



# BIOCHAR TESTING RESULTS REPORT

## Waste to Wisdom: Task 2

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## EXECUTIVE SUMMARY

One potential pathway to transform forest residuals and slash into a valuable product is by conversion into biochar. Biochar is primarily used as a soil amendment to increase water retention and decrease nutrient leaching, but it also provides co-benefits such as carbon sequestration. This report investigates the potential use of a biochar production machine as a mobile unit to process forest residuals during forest harvest operations. The focus of the testing and analysis was to determine the required feedstock quality, energy demand, environmental impact, labor requirements, and fire hazards of a commercial biochar production machine in a near-woods setting.

### Methods

A biochar machine manufactured by Biochar Solutions, Inc., as shown in the picture below, was tested at their production facility in Pueblo, CO during August 2014. The machine was instrumented to acquire mass and energy flow data during the test runs (see the parts and instrumentation diagram on the next page for details). Seven combinations of feedstock species, comminution methods, and contaminants were tested, including duplicate tests for each combination. Feedstock species included conifer, hardwood, and mixed pinyon and juniper. Comminution methods included grinding for each species and chipping conifer through both medium and small screens. Ground conifer was also tested with contamination of both 1/3 tops and 9% topsoil. The pinyon and juniper mixture was highly contaminated (>20% ash) when received due to harvesting methods.



Figure ES.1 Picture of biochar machine.

Data files from each test were analyzed to determine the mass and energy flows through the machine. Material samples of feedstock and biochar were tested in the lab to determine the proximate analysis, calorific value, particle size distribution, and bulk density.

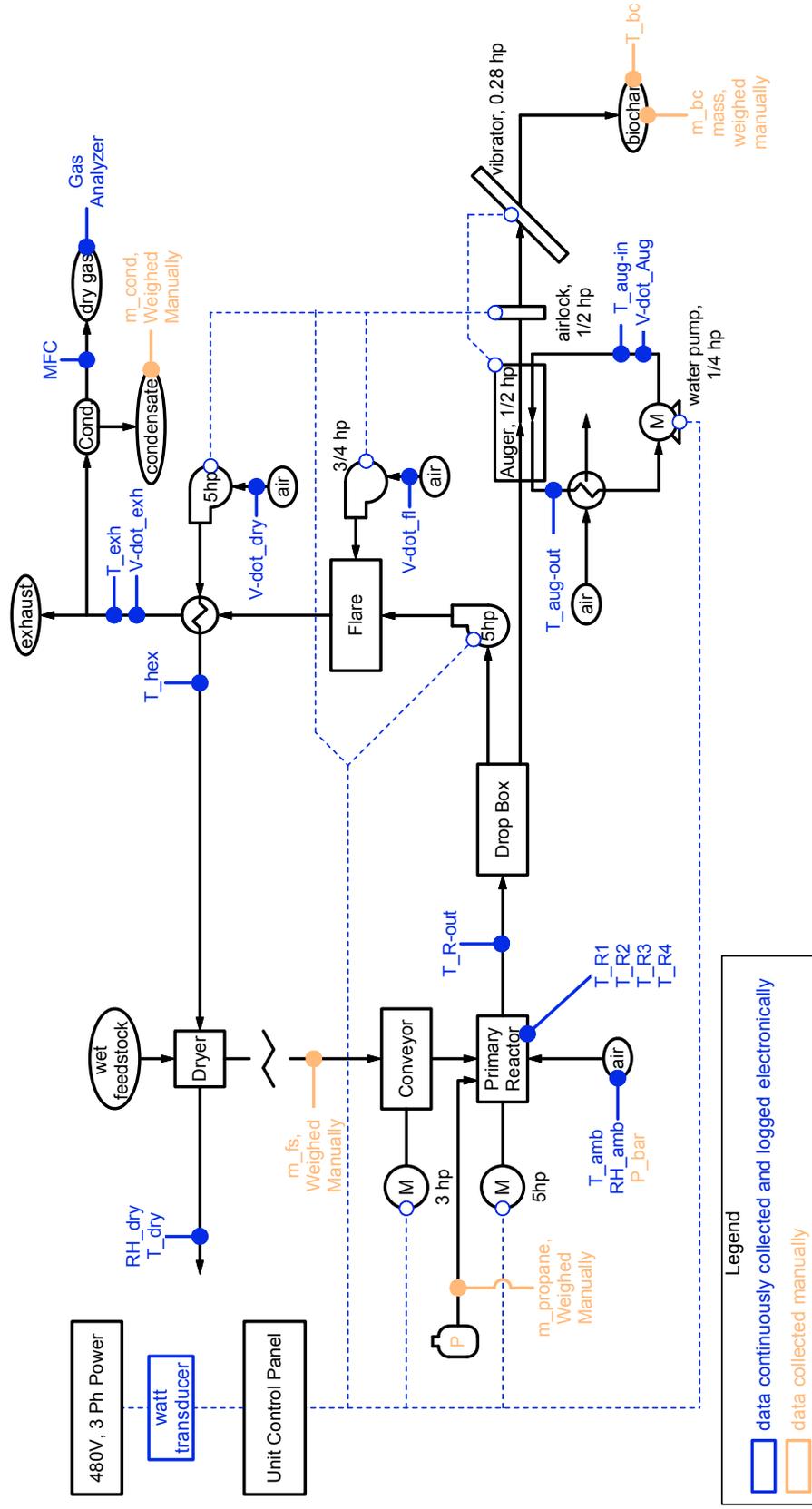


Figure ES.2 Piping and instrumentation diagram of biochar machine. Please see Table A.1 in Appendix A for a detailed list of the parameters and instruments.

## Results

The biochar machine processed feedstock at an average rate of 385 kg/hr on a wet basis with an average biochar production rate of 43 kg/hr. The test results show that this machine tolerates a wide range of feedstocks and particle size distributions, but the feedstock should be below 25% moisture content and 15% ash content or the resulting biochar will have low fixed carbon. As feedstock moisture and ash content increases, more fixed carbon is consumed during the gasification process, which reduces the yield of fixed carbon in the biochar.

Operational intensity was found to increase as a function of feedstock moisture and ash content. When using feedstocks below 25% moisture and 15% ash content, between 25 and 50 hours of labor are required to produce one tonne of biochar. Operating the machine with higher levels of these contaminants requires more time to manage gasification in the reactor and clean out the machine throughout the day. Clean and dry feedstocks not only produce higher quality biochar but also require less labor.

Electricity demand varied widely throughout each test and across different feedstocks. The average power demand was 12 kW with a peak demand of 26 kW. Electricity demand was not strongly correlated with any of the measured variables. It is hypothesized that reactor bed depth is causing the variability in electricity use. Higher bed depths require more power for the reactor stirring motor and more power for the blower that pulls combustion air through the reactor to overcome a greater pressure drop. The bed depth may also cause the varying power requirements observed on a minute-to-minute basis if it is not maintained at a constant height throughout production.

Exhaust gas produced from syngas combustion in the flare exited the stack at 750°C, carrying thermal and chemical energy at an average rate of 450 kW. Chemical energy from carbon monoxide and unburned hydrocarbons constituted 90 kW of the waste heat. This considerable amount of chemical energy exited as waste energy because airflow to the stack was insufficient for complete combustion. By increasing the air flow, this chemical energy would be converted to thermal energy. Approximately 15%, or 68 kW, of the total 450 kW of waste heat was recovered through a heat exchanger in the exhaust stack. This should be used as thermal input to a dryer to remove moisture from the incoming feedstock. Although the total waste heat may provide enough energy to power a waste heat to electricity conversion device, the current market prices of these generators coupled with the complexity of the system, which would require energy storage to meet maximum demand and supplemental fuel to provide power at startup, makes generating electricity from waste heat infeasible. It may be more economical to use a dedicated biomass gasifier to provide power to the machine, assuming that a gasifier generator can function under these conditions. An All Power Labs, Inc. PP20GT biomass gasifier, which is rated for an electrical output of 20kW, is currently undergoing testing as part of this project.

On average, emissions from the stack were relatively high in CO (3%), propane (320 ppm), NO<sub>x</sub> (<650 ppm) and SO<sub>2</sub> (<150 ppm) due to incomplete combustion in the flare because the flare air blower was undersized compared to the syngas flow. Experimental results show that replacing the blower and increasing the flow rate of combustion air from 400 scfm to 1,000 scfm will eliminate these high emission rates.

Several fire hazards were observed, including embers emitted from the stack, dust collecting around the machine, biochar exiting the machine at over 250°C, dust clouds forming above the reactor, and backfiring in the reactor. Safety measures have been outlined to address these risks by adding a spark arrestor to the flare, mandating daily cleanup of dust, improving the effectiveness of the heat dump before biochar exits the auger, removing fines from the feedstock, and regularly cleaning the machine to avoid clogs. After addressing these issues, the machine can be operated safely in a field setting.

## **Conclusion**

This testing and data analysis led to generating feedstock specifications and outlining improvements that will make the biochar machine acceptable for mobile field use in forest operations. Specifications of less than 25% moisture and 15% ash content are recommended to consistently produce high quality biochar with over 50% fixed carbon content. To operate as a stand-alone unit, electricity should be provided from an external source, such as a biomass gasifier or diesel generator, and waste heat from the biochar machine should be used to dry incoming feedstock. The machine can be made field ready by increasing the size of the flare blower to reduce emissions and mitigating the fire hazards by incorporating safety measures to modify the design and operation procedures.

Further field testing of the machine in 2016 will verify improvements made by the manufacturer and provide additional data on labor requirements and throughput in a commercial production setting. Additional testing in 2016 will attempt to demonstrate an integrated system by providing electricity for the machine with a biomass gasifier and remove moisture from incoming feedstock with waste heat from the biochar exhaust stack.



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# 1 INTRODUCTION

This report provides a summary of testing and data analysis of the biochar production unit performed by Schatz Energy Research Center during Year 1 of the Waste to Wisdom project. The work summarized here was completed under Subtasks 2.2, 2.8, and 2.9, which involve testing and monitoring the biochar production unit, assessing its potential for field deployment, and providing data and internal reports to the larger project team.

Field testing of the biochar machine took place at the Biochar Solutions, Incorporated's fabrication facility in Pueblo, Colorado in August 2014. The research and testing objectives for this study were organized into a set of five questions. The questions and main conclusions are summarized here:

*What feedstock quality is acceptable?*

The feedstock should be below 25% moisture content and 15% ash content for the machine to operate properly, maintain a low level of operator effort, and produce high quality biochar.

*How does feedstock quality affect the quality of biochar?*

Increased ash or moisture content in the feedstock produces biochar with a lower fixed carbon content and a lower calorific value.

*What are the operational and labor requirements for the biochar machine?*

Operational intensity increases as moisture and/or ash content of the feedstock increases. With feedstock within the specifications, operator effort ranges from 25 to 50 hours to produce one tonne of biochar.

*Is stand-alone operation possible?*

Using waste heat to provide all the electric power to the machine is not feasible without the use of an energy storage device. A biomass gasifier generator or diesel generator set are the best options to provide power to the machine at remote locations.

*What are the emissions and environmental impacts from this machine?*

The flare emitted relatively high concentrations of CO, SO<sub>2</sub>, and hydrocarbons due to lack of oxygen in the flare stack, but this problem is being addressed by increasing the combustion air supply to the flare. The machine has potential fire hazards, but mitigation measures have been outlined to eliminate these risks and make this machine suitable for in-field operation.

This report provides a description of the biochar machine and a summary of the main conclusions and qualitative results. It is organized to provide a brief background into biochar production, including a process description of the machine, in Section 2. The testing and analysis methods are described in Section 3 followed by a summary of the main results in Section 4. The results are interpreted and discussed in Section 5, and future test plans with the biochar machine are described in Section 6.

## 2 BACKGROUND

This section provides a brief overview of biochar and then describes in detail the biochar production machine produced by Biochar Solutions, Inc. (BSI).

### 2.1 Biochar Use and Production

Biochar is a carbonaceous material, or char, that can be produced from biomass, such as forest residues. Biochar is produced by gasification or pyrolysis of biomass in an oxygen-limited environment. As chemical compounds volatilize during thermal decomposition, the process produces a wood synthesis gas, or syngas, with reactive components consisting primarily of hydrogen and carbon monoxide. The residual, carbonaceous, solid material is biochar.

Biochar is used primarily as a soil amendment to improve moisture retention capacity and reduce nutrient leaching (Lehmann & Joeseeph, 2012). In comparison to other slash management practices, such as open burn or decomposition in-place, converting slash into char for use as a soil amendment has the potential to sequester carbon, avoiding greenhouse gas emissions such as carbon dioxide and methane.

### 2.2 BSI Biochar Production Unit

Biochar Solutions, Inc. (BSI) fabricated the machine tested in this study. This unit was built for the Redwood Forest Foundation, Inc. (RFFI), a project partner based in Mendocino County, California. The machine is rated by BSI to process 600 lb/hr of raw biomass (500 lb/hr of dried biomass) and produce 100 lb/hr of biochar. Annotated images of the biochar production unit are shown in Figure 1 accompanied by a description of the process flow.

To begin processing, a front-loading tractor loads raw biomass feedstock into the feed hopper (14). Biomass is manually transferred from the feed hopper (14) onto the conveyor (15), which transports feedstock into the reactor (1). The reactor blower (5) pulls air into the reactor (1), through the drop box (2) and forces gas through the exit to the flare (3). The reactor consists of two concentric cylinders with a small gap between the two cylinder walls and an approximately 6" gap between the bottom of the inner cylinder and the bottom of the outer cylinder. Feedstock is loaded into the inner cylinder to maintain a bed depth between 18" and 48". Steel stir bars in the reactor slowly rotate the bed. Biomass loaded into the top of the reactor is heated by partial combustion of feedstock as it moves downward through the reactor. As the oxygen levels are depleted near the bottom of the bed, biomass is converted into biochar through gasification.

After biochar is formed, the reactor blower (5) pulls it through the gap between inner and outer reactor cylinders and into the dropbox (2). Biochar and syngas are drawn by vacuum from the reactor into the drop box (2) where they encounter a baffle, which drops the biochar to the bottom of the dropbox while syngas exits through a pipe in the top of the dropbox. The syngas flows through the main blower and into the flare (3). The flare air blower (6) introduces fresh air into the flare, creating a combustible mixture of fuel and oxygen, which is combusted in the flare before it exits through the top of the stack.

The biochar, which has dropped to the bottom of the drop box, enters an auger (8) that is cooled by an external water jacket. The closed-loop auger cooling system rejects heat to the environment through a radiator (9). Biochar exits the auger through an air lock (10), which maintains negative pressure in the system while allowing solid biochar to exit, and is collected into metal drums (11).



- |                           |                     |                                |                          |
|---------------------------|---------------------|--------------------------------|--------------------------|
| 1: Reactor                | 2: Drop box         | 3: Flare                       | 4: Heat exchanger        |
| 5: Reactor blower         | 6: Flare air blower | 7: Heat exchanger inlet blower | 8: Biochar cooling auger |
| 9: Cooling auger radiator | 10: Air lock        | 11: Biochar collection drum    | 12: Control panel        |
| 13: Feedstock hopper      | 14: Conveyor        | 15: Heat exchanger outlet      | 16: Dryer hopper         |

Figure 1. Annotated images of biochar production unit.

The system is also equipped with a biomass drying system. Moist biomass loaded into the dryer hopper (16) is dried by waste heat from the flare. Fresh air from the heat exchanger inlet blower (7) is piped through a cross-flow heat exchanger (4) in the stack. The heat exchanger outlet piping (15) routes this hot air into the dryer hopper.

The control panel (12) includes individual power switches for each motor, an emergency shut down switch, and variable speed motor controls for the reactor stirrer, reactor blower, and heat exchanger blower.

The inputs and outputs of the biochar machine are characterized by the flow chart pictured in Figure 2. Propane is required to initiate combustion in the reactor and to ignite the flare. Electricity is used to power the motors and controls. During testing, electricity was provided from the grid, but this machine could also be powered through a diesel or syngas generator.

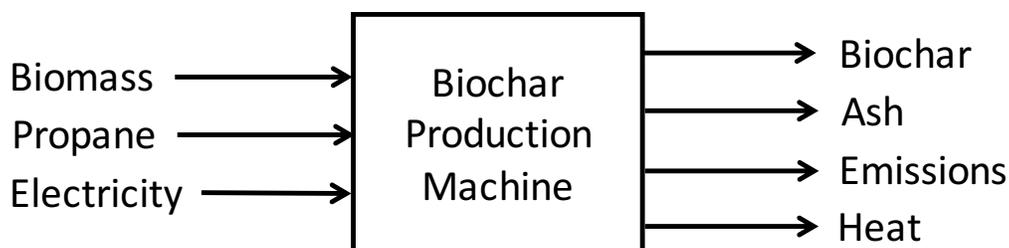


Figure 2. Input and outputs from biochar production unit produced by Biochar Solutions, Inc.

### 3 METHODS

This section describes the test methods used for field testing, data analysis, and material analysis.

#### 3.1 Data Collection Instrumentation

Instruments to collect mass and energy flow data were installed on the biochar production machine temporarily during the testing phase. A piping and instrumentation diagram for the biochar machine and a list of the data acquisition equipment are provided in Appendix A.

#### 3.2 Test Procedure

The biochar machine was tested to determine the effect of feedstock species and quality on operational parameters. Seven combinations of feedstock species, comminution methods, and contaminants were tested. Duplicate tests were performed for each of the seven combinations. A list of feedstock, contaminant, and comminution method combinations that were tested are provided in Table 1.

Table 1. Test matrix for biochar machine evaluation in Pueblo, Colorado.

<i>Species</i>	<i>Contaminant</i>	<i>Comminution Method</i>	<i>Test ID</i>	<i>Test Date</i>	<i>Test Start Time</i>
Conifer	none	ground	6A	8/6/14	09:40
			6B	8/11/14	07:50
Conifer	2/3 bole, 1/3 tops	ground	2A	8/8/14	08:46
			2B	8/11/14	14:03
Conifer	9% soil	ground	3A	8/7/14	12:53
			3B	8/12/14	15:00
Conifer	none	chip, medium	5A	8/5/14	13:43
			5B	8/11/14	10:45
Conifer	none	chip, small	4A	8/6/14	12:30
			4B	8/8/14	13:45
Hardwood	none	ground	1A	8/5/14	07:10
			1B	8/7/14	08:16
Pinyon/ Juniper	as received	ground	7A	8/12/14	08:00
			7B	8/13/14	07:21

Each test was performed with identical methods except as noted. The goal of each test was to obtain a steady state (SS) operation period consuming approximately five cubic yards of feedstock. To begin the test, feedstock from piles stored on site was loaded into the feed hopper on the biochar machine. Feedstock was manually shoveled or pushed from the feed hopper onto the conveyor, which moved material into the reactor. As the reactor began to fill up with feedstock, the blowers, stirrer, auger, and other electrical components were turned on. Next, a propane tank and torch were used to ignite the initial feedstock in the reactor. Feedstock was intermittently fed into the reactor while propane was used and blower speeds were adjusted to maintain combustion in the reactor. After thick smoke began to rise from the stack, the propane torch was used to ignite the syngas and air mixture evolving in the stack. Figure 3a) shows the thick syngas and air mixture exiting the stack before ignition, and Figure 3b) and c) show the flare after ignition. Steady state data collection can begin once the flare stays lit, a consistent quality of biochar is being produced, and the operational parameters, such as motor speeds, are relatively constant.

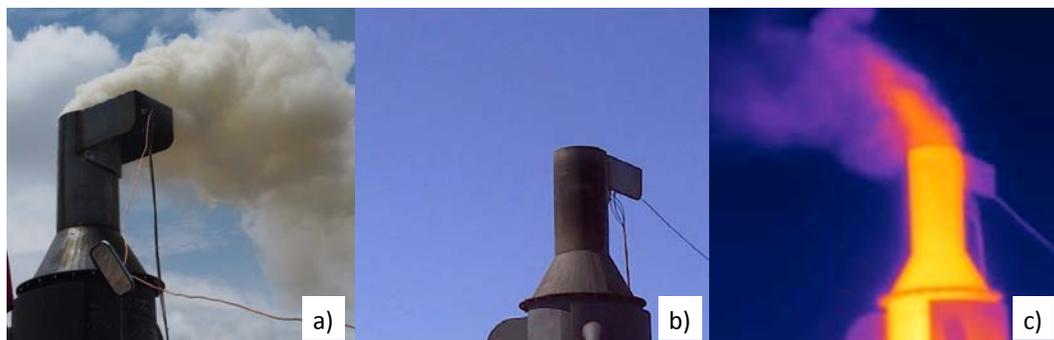


Figure 3. Image of flare (a) before ignition, (b) after ignition, and (c) infra-red image after ignition. Note that there are some clouds in the backdrop of image (a), but the yellowish smoke blowing to the right is exhaust gas.

As pictured in Figure 4, feedstock for the SS period was loaded into a self-dumping hopper, which was then weighed on a truck scale before the feedstock was poured into the feed hopper. Approximately five cubic yards of feedstock were used for each steady state period. Feedstock from the feed hopper was loaded onto the conveyor at the operator's discretion. The operator aimed to maintain consistent operational parameters and biochar production throughout the steady state period to the best of their ability. This led occasionally to inconsistent feedstock input rates throughout the tests and changing the bed depth. This was not the desired operational procedure, but it was required to keep the machine running consistently.



Figure 4. Loading feedstock into the self-dumping hopper to prepare for SS operation. A small feedstock pile is shown in the lower portion of the image.

Data were collected throughout SS operation. All of the data acquisition parameters were written to an electronic data file approximately every five seconds. Hand written parameters for other data were also collected during each run; an example data sheet is shown in Appendix B. Material samples of raw feedstock were collected from the feed hopper immediately prior to beginning a SS test. A biochar sample was collected part way through the SS testing period. Occasionally, a stack gas condensate sample was collected from a thermoelectric cooler in the stack gas sampling line upstream of the gas analyzer; an image of these samples is shown in Appendix C.

### 3.3 Data Analysis

The data collected on hand written datasheets and electronic data files were analyzed to calculate key parameters, which are discussed below. Details on the methods and equations used for data analysis are contained in Appendix D. The feedstock and biochar material samples were analyzed using standard methods to determine the moisture content, ash content, volatile matter, fixed carbon, gross calorific value, particle size distribution and bulk density. Details for these test methods are described in Appendix E.

## 4 RESULTS

The section provides results from the biochar production unit testing. The testing objectives were organized into five main questions, listed below. The main conclusions for each research question are highlighted here and detailed in the subsequent subsections.

What feedstock quality is acceptable? How does feedstock quality affect the quality of biochar?

- Feedstocks of different size distributions, species, comminution methods, moisture contents, and contaminant levels were tested. The biochar machine successfully processed all materials, but operation became particularly difficult and the quality of the biochar significantly decreased (in terms of fixed carbon content) when the ash content of the feedstock was above 15% or the moisture content was above 25% on a wet basis.
- Both ash and moisture content in the feedstock decreased the yield of fixed carbon in the biochar. As ash or moisture content increased in the feedstock, more fixed carbon was consumed during gasification in the reactor which decreases the fixed carbon yield. Since higher amounts of fixed carbon in the biochar lead to greater value as an energy product and also greater value as a soil amendment, low ash and moisture content in the feedstock are desirable.
- Biochar has more energy per mass than the feedstock, but typically less energy per volume. Densifying the biochar may provide a valuable energy product, such as biocoal. The HHV of biochar on a dry, ash-free basis was approximately equal to a high grade coal, between 25 to 30 MJ/kg

What are the operational requirements for this machine?

- Operational intensity was a function of the sum of moisture and ash content of the feedstock. As moisture and/or ash content increase, more labor is required to produce one tonne of biochar.
- Between 25 and 50 hours of labor are required to produce one tonne of biochar when using feedstocks below 25% moisture and 15% ash content.

Is stand-alone operation possible?

- During steady state testing, the average 100-second interval electric power demand is 12 kW with a minimum of 3 kW and a maximum of 26 kW. Operational conditions and bed depth in the reactor are hypothesized to have the greatest influence on electrical demand, where greater bed depth requires more power to overcome the increased head loss through the chip bed.
- A waste heat-to-power conversion device could potentially be used to power the biochar machine, however an energy storage device will likely be needed in the remote power system to meet peak power demands of the highly variable load. Additionally, a supplemental energy source such as propane or diesel fuel would be required for startup and shut down. This waste-heat-to-power system would not be cost effective with current market pricing. The most appropriate use of waste heat is to dry feedstock.
- The biochar machine produces a significant quantity of waste heat that could be used for feedstock drying. Results show that the feedstock moisture content



should ideally be below 25%. An integrated biomass dryer may be necessary to reduce the feedstock moisture content between comminution and biochar processing. The integrated batch drying system that was included on the machine did not operate effectively and should be redesigned.

What are the emissions and environmental impacts from this machine?

- The flare emitted relatively high concentrations of CO, SO<sub>2</sub>, and hydrocarbons due to incomplete combustion and lack of oxygen in the flare. Based on these results, a larger flare air inlet blower has been installed. Increasing the flow rate of air into the stack from 400 scfm to 1,100 scfm reduces the CO, SO<sub>2</sub>, and hydrocarbon emissions to below detectable levels while increasing the emissions of CO<sub>2</sub>. Lastly, the NO<sub>x</sub> emissions were too high to accurately measure on the gas analyzer and are not expected to change by increasing the flare air blower size because NO<sub>x</sub> formation is primarily dependent on combustion temperature.
- Several fire hazards were identified on the machine, including embers emitted from the stack, dust collection around the machine and above the reactor, biochar exiting the system at high temperature, and backfiring in the reactor. Mitigation measures have been outlined to eliminate the risk and make this machine suitable for in-field operation.

#### 4.1 Feedstock and Biochar Quality

Various lab tests, including particle size distribution, calorimetry, and proximate analysis, were used to determine the quality of the different feedstock and biochar. Images of the feedstock and the resulting biochar samples are shown below in Figure 5 and Figure 6, respectively.

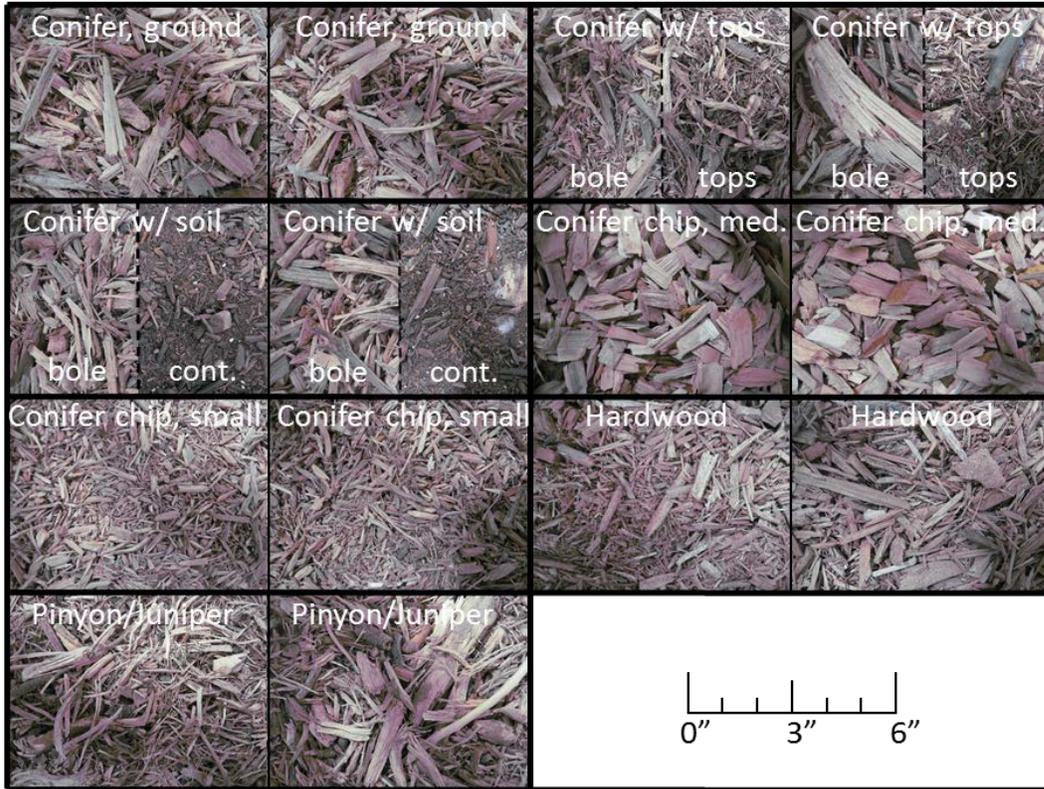


Figure 5. Biomass feedstock samples for each test including replicates.

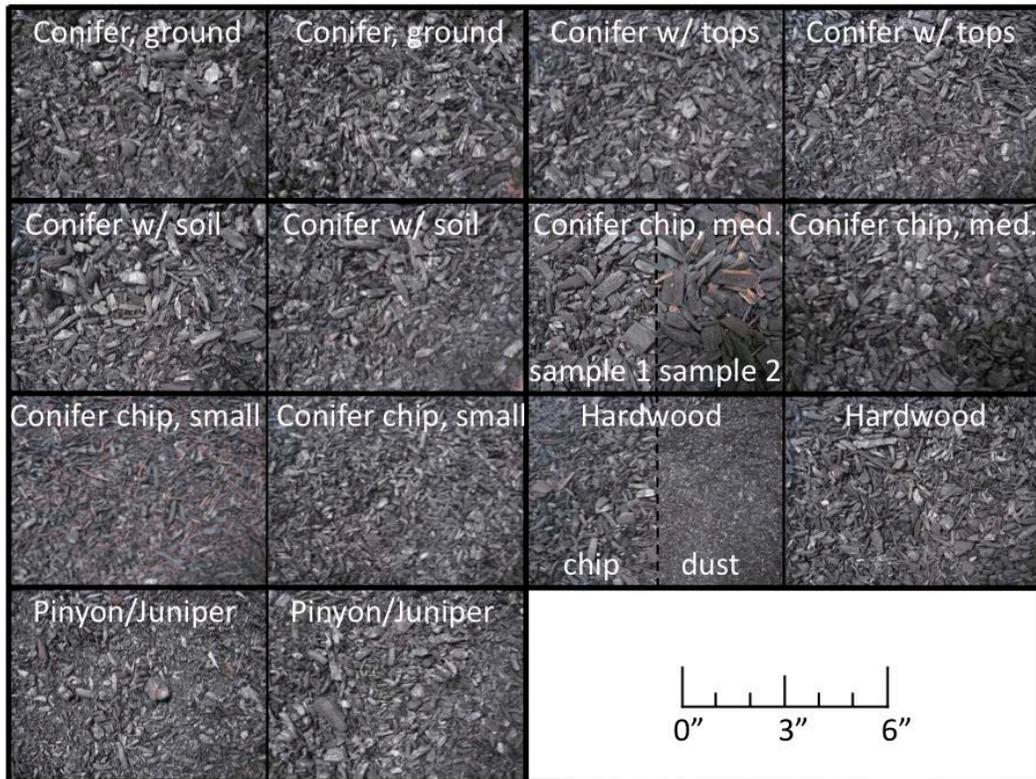


Figure 6. Biochar samples from each test including replicates.

The particle size distribution of the feedstock was measured with a stack of sieves. The cumulative mass percent passing through a sieve is plotted against the sieve size on a log scale in Figure 7. The table on the bottom of Figure 7 provides a breakdown of the particle size distribution into three categories of fine, medium, and large particles. Each feedstock was successfully processed in the machine showing that the machine can handle up to 10% fines (passing through 1 mm sieve) and 6% overs (retained in 50 mm sieve) by mass.

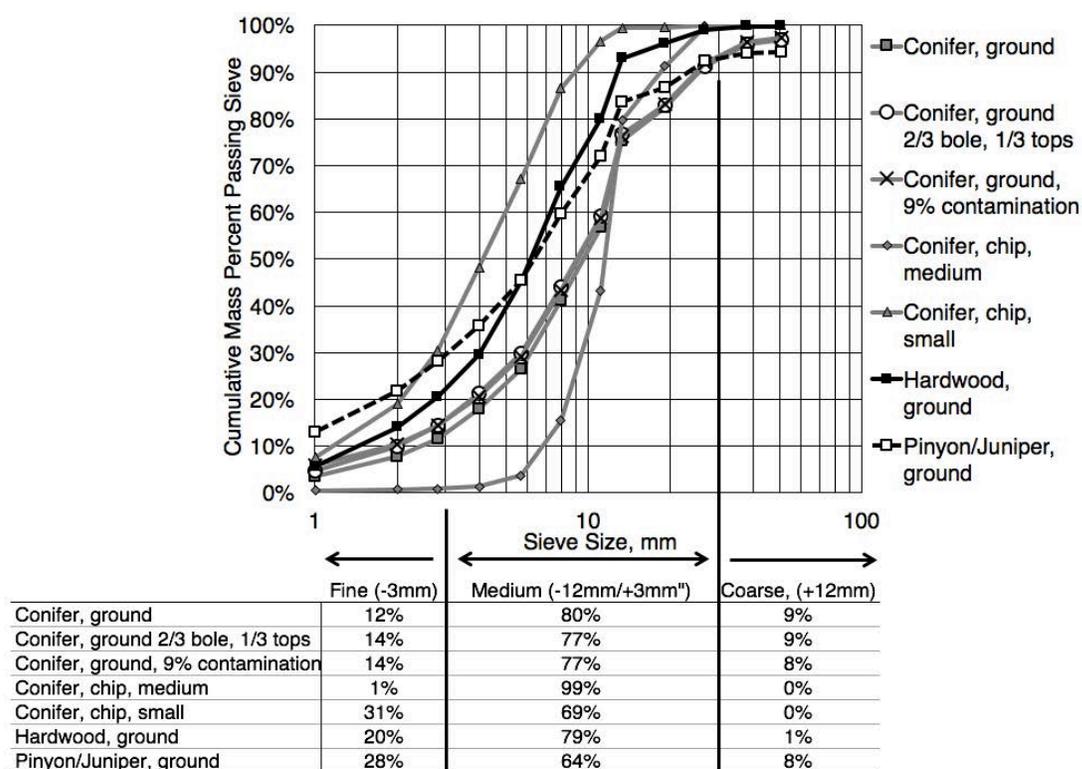


Figure 7. Cumulative particle size distribution of different feedstock mixtures plotted on a log scale.

Results from the proximate analysis of the feedstock and biochar samples are shown graphically in Figure 8 and Figure 9, respectively. The feedstock moisture content ranged from 10% to 37%, and ash content ranged from 0.3% to 24% on a wet basis. Biochar moisture content was less than 3%, the ash content ranged from 2% to 76%, and the fixed carbon ranged from 14% to 81% on a wet basis. The uncertainty for each test in the proximate analysis, quantified as the pooled standard deviation, is shown in Table 2. The methods for these calculations are provided in Appendix F. The propagation measurement error due to instrument inaccuracy was calculated on the order of  $10^{-3}$  % mass and was therefore neglected.

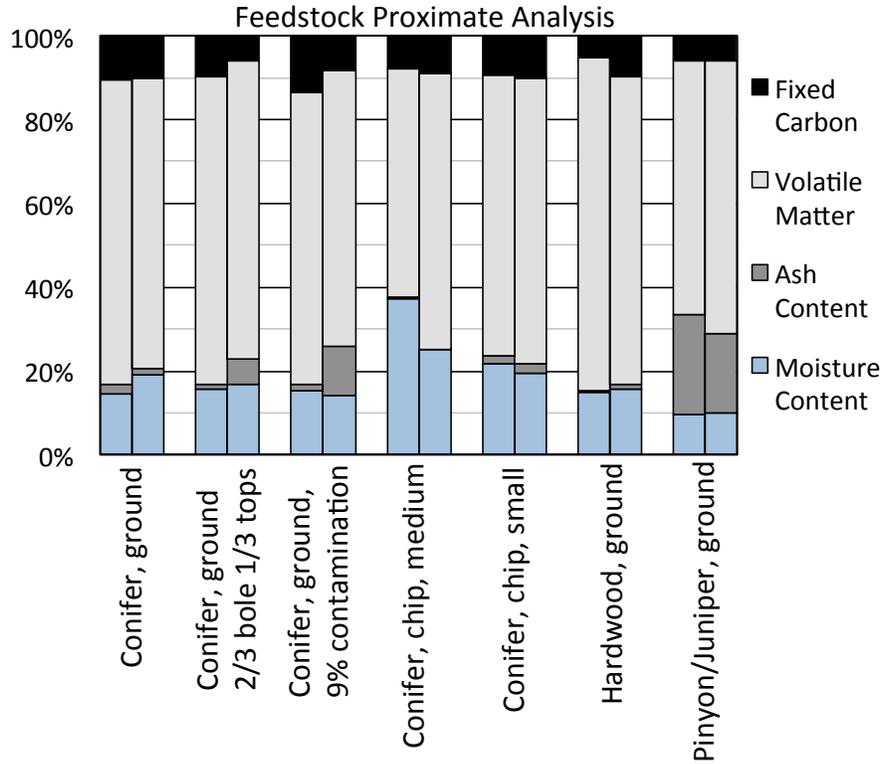


Figure 8. Proximate analysis of feedstock.

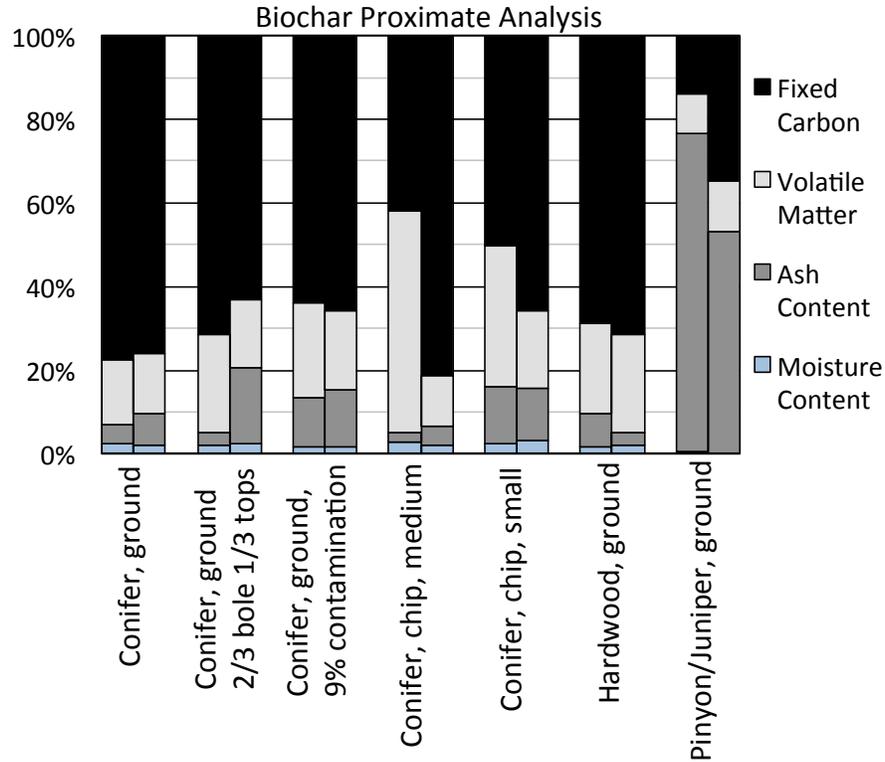


Figure 9. Proximate analysis of biochar.

Table 2. Pooled standard deviation for proximate analysis and bomb calorimetry tests.

Test	Pooled Standard Deviation	
	As Received	Oven Dry
Ash Content	2.0%	2.2%
Volatile Matter	1.0%	1.1%
Fixed Carbon	2.6%	2.6%
Calorific Value	0.75 MJ/kg	0.74 MJ/kg

The interaction between feedstock and biochar quality can be determined by comparing the proximate analyses. The first conclusion is that high moisture content and ash content in the feedstock decreases the fixed carbon in the biochar. The following two examples describe how this happens:

1. In the case of the first medium conifer chip experiment, the feedstock moisture content was 37%. The resulting biochar yielded only 42% fixed carbon and the highest volatile matter content of all the tests. During this test, a disproportionate amount of energy in the reactor was used to vaporize the moisture in the feedstock, and there was not enough energy or time to volatilize the short-chain carbon compounds, like during the other tests. This results in a low quality biochar with high volatile matter, low fixed carbon, and low heating value.
2. The highly contaminated pinyon/juniper feedstock with over 20% ash content also produced low quality biochar. Averaged between the two tests (7A and 7B), the biochar fixed carbon was 24% and the ash content was 65%. The ash content in the feedstock did not completely separate out into the bottom of the reactor; instead, some fraction of it exited directly with the biochar to contaminate the product.

The fixed carbon content in biochar can be used as a measure of its quality. Fixed carbon content is important for biochar as a soil amendment because fixed carbon is very stable and will remain in the soil for a long time. Fixed carbon can also act as a carbon sink because it will not readily decompose out of the soil and into the atmosphere. The biochar's heating value was directly related to the fixed carbon content as shown in Figure 10. The heating value of the highest quality biochar approached the heating value of anthracite coal, which is approximately 32.5 MJ/kg, indicating that the biochar is valuable for its energy density.

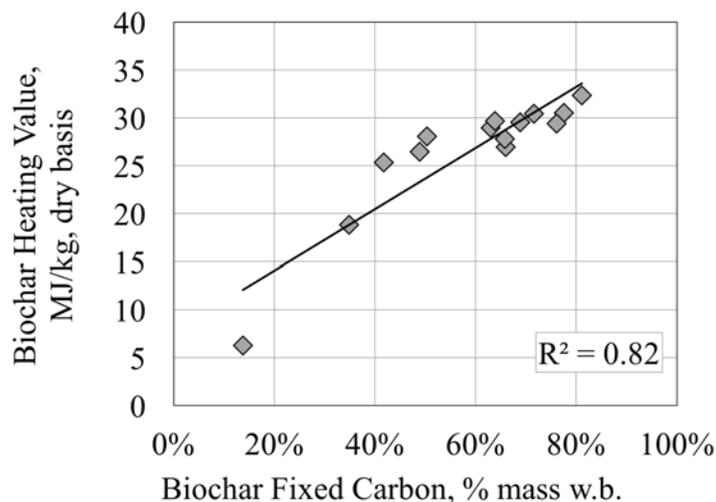


Figure 10. Biochar heating value versus fixed carbon.

While biochar has a energy density similar to coal on a mass basis and about 50% greater than raw biomass (Figure 11), the volumetric energy density is often lower than the biomass feedstock (Figure 12) and 3 to 9 times less than coal. Therefore, it may be economical to densify biochar before shipping it as an energy product.

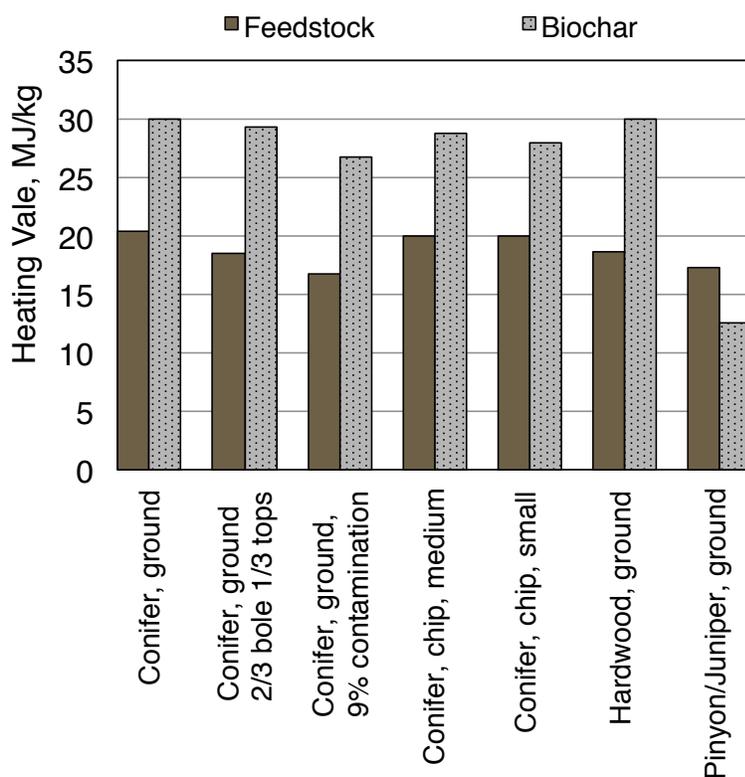


Figure 11. Gross calorific value on a dry weight basis of feedstock and biochar samples determined by bomb calorimetry.

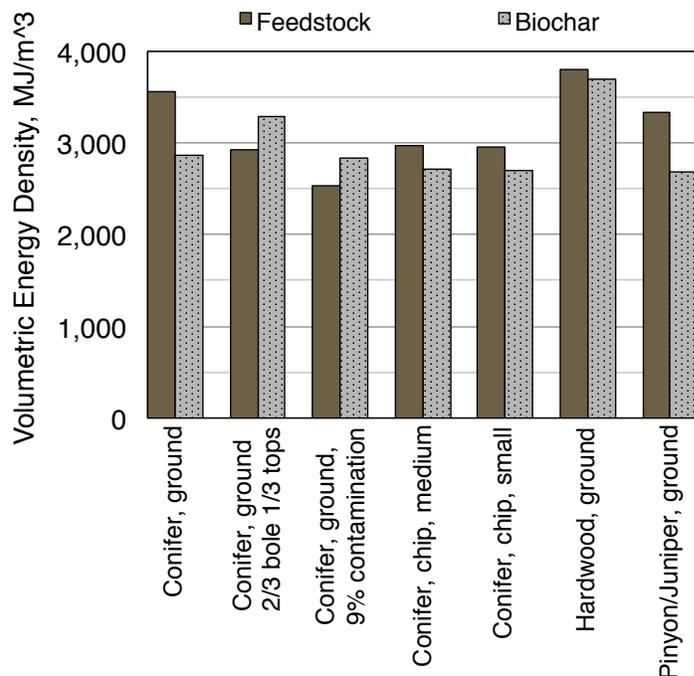


Figure 12. Volumetric energy density of biochar and feedstock. Bars represent the average between duplicate tests with each feedstock.

#### 4.1.1 Production Rates

Average biochar yield rates were 12% of the feedstock input rate. The steady state feedstock processing rates ranged from 250 to 575 kg/hr on a wet basis, and the biochar production rate ranged from 30 to 55 kg/hr, as shown in Figure 13. The mass throughput rates of contaminated feedstocks, however, are skewed by high mass fractions of ash in the feedstock, resulting in low quality biochar. To account for this, consider the fixed carbon throughput rates as shown in Figure 14. The percentage value shown above the bars in this chart show are the amount of fixed carbon lost during the biochar production process. Fixed carbon is consumed in the reactor to provide heat to the gasification process. Less heat required for the reaction means that more fixed carbon will come out as biochar.

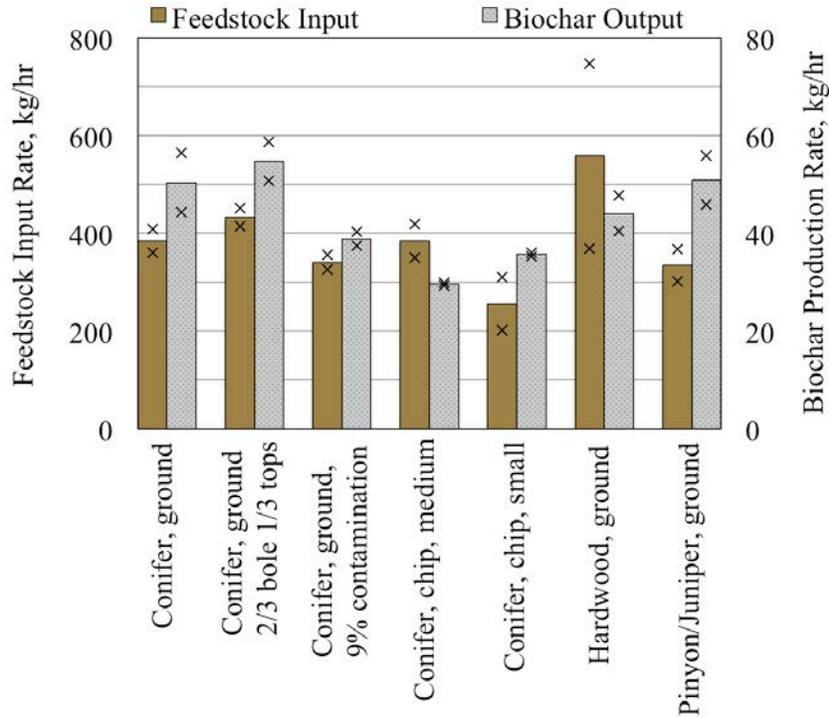


Figure 13. Average feedstock input rate (left axis) and biochar production rate (right axis) on an as-received, wet basis during steady state. The black 'x's represent the actual rates from duplicate test runs.

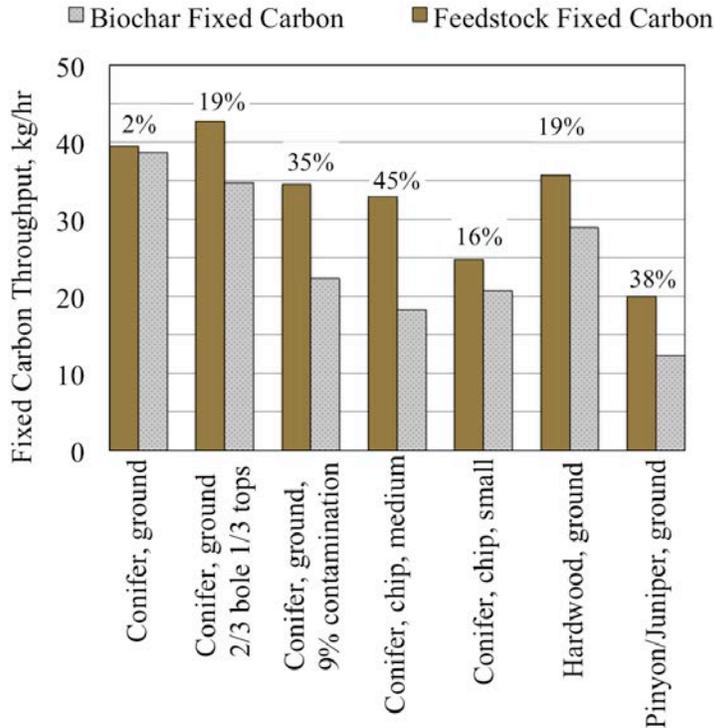


Figure 14. Throughput rate of fixed carbon in feedstock (brown) and biochar (light gray). The number above the bars indicates the percent of fixed carbon lost in the process.

The percent of fixed carbon lost during the process is a function of the quality of feedstock. Lower quality feedstocks, high in moisture or ash content, require more heat for the gasification process, and thus yield a lower amount of fixed carbon. This relationship is shown in Figure 15.

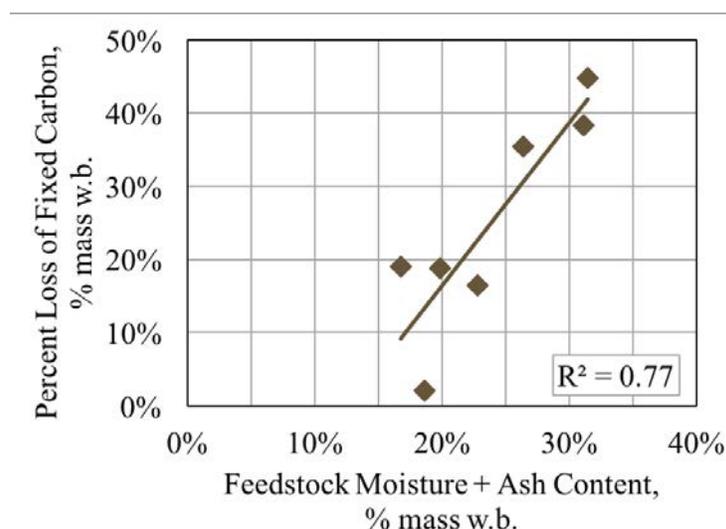


Figure 15. Percent of fixed carbon loss as a function of feedstock moisture and ash content.

## 4.2 Operational Intensity

This subsection first describes the main tasks involved with biochar production on a day-to-day basis. Then, operational intensity is quantified, showing that labor hours are positively correlated with moisture and ash content in the feedstock.

### 4.2.1 Feedstock Management

Feedstock management can be a time consuming, albeit very important aspect of operating the biochar machine. Feedstock must be prepared, dried, and staged on a continual basis. If the feedstock moisture content is too high, it must be spread out for air drying during the day or passed through a dryer and stored. If humidity is high overnight or if there is a chance of precipitation, feedstock must be gathered in piles and covered to avoid moisture gain. Furthermore, feedstock must be staged and prepared to load into the feed hopper every day, which may require uncovering the feedstock and moving the pile. The time required for feedstock management depends on the size of the tractor available, the size of the site, expected weather conditions, and the volume of chips processed every day. Mismanagement of feedstock can halt production, so it is important to proactively stage and manage the moisture content to avoid lost production potential.

### 4.2.2 Startup

To start biochar production, a small bed of chips is loaded into the reactor and ignited with a propane torch. Feedstock continues to be loaded into the reactor, using propane as necessary to maintain combustion in the reactor. After smoke begins to rise from the stack, the flare must be ignited to burn the exhausted syngas. The propane torch is used

to light the flare through a small opening in the bottom of the stack. The flare may lose ignition and need to be relit a few times before reaching steady operation.

#### 4.2.3 *Steady State*

During steady state operation there are several reoccurring and occasional tasks.

Common tasks involve:

- Manually shoveling or pushing biomass from the feed hopper onto the conveyor to keep the reactor at a functioning bed depth. An automated feed system is currently being developed by BSI but was not available at the time of testing.
- Observing reactor conditions by occasionally climbing a ladder to look inside the reactor and gauge the bed depth, height of the flame front, and packing density of material in the reactor. A fixed-mount mirror can also be used for this purpose.
- Removing, adding water to, sealing, and replacing biochar barrels as they fill up.
- Loading feedstock into the feed hopper with a front-loading tractor.

Tasks that must be performed on an as-needed basis include:

- Using propane to add heat to the reactor is necessary when syngas production is low or if the feedstock moisture content is high. This task requires the operator to climb a ladder, ignite a propane torch, and use it on the top of the reactor while monitoring combustion.
- Relighting the flare is necessary when the flare self-extinguishes due to the air and syngas mixture in the stack being outside of the combustible range. This task often requires more than one attempt at relighting the flare and adjusting either the blower speeds or bed depth in the reactor to sustain combustion.
- Occasionally, the biochar auger or air lock will clog due to high ash content in the feedstock or very fast biochar production. When this occurs, biochar production will stop until the problem is fixed. To clear the clog, the operator must identify where the clog is occurring and use mechanical force or electrical power to remove the biochar or ash from the machine. This task can take anywhere between ten minutes and three hours depending on the severity of the clog. Note that BSI subsequently solved this problem by increasing the diameter of the outlet airlock from four inches to six inches.
- Ash must be removed from the bottom of the reactor. Ash, rocks, and contamination from the feedstock builds up in the bottom of the reactor and, if not removed, will clog the reactor, fall out into the drop box, and end up in the biochar collection barrel, which results in a few hours of maintenance. To avoid a major clog, the bottom of the reactor should be cleaned out occasionally. When using relatively clean feedstocks the reactor should be cleaned out once or twice per week, but with highly contaminated feedstocks, such as the pinyon/juniper that was tested, the reactor may need to be cleaned out once or more per day. A plate at the bottom of the reactor can be removed, allowing for easy cleanout. The process of cleaning the reactor requires the machine to cool for at least one or two hours to avoid explosion and fire danger. Opening the plate and removing ash takes approximately 30 minutes, and restarting the machine can take up to one hour. It is most efficient if the operators perform cleanouts at the beginning of the workday because the reactor is already cool.

#### 4.2.4 Shut Down

To shut down the machine, the feedstock must be completely converted to char or burned in the reactor. The shut down process takes approximately 30 minutes. First, conveyance of feedstock into the reactor is stopped. The bed of feedstock in the reactor is converted into char as usual until the bed depth is reduced below the bottom of the inner cylinder. At this point air is allowed to flow directly through the reactor and over the char without forcing char into the drop box.

This initiates a heating process to attempt to decoke the machine. The main blower speed is increased and the air is heated substantially while flowing over the burning bed of residual char in the reactor. The hot air flows through the machine with the purpose of burning off any tars collected in the piping or on the blower fins. The process lasts approximately 15 minutes.

#### 4.2.5 Required Labor Hours

The operational intensity is determined to be a function of the sum of the moisture and ash content in the feedstock, as shown in Figure 16, which quantifies operational intensity as the labor hours required to produce one tonne of biochar on an as received basis. Labor hours were estimated as a function of operational parameters including the amount of propane consumed, the number of times the flare was relit, and the amount of ash cleaned out of the reactor. See Appendix G for detail on this calculation. This calculation does not take into account feedstock management.

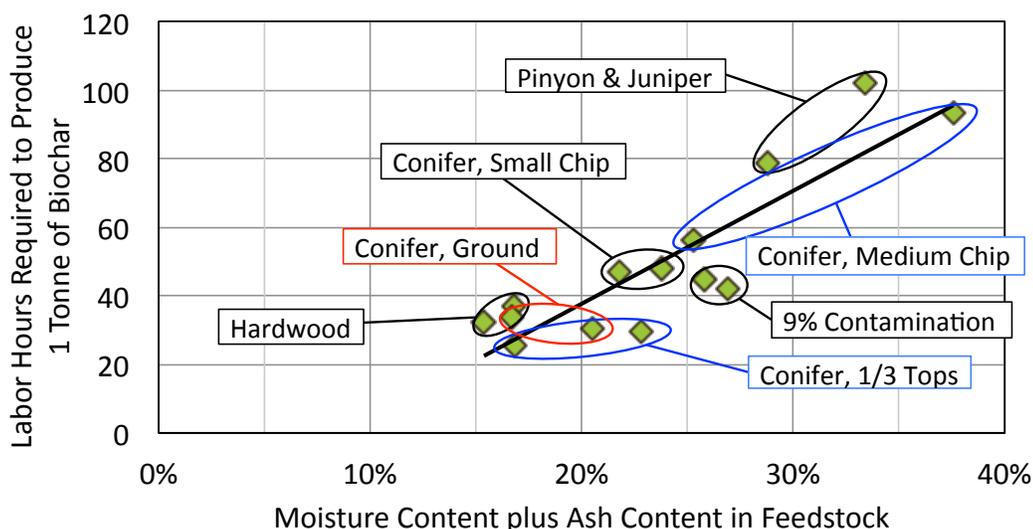


Figure 16. Labor hours to produce one tonne of biochar versus the sum of moisture and ash content in the feedstock.

#### 4.2.6 Long-Term Operation and Maintenance Requirements

Long-term O&M requirements, which are not incorporated in the above labor hours calculation, include:

- Add lubrication to the bearing's grease fittings.
- Check wiring and motors for loose electrical connections and melted cable housing. The high surface temperatures of the machine emit enough radiation to

melt cable housing on and around the machine, which may short wire connections.

- Clean the fins on the cooling auger radiator to improve heat transfer effectiveness.
- Replace equipment as it wears out.

Under this project, BSI has developed a field-ready toolbox, which includes tools and equipment required for ongoing and occasional maintenance in the field. Documentation of this toolbox is provided in Appendix H.

### 4.3 Energy Consumption

The biochar machine requires consistent electrical power and occasional heat input from a propane torch. As described in the following subsection, the electric demand is a function of operational conditions such as reactor bed depth, and the propane demand is a function of feedstock moisture content.

#### 4.3.1 Electricity Demand

Electric power demand during steady state for each test run is shown in Figure 17, below. Across all feedstocks, the 100-second interval power demand ranged from 3 kW to 26 kW with an average of 12 kW.

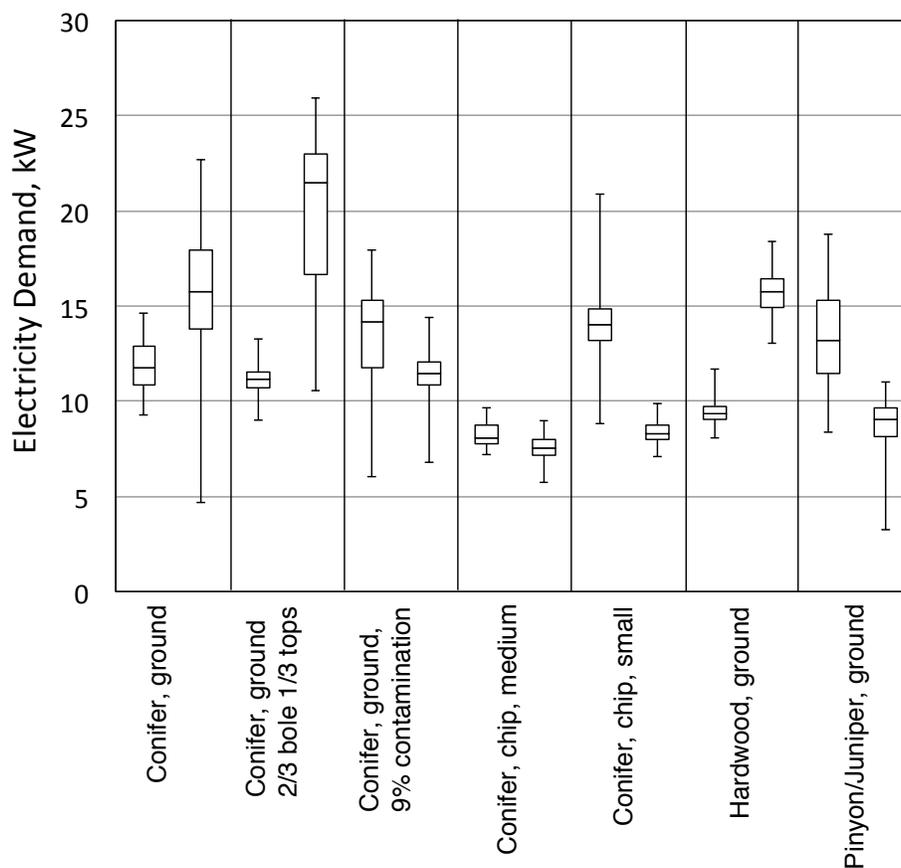


Figure 17. Distribution of 100-second interval average electricity power demand. The two sets of values for each feedstock represent duplicate test runs on different days.

There is significant variation across different feedstocks and even between duplicate tests of the same feedstock. The electric power demand was not strongly correlated to any of the measured variables, but a weak correlation was found between biochar production rate and average electric power demand ( $R^2 = 0.34$ ), as shown in Figure 18. SERC researchers hypothesize that the variation observed in electric power demand is mostly a function of 1) bed depth in the reactor and 2) the operator's learning curve. Firstly, the bed depth influences the kinetics of biochar production but also impacts the electricity consumption of the machine. With a higher bed depth, the reactor blower has to overcome a larger pressure drop and the stirrer motor has to rotate a greater mass, both of which increase the energy consumption even if the motor speed is constant. Bed depth was not consistently recorded, and thus this hypothesis could not be confirmed. Secondly, as SERC staff worked through the tests, they continually learned new techniques at improving operational conditions. Before testing began, the operators decided their objective was to operate the machine to produce the highest quality biochar in each test rather than operating the machine under the exact same conditions during each run. As the operators gained experience, different reaction conditions were realized and often different bed depths were used.

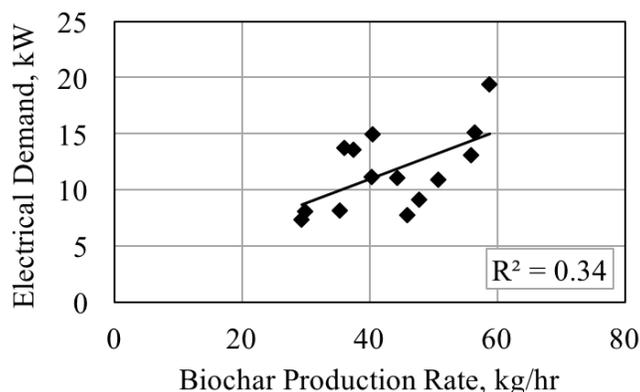


Figure 18. Relationship between average electricity demand and biochar production rate.

Overall, the set of electrical power demand data collected represents a realistic range of loads that could be expected with this machine in the field. Based on these data it is not clear if feedstock quality influences power demand because it appears that operational conditions, such a reactor bed depth, have a greater influence on the load profile.

#### 4.3.2 Propane Consumption

A small amount of propane is required to operate the machine. During steady state operation with a good quality feedstock, external heat is not required because the reaction is autothermal. Thermal input is required to start the machine in order to initiate combustion in the reactor and to ignite the flare. Propane is also occasionally used during steady state operation to add heat to the reactor. Propane consumption was found to be a function of feedstock moisture content, as shown in Figure 19. The clear outliers are the pinyon/juniper tests, which were relatively dry but required more propane than would be expected due to their high level of contamination.

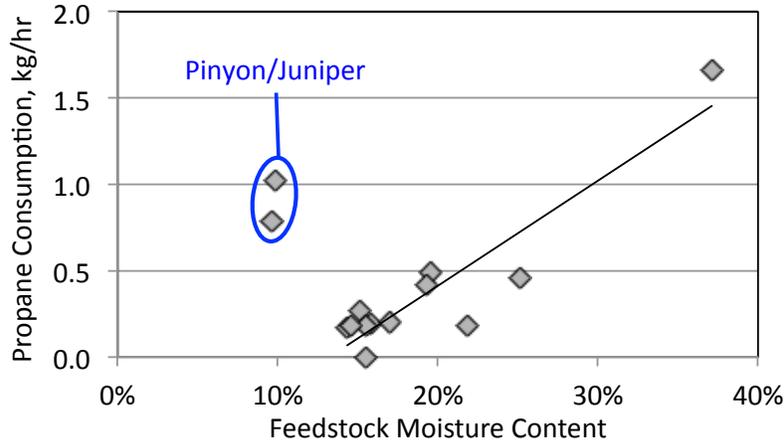


Figure 19. Propane consumption as a function of feedstock moisture content. The trendline does not include the two highly contaminated pinyon/juniper tests.

#### 4.4 Heat Production

Waste heat is emitted from the stack at temperatures averaging around 750°C and an average flow rate of 330 SLPM. Chemical energy is also emitted from the stack in the form of carbon monoxide and unburned hydrocarbons (see discussion below in Section 4.6). The average rate of waste heat production is 360 kW while the average rate of chemical energy production is 93 kW. Figure 20 shows the distribution of the total power emitted from the stack during steady state including thermal and chemical energy emission rates. The thermal power includes heat exiting the stack and heat transferred to air passing through the dryer heat exchanger. Thermal power is calculated as the rate of energy that can be extracted from the gas by cooling it to 25°C. Chemical power is calculated on a higher heating value basis.

Waste heat conversion devices could allow the conversion of some of this waste power into electricity. These machines, such as organic Rankine cycles (ORC) or thermoelectric generators, operate at efficiencies typically less than 10%. The median electricity demand (Figure 17) ranges from 1.3% to 5.0% of the median waste power production for each test run, which means that heat to electricity efficiencies less than 10% would be able to meet the demand in the median. However, when comparing the maximum electrical demand to the minimum waste heat production for each test run, the values range from 2.7% to 85%. This quick comparison shows that on average there may be enough waste heat to provide all the electricity to the machine during steady state, but without thermal or electrical storage waste heat will not be able to offset the entire electrical load at corresponding peaks and troughs. Furthermore, for start up and shutdown, when there is little to no waste heat available, the biochar machine will need supplemental electrical storage or secondary fuel utilization such as diesel or propane.

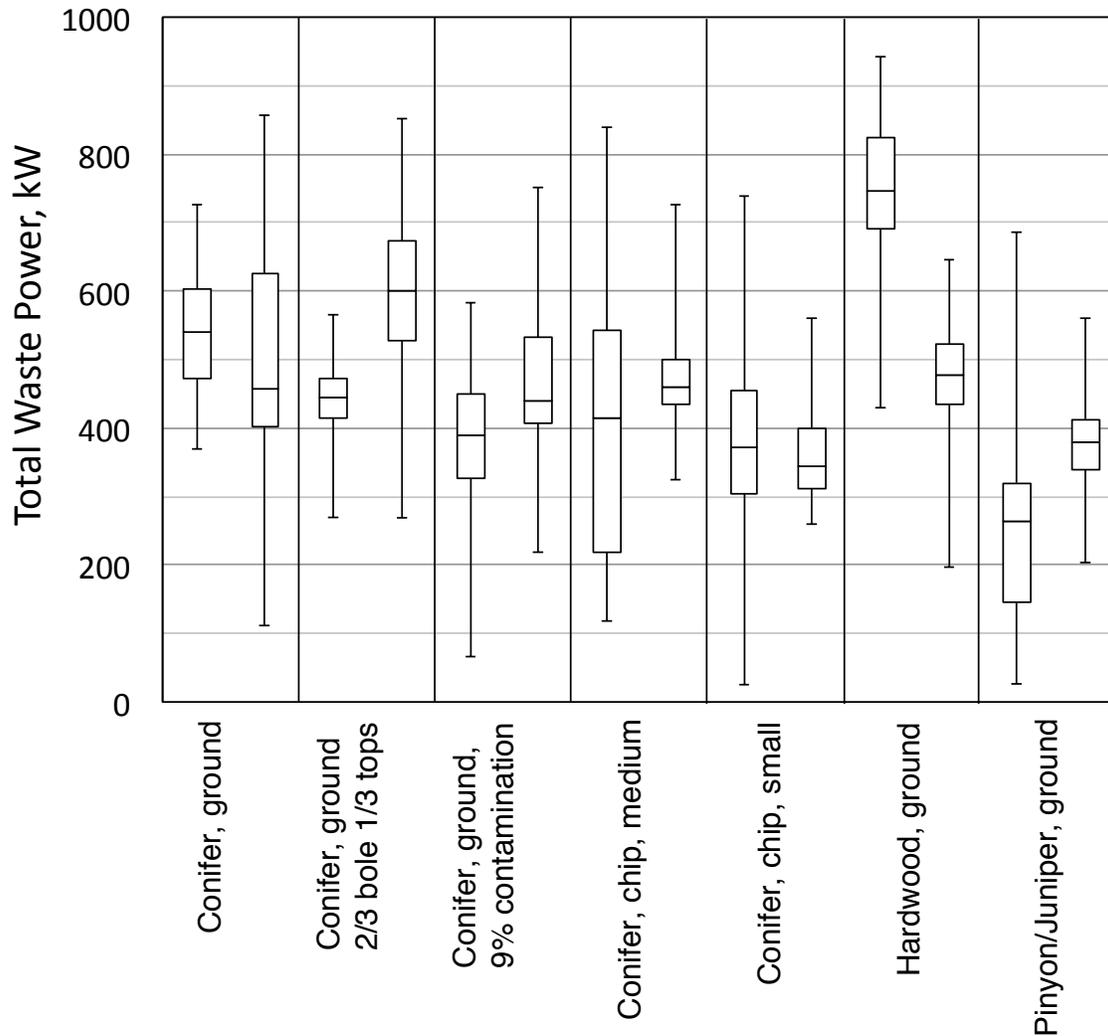


Figure 20. Distribution of total power emitted from stack during steady state including thermal and chemical power. The two sets of values for each feedstock represent duplicate test runs on different days.

Schatz Energy Research Center conducted an economic and technical analysis and determined that it is not viable to use waste heat for production of electricity to operate the machine (report forthcoming). Based on that analysis, it is more cost effective to use a dedicated biomass gasifier to produce electricity and use the waste heat to dry incoming feedstock. These results are mainly influenced by 1) the complexity of the waste-heat-to-power system, which would require energy storage and a supplemental fuel source, and 2) from the currently high market prices and low efficiencies of ORC generators.

#### 4.5 Dryer Heat Demand

The original batch dryer installed on the biochar machine was ineffective because the biomass was in a fixed bed and the inlet air to the dryer was hot enough to burn the wet feedstock. First, the dryer was a fixed bed batch reactor in a five cubic yard dumper hopper. Wet biomass was loaded onto a grate welded into the bottom of the hopper and

hot air was ducted into the bottom of the hopper beneath the grate. Second, the heat exchanger in the biochar exhaust stack produced gas at average temperatures of 210°C, which was too hot for a fixed bed and resulted in biomass combustion in the dryer hopper.

SERC and BSI collaborated to design a concept for a new heat exchanger to provide air at 100°C to the batch dryer. SERC engineers provided heat exchanger sizing calculations and BSI developed the exact design. The memo and calculations provided by SERC to BSI are included in Appendix I. BSI built and installed a new heat exchanger before shipping the biochar production unit to RFFI. Ongoing testing activities for this project are scheduled for Spring 2016 to investigate the effectiveness of a new dryer design.

#### 4.6 Emissions

Emissions from the flare exhaust were relatively high in CO, propane, NO<sub>x</sub>, and SO<sub>2</sub>. Emission data measured with a continuous gas analyzer (Enerac M700) for CO, CO<sub>2</sub>, propane, and O<sub>2</sub> are shown in Table 3. The gas analyzer was also equipped with NO<sub>x</sub> and SO<sub>2</sub> sensors, but these sensors were continually oversaturated because there was more NO<sub>x</sub> and SO<sub>2</sub> in the gas stream than the analyzer was calibrated to measure. The maximum readings for the sensors were 150 ppm, 600 ppm, and 150 ppm for NO, NO<sub>2</sub>, and SO<sub>2</sub>, respectively. The stack gas was likely over these thresholds for the majority of the testing period. A detailed specifications sheet for the exhaust gas analyzer is provided in Appendix J.

Table 3. Average exhaust gas emissions on a dry gas basis.

	Test #	CO, mole %	CO <sub>2</sub> , mole %	Propane, ppm	O <sub>2</sub> , mole %
Conifer, ground	1	4.8%	17.0%	401	0.3%
	2	2.9%	16.0%	254	2.6%
Conifer, ground, 1/3 tops	1	5.5%	16.6%	547	0.4%
	2	4.7%	17.2%	360	0.1%
Conifer, ground, 9% contaminant	1	3.2%	16.7%	213	1.1%
	2	1.7%	15.6%	102	2.9%
Conifer, chip, medium	1	2.8%	11.2%	634	7.3%
	2	1.4%	17.7%	101	1.1%
Conifer, chip, small	1	1.2%	14.2%	127	0.3%
	2	1.7%	17.2%	163	2.6%
Hardwood, ground	1	9.6%	15.9%	1150	0.8%
	2	3.0%	17.8%	188	0.3%
Pinyon/Juniper, ground	1	0.51%	11.5%	207	8.4%
	2	1.1%	17.3%	60	2.1%

High levels of CO and propane are attributed to low levels of oxygen and incomplete combustion in the flare. To determine the appropriate flow rate of air into the flare, a second blower was connected to the flare air inlet temporarily for a test. The results from this experiment are shown in Figure 21. The data point at 400 scfm is where the unit typically operates without an auxiliary blower. At this point there is no excess oxygen exiting the top of the stack. As the auxiliary blower motor is sped up, oxygen begins to be detected at the outlet around 700 scfm. By an air flow rate of 1,100 cfm, the CO,

C<sub>3</sub>H<sub>8</sub>, and SO<sub>2</sub> emissions are essentially eliminated. The bottom chart in Figure 21 shows that, even though the temperature decreases as additional air is added, the waste heat production actually increases with a higher air flow rate.

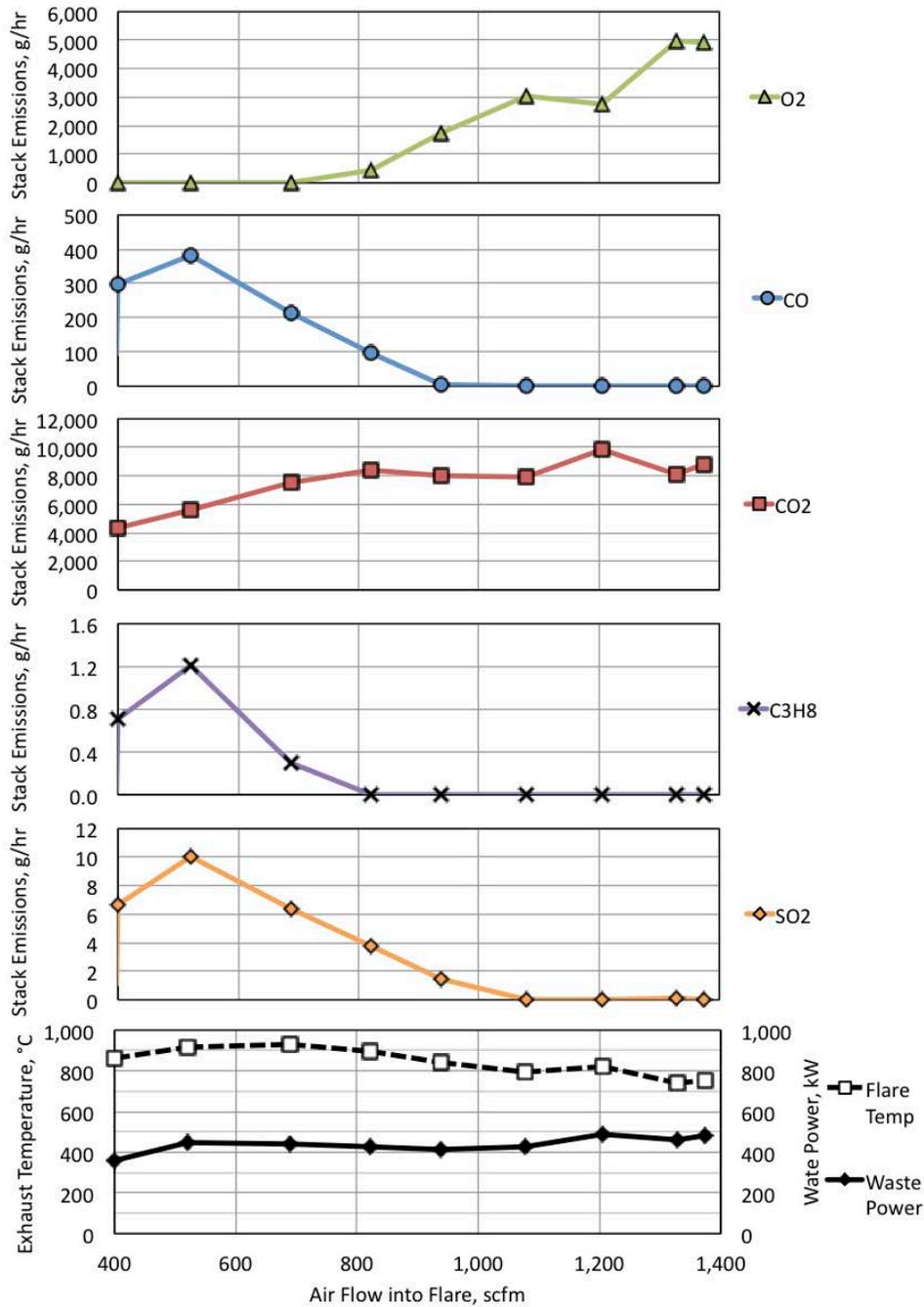


Figure 21. Gas emission rates, exhaust gas temperature, and waste heat production as a function of fresh air flow rate into the flare.

#### 4.7 Fire Hazard

Fire hazards were observed in several areas, which are detailed below.

- Embers emitted from the stack fell throughout the surrounding area based on the wind speed and direction. The embers were emitted frequently and burned holes through fabric, paper, and tarps. Adding a spark arrestor to the top of the exhaust stack could reduce or eliminate this hazard. BSI has built and installed a spark arrestor on this machine for RFFI. Verification and testing of this addition are currently in process.
- Biomass dust collected around the machine extending approximately 15 feet away from the machine's edges. The dust primarily collected around the conveyor when loading the feed hopper or when the conveyor was in use, see Figure 22. The dust accumulated up to 1" in depth. This dust poses a problem because embers from the stack or other ignition sources can easily ignite them. In one situation, a smoldering patch of dust was found on the ground near the reactor during testing. It was likely ignited by a falling ember.



Figure 22. Dust collection around the conveyor after three weeks of use.

The fire risk from dust can be mitigated proactively by reducing material loss from the feed hopper and conveyor or retroactively by cleaning the worksite on a daily basis.

- A dust cloud can form above the reactor between the top of the bed and the bottom of the conveyor. One observation noted that a dust cloud above the reactor was on fire but self extinguished as the dust turned to ash. This poses a serious risk to operators. Figure 23 shows a picture looking down into the reactor and feedstock bed with a noticeable amount of dust suspended in the air.



Figure 23. Picture from top of reactor looking downward. Notice the flame front extending upwards and dust suspended in the air. Biomass also collects on the top of the stir bar and the corners of the reactor inlet as seen in the top right and bottom left of the picture, respectively.

The risk can potentially be abated as long as the reactor blower has enough force to draw any dust that accumulate above the reactor into the chip bed. This technique will not completely eliminate this risk, however, which is inherent in any machine with fine, flammable particles, hot surfaces, and open flames. Alternatively, feedstock can be screened before use to eliminate dust, which would have the additional effect of reducing feedstock ash content.

- Biochar exits the machine into the collection drums at temperatures over 200°C, as shown in the infrared image in Figure 24. After removing the drum, operators at BSI add water to the drum to reduce the temperature of the biochar then seal the top of the drum. If the biochar were not cooled directly with water, it would smolder and turn into ash, which poses fire risk. Since water is expensive and not easily accessible at forest operations sites, this is not the ideal solution for biochar cooling. In addition, adding water to the biochar drum degrades its quality and reduces the heating value on a mass basis.



Figure 24. Infrared image of biochar collection with temperatures up to 261°C.

To mitigate this problem, the biochar cooling system needs to be more effective. The current system recirculates water in an exterior jacket on the biochar auger. Heat from the water is dumped to the air with a radiator. This radiator is ineffective at removing heat because it is mounted vertically and only utilizes free convection. Repositioning and/or redesigning this heat dump to used forced air cooling could mitigate this fire hazard.

- The reactor can backfire when a small syngas explosion occurs between the reactor and the flare and forces feedstock in the reactor to fly upwards. This creates a risk for both the surrounding environment and the operator. This backfiring was observed when the pathway between the reactor and the dropbox became clogged due to ash and slag buildup during various test runs. As the clog is developing, the first sign is that the flow rate in the exhaust stack begins to decrease. This was observable during testing with the flow meter installed on the stack. However, during normal operations there is no flow meter to provide advanced notice of a clog. A clog can be overcome if the operator catches the situation ahead of time and increases the speed of the reactor blower. Otherwise, the operator will notice the flare go out due to a lean mixture in the stack. If the system clogs, syngas flow in the reactor stagnates because syngas is no longer being drawn down through the reactor. In this state, oxygen, syngas, and heat can combine in the machine causing an explosion that sends feedstock and embers out of the top of the reactor. The best ways to mitigate this issue are to perform regular clean outs and de-coking to reduce the buildup that causes clogging and to train the operator to identify a clog in the early stages. As an additional measure, an alarm could be configured if an exhaust stack flow meter was added to the machine.
- The original dryer system posed a fire risk because the air going to the dryer was so hot that it would burn the biomass in the dryer. Figure 25 shows an example of the dryer hopper after catching on fire. After attempting to use the dryer twice with inlet gas over 200°C and noticing combustion in the dryer, dryer testing was aborted due to the hazard. The dryer system was redesigned (see Appendix I) by BSI before shipping the unit to RFFI. Based on the latest observations, this risk has been eliminated.



Figure 25. Dryer hopper being transported away from the biochar production machine after combustion started. Notice the smoke rising from the air inlet port.

## 5 DISCUSSION

This section provides a brief discussion of the results presented above.

### 5.1 Feedstock and Biochar Quality

Based on the test results outline above, the biochar machine has a wide range of acceptable feedstocks. The main requirements are that the feedstock have less than 25% moisture content and less than 15% ash content. Ash or moisture content levels above these specifications require substantially more labor to process and, furthermore, negatively impact the fixed carbon content of the biochar. In addition, ash content above 15% leads to frequent clogging in the machine, which can cause safety hazards such as explosions or backfiring in the reactor.

If these quality specifications are not met, the feedstock should be dried or screened before use. If less than 25% moisture content cannot be achieved through harvesting methods and seasonal drying, a dryer could be integrated with the biochar machine to use waste heat as thermal input to the dryer. Feedstocks exceeding the 15% ash content threshold should be screened to remove the fine particles, which are typically higher in ash content. By integrating a dryer and a screener into the biochar production facility, the range of acceptable feedstock can be increased.

In addition to using biochar as a soil amendment, it also has potential value as an energy product due to its high energy density on a mass basis. The market for biochar/biocoal as a soil amendment or energy product will dictate the economics of utilizing this machine in conjunction with timber harvesting operations.

### 5.2 Operational Intensity

There are several technical improvements that could be made to reduce the operational intensity of the biochar production machine, some of which are currently in development. A few labor-reducing improvements are outlined below:

- Install an automated feed control to move biomass from the feed hopper onto the conveyor. Currently, one of the most time consuming tasks for the operator is to push feedstock from the feed hopper onto the conveyor. One potential solution is to place an auger at the bottom of the feed hopper than can be turned on and off by the operator instead of manually moving the material with a shovel. RFFI has independently developed an automated feed unit for their unit for commercial operations in Northern California.
- As tested, the operator had to watch the reactor bed depth to maintain an acceptable level. BSI is currently developing an automated level control system, which will maintain a specified bed depth by automatically loading feedstock into the reactor. This improvement will also address the previous bullet point by automatically loading the reactor.
- Improving the effectiveness of the char cooling auger such that char exits near ambient temperature and does not pose a fire hazard. By making this improvement, water consumption to cool the biochar will be avoided and operator labor will be reduced by requiring less steps to package the char. Furthermore, if char exits near ambient temperature, it can be loaded directly into supersacks instead of steel drums which will decrease the shipping weight and increase transportation efficiency.
- Adding a propane inlet and electronic ignition to the flare and reactor will reduce labor required for start-up and remove potential safety hazards for the operator. These improvements would allow the operator to ignite the flare remotely and to add heat to the reactor without standing directly above it.

Including these technical improvements to help automate the machine and reduce labor requirements will allow one operator to run the machine more effectively while simultaneously making it safer.

### **5.3 Stand Alone Operation**

Meeting the electrical demand of the machine with waste heat may be possible during periods of steady state operation. However, meeting peaks in electrical demand and startup and shutdown requirements with a waste heat to power device is not feasible without some sort of energy storage device.

The most feasible options for power generation are to use either a diesel or syngas generator. A small gasifier can be operated with a sidestream of biomass to produce syngas fuel for a generator. Future testing will verify the capabilities of a gasifier generator set and, based on this success, will be connected to the biochar machine directly for testing at a remote field site.

### **5.4 Fire Hazard Mitigation**

The fire hazards and potential ways to mitigate the risks are described in Section 4.7, above. Possible mitigation measures for each risk are summarized here in Table 4.

Table 4. Summary of fire hazards and mitigation measures.

<i>Fire Risk</i>	<i>Mitigation Measure</i>
Embers emitted from stack	Install spark arrestor
Dust collection around machine	Clean machine daily Install dust collection device around conveyor Screen out fine particles before feed hopper
Dust cloud above reactor	Install dust collection device above reactor Screen out fine particles before feed hopper
Biochar exits machine very hot	Reposition radiator for biochar auger cooling system
Reactor backfire	Perform regular clean outs and decoking to avoid clogs Install flow meter in stack to detect clogs
Dryer air burns chips	Reduce dryer heat exchanger outlet air temperature

## 6 FUTURE WORK

BSI will continue to develop their process and technology. Following the Statement of Project Objectives, Subtask 2.1, BSI will:

- add automated feedstock loading into the reactor to maintain bed depth and reduce operator effort,
- develop and add stack fire protection to improve fire safety in field operations, and
- double the throughput capacity of the unit.

Future reports will document the implementation and results from these tasks.

The majority of SERC's data collection on the biochar production machine is complete, but real world operational data will be collected in field conditions during operation by RFFI in northern California. Data collection will primarily focus on:

- labor-hours required with actual operators and
- feedstock input and biochar production rates.

During spring 2016, SERC will test an integrated, stand-alone system that incorporates a belt dryer to dry incoming feedstock and a 20kW gasifier generator to produce electricity for the system. A preliminary flow diagram for this test system is shown below in Figure 26, which is modeled after the BSI biochar machine, the All Power Labs PP20GT gasifier, and a Norris Thermal Technologies Belt-o-matic dryer.

In this flow diagram, the brown shaded ovals represent biomass flow rates, and the percentage value indicates their moisture content. The white oval with black outline is biochar output from this process. Thin black arrows connect material flow through the machines and wide, shaded arrows show thermal and electrical energy flows.

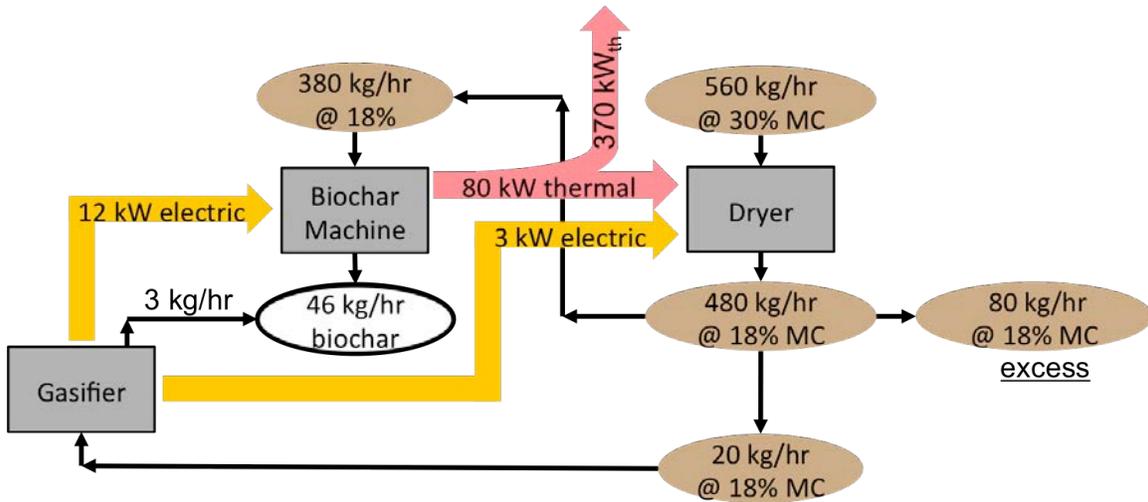


Figure 26. Flow diagram of stand-alone biochar production system. Biomass flow rates (wet basis) are shown as brown shaded ovals where the percentage value indicates the moisture content.

Biomass at 30% moisture content enters the dryer, which reduces the moisture content of the biomass by using 80 kW of waste heat from the biochar machine. Biomass exits the dryer at 18% moisture content and is diverted in three directions: 380 kg/hr to the biochar production machine, 20 kg/hr to the gasifier to produce electricity for the process, and 80 kg/hr are left over. The biochar machine converts produces 43 kg/hr of biochar and the gasifier produces 3 kg/hr of biochar as a byproduct.

## 7 CONCLUSION

In conclusion, this testing outlined performance characteristics and minimum feedstock specifications for the biochar production machine. The results indicate that:

- The feedstock should have less than 25% moisture content and less than 15% ash content to produce acceptable biochar and keep required labor at a minimum.
- Average feedstock consumption is 380 kg/hr with an average biochar production rate of 43 kg/hr.
- Electrical power requirements for this machine must be able to sustain the 12 kW average electrical demand while meeting the 26 kW peak demand.
- Propane consumption, typically less than 0.5 kg/hr, increases with feedstock moisture content.
- Waste heat is emitted at an average rate of 450 kW at approximately 750°C from the exhaust stack. Using a waste heat-to-power device to generate electricity for this machine it is not cost effective when compared to a biomass gasifier or diesel generator. The best use of waste heat is to dry incoming feedstock.
- Gaseous emission of CO, propane, NO<sub>x</sub>, and SO<sub>2</sub> from the stack were relatively high, but they can be reduced to acceptable levels by increasing the amount of combustion air in the flare.

- During testing the machine posed a moderate fire hazard. Measures to address these potential fire risks have been outlined in this report and, if addressed successfully, the machine should be suitable for field operation.

Additional work on the biochar machine will continue in 2016. Parameters such as labor hours and throughput rates will be measured while the machine is in commercial operation by RFFI during their 2016 season.



## 8 REFERENCES

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## APPENDIX A PIPING AND INSTRUMENTATION DIAGRAM

A piping and instrumentation diagram (P&ID) of the biochar unit with the data collection equipment is shown in Figure A.1. A description of the equipment used for each measurement is described in Table A.1. The instruments shown in dark blue in Figure A.1 were channeled through a National Instruments data acquisition system and written to a file in real-time with LabVIEW software. The measurements obtained from the instruments shown in light orange in Figure A.1 were collected manually and recorded on the data collection form shown in Appendix B.



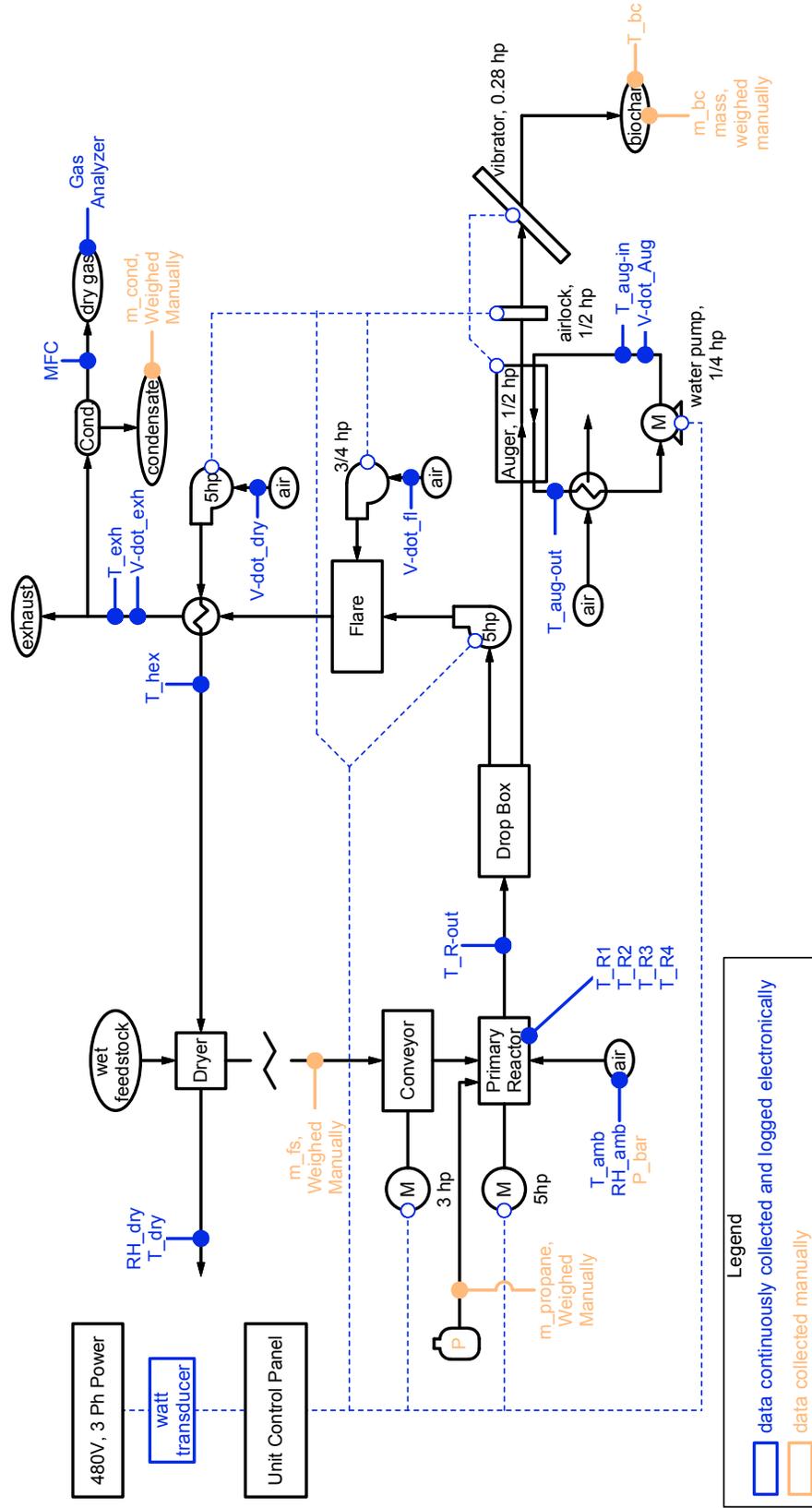


Figure A.1. Piping and instrumentation diagram of biochar production machine with added data collection instrumentation provided by SERC

Table A.1. Description of data collection instrumentation.

<i>Sensor Name</i>	<i>Parameter</i>	<i>Manufacturer</i>	<i>Part Number</i>	<i>Specifications</i>
Gas Analyzer	Gas composition of exhaust gas	Enerac	M700	0-25% O <sub>2</sub> , 0-20% CO <sub>2</sub> , 0-15% CO, 0-3% ppm C <sub>3</sub> H <sub>8</sub> , 0- 600 ppm NO, 0-150 ppm NO <sub>2</sub> , 0-650 ppm NO <sub>x</sub> , 0-150 ppm SO <sub>2</sub>
m_bc	Mass of biochar exiting machine	Pelouze	Model 4040	0-400±0.5 lb
m_cond	Mass of condensate collected from wet gas sample	Adam Equipment ACBplus 600H (0.02 g resolution)	ACBplus	0-600±0.02 g
m_fs	Mass of feedstock	Truck scale	n/a	20 lb resolution
m_propane	Mass of propane consumed during test	Pelouze	Model 4040	0-400±0.5 lb
MFC	Mass flow of dry gas to gas analyzer	MKS	1179A53 CS1BB-S	0-2000 sccm
P_bar	Atmospheric pressure	Omega	OM-CP- PRHTEM P101	0-30 psia
RH_amb	Ambient relative humidity	Omega	HX92BC- RP1	0-100%RH
RH_dry	Relative humidity of air directly above biomass in dryer	Omega	HX93BC- RP1	0-100%RH
T_dry	Temperature of air directly above biomass in dryer			-30-75°C
T_amb	Ambient temperature	Omega	KQSS- 116U-12	Type K Thermocouple probe, °C
T_aug-in	Surface temperature of cooling water tubing upstream of auger before entering radiator	Omega	SA1XL- K-SRTC	Type K Thermocouple surface mount, °C
T_aug-out	Surface temperature of cooling water tubing downstream of auger	Omega	SA1XL- K-SRTC	Type K Thermocouple surface mount, °C
T_bc	Temperature of biochar at auger exit	Omega	KQSS- 116U-12	Type K Thermocouple probe, °C

<i>Sensor Name</i>	<i>Parameter</i>	<i>Manufacturer</i>	<i>Part Number</i>	<i>Specifications</i>
T_exh	Temperature of exhaust stack gas	Omega	CASS-116U-12-NHX	Type-K thermocouple, ceramic connectors, °C
T_hex	Temperature of dryer air at heat exchanger outlet	Omega	CASS-116U-12-NHX	Type-K thermocouple, ceramic connectors, °C
T_R1	Surface temperature of inner reactor in top quadrant	Omega	KQSS-116U-12	Type K Thermocouple probe, °C
T_R2	Surface temperature of inner reactor in middle-top quadrant	Omega	KQSS-116U-12	Type K Thermocouple probe, °C
T_R3	Surface temperature of inner reactor in middle-bottom quadrant	Omega	KQSS-116U-12	Type K Thermocouple probe, °C
T_R4	Surface temperature of inner reactor in bottom quadrant	Omega	KQSS-116U-12	Type K Thermocouple probe, °C
T_R-out	Internal temperature of tube connecting reactor to drop box	Omega	KQSS-116U-12	Type K Thermocouple probe, °C
V-dot_Aug	Cooling water volumetric flow rate	Omega	FTB4607	Paddle Flowmeter, 0.22 – 20 US gpm
V-dot_dry	Air flow into dryer heat exchanger blower	Nailor	36 FMS, 6"	Averaging pitot tube, 0-500 cfm
		Dwyer	616-2	Pressure Transducer, 0-6 in w.c.
V-dot_exh	Air flow out of exhaust stack	Nailor	36 FMS, 18"	Averaging pitot tube, 0-4800 cfm
		Dwyer	616-2	Pressure Transducer, 0-6 in w.c.
V-dot_fl	Air flow into flare air inlet blower	Nailor	36 FMS, 4"	Averaging pitot tube, 0-215 cfm
		Dwyer	616-2	Pressure Transducer, 0-6 in w.c.
Watt Transducer	Power Consumption	Continental Control Systems, LLC	WNB-3D-240-P	0-200 A with current transformers

## APPENDIX B EXAMPLE WRITTEN DATASHEET

An example hand written datasheet collected during test 6A is shown below in Figure B.1.

General								
Run Code: <b>6A</b>	Date: <b>8/6</b>	Weather Conditions: <b>Mostly clear, Med Hot</b>	Operators: <b>DC, MM, MS, Alan</b>					
Time								
Run Start Time: <b>0940</b>	SS Start Time: <b>1034</b>	SS End Time: <b>11:50</b>	Run End Time: <b>1206</b>					
Feedstock								
Feedstock (Type/Size/%Tops): <b>Conifer, 5-7" screen no tops, 60% bark</b>	Feedstock Mass: <b>1140#</b>	Moisture Content Spot Check (Low/Average/High): <b>7.5% / 45.3% / 34.6%</b>						
Contamination								
Contaminant Type: <b>none</b>	Contaminant Mass: <b>-</b>	Clean Out After Test?:	Contaminant Mass Cleaned Out:					
BioChar Production								
Barrel	Type	Start Time	End Time	Tare #	Final #	Total	Temperature	
<b>N</b>	<b>chip + dust</b>	<b>0940</b>	<b>1104</b>	<b>35.0</b>	<b>83.5</b>		<b>125-150°C surf. 160-185°C R<sup>o</sup></b>	
<b>sample 6A</b>	<b>chip + dust from 6A</b>	<b>→</b>	<b>1115</b>			<b>500g</b>		
<b>M</b>	<b>chip + dust</b>	<b>1104</b>	<b>1132</b>	<b>34.5</b>	<b>87.5</b>		<b>45-65°C surf 225-260°C 12"</b>	
<b>L</b>	<b>chip + du</b>	<b>1132</b>	<b>1150</b>	<b>32</b>	<b>60.0</b>		<b>45-65°C surf 225-260°C 12" 87-140°C 0" 220-225°C 12"</b>	
Motor Speeds				Propane		Flare		
Time	Mode	Stirrer	Reactor	HEX	Mass	Time	Status	Time
<b>940</b>	<b>SS start</b>	<b>1</b>	<b>5.5</b>	<b>7</b>	<b>25.0 w/ hose</b>	<b>run start</b>	<b>on</b>	<b>SS start</b>
					<b>27.5 w/ hose</b>	<b>run end</b>	<b>on</b>	<b>entire time</b>
					<ul style="list-style-type: none"> <li>• used ? twice on ret</li> <li>• light flare pre SS</li> <li>• none during SS</li> </ul>			
Checklist								
<input checked="" type="checkbox"/> Feedstock Sample	<input checked="" type="checkbox"/> BioChar Chip Sample	<input checked="" type="checkbox"/> BioChar Dust Sample						
<input checked="" type="checkbox"/> Contaminant Sample	<input checked="" type="checkbox"/> Reactor IR Image	<input checked="" type="checkbox"/> Stack IR Image						
<input checked="" type="checkbox"/> BioChar IR Image	<input checked="" type="checkbox"/> Dryer IR Image							
Stack Gas Condensate								
Start Time: <b>1036</b>	End Time: <b>1150</b>	Tare Mass: <b>1578.23g</b>	Final Mass: <b>31.64g</b>	Final Mass: <b>1572.29g</b>	Sample Collected? Yes / <input checked="" type="radio"/> No			

GREAT RUN. EASY. NO PROBLEMS

Figure B.1. Datasheet collected during test 6A with ground conifer.

## APPENDIX C STACK GAS CONDENSATE SAMPLES

Figure C.1 shows an image of the four stack gas condensate samples taken during the testing. There are no current plans to analyze these samples. The main conclusion from observation of these samples is that there is some particulate matter and many more condensables in the condensate besides water.



Figure C.1. Samples of stack gas condensate from test runs 1A, 1B, 3A, and 5A (from left to right).

## APPENDIX D DATA ANALYSIS METHODS

This section describes the theory and calculations used to calculate mass and energy flows through the machine using measurements collected with the sensors described in Table A.1 Appendix A above.

### D.1 Correcting Volumetric Flow Rate Measurements from Pitot Tubes

Pitot tubes were used to measure the gas velocity at the inlet to the dryer air blower, the inlet to the flare air blower, and the outlet of the exhaust stack. There were four pairs of ports on each pitot tube to measure upstream and downstream pressure across a cross section of the duct. All four pairs of ports were connected to the one pair of outlet tubes used to measure an average differential pressure.

Each pitot tube was issued from the factory with a calibration factor,  $K$ , which correlates the differential pressure to a volumetric flow rate in the form of

$$\dot{V} = K\sqrt{\Delta P} \quad (\text{D.1})$$

where

$\dot{V}$  is the volumetric flow rate [acfm],

$K$  is the factory-issued calibration factor [ $\text{cfm} \cdot \text{in} - \text{wg}^{-0.5}$ ], and

$\Delta P$  is the differential pressure [in-wg].

The specifications and calibration factors are listed in Table D.1.

Table D.1. Pitot tube specifications.

Location	Design Duct Diameter	Factory Calibration Factor, $K$ [ $\text{cfm} \cdot (\text{in} - \text{wg})^{-0.5}$ ]	Measure d Duct Diameter	Pitot Tube Constant, $c$
Flare Air	4"	215	4"	0.6141
Dryer Air	6"	500	6.25"	0.6347
Stack Gas	18"	4800	18.08"	0.6770

According to the pitot tube manufacturer the calibration factors were determined by measuring the volumetric flow rate when the pitot tube has a differential pressure of 1 in-wg with air at standard temperature and pressure (STP) (Nailor, 2014). The factory-issued calibration factor, therefore needs to be corrected to reflect the actual temperature and pressure at the test site, the measured duct size at the installation location, and the actual gas composition through the duct. To perform this adjustment, the pitot tube constant,  $c$ , must be calculated to reflect the real parameters at the site by backing out the factory-issued calibration factor,  $K$ .

The general formula to calculate the volumetric flow rate from a pitot tube is derived from Bernoulli's equation as

$$\dot{V} = A_{CS} \sqrt{\frac{2 \cdot \Delta P}{\rho}} \quad (\text{D.2})$$

where

$A_{CS}$  is the cross sectional area of the duct [ $\text{ft}^2$ ] and

$\rho$  is the density of the fluid [ $\text{lb} \cdot \text{ft}^{-3}$ ]

This equation is expanded to reflect unit convention and to calculate the actual fluid density as

$$\dot{V}[\text{cfm}] = \pi \left( \frac{D[\text{in}]}{2 \left[ \frac{12 \text{ in}}{\text{ft}} \right]} \right)^2 c \sqrt{\frac{2 \cdot \Delta P[\text{in} - \text{wg}] \left[ \frac{\text{lb}_f}{\text{in}^2} \right] \left[ \frac{144 \text{ in}^2}{\text{ft}^2} \right]}{\frac{P \left[ \frac{\text{lb}_f}{\text{in}^2} \right] \left[ \frac{144 \text{ in}^2}{\text{ft}^2} \right]}{1545 \left[ \frac{\text{ft} \cdot \text{lb}_f}{\text{lbmol} \cdot ^\circ \text{R}} \right]} \cdot \left( T[^\circ \text{C}] \frac{9[^\circ \text{F}]}{5[^\circ \text{C}]} + 32 + 459.7[^\circ \text{R}] \right)} \left[ \frac{\text{lb}_f}{32.17 \frac{\text{lb}_m \cdot \text{ft}}{\text{s}^2}} \right]} \quad (D.3)$$

where

$D$  is the inner diameter of the duct [in],

$c$  is the pitot tube constant [unitless],

$P$  is the absolute static pressure [ $\text{lb}_f \cdot \text{in}^{-2}$ ],

$M$  is the molar mass of the gas [ $\text{lb}_m \cdot \text{lbmol}^{-1}$ ], and

$T$  is the temperature of the gas [ $^\circ \text{C}$ ].

The pitot tube constant,  $c$ , is calculated by entering the values from the factory issued test with dry air ( $M = 28.97 \text{ lb}_m/\text{lbmol}$ ) at STP ( $P = 14.70 \text{ psi}$ ,  $T = 70^\circ \text{F}$ ), substituting 1 in-wg for  $\Delta P$ , and setting  $\dot{V}$  equal to  $K$  for each respective duct diameter,  $D$ . The calculated unitless pitot tube constants are shown in Table D.1 above.

After calculating the pitot tube constants, the volumetric flow rate for each measured data point is calculated using the differential pressure measurement, the ambient air temperature measurement, the absolute pressure measurement, the measured duct diameter, and the calculated molar mass in equation ( D.3 ) above. The method for determining the molar mass is described in the following section.

## D.2 Calculating Molar Mass of Gas through Pitot Tubes

To calculate the molar mass of the air through the dryer blower and flare inlet blower, first, the absolute humidity of the air must be determined. The water vapor pressure can be determined as the product of the measured relative humidity and the saturation pressure of steam at the measured ambient temperature. Following Dalton's law of partial pressures, the ratio of water vapor pressure to total air pressure is equal to the volume percent of water in air. Assuming wet air is an ideal gas, the volume percent is equal to the molar percent. Thus, the molar percent of water vapor in air is equal to

$$x_{H_2O} = \frac{\phi \cdot P_{H_2O, \text{sat}}|_{T_{\text{amb}}}}{P_{\text{total}}} \quad (D.4)$$

where

$x_{H_2O}$  is the mole fraction of water vapor in air,

$\phi$  is the relative humidity,

$P_{H_2O, \text{sat}}|_{T_{\text{amb}}}$  is the saturation pressure of water at ambient temperature [psia], and

$P_{\text{total}}$  is the absolute air pressure [psia].

After calculating  $x_{H_2O}$ , the molar mass of moist ambient air is calculated to be

$$M_{moist\ air} = (1 - x_{H_2O}) 28.97 \frac{lbmol_{air}}{mol} + (x_{H_2O}) 18.0153 \frac{lbmol_{H_2O}}{mol} \quad (D.5)$$

To calculate the molar mass of the stack gas, the complete composition must be estimated. A gas analyzer (Enerac M700) was used downstream of a thermoelectric condenser to measure the composition of dry stack gas. The gas analyzer was capable of measuring O<sub>2</sub>, CO, CO<sub>2</sub>, hydrocarbons, NO<sub>x</sub>, NO, NO<sub>2</sub>, and SO<sub>2</sub>. The following assumptions were made for estimating the dry gas composition:

- The measurements for NO, NO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub>, were ignored due to the sensors being continually saturated during the tests
- The 'hydrocarbon' reading was assumed to be completely propane (C<sub>3</sub>H<sub>8</sub>). This measurement was performed with a non-dispersive infrared sensor reading the IR absorbed around the band for propane
- The difference between 100% and the sum of the concentrations measured on the gas analyzer is assumed to be N<sub>2</sub>.

Therefore, the concentration of CO, CO<sub>2</sub>, O<sub>2</sub>, and C<sub>3</sub>H<sub>8</sub> were measured and the concentration of N<sub>2</sub> was inferred.

The moisture content of the stack gas was estimated by measuring the mass of condensate collected in the condenser upstream of the gas analyzer and measuring the total mass flow rate of dry gas through the gas analyzer, assuming that the condensables are 100% water. The moisture content of the stack gas is calculated as

$$MC_{stack} = \frac{m_{condensate}}{m_{dry\ gas} + m_{condensate}} \quad (D.6)$$

where

$m_{condensate}$  is the total mass of condensate collected during steady state [g] and  
 $m_{dry\ gas}$  is the total mass of dry gas through the gas analyzer during steady state [g].

The total mass of dry gas through the gas analyzer during steady state is determined from volumetric flow rate measurements from a mass flow meter. The mass flow meter used during the tests was calibrated for CO<sub>2</sub> and needs to be adjusted to reflect the actual gas composition because the response of a thermal mass flow meter depends on the heat capacity and density of the gas. A gas correction factor (GCF) is used to adjust the reading from the mass flow controller to reflect the actual composition. A GCF for mixtures of gas is calculated by a method described by the manufacturer, MKS (2014a) The GCF for the dry stack gas is calculated as

$$GCF = \frac{1}{0.7} \left( \frac{0.3106(1.0 \cdot x_{N_2} + 1.0 \cdot x_{O_2} + 1.0 \cdot x_{CO} + 0.941 \cdot x_{CO_2} + 0.88 \cdot x_{C_3H_8})}{x_{N_2} \rho_{N_2} c_{p,N_2} + x_{O_2} \rho_{O_2} c_{p,O_2} + x_{CO} \rho_{CO} c_{p,CO} + x_{CO_2} \rho_{CO_2} c_{p,CO_2} + x_{C_3H_8} \rho_{C_3H_8} c_{p,C_3H_8}} \right) \quad (D.7)$$

where

$x_i$  is the molar fraction of the  $i$ th component on a dry basis,

$\rho_i$  is the density of the  $i$ th component [g/L], and

$c_{p,i}$  is the specific heat capacity of the  $i$ th component [cal/g/°C].

The manufacturer supplied the constants for the above equation (MKS 2014b).

The adjusted mass flow rate is now calculated as

$$\dot{m}_{MFM} = \dot{V}_{MFM} GCF (x_{N_2} \rho_{N_2} + x_{O_2} \rho_{O_2} + x_{CO} \rho_{CO} + x_{CO_2} \rho_{CO_2} + x_{C_3H_8} \rho_{C_3H_8}) \left[ \frac{L}{1000 \text{ cm}^3} \right] \quad (\text{D.8})$$

where

$\dot{V}_{MFM}$  is the uncorrected volumetric flow [scfm] and  
 $\dot{m}_{MFM}$  is the mass flow rate [g/min]

The mass flow rate must be converted to the total mass flow throughout the course of the run because condensate was only collected in one batch throughout the entirety of the test. The total dry gas mass through the mass flow meter is calculated as

$$m_{MFM} = \sum_i \dot{m}_{MFM_i} \Delta t_{1/2_i} \quad (\text{D.9})$$

where

$m_{MFM}$  is the total mass of dry gas going to the gas analyzer over the course of a run [g],  
 $i$  represents an instantaneous data point, and  
 $\Delta t_{1/2_i}$  is half the time between the previous data point and following data point [min],  
 which is calculated as

$$\Delta t_{1/2_i} = \left( \frac{(t_{i+1} - t_i)}{2} + \frac{(t_i - t_{i-1})}{2} \right) \quad (\text{D.10})$$

The moisture content of the stack gas is calculated as the mass fraction of water in the moist sample gas using equation ( D.6 ) above. Before calculating the mole fractions of each component in the stack gas on a wet basis, the moisture content must be converted to the molar concentration of water in the moist sample gas.

$$x_{H_2O} = \frac{\frac{m_{condensate}}{M_{H_2O}}}{\frac{m_{condensate}}{M_{H_2O}} + \frac{m_{MFM}}{M_{stack,dry_{avg}}}} \quad (\text{D.11})$$

where

$x_{H_2O}$  is the mole fraction of water vapor in the sample gas,  
 $M_{H_2O}$  is the molar mass of water [ $\text{lb}_m \cdot \text{lbmol}^{-1}$ ], and  
 $M_{stack,dry_{avg}}$  is the weighted average of the molar mass [ $\text{lb}_m \cdot \text{lbmol}^{-1}$ ] of the stack gas over the course of the test, which is calculated as

$$M_{stack,dry_{avg}} = \frac{\sum_i \left( (\sum_j x_j M_j)_i \Delta t_{1/2_i} \right)}{\sum_i \Delta t_{1/2_i}} \quad (\text{D.12})$$

where

$j$  represents the different gas components that comprise the dry stack gas,  
 $x_j$  is the mole fraction on a dry basis of the  $j^{\text{th}}$  component of the stack gas,  
 $M_j$  is the molar mass of the  $j^{\text{th}}$  component of the stack gas [ $\text{lb}_m \cdot \text{lbmol}^{-1}$ ], and  
 $i$  represents an instantaneous data point.

The molar fraction of each component exiting the stack on a wet basis is now calculated as

$$x_{i,wet} = x_{i,dry} (1 - x_{H_2O}) \quad (\text{D.13})$$

The molar mass of the entire exhaust gas stream on a wet basis is calculated as the weighted sum of the individual gas components.

### D.3 Calculating Energy Content in Stack Gas

The energy content in the stack gas consists of both thermal energy and chemical energy from unburned syngas. To calculate these quantities, first, the volumetric flow rate of stack gas is converted from the actual flow rate at the stack temperature to the flow rate at standard conditions. This way all of the flow rates are in the same units: standard-wet-cubic-feet-per-minute (scfm), where standard refers to 25°C, 14.969 psia. Assuming an ideal gas, the flow rate is converted from acfm to scfm with the ideal gas law, where

$$\frac{\dot{V}_{stack}}{T_{stack}} = \frac{\dot{V}_{std}}{T_{std}} \quad (D.14)$$

The density of the stack gas at standard conditions is determined by

$$\rho_{std} = \frac{P_{std}}{\frac{R}{M_{stack}} T_{std}} \quad (D.15)$$

where

$M_{stack,wet}$  is the molar mass of the wet stack gas [ $lb_m \cdot lbmol^{-1}$ ].

Next, the molar flow rate of gas is calculated as

$$\dot{n} \left[ \frac{mol}{s} \right] = \dot{V}_{std} \left[ \frac{ft^3}{min} \right] \rho_{std} \left[ \frac{lb_m}{ft^3} \right] \frac{1}{M_{stack,wet}} \left[ \frac{lbmol}{lb_m} \right] \quad (D.16)$$

The enthalpy of each gas is calculated at the stack temperature and ambient temperature. Coefficients,  $a_i$ , for the fourth-order polynomial to calculate enthalpy with respect to temperature were taken from NASA (McBride et al., 1993). The equation is in the form of

$$H^0(T) = RT \left( a_1 + a_2 \frac{T}{2} + a_3 \frac{T^2}{3} + a_4 \frac{T^3}{4} + a_5 \frac{T^4}{5} + \frac{b_1}{T} \right) \quad (D.17)$$

where

$H^0(T)$  is the enthalpy at temperature  $T$  for one component [kJ/mol].

The rate of energy released by cooling the entire flow of exhaust gas from the stack temperature to ambient temperature is calculated as

$$\dot{Q}_{exh} = \dot{n} \sum_j x_j (H^0(T_{stack})_j - H^0(T_{amb})_j) \quad (D.18)$$

where

$j$  represents the different chemical components of the stack gas.

There is also chemical energy exiting through the stack. The rate of chemical energy released through the stack is calculated on a higher heating value (HHV) basis. The only two combustible gases exiting the stack that were measured with the gas analyzer are CO and 'hydrocarbons', which are assumed to be propane. The higher heating values

for these two fuels are shown below in Table D.2. The total rate of chemical energy leaving the stack is calculated by

$$\dot{C}E_{stack} = \dot{n} \sum_j x_j (HHV_j) \quad (D.19)$$

Table D.2. Higher heating values for unburned fuels exiting the stack.

Fuel	HHV [kJ/mol]
CO	283
C <sub>3</sub> H <sub>8</sub>	2,200

Lastly, the thermal energy transferred from the stack gas to the air flowing through the dryer heat exchanger must be calculated. The energy lost from the stack gas is equal to the energy gained by the air in the dryer heat exchanger. This is calculated by

$$\dot{Q}_{HEX} = \dot{n} \sum_k x_k (H^0(T_{HEX})_k - H^0(T_{amb})_k) \quad (D.20)$$

where

$k$  represents the different components in moist air.

The total thermal power in the stack is

$$\dot{Q}_{stack} = \dot{Q}_{exh} + \dot{Q}_{HEX} \quad (D.21)$$

and the total power in the stack is

$$P_{stack} = \dot{Q}_{exh} + \dot{C}E_{stack} + \dot{Q}_{HEX} \quad (D.22)$$

#### D.4 Calculating Electricity Demand

Electricity demand was calculated as a moving average of the rate of change of cumulative electricity consumption over 20 data points, or approximately 100 seconds. Instantaneous outlier data points were removed.

## APPENDIX E ANALYSIS OF FEEDSTOCK AND BIOCHAR SAMPLES

Feedstock and biochar samples were collected during testing. The samples were analyzed at Humboldt State University to characterize the particle-size distribution, bulk density, gross calorific value, and the proximate analysis, which measures the moisture content, ash content, volatile matter, and fixed carbon. The methods used for sample collection and analysis are described below. The tests were performed in the following order: Moisture content, particle size distribution, bulk density, ash content, volatile matter, gross calorific value.

### E.1 Sample Collection

One feedstock sample was collected for each test run. Since duplicate test runs were performed, at least two samples of each feedstock were collected. For tests that had a mixture of feedstocks, for example two-thirds bole with one-third tops, a separate sample of each component was collected prior to mixing. Each sample was analyzed separately, and the properties of the mixture were calculated as the weighted sum of the individual components.

Feedstock samples were collected prior to each biochar test run by removing handfuls of the feedstock from different depths and locations in the self-dumping hopper until a one-gallon, airtight plastic bag was full. These samples were double-bagged to avoid moisture loss between the time of collection and the time of analysis.

Biochar samples were collected directly from the discharge of the machine. Samples were collected into a one-quart paint can and sealed with a lid. The samples were allowed to cool overnight before being transferred to a one-gallon, airtight plastic bag. These samples were double-bagged to avoid moisture loss between the time of collection and the time of analysis.

### E.2 Moisture Content

The moisture content is measured by weighing the sample before and after drying overnight in a 105°C oven. This method used was developed by following ASTM Method E 871-82, deviating from the ASTM method only by drying the samples in a 105°C oven instead of a 103°C oven. The measurement procedure is described below.

1. Place a clean aluminum pan in the oven at 105°C for 30 minutes to remove moisture from its surface.
2. Remove the pan from the oven. Immediately place pan in desiccator. Cool to room temperature in a desiccator.
3. Weigh the pan to the nearest 0.01 grams. This is the container mass.
4. Remove the moist feedstock sample from the plastic bag.
5. Pour the feedstock into the pan, using two pans if necessary.
6. Weigh the feedstock and the pan together to the nearest 0.01 grams. This is the initial mass.



7. Place sample in the oven at 105°C for 16 hours.
8. Remove sample and cool to room temperature in a desiccator, about 50 minutes.
9. Weigh sample to the nearest 0.01 grams. This is the final mass.
10. Return the sample to the 105°C oven for 2 hours.
11. Repeat steps 8 – 10 until the mass is constant to within 0.2%.
12. Calculate the moisture content as

$$MC = \frac{m_i - m_f}{m_i - m_c} \quad (\text{E.1})$$

where:

$MC$  is the moisture content on a percent as received basis,

$m_i$  is the initial mass [g],

$m_f$  is the final mass [g], and

$m_c$  is the container mass [g].

13. After the samples are dry, return sample to airtight plastic bag to avoid re-moistening the sample.

### E.3 Particle Size Distribution

The particle-size distribution is measured by separating a sample through a set of sieves. Two sets of brass sieves were used for this measurement. The first set of sieves was 12" in diameter, 3 1/2" depth with mesh sizes ranging from 5/8" to #18. The second set of sieves was 8" diameter, 2" depth with mesh sizes ranging from 2" to 0.525". Two sets of sieves were used to obtain a sufficient range of mesh sizes that were not available within the same sieve diameter. The range of sieve sizes in each stack is presented in Table E.1.

Table E.1. Mesh sizes in sieve stacks for particle size distribution test. Sieve mesh sizes are listed in inches (") or US Mesh size (#).

12" Diameter Sieve Stack	8" Diameter Sieve Stack
5/8"	2"
7/16"	1.5"
5/16"	1.05"
#3 1/2	3/4"
#5	0.525"
#7	Pan
#10	
#18	
Pan	

After drying the samples in a 105°C oven and storing them in one-gallon, airtight plastic bags, the particle size distributions were measured with the following method.

1. Place sample in the top sieve of the 12" diameter stack.
2. Insert 12" diameter stack into shaker and shake for four minutes.
3. Remove the stack from the shaker.
4. Empty the contents of each sieve into a tared container and weigh to the nearest 0.01 grams. This is the dry weight.
5. Measure and record the dry weight retained in each sieve.
6. Empty the contents retained in the 12" diameter 5/8" sieve into the top of the 8" diameter stack.
7. Insert the 8" diameter stack into the shaker and shake for four minutes.
8. Remove the stack from the shaker.
9. Empty the contents of each sieve into a tared container and weigh to the nearest 0.01 grams.
10. Measure and record the dry weight retained in each sieve.

Due to overlap in the mesh sizes from the two sieve stacks, the mass collected in the 12" diameter 5/8" mesh sieve was ignored. The mass collected in the pan of the 8" diameter stack was summed with the mass retained by the 12" diameter 7/16" mesh sieve to calculate the mass retained by a 7/16" sieve.

#### E.4 Bulk Density

Bulk density was not measured in the field. Instead, the bulk density on a dry basis of the approximately one-gallon sample was determined in the lab following test method SCAN-CM 46:92 developed by the Scandinavian Pulp, Paper and Board Testing Committee (1992). This method measured the tapped bulk density by filling a cylinder with the sample then dropping a small weight on the top of it. The apparatus is described below.

A cylinder and mass were constructed similar to the apparatus used in the test method, but deviating in dimension. The cylinder was a height of 28.5" with the top of the gate valve at 19.375". The inner diameter of the cylinder was 5.875" with an outside diameter of 6.4375". A cylindrical block of wood with height of 3" and a diameter of 5.75" was used as the dropping mass. Eight 1/2" diameter, equally spaced holes were drilled through the wood on a 1.75" circle diameter to allow air to flow through the mass while it falls. The wood was 3" in height with a mass of 779 g, which delivers a pressure of 437 Pa to the top of the sample.

The test was performed with the following method.

1. Place a large pan, approximately 24"x16" on a scale. Weigh the pan to the nearest 0.1 g. This is the container mass,  $m_c$ .
2. Place the cylinder apparatus in the pan with the gate valve near the top.
3. Insert the gate valve.
4. Empty the sample into the top of the cylinder on top of the gate valve.
5. Remove the gate valve, allowing the sample to drop to the bottom of the cylinder.
6. Place the wood block mass inside the cylinder and drop it on top of the sample.
7. Measure the distance from the top of the wood block to the top of the cylinder, this is  $x$ .

8. Slowly remove the cylinder and wood block from the pan, allowing the sample to fall into the rest of the pan.
9. Weigh the pan and sample to the nearest 0.1 g. This is the final mass,  $m_f$ .
10. Calculate the tapped bulk density on a dry basis [ $\text{kg}/\text{m}^3$ ] as:

$$\rho = \frac{(28.5\text{in} - x - 3")\pi \left(\frac{5.875\text{in}}{2}\right)^2}{m_f - m_c} \frac{\text{m}^3}{(0.0254)^3\text{in}^3} \quad (\text{E.2})$$

### E.5 Sample Comminution

The particle size of the samples must be reduced to fine grains in order to measure the ash content, volatile matter, fixed carbon, and gross calorific value. The sample is comminuted by the following method.

1. Separate a subsample by emptying the entire dry sample onto a flat surface, letting it fall naturally. Remove a wedge-shaped slice of the sample pile by hand that is approximately 200 grams.
2. Place subsample into blender and blend for 2 minutes.
3. Place the comminuted subsample in 105°C oven overnight to remove any moisture accumulated in the sample during the particle-size distribution and bulk density measurements.
4. Store subsample in desiccator for use in the following tests.

### E.6 Ash Content

The method for measuring ash content is consistent with ASTM Method E 1534-93 and Forest Concepts LLC (2011) to the extent possible. The procedure is outlined below.

1. Place empty 50 mL porcelain ashing crucible in muffle furnace at 575°C overnight.
2. Remove crucible from furnace. Place immediately into desiccator. Cool for 45 minutes.
3. Weigh the tare weight crucible to the nearest 0.0001 gram.
4. Remove two smaller samples from the subsample to perform simultaneous replicate test.
5. Add approximately 1 gram of the sample to the crucible and weigh to the nearest 0.0001 gram. This is the initial weight.
6. Place the crucible in a holder above a Bunsen burner.
7. Allow the sample to burn until the flame disappears, then remove sample from above the Bunsen burner.
8. Insert sample directly into muffle furnace at 575°C for 8 hours.
9. Remove sample from muffle furnace.
10. Allow sample to cool in desiccator for 45 minutes.
11. Weigh the sample to the nearest 0.0001 gram.
12. Place sample back in muffle furnace at 575°C for 1 hour.

13. Repeat steps 11 to 14 until the mass is consistent within  $\pm 0.0003$  gram.

Calculate the percent ash content on a dry basis as

$$ash_{dry} = \frac{m_f - m_t}{m_i - m_t} \quad (\text{E.3})$$

where  $m_f$  is the final weight [g],  
 $m_t$  is the tare weight [g], and  
 $m_i$  is the initial weight [g].

The ash content on an as-received basis is calculated as

$$ash_{AR} = ash_{dry}(1 - MC) \quad (\text{E.4})$$

### E.7 Volatile Matter

The method for measuring volatile matter is consistent with ASTM Method E 872-82 to the extent possible. ASTM specifies the use of a vertical electric tube furnace, but a muffle furnace was used instead. The procedure is outlined below.

1. Insert empty 35 mL Inconel crucibles into a muffle furnace at  $950^{\circ}\text{C}$  for at least 7 minutes to stabilize weight and remove volatiles from crucible.
2. Remove crucibles and place immediately in desiccator.
3. Let crucibles cool for 45 minutes.
4. Weigh the tare weight of the crucible to the nearest 0.0001 gram.
5. Add approximately 1 gram of sample to the crucible and weigh to the nearest 0.0001 gram.
6. Place sample in muffle furnace at  $950^{\circ}\text{C}$  for exactly 7 minutes.
7. Remove sample from muffle furnace and place directly into desiccator.
8. Let sample cool in desiccator for 45 minutes.
9. Weigh final weight of the sample to the nearest 0.0001 gram.
10. Empty and clean the crucible with water.
11. Calculate the percent volatile matter on a dry basis as the mass removed during this test with the following equation

$$VM_{dry} = \frac{m_i - m_f}{m_i - m_t} \quad (\text{E.5})$$

The volatile matter on an as-received basis is calculated as

$$VM_{AR} = VM_{dry}(1 - MC) \quad (\text{E.6})$$

### E.8 Fixed Carbon

Fixed carbon is calculated as the remainder out of 100% after subtracting the moisture, ash and volatile matter. The amount of fixed carbon on an as-received basis is calculated with the following equation

$$FC = 100\% - MC - ash_{AR} - VM_{AR} \quad (\text{E.7})$$



Fixed carbon on a dry basis is calculated with the following equation

$$FC = 100\% - ash_{dry} - VM_{dry} \quad (\text{E.8})$$

### E.9 Gross Calorific Value

The gross calorific value was measured by bomb calorimetry using a Parr Adiabatic Calorimeter Model 1241 equipped with Parr Digital Thermometer Model 6775A. The measured value is the higher heating value on a dry basis. Two bombs were used with the calorimeter. Each bomb was calibrated with a standard of benzoic acid with six runs, the resulting values are shown in Table E.2.

$$EE = \frac{m_{BA} \cdot 6318 \frac{\text{cal}}{\text{g}} + (m_{fuse,i} - m_{fuse,f}) \cdot 1400 \frac{\text{cal}}{\text{g}}}{T_f - T_i} \quad (\text{E.9})$$

where  $EE$  is the energy equivalence of the bomb [ $\text{cal}/^\circ\text{C}$ ],

$m_{BA}$  is the mass of benzoic acid [g],

$m_{fuse,i}$  is the initial mass of the fuse wire [g],

$m_{fuse,f}$  is the final mass of any excess fuse wire [g],

$T_f$  is the final temperature of the water bath [ $^\circ\text{C}$ ], and

$T_i$  is the initial temperature of the water bath [ $^\circ\text{C}$ ].

Table E.2. Results from calibration of bomb calorimeter with 1 g of benzoic acid. Sample size is 6 runs.

Bomb ID	Energy Equivalence, Average $\text{cal}/^\circ\text{C}$	Standard Deviation, $\text{cal}/^\circ\text{C}$
A	2402.6	2.88
B	2401.2	0.81

Duplicate tests of each sample were performed following the method described below.

1. Clean bomb with towel to remove any soot and moisture.
2. Place sample cup on analytical balance and zero the scale.
3. Add approximately 1 g of sample to the cup. Weigh to the nearest 0.0001 g. This is the sample mass.
4. Cut a length of fuse wire approximately 10 cm long. Weigh to the nearest 0.0001 g. This is the initial fuse wire mass.
5. Insert cup into bomb and thread fuse wire to the electrodes. Ensure that fuse wire is firmly set and contacting the sample.
6. Put the bomb back together and tightly close the cap.
7. Pressurize the bomb with 25 atm of oxygen. The bomb is now prepared.
8. Remove the water bucket from the calorimeter. Place the empty bucket on a scale and zero the scale. Add exactly 1000.0 g of deionized water.
9. Place the water bucket back in the calorimeter.
10. Slowly lower the pressurized bomb into the water bucket and attach the electrode leads.

11. Close the bomb calorimeter lid and turn the power on.
12. Wait until the adiabatic water jacket temperature equilibrates with the inner water bucket.
13. After the temperatures are within 0.020°C and stable for at least one minute, ignite the bomb. Record the temperature of the water bucket. This is the initial temperature.
14. The temperature of the water baths will slowly rise. Wait until the temperature becomes stable to the nearest 0.001°C for at least one minute. Record the temperature of the water bucket. This is the final temperature.
15. Open the lid of the calorimeter. Remove the bomb. Depressurize the bomb.
16. Remove the sample cup from the bomb. Inspect for any pieces of unburnt fuse. Collect the excess fuse pieces. Discard any oxidized pieces. Weigh the remaining pieces to the nearest 0.0001 g. This is the final fuse wire mass.
17. The higher heating value of the sample in MJ/kg on a dry basis is calculated with the following equation

$$HHV = \frac{(T_f - T_i) \cdot EE - (m_{fuse,i} - m_{fuse,f}) \cdot 1400 \frac{\text{cal}}{\text{g}} \left( \frac{4.184 \times 10^6 \text{MJ}}{\text{cal}} \right) \left( \frac{1000 \text{g}}{\text{kg}} \right)}{m_{sample}} \quad \left( \begin{array}{l} \text{E.10} \\ \end{array} \right)$$

## APPENDIX F      CALCULATING UNCERTAINTY IN PROXIMATE ANALYSIS

The uncertainty in the proximate analysis tests was estimated as the pooled standard deviation. The propagation of error due to instrument inaccuracy was neglected because it was 3 orders of magnitude less than the pooled standard deviation. The pooled standard deviation for each test is calculated as the square root of the pooled variance:

$$s_p = \sqrt{\frac{\sum_{i=1}^k (n_i - 1) s_i^2}{\sum_{i=1}^k (n_i - 1)}} \quad (\text{F.1})$$

where  $s_p$  is the pooled standard deviation,  
 $n_i$  is the sample size of sample  $i$ ,  
 $s_i^2$  is the variance of sample  $i$ , and  
 $k$  is the number of different samples tested with the same method.

The sample variance, or mean squared deviation,  $s_i^2$ , is calculated by:

$$s_i^2 = \frac{1}{n} \sum_{j=1}^n (x_j - \bar{x})^2 \quad (\text{F.2})$$

where  $x_j$  is the measured value and  
 $\bar{x}$  is the mean of all tests,  $j=1$  to  $n$ .

Measurements of ash content, volatile matter, and heating value were performed twice for each sample of biomass and biochar. The pooled standard deviation assumes that the variance between the two measurements of each sample is the same.

## APPENDIX G ESTIMATING LABOR HOURS

Labor hours were estimated for each test run as a function of measured operational parameters including:

- the amount of propane used as supplemental fuel per hour [kg/hr],
- the mass collected at the bottom of the reactor [kg/hr], and
- the number of times the flare was relit during steady state testing [#].

Each of these parameters increases the operational intensity and labor hours required to produce one unit of biochar. After testing was complete, the operators from SERC were surveyed to help determine the coefficients used to correlate the above parameters to labor hours. The equation to determine number of labor hours for one hour of biochar production was determined to be:

$$LH_{hr} = 1\text{hr} + \frac{\dot{m}_p}{\dot{m}_{p,5A}} + 2 \frac{\dot{m}_{CO}}{\dot{m}_{CO,7B}} + FR \frac{5}{60}\text{hr} \quad (\text{G.1})$$

where  $LH_{hr}$  is the labor hours required for one hour of biochar machine operation,  
 $\dot{m}_p$  is the mass flow rate of propane consumption [kg/hr],  
 $\dot{m}_{p,5A}$  is the mass flow rate of propane consumption for test 5A [kg/hr],  
 $\dot{m}_{CO}$  is the mass collected in the bottom of the reactor [kg/hr],  
 $\dot{m}_{CO,7B}$  is the mass collected in the bottom of the reactor during test 7B [kg/hr],  
 $FR$  is the number of flare relights.

The first term in equation above says that 1 person must always be present for the machine to operate. The next terms scales the propane consumed in the current test run to test 5A, such that test 5A required an additional labor-hour to operate the machine. The third term compares the mass accumulated in the bottom of the reactor to test 7B, such that test 7B required two additional labor hours to operate the machine for one hour. The last term states that it takes five additional minutes of labor to light the flare.

To calculate the number of labor hours required to produce one tonne of biochar, the following equation is used:

$$LH_{1mT} = \frac{LH_{hr}}{\dot{m}_{BC}} 1,000 \frac{kg}{mT} \quad (\text{G.2})$$

where  $LH_{1mT}$  is the labor hours to produce one tonne of biochar and  
 $\dot{m}_{BC}$  is the mass flow rate of biochar [kg/hr].

As a note, the mass accumulated in the bottom of the reactor was not measured for every test because the reactor was too hot to cleanout when feedstocks were switched at midday. For the test that could not be measured, an empirical correlation was used to estimate the mass accumulated in the reactor as a function of ash content and feedstock input rate.

## APPENDIX H FIELD TOOLBOX DOCUMENTATION

Field toolbox documentation, prepared by Biochar Solutions, Inc., is presented below.

To date the in-field tooling kit includes:

- Personal Protective Equipment (PPE) – eye shields, full face shield, ¼ P100 respirator
- PPE manual
- ASME standard mechanical tools up to 2 inch
- Mechanical manual
- Electrical tooling to include pliers, strippers, multi meter (single and three phase, volts test, amp test), lock out tag out ties, can of compressed air to blow out box, dielectric grease
- Electrical manual
- High temp grease and associated gun
- Infrared (IR) thermometer, range up to 800°C
- Replacement K-type thermocouples and associated wire
- Pressure sensor replacement parts
- Impeller wheel
- Standard 5 horsepower motor or listing for purchase the same
- High temperature air line and associated hose clamps
- RTV high temperature caulking gasket, braded high temp rope, and spray glue to set the rope
- Nuts, bolts, and washers
- Compressed air or high duty electric tooling



## APPENDIX I HEAT EXCHANGER REDESIGN MEMO



### MEMORANDUM

Date: August 22, 2014  
To: Jonah Levine; Colorado Biochar Resources  
Cc: Brad Dunmire, Brian Frazier; Pueblo Wood Products  
Arne Jacobson; Schatz Energy Research Center  
From: David Carter, Mark Severy, Marc Marshall; Schatz Energy Research Center  
Re: Biochar Machine Testing Results- Dryer Heat Exchanger Calculations

---

#### **Introduction**

Based on data collected while testing the biochar production machine and conversations onsite with you, Brad, and Brian, we performed heat transfer calculations to determine the apparent best size, length, and number of pipes for the dryer heat exchanger. Our recommendation is to wrap a number of tubes around the drop box to transfer heat from the drop box surface to the air flowing through the pipes. The tubes can be plugged to change the air temperature to the dryer.

According to our conversations, the target air flow to the dryer is 850 cfm at 212°F<sup>1</sup>. The surface temperatures of the drop box range from 383°F to 840°F as shown in Figure 1. In our opinion the target location for the heat exchanger pipes is below the reactor outlet pipe where the average surface temperature is approximately 703°F during steady state operation.

---

<sup>1</sup> Once you select the actual blower you are going to use we will re-run the calculation based on a revised flow condition upon request.

Humboldt State University • Arcata, CA 95521-8299 • 707.826.4345 • fax 707.826.4347 • [www.schatzlab.org](http://www.schatzlab.org)

DropBox Surface Temperatures, °F				
	Reactor Outlet Side	Auger & Flare Side	Conveyor Side	Average
Top	658	763	655	692
Reactor Outlet Pipe	840	786	707	778
	684	707	720	703
	Place heat exchanger pipes at this height.			
Bottom	383	430	455	423

Figure 1. Drop box surface temperature measured with IR thermometer during steady state operation.

### **Analysis**

To perform the heat transfer calculations, we assumed that the surface temperature of the heat transfer piping is equal to the surface temperature of the drop box at the target location. This assumption should be valid when the machine is warmed up and operating in a steady state and assuming that the heat exchanger is constructed as discussed below. The outlet air temperature from the heat exchanger was calculated for convection heat transfer from a hot pipe to an internal flow. Table 1 shows the final input parameters and output values for the convection heat transfer model. Based on this analysis, we recommend that the heat exchanger pipes be 2" schedule 40 pipes (ID = 2.07") with a length of 56 ½".

Table 1. Input parameters and output values from convection heat transfer calculations.

Variable	Value	Unit	Notes
Air Inlet Temperature (ambient)	68	°F	
Target Outlet Temperature (to dryer)	212	°F	
Volumetric Air Flow Rate	850	CFM	
HEX Pipe Surface Temperature	703	°F	assuming HEX pipe equals DropBox surface temperature
Nominal Pipe Diameter	2	in	
Actual Pipe ID	2.07	in	for Schedule 40 pipe
Pipe Length	56.5	in	assuming pipe equal to half the DropBox circumference
Number of Open Pipes	5		can change this value
Air Velocity in Pipes	37.0	ft/s	
Reynolds Number	102,270		turbulent flow
Prandtl Number	0.708		for air at average temperature
Nusselt Number	204.0		calculated using Dittus-Boelter equation
Heat Transfer Coefficient, h	110.7	W/m <sup>2</sup> /K	
Log-Mean Temperature Difference	592	°F	
Convection Heat Transfer from Pipe Surface to Internal Air Flow	139,580	BTU/hr	
Final Air Temperature	237	°F	

Changing the number of open pipes in the heat exchanger will affect the outlet air temperature to the dryer. Figure 2 graphs the outlet air temperature as a function of number of open pipes and air flow rate for 56 ½" long 2" OD pipes. From this chart you can see that at a flow rate of 800 CFM with 5 open pipes the estimated air outlet temperature is 240°F (point A). If there are only 2 open pipes at a flow rate of 800 CFM, the outlet temperature reduces to 190°F (point B).

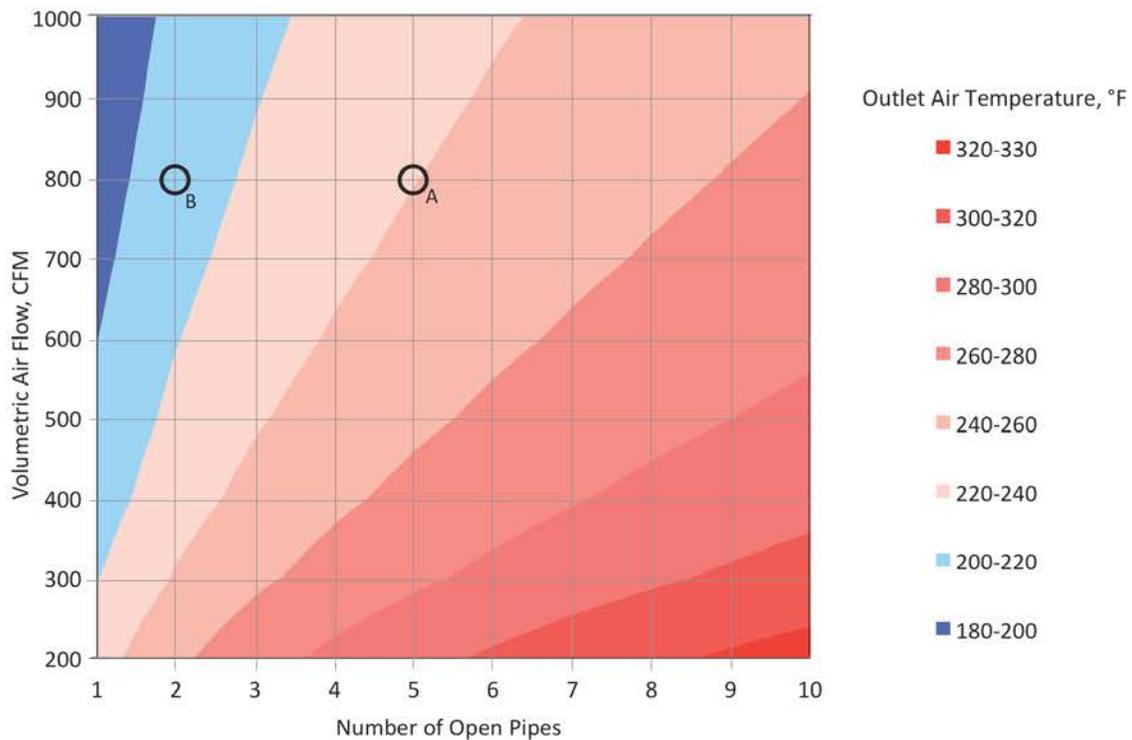


Figure 2. Estimated outlet air temperature to the dryer as a function of number of pipes and volumetric air flow rate.

Furthermore, changing the number of open pipes will change the head loss through the heat exchanger and affect the air flow rate through the blower. While this analysis does not directly account for any reduction in airflow associated with increased friction that would result from capping pipes in the heat exchanger, the impact of flow rate on the outlet temperature can be seen in Figure 2.

### **Recommendations**

Based on the range of desired temperatures and the uncertainty involved with the assumptions leading into this calculation, we recommend:

- the heat exchanger pipes should be installed at a height just below the reactor outlet tube on the dropbox
- a blower sized to deliver 850 CFM (see footnote 1 on previous page)
- 6 pipes total (gives a range 190°F - 245°F by changing the number of open pipes)
  - The ambient air temperature used was 68 degrees Fahrenheit. For a higher ambient air inlet temperature, additional pipes may need to be capped to achieve the desired air temperature for drying.
- 2" OD schedule 40 pipes mounted in gussets that are welded to the dropbox
- 56 ½" pipe length (about half of the drop box circumference)
- the 6 pipes should be enclosed in a steel box wrap that is welded to the exterior of the dropbox to reduce external convection heat loss.
- We recommend that the inlet end of the heat exchange box be fitted with a gasketed plate that can be removed to cap or uncap pipes in the heat exchanger as needed in order to tune the outlet temperature as needed for site specific conditions.

We hope that you find this information helpful. Please don't hesitate to contact us with any questions or comments you may have about this memo.

## APPENDIX J EXHAUST GAS ANALYZER SPECIFICATIONS

Exhaust gas composition was measured with a portable gas analyzer manufactured by Enerac, model number 700. The measured components, sensor type, and sensor range are shown in Table J.1. Complete details for the analyzer can be found through the manufacturers website (Enerac, 2015)

Table J.1. Sensor types and ranges for the exhaust gas analyzer.

Component	Sensor Type	Max. Sensor Range
CO	Electrochemical, Dual Range	100/300 ppm
	NDIR	15%
CO <sub>2</sub>	NDIR	20%
Hydrocarbon	NDIR (calibrated for propane)	3%
O <sub>2</sub>	Electrochemical	25%
NO	Electrochemical, Dual Range	200/600 ppm
NO <sub>2</sub>	Electrochemical, Dual Range	50/150 ppm
SO <sub>2</sub>	Electrochemical, Dual Range	50/150 ppm