

# **NOVEL LOW-COST PROCESS FOR THE GASIFICATION OF BIOMASS AND LOW-RANK COALS**

## **TOPICAL REPORT**

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**Task 46**

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## **DISCLAIMER**

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## ABSTRACT

Farm Energy envisaged a phased demonstration program, in which a pilot-scale straw gasifier will be installed on a farm. The synthesis gas product will be used to initially i) generate electricity in a 300 kW diesel generator, and subsequently ii) used as a feedstock to produce ethanol or mixed alcohols. They were seeking straw gasification and alcohol synthesis technologies that may be implemented on farm-scale. The consortium, along with the USDA ARS station in Corvallis, OR, expressed interest in the dual-bed gasification concept promoted by WRI and Taylor Energy, LLC. This process operated at atmospheric pressure and employed a solids-circulation type oxidation/reduction cycle significantly different from traditional fluidized-bed or up-draft type gasification reactors.

The objectives of this project were to perform bench-scale testing to determine technical feasibility of gasifier concept, to characterize the syngas product, and to determine the optimal operating conditions and configuration. We used the bench-scale test data to complete a preliminary design and cost estimate for a 1-2 ton per hour pilot-scale unit that is also appropriate for on-farm scale applications.

The gasifier configuration with the 0.375" stainless steel balls recirculating media worked consistently and for periods up to six hours of grass feed. The other principle systems like the boiler, the air pump, and feeder device also worked consistently during all feeding operations. Minor hiccups during operation tended to come from secondary systems like the flare or flammable material buildup in the exit piping. Although we did not complete the extended hour tests to 24 or 48 hours due to time and budget constraints, we developed the confidence that the gasifier in its current configuration could handle those tests. At the modest temperatures we operated the gasifier, slagging was not a problem. The solid wastes were dry and low density. The majority of the fixed carbon from the grass ended up in the solid waste collected in the external cyclone. The volatiles were almost all removed in the gasifier.

While the average gas heating value of the collected gas products was 50 BTUs/scf or less, addition of the second gas exit for combustion gases would increase that value by a factor of two or three. Other changes to the current design such as shortening the gasifier body and draft tube would lead to lower air use and shorter heating times. There was no evidence of steam reforming at the current operating temperature. Likewise there was no indication of significant tar production. Reconfiguration of the gasifier at the on farm site may yet yield more significant results that would better qualify this gasifier for small scale biomass operations.

## EXECUTIVE SUMMARY

Farm Energy envisaged a phased demonstration program, in which a pilot-scale straw gasifier will be installed on a farm. The synthesis gas product will be used to initially i) generate electricity in a 300 kW diesel generator, and subsequently ii) used as a feedstock to produce ethanol or mixed alcohols. They were seeking straw gasification and alcohol synthesis technologies that may be implemented on farm-scale. The consortium, along with the USDA ARS station in Corvallis, OR, expressed interest in the dual-bed gasification concept promoted by WRI and Taylor Energy, LLC. This process operated at atmospheric pressure and employed a solids-circulation type oxidation/reduction cycle significantly different from traditional fluidized-bed or up-draft type gasification reactors.

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## **BACKGROUND**

This project was conceived to develop a small low cost gasifier that would enable a farmer to take locally produced waste biomass and generate electricity or liquid fuels for use on the farm. Grass seed agriculture occupies over 560,000 acres in the U.S. Pacific Northwest (PNW). Significant reductions in field burning in Oregon (90%) and Washington (100%), with similar outcomes expected for Idaho grass seed, have left most grass seed farmers with more than 1-million tons of straw annually. Seed farmers receive very little if any income from straw that is baled and shipped as animal feed. Grass seed farmers, with assistance from the USDA Agricultural Research Service (ARS) and other entities, have been investigating methods to better utilize this resource.

It was recognized that on-farm-scale energy product production from grass seed straw is a preferred choice for the Pacific Northwest region. Grass seed farmers cannot afford to ship their straw great distances and realize any profit from it. Therefore, the greatest profit returns will be realized if the straw is utilized on the farm. A non-profit consortium, Farm Energy, has been set up to address the issue of grass straw utilization in Spokane County, WA. The objectives of the consortium are:

- To identify technical options for on-farm power generation and liquid fuel production using grass seed straw as a feedstock.
- Conduct pilot-plant testing at a grass seed farm in Spokane County.

Farm Energy envisaged a phased demonstration program, in which a pilot-scale straw gasifier will be installed on a farm. The synthesis gas product will be used to initially i) generate electricity in a 300 kW diesel generator, and subsequently ii) used as a feedstock to produce ethanol or mixed alcohols. They were seeking straw gasification and alcohol synthesis technologies that may be implemented on farm-scale.

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This final report, while comprehensive, emphasizes the latter stages of the testing research which best describes the capabilities and drawbacks of the recirculating gasifier.

## **OBJECTIVES**

The objectives of this project were:

- Perform bench-scale testing to determine technical feasibility of gasifier concept, to characterize the syngas product, and to determine the optimal operating conditions and configuration.
- Use the bench-scale test data to complete a preliminary design and cost estimate for a 1-2 ton per hour pilot-scale unit that is also appropriate for on-farm scale applications.

## **EXPERIMENTAL**

The experimental program consisted of seven tasks with multiple subtasks. The initial tasks were design and fabrication of the gasifier, including shakedown. The next set of tasks was to make alterations in the hardware and operational conditions to optimize the gasifier performance. The last task consisted of moving the gasifier to Spokane and running the device as an on farm trial. The last task was conducted primarily under the supervision of the USDA and without significant WRI contribution.

### **Task 1. Design the Recirculating Gasifier**

This gasification process operated at atmospheric pressure and employed a solids-circulation type oxidation/reduction cycle significantly different from traditional fluidized-bed or up-draft type gasification reactors. The reducing side of the process utilized a novel counter-current processing sequence. A heat carrier (comprised of spherical solids) and char travelled down via gravity, while gases travelled up via differential pressure. Gas-solids contacting was enhanced using hourglass shapes that promoted heat and mass transfer. The volatile fraction moving upward contacted ever-hotter descending solids, enabling the tars, oils, and volatiles to be cracked into low-molecular fuel gases. In the upper stages (hottest gasifying section) the fuel gases were reformed into synthesis gas.

The oxidation side of the process used an entrained flow transport reactor. A hot air and steam driven pneumatic circulation loop served to oxidize the residual carbon char and provide process heat, while carrying the combined solids (heat carrier and char) back up to the top of the reactor to complete the circulation loop.

### **Task 2. Construct the Recirculating Gasifier**

The gasifier was fabricated of cast iron sections bolted together. (Figure 1) This method of construction was used to allow improvements and alterations to be made quickly. The gasifier had two principal sections each supported separately and combined with a flexible joint to account for thermal expansion during operation. The gasifier was placed in a building with a 10 foot below ground basement area and an elevated roof. This configuration allowed the grass feeding auger to be placed at ground level and eliminated the need to hang the considerable weight of the auger above ground. The exit piping ran through the walls and roof to the remote flare. A cyclone was mounted in the exit piping to reduce char carry over to the flare. Compressors were placed in out buildings to reduce noise.





- Cold flowed ceramic transport material.
- Hot flowed the reactor after insulation was added.
- Conducted preliminary shakedown tests with biomass feed input.

#### **Task 4. Improved Hardware and Trials to Characterize Reactor Performance**

##### Task 4.1 Modifications to the Gasifier

- A steam generator was installed with delivery points of steam at four places on the gasifier. There were two injection points at the bottom of the gasifier within the area where balls and char approached the draft tube, and two injection points above the level of the balls but close to the grass feeder.
- The flare was modified with propane to operate under all conditions of gas flow and steam injection.
- A draft tube holding device was installed that locates the bottom opening of the draft tube at a fixed point above the orifice where air is injected. The top of the draft tube was allowed to float to account for thermal expansion.
- The gasifier was filled to just below the grass feed point with 0.375" diameter stainless steel balls.
- Additional insulation was placed over the length of the gasifier.
- Multiple ports were added over the length of the gasifier to measure differential pressure.
- A pitot tube device was obtained to measure gas flow rates at several points in the system.
- A stack analyzer was obtained to assist in gas chemical analysis.
- A larger pulley was installed on the motor of the compressor to increase the speed and therefore the air output of the compressor.

##### Task 4.2 Evaluation of the Biomass Feeder System.

Conduct trials to evaluate the performance of the biomass feed input system utilizing chopped Kentucky bluegrass straw and quantify the variability among a minimum of three replicated tests, with each test consisting of the reactor operating continuously for three hours. The feeder was fitted to the reactor using a high temperature compression seal and the operation of the system tested in three replicated trials in which input/output is quantified at two different feed rates. Feeding rates were achieved by slowly increasing the feed amount from initial start-up time.

#### Task 4.3 Impact of Steam Injection on Synthesis Gas Quality and Quantity.

Three replicated three-hour tests were conducted under optimal conditions utilizing compressed air to circulate the heat transfer media and measure the synthesis gas quality and quantity (input/output analyses). The gasification reactor was then fitted with a steam generator and three replicated tests conducted to quantify the optimal rate of steam introduction that can sustain continuous circulation of the heat transfer media. After that, three replicated three-hour tests were conducted under optimal steam introduction conditions to quantify the impact of steam on synthesis gas quality and quantity (input/output analyses). The replicated experiments were conducted in a manner that permitted direct comparison of steam versus air media as a fluidizing medium.

#### Task 4.4 Operation of Gasification Reactor using Char after Natural Gas Startup.

The hypothesis underlying the design of the dual vessel gasification system is that oxidation of the char remaining after gasification in the central draft tube (combustor) will supply all the energy needed for the endothermic gasification reactions. Currently this energy is supplied by burning natural gas. Replicated trials were conducted to test this hypothesis by gradually reducing the supply of natural gas after startup and replacing it by char combustion. The percent energy self-sufficiency was determined by energy balance.

#### **Task 5. Operation of the Reconfigured Reactor**

Trials were to be conducted to evaluate unit stability at operating conditions. Temperature and pressure profiles along the length of the reactor will be established at specific times during extended operation and under optimal conditions. A heat and mass balance analysis of system inputs and outputs will be conducted where steam flow, natural gas use, and straw input versus synthesis gas volume produced will be quantified to ensure closure. All measurements were coordinated through a data monitoring computer. Synthesis gas constituents were analyzed over the length of the operation.

#### **Task 6. Data Analysis**

Data was provided to USDA-ARS that quantify replicated estimates of the following: straw conversion to synthesis gas production efficiency, evidence of gas reforming, ash produced, slag formation, char combustion rates, tar production, temperature profiles, pressure profiles, and syngas energy content, and synthesis gas composition. Temperature profiles were based on an insulated reactor. The completed straw analyses included proximate and ultimate analyses, elemental analysis of the straw ash, and ash fusion temperature.

#### **Task 7. Reconstruction of the Gasifier on Site**

It was initially planned by WRI and the USDA that the gasifier would be moved to Spokane for on farm testing. The gasifier and related equipment transferred from WRI for temporary research use by ARS at the Gady Farm were ultimately not utilized in the on-farm research project. Internal consultations between ARS and Farm Power resulted in a decision to construct an alternative gasification research platform. Construction of the new equipment is not

yet complete, and consequently, the new equipment is not functional and no data have been generated. Components of the original gasifier were returned to WRI by truck and stored.

## RESULTS

Initial experiments of the original design produced the following results:

Recirculation of the media was first accomplished on November 22<sup>nd</sup>, 2004. The first heat up of the reactor was conducted on December 10<sup>th</sup>, 2004. The first experiment including the feed of straw occurred on December 16<sup>th</sup>, 2004. During the next period included a number of experiments in which the variety of media were investigated, the problems with feeding straw into the smaller eight inch T-section and the natural gas plumbing was completed. Christmas season interrupted the work to a degree, but progress continued on putting in the side are and changing the feeder tube. The draft tube was replaced after the excess heating incident, and the burner was moved to outside of the reactor.

The first gas product tests were conducted on February 9<sup>th</sup>, 2005. These gas samples were taken from the same position as TC3. The reactor was only partially filled with media and the position of TC3 was above the media bed. The gas composition only showed nitrogen, oxygen, carbon dioxide and water as to be expected with effort to separate pyrolysis products from the air and oxidation products. After these experiments the reactor was filled to just below the feeder with the smaller steel shot media (2-3mm).

The first two experiments that included all the reactor modification, the smaller media, the improved insulation and the media bed up to the feeder were conducted on February 22<sup>nd</sup> and February 23<sup>rd</sup>, 2005. The two experiments were similar in which there was an initial period of reactor heat up followed by a period of straw feed. Each experiment lasted approximately 6 hours.

### February 22, 2005

The profiles of the thermocouple-measured temperatures versus time are shown in Appendix B. For the portion of the lower reactor in which pyrolysis occurred (TC2, TC3, TC4) the temperatures ranged from 500°F to 800°F. Straw feed was begun at 140 minutes at a motor rate of 14 Hz that corresponds to a feed rate of 4.8 pounds of straw per minute. The airflow rate was 120 scfm. The GC data is also in Appendix B. Dry analysis of the sample gases is shown in the following table with numbers equal to volume percent. The first sample was after straw feed was initiated; the later samples were after feed had occurred for two hours. The straw feed was at a low level for this experiment

**Table 1**

Sample #	Time	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO	CH <sub>4</sub>	CO <sub>2</sub>
A2	130	0.5	77.7	0	3.4	0.5	18.7
C	270	1.0	56.4	2.5	10.1	0.9	29.1
D	277	0.9	57.3	0	10.0	0.7	31.0

February 23, 2005

The profiles of the thermocouple-measured temperatures versus time are shown in Appendix C. For the portion of the lower reactor in which pyrolysis occurred (TC2, TC3, TC4) the temperatures ranged from 500°F to 800°F. The feed rate for sample B was 21 Hz (5.6 lbs/min), the feed rate for sample C was 30 Hz (8.2 lbs/min), and the feed rate for samples D, E and F was 40 Hz (11.3 lbs/min). The gas results for samples B and C were similar to samples C and D for the 2/22 experiment under the same conditions. The airflow and natural gas feed were reduced before samples E and F, although those effects were less obvious in the sample gas concentrations than the increase in straw feed rate. Samples D and E produce Higher Heating Values just over 100 BTUs/scf.

**Table 2**

Sample #	Time	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO	CH <sub>4</sub>	CO <sub>2</sub>
B	215	0.5	54.4	0	10.5	0.9	32.8
C	235	0.9	59.5	0.5	9.5	1.6	28.0
D	255	2.7	31.1	2.1	17.0	4.7	42.9
E	275	3.5	44.4	2.7	11.8	5.7	32.3
F	300	1.6	37.3	3.0	15.5	3.6	39.4

The results of the initial design were modest. Tasks 4 – 6 were developed to allow alterations to the hardware and operate the gasifier in a more optimal configuration. The following results are the accomplishments of that latter period of experimentation.

There were nine days of investigation during the test period. Staff from the USDA-ARS was present during most of these tests. Although the best effort was made to keep to the test matrix, developments from one day generally led to operational parameters for the next day. While the individual day's results are described here, the next section on analysis is used to compare the results from the different day's testing. Prior to the initiation of this test matrix, the gasifier had been reassembled and operated twice for short periods of recirculation of the balls and grass feed at temperature.

A typical test day ran like this. The air compressor would be started at full flow. The steam boiler would be turned on to begin heating. Natural gas would be added to the burner and lit. Heat-up of the gasifier would take from one to three hours depending on gas usage. The balls would begin circulating shortly after the burner had been lit with the extra lifting power of the heated air. Steam would be introduced. The flare would be lit. When the bottom thermocouple in the gasifier was above 850°F, grass feed would be initiated. Gas samples would be taken at intervals. Changes were made to grass feed rates, steam levels, natural gas rates, and air rates between samples at intervals from twenty minutes to an hour. During fast grass feed rates, short breaks in the grass feed were necessary to allow the ash collection barrel below the exit cyclone to be changed. At the end of a test, the grass feed was halted, the natural gas turned off, and the air turned off when cooling was underway. A typical day from the initiation of heating to final turnoff of the air was eight hours.

### July 25, 2005

The heating of the gasifier was started at 07:05. Initially the natural gas burn rate was 300 scfh, though this was reduced to 200 scfh by 08:43 without affecting the circulation of the balls. Steam was introduced into the gasifier at 09:56 and grass feed begun at 90 lbs/hr at 10:00 AM. The bottom area of the gasifier was approximately 800°F, and the top surface of the balls was approximately 650°F. At 10:30 circulation of the balls stopped and various methods were used to start recirculation such as bouncing the air feed and reducing the grass feed. The attempts to smoothly operate the recirculation were unsuccessful, and the experiment was halted.

### July 26, 2005

This day was used to modify the draft tube holding component to allow better flow of the balls into the orifice area. There was some cake-like char found on the surface of the orifice bowl that was thought to be the problem with balls flowing freely. The grass feed unit was also recalibrated.

### July 27, 2005

After filling the gasifier with balls, a late test was started at 13:28. Grass feed was initiated at 65 lbs/hr at 14:30 when the bottom of the gasifier was 638°F (TC2) and the top of the balls was 620°F (TC4). The natural gas rate was 200 scfh. The first gas sample was taken near the bottom of the gasifier at 15:00. There was no noticeable effect on circulation of the balls due to char. Steam was initiated at 10 lbs/hr at 15:29. A second gas sample was taken at 15:34, and a third at 15:59. At 16:06 the grass feed and steam were stopped after 96 minutes of operation under grass feed.

### July 28, 2005

The goal of the day's experiment was to get a full day's baseline operation under steady conditions. The test was started at 08:46. The gasifier was heated with natural gas at 210 scfh, and the rate was dropped to 200 scfh at 09:49. Grass feed was started at 65 lbs/hr at 10:16 when the bottom of the gasifier was 748°F (TC2) and the top was 460°F (TC4). Steam at 8 lbs/hr was started at 10:36. By 12:06 TC2 was up to 976°F and natural gas to the burner was reduced to 175 scfh. Multiple gas samples were taken. The lower thermocouple TC2 topped out just above 1000°F for the last 90 minutes of operation. The grass feed was halted at 15:17 after 301 minutes of operation.

### July 29, 2005

The goal of the day's experiment was to test the gasifier at different rates of grass feed. The new pulley was put onto the compressor motor before this experiment to give some additional airflow if necessary. The test was started at 09:41. The gasifier was heated with natural gas at 250 scfh, and the rate was dropped to 180 scfh at 11:36. Grass feed was started at 65 lbs/hr at 10:50 when the bottom of the gasifier was 650°F (TC2) and the top was 350°F (TC4). Steam at 8 lbs/hr was started at 11:36. The feed rate was increased in 12 lb/hr steps from 65 to 125 lbs/hr over several hours. Gas samples were taken at each stage. The lower

thermocouple TC2 topped out between 850 and 900°F for the last 240 minutes of operation. The grass feed was halted at 13:53 after 183 minutes of operation. Near the end of the experiment the natural gas was reduced to the lowest possible rate that would sustain a flame that seemed to be about 80 to 100 scfh.

#### August 1, 2005

The goal of the day's experiment was to run a steady higher grass feed rate at higher steam. The initial start at 08:20 was aborted when then the belts on the compressor were found to be slipping leading to lower airflow and significant noise. The experiment was restarted at 10:08, and feed was initiated at 125 lbs/hr at 12:42. Steam was fed at 10 lbs/hr. Several gas samples were taken. The experiment was halted at 14:17 due to a small chimney fire in the pipe leading to the flare that was controlled as soon as airflow was halted. Total operation time under feed was 90 minutes.

#### August 2, 2005

The goal of the day's experiments was to further increase the grass and steam feed rates. Minor repairs and cleanout of the exit piping led to a late start at 11:02. Feed was started at 12:35 when TC2 was at 750°F. The feed rate was increased over time to a maximum of 180 lbs/hr and steam to 30 lbs/hr. Gas samples were taken at different feed rates. The temperature at TC2 reached just over 1000°F and the temperature at the top of the balls was over 600°F. The experiment was halted at 14:59 after 144 minutes of feed.

#### August 3, 2005

The goal of the day's experiment was to reduce air and natural gas flow to the gasifier while increasing grass feed. No steam was to be used. The experiment was started at 7:58. Grass feed was started at 9:35 and tested at several levels up to 180 lbs/hr. Gas samples were taken at each level. Some air was bypassed leading to a lower amount of air in the gasifier. The temperature at TC2 was allowed to reach 1050°F while the temperature at the top of the balls reached just over 800°F. The experiment was halted at 12:58 after 203 minutes of operation under feed.

#### August 4, 2005

On this last day of the series of tests, the goal was to push the gasifier with respect to temperature and feed rates with no steam added until the end. The experiment was started at 07:32 and the feed of grass was started at 125 lbs/hr at 09:23. The feed rate was increased to 180 lbs/hr at 10:25 and a gas sample was taken. The temperature at TC2 was over 1100°F by 10:26 and TC4 was 630°F. The temperature at TC2 was allowed to reach 1200°F by 10:50 and remained at that level for the rest of the experiment. Other temperatures within the gasifier slowly increased until the top of the balls were over 800°F. Grass feed was increased to 250 lbs/hr by 12:36. Some air was bypassed at 13:43 to reduce nitrogen dilution. Steam was added to the gasifier at 14:04 at 30 lbs/hr. By 14:26 the experiment was halted giving a total of 303 minutes under grass feed.

## ANALYSIS

Ideally the gasifier would operate with a sufficiently positive net energy production that combustion of the grass char would be sufficient to provide all the heat necessary to pyrolyze the grass. After the initial heat up under natural gas, introduction of the grass feed would replace the natural gas as the heat source. The scale of the gasifier is critical to this energy efficient operation as an excess of radiating surfaces makes heat retention difficult. If we do not reach net positive energy production with the current gasifier design, we hope that these experiments suggest those changes to the design that could lead to that condition. It is clear that this first large prototype is not the optimized design, but the eight days of operation did produce enough data to draw some conclusions.

### **Circulation of the Media**

Although we had the early problem of char interfering with the circulation of the 0.375" stainless steel balls, some adjustments in the orifice/bowl/draft tube holder hardware seemed to solve that problem. With the increased volume of air supplied by the compressor with the larger drive pulley (~210 scfm), there was nearly sufficient air to circulate the balls cold. By burning some natural gas with the input air, the added heat and the expansion of the gas volume led to smooth and steady recirculation of these rather heavy balls. The circulation system operated for over 21 hours without major issue once those adjustments had been made. It is expected that shortening of the draft tube would be appropriate in the Beta unit, which would require a lower airflow rate to circulate the same media.

### **Temperature in the Gasifier**

The heat up rate of the gasifier was controlled by the rate of natural gas usage during the start up period. It was clear that the addition of a second layer of insulation improved the heat retaining properties of the gasifier. The heat capacity of the stainless steel balls was also evident in the slow rate of heat loss of the gasifier after shut down. Often portions of the gasifier were still above 400°F eighteen hours after the previous day's shutdown. Thermocouple 1 was near the burner, thermocouple 2 was within the lowest area of balls, thermocouple 3 was about the midpoint of the height of the balls, thermocouple 4 was moved once, but for most experiments was very close to the top of the balls in the gasifier. Thermocouple 1 increased to 900°F very quickly after igniting the natural gas. Each thermocouple above measured the temperature increase with time, but the temperature distribution was almost always hottest at the bottom and dropping evenly to the top of the media bed. After thermocouple 2 reached the desired temperature, it was possible to reduce the natural gas usage rate to maintain a steady temperature at thermocouple 2. With time, the thermocouples above TC2 continued to rise in temperature until the range of temperature distribution throughout the media bed was reduced to 200 degrees or less. It is still to be determined whether in long term operation of such a gasifier whether the gasifier would perform better with an isothermal media bed or a bed with a controlled temperature differential.

In general, the grass feed start was based on the temperature at TC2. A temperature above 650°F was considered sufficient to begin adding grass to the gasifier. It was clear that operating at higher temperatures between 900 and 1100°F allowed a higher grass feed rate and better pyrolysis of the grass. Secondary interactions such as steam reforming might require other



temperature ranges and gradients. There are significant materials issues with the current gasifier design. The structural cast iron components will have oxidation and thermal cycling problems if forced above 1300°F regularly. The central draft tube is a 9CR12Mo alloy that can better withstand the thermal conditions in air, but a previous experience with the tube catching fire showed that the mechanical abrasion of the surface in high airflow rates and thermal hot spots could lead to material failure. A temperature of 1200°F in the lower section of the gasifier was reachable and controllable, but is probably the upper limit of operational conditions.

### **Pressure**

A series of ports was added to the gasifier along the entire length. Early differential pressure measurements between the top and bottom and middle and bottom of the gasifier showed very little measurable differential pressure with a liquid manometer and a S.G. - 1.0 fluid. There was no evidence of any high-pressure areas within the gasifier.

### **Slag Formation**

During the first day's operation on 7/25/05, there was a difficulty recirculation the balls after one half hour of grass feed. On disassembling the orifice area of the gasifier, a handful of adherent char was found within the bowl of the orifice plate. The char was in the form of brittle cake and could be broken easily. This small amount of material did not reoccur and was the only sign of slag formation during the eight day's of testing. All other solid materials removed from the exit cyclone were light and dry with no evidence of melting or agglomeration.

### **Ash/Char Composition**

The material collected from the exit cyclone was black, fibrous and very low density. The attached analysis (Figure) indicates that the solid was approximately 68% carbon and 28% ash. Based on the ash carbon ratio, obviously the largest proportion of fixed carbon (~80%) does not combust within the gasifier draft tube, but is transported into the solid waste. There are several reasons for this including the modest temperature and the low residence time in the draft tube. The carbon fraction defined as volatile versus fixed has dropped to 27:41 from the original 72:13 in the straw, indicating that only a small proportion of the volatile carbon was not removed in the gasifier. Given that 80% of the fixed carbon has transported over, the calculation shows that only 10% of the volatile carbon remains in the waste and 90% of the volatile carbon in the straw was removed in the gasifier.

The ash composition is potassium silicate plus 10% iron oxide and smaller amounts of phosphate, calcium oxide, aluminum oxide and magnesium oxide. The high level of potassium was expected considering the composition of the biomass, but was not so high that slagging was an issue at the operational temperature of the gasifier. The melting point of  $\text{KSiO}_4$  is 1313 K, or 1900°F, well above where we operated the gasifier. There is an iron/silicon/potassium oxide phase that melts at higher temperatures.

Approximately one third of the sulfur from the straw remained in the solid waste.

## **Gas Products Composition**

The principle constituents as measured by gas chromatography of samples taken from the gasifier include water, carbon dioxide, carbon monoxide, nitrogen, oxygen, hydrogen, and methane. There was little correlation for composition with the sampling region of the gasifier. The most consistent samples with respect to gas composition came were sampled within the gasifier just above the grass feed area. There was no obvious correlation of gas composition with temperature of the gasifier, or rate of grass feed. The samples that showed the highest heating value were taken when no steam was added to the gasifier. The highest heating value sample found contained 9% carbon monoxide, 1.7% hydrogen and 1.6% methane giving a value of 56 BTU's per scf which occurred on 8/4/05 with a high grass feed rate and no steam addition. This value was less than the best numbers previously recorded for the gasifier that were above 100 BTU's per scf.

## **Steam Reforming**

There is little difference between the composition of gas samples that were taken when steam was injected into the gasifier and when the grass was fed dry. We were expecting that the presence of water with all the nickel surfaces of the stainless steel and the moderate temperatures might lead to higher hydrogen concentrations, but the evidence of the gas chromatography results do not support that. Hydrogen concentrations were modest, 1 to 2 percent for almost all gas samples. While the hydrogen concentration is less important with respect to energy value of the gas for operating a reciprocating engine, the hydrogen concentration is very important for the gas use in a liquid fuels production capacity. It is likely that temperatures would have to be significantly higher in portions of the gasifier for steam reforming to occur at any measurable rate.

## **Mass and Energy Balances**

Although a pitot tube was inserted into the exit piping of the gasifier, the large diameter and the low flow velocity in that pipe did not produce consistent measurements of exit flow. Therefore it is difficult to calculate total mass and energy balances.

### **Energy Input**

On 8/04/05 we were operating with 180 lbs/hr grass feed. The grass analysis indicated that for the moisture free/ash free analysis, there was 85% volatile carbon and 15% fixed carbon with a predicted energy content of 8295 BTUs/lb. The ash analysis showed that little of the fixed carbon was used by the gasifier, so 85% of the energy value, or approximately 7000 BTUs/lb were available. At a grass feed rate of 180 lbs/hr and 25% solid waste, 75% of the 180 lbs, or 135 lbs was volatile carbon used by the gasifier, giving an energy value of  $9.5 \times 10^5$  BTUs/hr (135 lbs/hr x 7000 BTUs/lb). The natural gas burn rate was 180 scfh x 1000 BTUs/scf or 180,000 BTUs/hr. This gives a total energy input to the gasifier at approximately 1.13 million BTUs/hr.

### **Mass Input**

When the compressor was operating with a 10% air bypass, we were introducing 190 scfm of air into the gasifier. That is the equivalent of 196 lbs/hr of oxygen input. The elemental analysis of the grass indicated 43% carbon, 31% oxygen and 5% hydrogen. With 135 lbs/hr

grass feed, that gives 58 lbs/hr carbon, 42 lbs/hr oxygen and 7 lbs/hr hydrogen. Adding in the oxygen from the air feed and the carbon and hydrogen from 180 scfh of natural gas gives a total mass input of:

- 64 lbs/hr carbon (2406 moles)
- 238 lbs/hr oxygen (3373 moles)
- 9 lbs/hr hydrogen (1952 moles)
- 640 lbs/hr nitrogen (10,374 moles)
- 45 lbs/hr inert solids

#### Mass Output

For a best possible scenario which, use the GC results for sample 1114-106-1218, we have the following gas composition:

- 1.7% H<sub>2</sub>
- 3.2% O<sub>2</sub>
- 9% CO
- 1.6% CH<sub>4</sub>
- 10.5% CO<sub>2</sub>
- H<sub>2</sub>O copious but not quantified

Assigning this composition to the hourly mass inputs calculated above, the results are:

1197 moles CO<sub>2</sub> + 1026 moles CO + 182 moles CH<sub>4</sub> = 2406 moles carbon

1197 moles CO<sub>2</sub> + 1026 moles CO + 365 moles O<sub>2</sub> + xH<sub>2</sub>O = 3373 moles oxygen

182 moles CH<sub>4</sub> + 194 moles H<sub>2</sub> + xH<sub>2</sub>O = 1952 moles hydrogen

#### Energy Output

Using the best possible scenario used above for the mass calculations, with a mass output of 1000 moles CO, 200 moles CH<sub>4</sub> and 210 moles H<sub>2</sub>, the energy output is:

- 182 moles CH<sub>4</sub> = 182463 BTUs/hr
- 210 moles H<sub>2</sub> = 61262 BTUs/hr
- 1000 moles CO = 359223 BTUs/hr
- **Total = 602,948 BTUs/hr**
- **Total net energy (minus natural gas input) = 422,948 BTUs/hr**
- **Percent conversion of energy from grass volatile compounds = 44.5%**

## CONCLUSIONS

The current gasifier configuration with the 0.375" stainless steel balls recirculating media worked consistently and for periods up to six hours of grass feed. The other principle systems like the boiler, the air pump, and feeder device also worked consistently during all feeding operations. Minor hiccups during operation tended to come from secondary systems like the flare or flammable material buildup in the exit piping. Although we did not complete the extended hour tests to 24 or 48 hours due to time and budget constraints, we developed the confidence that the gasifier in its current configuration could handle those tests.

At the modest temperatures we operated the gasifier, slagging was not a problem. The solid wastes were dry and low density. The majority of the fixed carbon from the grass ended up in the solid waste collected in the external cyclone. The volatiles were almost all removed in the gasifier.

While the average gas heating value of the collected gas products was 50 BTUs/scf or less, addition of the second gas exit for combustion gases would increase that value by a factor of two or three. Other changes to the current design such as shortening the gasifier body and draft tube would lead to lower air use and shorter heating times.

There was no evidence of steam reforming at the current operating temperature. Likewise there was no indication of significant tar production.

Reconfiguration of the gasifier at the on farm site may yet yield more significant results that would better qualify this gasifier for small scale biomass operations.