heater (166 lb/hr)

Steam to Second Stage FW Heater (936 lb/hr)

Total Power Output (111 kW) [94% Power Efficiency]
Prefeasibility Summary for the Moving Bed Torrefaction Reactor

This report gives a narrative to be included with the process flow diagram submitted for the completion of milestone 1 of the task, to develop and demonstrate a moving bed torrefaction reactor capable of providing solid fuel for the boiler/generator system. The narrative is intended to document and give a brief description of each process stream flow for the torrefaction reactor. 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 incoming biomass
2) 20% 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/h or 1.0 m³/hr. The work summarized in this section completes the work for the prefeasibility design for the reactor. The design components for the system are summarized below.

1. Biomass Flow System
   
   Feed Hopper (H01)
   The biomass feed hopper is intended to be designed such that, at a minimum, three hours’ worth of biomass material can be loaded during operation. The hopper will be loaded by lifting super sacks of pre-dried, raw material using the Coleraine overhead crane to a holding platform approximately 24 feet above the floor. A second, Syngas-designed lift system will then be used to raise the super sacks the remaining distance for loading the hopper. The raw material is assumed to be dried to a moisture content of 10% maximum.

   Feed Rate Control (RV01)
   The feed rate of raw material into the plant will be set by a rotary valve. The valve will remove material from the feed hopper and discharge into the biomass heating conveyor. The valve will be operating under atmospheric conditions and room temperatures.

   Biomass Heating Conveyor (C01)
   The raw material will flow through a heating conveyor prior to entering the reactor system. The conveyor may be inclined to meet ceiling requirements at the Coleraine facility. The conveyor will be operated such that the material flow rate through the conveyor is greater than the discharge rate of the rotary valve, RV01, thus ensuring that it is never flood fed. The material must be heated to a minimum of 121°C, so that it will not cause condensation upon mixing with steam. The conveyor will be designed as a steam-jacketed mixing conveyor. The
jacket-side steam is intended to be provided by a small stream of saturated steam that will be taken from the boiler.

**Reactor Inlet Pressure Seal (KV01, DV01 & DV02)**
A pressure seal must be created to prevent backflow of gasses from the reactor into the feed system. To maintain both material flow and a pressure seal, a double dump system will be used. The raw material will discharge the heating conveyor (C01) and pass through a knife valve, KV01, and first dump valve, DV01. The second dump valve, DV02, will remain closed to maintain reactor pressure. Once the material fills to a set level, KV01 will close, followed by DV01. KV01 must close prior to DV01 to stop material from flowing onto DV01 so that it will create a proper pressure seal when it closes. Once a pressure seal is established, the dump chamber will be purged using inert gas to remove all of the oxygen present. Once purged, the chamber will pressurize to the reactor pressure, and DV02 will open allowing material to discharge. DV02 will then close, the pressure will be relieved, and DV01 and KV01 will be re-opened. The cycle will then be repeated. The rate of valve cycling will depend upon the volume accumulated in between the dump valves and the time required to purge the dump chamber.

**Horizontal Conveyor (C04)**
A short horizontal screw conveyor will move the raw material discharged from the inlet pressure seal into the top of the moving bed reactor. The conveyor will be designed with higher capacity and flow rate than the raw material feed rate, thus ensuring it is never flood fed.

**Reactor ABNR**
Material flow through the moving bed reactor will be controlled using an internal agitation device, or anti-bridging nub rotator (ABNR). The ABNR will be rotated axially from the top of the reactor via an electric motor and VFD. The shaft will contain equally spaced, protruding “nubs” that act to prevent bridging and maintain material flow. Two sectional screw flights will be attached at the bottom of the reactor. The flights enable the material flow rate through the reactor to be variably controlled and match the feed rate of biomass entering the reactor.

**Moving Bed Reactor (R01)**
The moving bed reactor, R01, will be vertically oriented with co-current solids and gas flow. The reactor will be fabricated from sections of pipe of increasing diameter from top to bottom. 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 dimensions of the reactor and material residence time will be designed based upon corresponding research that is
currently underway in Elk River. The reactor will be designed to be operated at a maximum pressure of 1.7 bar.

**TGEU**
The combined stream of torrgas and steam will be separated from the solids material at the bottom of the reactor through the *Torrgas Extraction Unit (TGEU)*. The TGEU inner diameter is designed to match the reactor wall inner diameter to reduce any solids hang up.

**Primary Cooling Conveyor (C02)**
The solids material discharge from the reactor and ABNR will feed directly into the primary cooling conveyor, C02. The conveyor will be designed as a horizontal mixing conveyor, and will be operated at a capacity and flow rate greater than that of the discharge of the ABNR. The conveyor is required to cool the solids to below 220°C, but above a minimum of 150°C. The solids and conveyor internals must be kept above the dew point of steam at the operating reactor pressure to prevent condensation.

**Reactor Outlet Pressure Seal (KV02, DV03 & DV04)**
The solids discharge from the primary cooling conveyor, C02, will feed directly into the reactor outlet pressure seal. The pressure seal operates using the same procedure as the reactor inlet pressure seal, described above, 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 double dump system is depressurized before the solids are unloaded and repressurized after, instead of the reverse.

It also functions to maintain a gas tight pressure seal in the reactor while still allowing for solids flow. The rate of valve cycling will depend upon the volume accumulated in between the dump valves and the time required to purge the dump chamber.

**Secondary Cooling Conveyor (C03)**
The Coleraine facility requires that the processed materials be cooled to a maximum temperature of 82°C. To accomplish this, a secondary cooling conveyor, C03, will be used to cool the material discharged from the reactor outlet pressure seal. The conveyor will be designed as a jacketed mixing conveyor and may be inclined depending upon facility height constraints. Cooling water will act as the jacket cooling fluid. The conveyor will also act to transport the product and will tie into the existing bucket elevator present at the Coleraine facility. The Coleraine facility also requires that the product be blanketeted with nitrogen as a safety measure.
2. Steam Flow System

   Boiler
A high-pressure boiler system (7-10 bar) is required to generate the high-
temperature steam necessary for the torrefaction process. Both natural gas and
electric boilers are being evaluated. It is our understanding that state regulations
require that a certified boiler technician be present onsite during operation of
boilers running above 1 bar. Coleraine is reviewing this requirement.

   Superheater (HX01)
A superheater, HX01, will be required to obtain the inlet steam temperature
required by the process, currently estimated at a maximum of 482°C. Both natural
gas and electric heaters are being evaluated, and the possibility of a packaged
boiler-superheater unit is being looked into. Due to the nature of highly
superheated steam, heat losses will be minimized by positioning the superheater
as close to the steam injection point on the reactor as possible.

3. Torrgas Flow System

   Flare
The combination torrgas and steam exiting the reactor can be directed to two
locations: a flare or a combustor. Both are designed to combust the torrgas
components. The flare is expected to simply be the existing Coleraine facility’s
drier burner. To prevent condensation and the formation of difficult to process
resins, the line running to the dryer will be steam traced.

   Air Compressor (CM01)
An air compressor is required to produce the airflow needed for combustion in
the combustor, R02. The compressor will be electric and achieve an air flow rate
of 411 kg/hr.

   Air Heater (HX02)
An air heater, HX02, is required to preheat the combustion air fed to the
combustor, R02. Preheating is necessary to prevent condensation and provide the
heat required for steady combustion in R02. The heater will be electric.

   Combustor (R02)
In addition to the flare described above, the combustible material present in the
torrgas / steam flow stream exiting the reactor can be processed in a combustor,
R02. The combustor will be designed to burn material using a catalyst.

   Heat Exchanger (HX03)
A heat exchanger, HX03, will be required to cool the off-gas from the combustor,
R02, and condense the spent process steam. Cooling water will act as the cooling
fluid.
Condensate Knock Out Pot (KO01)
A condensate knock out pot, KO01, will be required to separate the steam condensate and combustor off-gas.

Vent
It is intended to vent the off-gas from KO01 to the outside of the Coleraine facility.

Condensate Pump and Treatment (P01)
A pump, P01, will be used to transport the condensate from the knock out pot, KO01. The pump will transfer the condensate into a holding tank(s) where it can be tested and potentially pH-adjusted prior to sending it to the drain.

4. Cooling Water Flow System
Cooling water is designed to be used in many of the heat exchange process equipment. The combustion off-gas and steam condenser heat exchanger, HX03, has the largest duty required and temperatures in the range of 15°C. To meet the cooling water requirements, a cooling tower will be designed to cool and recycle the cooling water utility streams.

5. Safety Purge System
An inert gas purge system will be designed as a safety measure in the event of material ignition. It is intended that nitrogen will be provided by either a nitrogen generator onsite, or a nitrogen holding tank(s).

6. Site Control Plan for the XCEL Moving Bed Torrefaction Reactor
Syngas Technology, LLC will be sub-contracting the design and fabrication of the Torrefaction Unit to Gradient Technology, located in Elk River, Minnesota. Gradient is a majority shareholder of SynGas Technology, LLC. The fabrication and assembly of all components will be performed at our Elk River facility. The unit will be constructed in modules for ease of shipping and installation at Coleraine. All components and integrated systems will be tested for fit and function at our facility prior to shipping to Coleraine.

Appendix (Moving Bed System)

LEGAL NOTICE
THIS REPORT WAS PREPARED AS A RESULT OF WORK SPONSORED BY THE RENEWABLE DEVELOPMENT FUND AS MANAGED BY XCEL ENERGY. IT DOES NOT NECESSARILY REPRESENT THE VIEWS OF XCEL ENERGY, ITS EMPLOYEES, OR THE RENEWABLE DEVELOPMENT FUND ADVISORY GROUP. XCEL ENERGY, ITS EMPLOYEES, CONTRACTORS, AND SUBCONTRACTORS
MAKE NO WARRANTY, EXPRESS OR IMPLIED, AND ASSUME NO LEGAL LIABILITY FOR THE INFORMATION IN THIS REPORT; NOR DOES XCEL ENERGY, ITS EMPLOYEES OR THE RENEWABLE DEVELOPMENT FUND ADVISORY GROUP REPRESENT THAT THE USE OF THIS INFORMATION WILL NOT INFRINGE UPON PRIVATELY OWNED RIGHTS. THIS REPORT HAS NOT BEEN APPROVED OR DISAPPROVED BY NSP NOR HAS NSP PASSED UPON THE ACCURACY OR ADEQUACY OF THE INFORMATION IN THIS REPORT.
The information contained in this drawing is the sole property of SynGas Technology. Any reproduction in part or as a whole without the written permission of SynGas Technology is prohibited.