ENERGY INNOVATIONS SMALL GRANT NATURAL GAS PROGRAM

FINAL REPORT

Syngas Process Development for Renewable-Methane Production

EISG AWARDEE

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Abstract

Based on the results of this research, the new process was able to produce a synthetic gas containing 44-percent of the energy content as Renewable Methane using Refuse Derived Biomass recovered from MSW as the energy feed. The potential net annual economic benefit to California is estimated to be $ 2.1-billion per year, including $1.1-billion in Renewable Methane revenue and $1-billlion derived from MSW disposal cost savings.

California's 39-million residents generate 4.7-pounds of Municipal Solid Waste (MSW) per person every day, which is then disposed into 80-landfills across the state. About 64,000 tons of California MSW is available daily with energy content of 6,000 Btu/lb. This is equal to about 128,000 barrels of oil per day.

The researchers tested mild hydrogasification of Refuse Derived Biomass recovered from MSW that included 20-percent plastics, which contribute hydrogen content to the process. Tests showed that mild hydrogasification reactions intensify using pulse-compression-waves that power a Jet-Spouted-Bed.

The researchers confirmed power output to be greater 60-kW$_{th,}$ based on propane input. The firing frequency of the pulse-deflagration prototype was 21-Hz; the firing frequency of the pulse-detonation prototype was 3-Hz. The authors also confirmed the bed materials were durable, with <10-percent shattered or deformed balls after 48-hours operation. No significant cracks resulted from pulse-combustor operation. The expanded bed height was >24" during jet-spouting using 0.5-mm & 1-mm steel beads, and 2-mm & 5-mm ceramic balls. The feed rate input was 3-lb/minute.

Sustainability benefits are obtained by diverting MSW destined for landfill, and using that energy resource to generate Renewable-Methane, a clean-fuel that can be distributed using the existing pipeline infrastructure, for transportation, advanced power generation, and for the production renewable chemicals.

Key Words: waste gasification, biomass gasification, pulse-combustion, pulse-deflagration, pulse-detonation, refuse derived biomass, hydrogasification, renewable methane.

Executive Summary

Introduction

The purpose of this project was to test a new method for producing Renewable-Methane using a high-intensity thermal processing method. The researchers tested a mild hydrogasification process using Refuse Derived Biomass (RDB) as the energy feed. Prototype pulse-POx-combustors were developed and integrated with a Jet Spouted Bed to accomplish the process intensification. California generates approximately 64,000 tons per day of RDB, which is presently sent to landfill as Municipal Solid Waste (MSW). The energy content is equal to about 128,000 barrels of oil per day.

Project Objectives

1. Provide drawings showing key sub-components to be fabricated and installed on existing Process Development Unit (PDU).
2. Demonstrate pulse-POx-combustor with input greater than 60-kW per hour input capacity, based on propane input.
3. Demonstrate test-system is capable of measuring performance parameters within an error of +/- 5 percent.
4. Demonstrate pulse-POx-combustor greater than 30-volume percent H_2 output.
5. Demonstrate pulse-POx-Combustor frequency greater than 7-Hz.
6. Demonstrate durability of bed-material -- shattered or deformed balls less than10 percent after 48-hrs operation.
7. Demonstrate zero significant *cracks* that could result in failure of pulse-combustor.
8. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using steel balls greater than 1-mm diameter.
9. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using ceramic balls less than 12-mm diameter.
10. Demonstrate RDB feed input of greater than 0.5-lb/min.
11. Demonstrate greater than 50-percent energy content as CH_4 in fuel-gas products.
12. Demonstrate carbon-char products fractions are less than 25-weight percent of the dry-feed input.
13. Confirm from the project findings that a production cost of $8/mmBtu Renewable-Methane is supported.
14. Confirm from the project findings, using GREET Analysis, that the projected carbon footprint, using RNG for vehicle fuel, that WTW GHGs are less than 20 g CO_2e/MJ, and -80 percent GHGs compared to gasoline.

Project Outcomes

1. The research team prepared drawings for fabrication of multiple prototypes, including three pulse-deflagration prototypes and three pulse-detonation prototypes.
2. Power output was greater than 60 kW$_t$ per hour based on propane input: The research team operated the pulse-burner prototype with an average firing capacity of 137-kW (thermal) per hour, based on a measured average flow of 3.1-scfm (186-scfh.)
3. The test system was capable of measuring performance parameters within an error of +/- 5 percent. The best precision measured for methane (under actual operating conditions, when the product gases included additional low-molecular-weight hydrocarbon gases) was +/- 6.46 percent, and the worst was +/- 42 percent. The precision of the methane analysis was observed to decrease roughly in proportion with the increasing presence of other low-molecular-weight hydrocarbon gases. Real-time measurement of methane -- using an NDIR type analyzer -- is somewhat more difficult than is purported by the instrument supplier.
4. The research team demonstrated hot-syngas output from the pulse-deflagration prototype with 31-volume percent H2 content (with N2 content removed from the gas composition.)
5. The frequency of the pulse-combustor was greater than 7-Hz: The pulse-deflagration prototype operated at 21-Hz; whereas, the pulse-detonation prototype operated at 3-Hz.
6. The bed materials were durable, with one percent shattered or deformed balls after 48-hrs operation.
7. Researchers observed no significant cracks after operating the pulse-combustor prototypes.
8. The research team operated with an expanded bed height of 60-inches when operating with a bed composed of 0.5-mm stainless steel beads; 1-mm steel beads were observed to form a fountain higher than 24-inches, but the performance (as a means of ablation) was not as robust compared to smaller (lighter) bed materials.
9. The research team confirmed that the expanded bed height was greater than 24-inches during jet-spouting using ceramic balls with diameters of 2-mm and 5-mm: A fountain height of 80-inches and 60-inches respectively was observed when operating with ceramic beads, with diameter of 2-mm and diameter of 5-mm.
10. The research team demonstrated Refuse Derived Biomass feed input of 3-lbs/minute.
11. The research team has not demonstrated that >50-percent energy content as CH4 is present in fuel-gas products. The maximum CH4 content measured for methane was 43.69-percent by volume, when measured as a fraction of the total chemical energy content in the product gases. The project goal was 50-percent of gas-phase energy in the form of methane.
12. The research team has not demonstrated greater than 50-percent energy content as CH4 in fuel-gas products: The data shows that the carbon-char fraction, when measured on a dry-basis, is 10.77-wt percent of the dry-feed.
13. The research team has not demonstrated carbon-char products fractions are less than 25-weight percent of the dry-feed input. This work was not completed because the methane content in the syngas product was not sufficient to warrant further analysis based on the project concept of a stand-alone renewable methane production facility.
14. The research team has not confirmed from the project findings, using GREET Analysis, that the projected carbon footprint, using RNG for vehicle fuel, that WTW GHGs are less than 20 g CO2e/MJ, and -80 percent GHGs compared to gasoline. This work was not completed because the methane content in the syngas product was not sufficient to warrant further analysis based on the project concept of a stand-alone renewable methane production facility.

Conclusions

The researchers successfully accomplished 11 of the 14 project objectives. There are some indications that through continuing efforts the process may be improved by a few percent; the remaining quantitative goals could then be demonstrated with favorable results if performed for the co-production F-T liquids and renewable methane.

Not enough favorable data has been generated to support the key project goal, renewable methane with greater than 50% of the energy content in the form of CH4, and a new process cannot be commercialized without more substantive performance data.

However, both the pulse-deflagration and pulse-detonation burner technology, integrated with Jet Spouted Bed operation, have been reduced to practice; further developments will constitute refinements of the technology approach and may lead to the demonstration of a new co-production process that generates both hydrocarbon liquids and renewable methane.

Recommendations

A successful commercial process would necessarily use the carbon-char as the primary fuel to provide hot-reducing gases to accomplish gasification and methane formation within an H2-rich processing environment. The ASPEN modeling work has identified a key processing issue; that is, carbon-char (used in a POx reaction with oxygen and steam) may not be as good a source of reducing gases as propane.

According to the model, carbon-char does not reach chemical equilibrium; probably, a catalyzed means of increasing the rate of carbon conversion into carbon monoxide needs to be demonstrated; probably using potassium salts and, and possibly including a low-cost source of iron oxide as a minor component of the feed would help catalyze the carbon reactions.
The additional proof-of-concept testing is need to demonstrate *nearly* 50-percent of the energy content can be produced as CH4 content in fuel-gas products. The present work shows the methane formation rate is 43.7 percent of the energy content; not *nearly* 50-percent. Increasing the number to 45-percent or 47-percent would be significant to the over all process economics.

The GREET analysis is expected to be favorable because the feedstock is renewable. Carbon-char can be recycled to the front-end of the thermal process and consequently the carbon-char content in the ash is not particularly significant to the process economics.

Additional proof-of-concept testing is needed to show that mile steam-hydrogasification reactions that produce renewable methane can be intensified using supersonic shockwaves that result from pulse-detonations emanating from a high-temperature syngas-generator. Great potential still exists to deploy a high-risk / high-reward methodology that uses a pulse-detonation burner to generate high-energy low-cost shockwaves -- that compress and mix the reactor contents when passing through, rather than compressing the entire contents of the reactor externally.

Public Benefits to California

Based on the results of this research, the process was able to convert 44-percent of the energy content in the energy feed into CH4. The potential annual economic benefits to California is $ 2.13-billion per year, based on the following analysis: In California, the resource potential is 4.7-pounds of Municipal Solid Waste (MSW) per person per day. Approximately 70-percent of MSW can be recoverable as Refuse Derived Biomass (RDB), the energy feed, which is a low-density, high surface area feedstock well suited for thermal chemical conversion into renewable methane. Gasification typically converts 70-percent of RDB into synthetic gas. The results indicate that 44-percent of the net energy contained in RDB can be converted into 465-mmscfd Renewable-Methane, resulting in energy value benefits using the following assumptions and conversion factors:

<u>Conversion Factors</u>

- There are 39 million people in California
- Per capita MSW generation is 4.7-pound per day
- The MSW disposal cost is $45/ton
- RDB is recovered from MSW with 70-percent recovery
- Thermal Gasification converts RDB into synthetic gases with 70-percent efficiency
- After drying, RDB contains approximately 7,500 BTUs per pound
- 44-percent net conversion into Renewable Methane (CH4)
- CH4 contains 910 Btu per standard cubic foot (Btu/scf)
- Renewable Methane is valued at $10/mmBtu

The daily volume of Renewable Methane is calculated as follows:

39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB = 128, 310,000 pounds per day of RDB
128,310,000 pounds per day of RDB x 7,500 Btu/lb = 962,325 mmBTU per day as RDB
962,325 mmBTU/day as RDB x 0.70 gasification efficiency = 673,627 mmBTU per day as synthetic gas
673,627 mmBTU/day / 910 Btu/scf CH4 x 0.44 net conversion efficiency = 325 mmscfd.

The daily economic value is calculated as follows:

39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB = 128, 310,000 pounds per day of RDB
128,310,000 pounds per day of RDB x 7,500 Btu/lb = 962,325 mmBTU per day as RDB
962,325 mmBTU/day as RDB x 0.70 gasification efficiency = 673,627 mmBTU per day as synthetic gas
673,627 mmBTU/day x 0.44 net conversion efficiency x $10/mmBtu = $ 2,963,950 per day

The daily disposal cost savings is calculated as follows:

MSW also has an associated disposal cost of $45/ton.
39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB/2000 lbs/ton x $45/ton = $2,886,975/day

Potential annual economic benefits are summarized below:		**Annual Benefits**
Methane Value:		
$ 2,963,950 per day x 365 days/year =		$ 1,081,841,000 /year
Disposal Savings:		
$ 2,886,975/day x 365 days/year =		$ 1,053,745,000 / year
Cumulative value (methane value plus disposal savings):	=	$ 2,135,586,000 /year

Sustainable communities benefit from increased reliability when more distributed sources of renewable-methane are input to the pipeline distribution system. Moreover, renewable methane production facilities would be available to operate as stand-along fuel source in times of emergency.

Introduction

The subject of this research is the production of Renewable Methane (RM) using the organic fractions present in Municipal Solid Waste (MSW). Competitive methods fall within two general categories: (i) the biological paths that include anaerobic digestion (AD), (ii) and the thermal-chemical paths that include gasification-methanation and hydrogasification.

Anaerobic Digestion (AD) systems do not benefit from the presence of plastic fractions in MSW (Gershman, 2012). Whereas, the proposed technology is intended to use the plastic fractions in MSW as a source of H2 contributing to the steam-hydrogasification process to enable the rapid conversion of biomass into methane-rich fuel-gases.

The subject energy feedstock is an RDB (Refuse Derived Biomass)-fluff that is recovered from MSW by shredding in two stages using rotary-shear type shredders, size-classification to <2-inch, then air-stripped to remove glass, sand, grit, and debris, from the light fractions. The resulting *RDB-fluff* contains most the chemical energy available in MSW, including the plastic fractions. RDB is dried to 14-wt-percent to 18-wt-percent moisture content during storage, resulting in a homogeneous organic feed with low-density and high surface area that is well suited for thermal-chemical processing methods.

The research team is aware of comparative production costs cited in the literature for AD systems available at commercial scale, including the AD Technology presently being deployed by CR&R in Riverside County for digestion of biomass. According to Gershman, et al. (2012) Sempra Energy Utilities estimates the AD cost for conditioned biomethane at $9-12/mmBtu (When derived from landfill gas, the cost for RM is said to be about $5.50/mmBTU with capacities greater than 1.5 mmscfd.)

Thermal-chemical processes are typically 100-times more intensive when compared to biological paths. For example, AD requires 7-days to complete the biological conversion of organic materials into RM; whereas, the thermal-chemical paths are typically completed in about 3-minutes.

Commercial processes are available that employ solid carbon feeds for production of Substitute Natural Gas (SNG). Most prominent is *gasification integrated with methanation.* Carbon feeds are gasified via partial oxidation with oxygen to form synthesis gases (syngas) that are conditioned, cleaned, and then reacted over a methanation catalyst to produce SNG composed of 95% methane. The pertinent chemical reactions that generate methane using syngas as the chemical intermediate are summarized:

$$CO + 3H2 = CH4 + H2O \qquad 2CO + 2H2 = CH4 + CO2 \qquad CO2 + 4H2 = CH4 + 2H2O$$

The gasification-methanation path is available for large commercial applications. For example, Shell offers a coal gasification process for integration with the Haldor Topsoe TREPM methanation technology. The base-case cost estimates are for producing 78 billion ft3/yr of SNG that is of pipeline quality. The Shell gasification process and similar SNG technologies -- based on coal gasification integrated with methanation -- are being deployed at very large scale in China and elsewhere in the world where landed prices for LNG are greater than about $12/mmBtu (Vandenburgh, et al, 2012). The gasification-methanation path to SNG (using syngas as the intermediate) is applicable to any carbon source, including RDB.

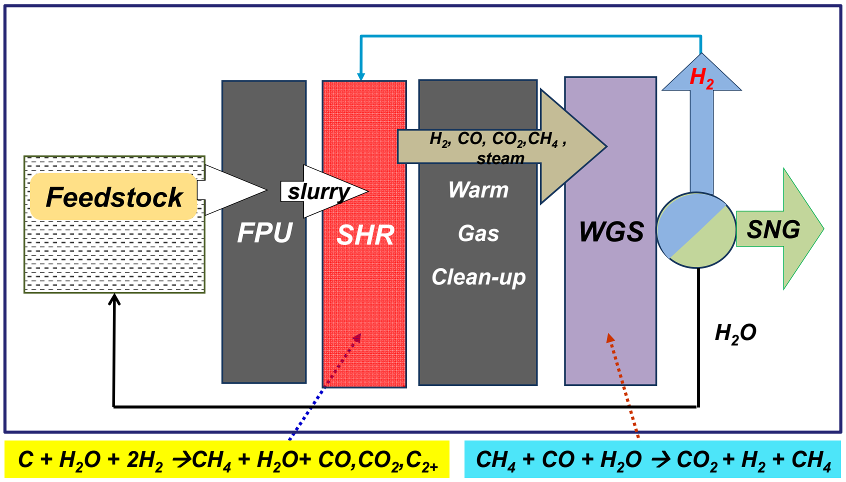
However, to date, the process complexity and the resulting high cost has prevented commercialization at small-scale applicable to RDB in California – the scale is 1,000 ton/day for California RDB, verses the 10,000 to 100,000 ton/day scale used for coal resources.

Regarding process complexity, the syngas intermediate product resulting from carbon gasification has to be cooled and cleaned using multiple processing steps prior to methanation to prevent catalyst contamination. The process complexity creates an overriding problem: the cost of syngas produced at large-scale from coal, for example, is about $0.06/lb; based on syngas with 10,000 Btu/lb, the syngas cost is therefore equal to about $6.00/mmBtu. Purified-syngas is a relatively costly chemical intermediate when used for production of CH4 via methanation.

Dry-hydrogasification applied to various carbonaceous feeds is the other relatively well-known path for production of SNG. Hydrogasification of coal and biomass have been used for SNG production since the 1930's. Carbon is gasified in an H2-rich atmosphere at about 100 atmospheres. Hydrogen is typically supplied through the water-gas shift reaction with carbon, or by steam-reforming of residual process gases. The pertinent chemical reaction that generates methane is summarized:

C + 2H2 = CH4 + others. However, dry-hydrogasification has not seen wide spread commercial deployment, although the mass and energy balance are improved by about 10% when compared to the gasification-methanation path (Drake, 2014).

Steam-hydrogasification has recently shown benefits at process development scale that are superior to dry-hydrogasification. Water is introduced to the reaction. CE-CERT's process is summarized below in **Figure-1**. CE-CERT has found that addition of water increases the chemical reaction rate; the efficiency is increased at lower temperature, and the process efficiency is also increased at lower pressure (Gershman, 2012).



$C + H_2O + 2H_2 \rightarrow CH_4 + H_2O + CO, CO_2, C_{2+}$

$CH_4 + CO + H_2O \rightarrow CO_2 + H_2 + CH_4$

Figure-1. Steam Hydrogasification Process developed at CE-CERT

The Center for Environmental Research & Technology, University of California, Riverside (CE-CERT) Steam-Hydrogasification process employs approximately 10-atm, 700-800 C, for the optimized conversion of biomass-carbon into CH4. Alternatively, the proposed process would generate more residual carbon-char (recycled back into the process as hot-syngas), but would operate at less than half the pressure, <40-psig, which is a more cost-effective range for large-scale waste processing facilities.

The Principal Investigator developed a steam-hydrogasification process at the Western Research Institute aka, The Research Corporation of the University of Wyoming. The subject coal-to-SNG process employed several counter-current stages of steam-hydrogasification integrated with counter-current char-oxidation to generate process heat. The jointly sponsored research project was co-funded by the researchers and the DOE under DE-FC26-98FT40323 during the 2003 – 2006 time frame; after testing at PDU scale, the process was selected by GE for commercial development just as shale-gas production began to increase dramatically, lowering the cost of pipeline gas in the USA, which resulted in shutdown of the GE coal-to-SNG program at WRI. The process was designed to convert Powder River Basin Coal (PRB-coal) into SNG. The reactor configuration employed a robust type of counter-current cyclonic processing methodology employed at very large-scale by the cement industry for calcining limestone. An objective of the process was to reduce the operating pressure by using a low-cost mineral catalyst, activated by calcining the minerals and carbon-char in the counter-current oxidation side of the process.

This program Statement-of-Work focused on proof-of-concept testing of a novel *steam-hydrogasification* method; this program was intended to proved that a pulse-POx-combustor generating hot-syngas, as shown in the Process Flow Diagram, Figure-2 below, can be used to drive a Jet Spouted Bed and generate methane-rich fuel gases. Note that the input to the pulse-combustor includes fuel, oxygen enriched air, and can include steam. The objective was to generate hot-syngas products that are directed into bottom of the Jet Spouted Bed. The over-all objective was to produce *methane-rich fuel gas*.

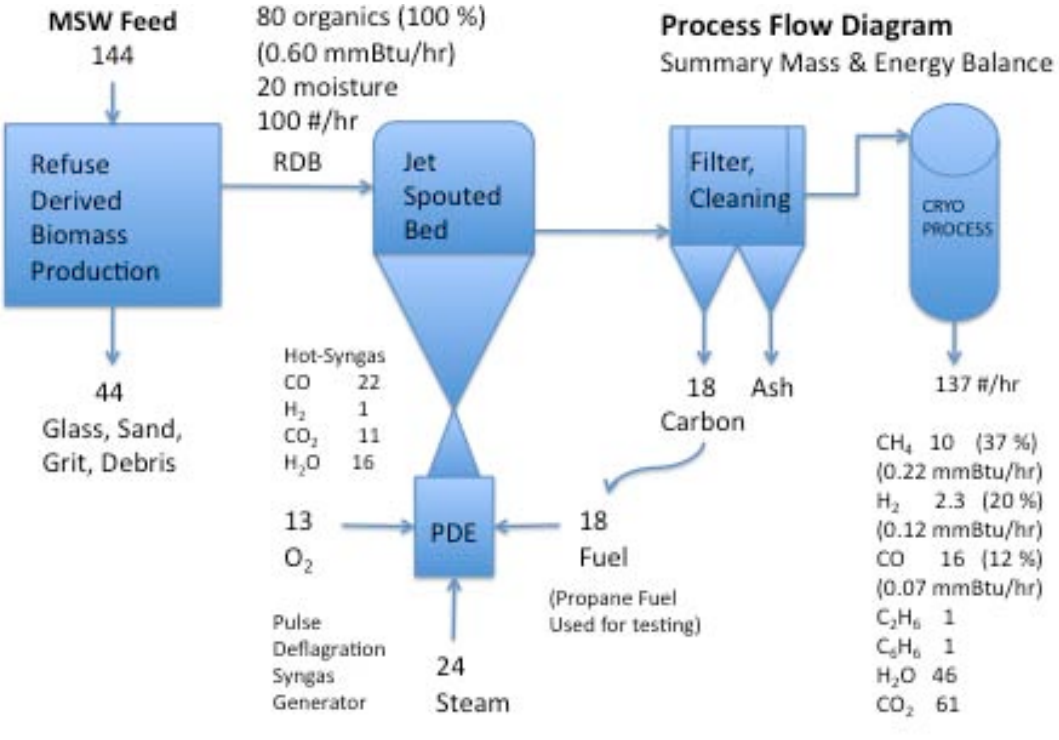


Figure-2. Process Flow Diagram with mass and energy balance

According to Melaina & Eichman (2015), the operating range for pulse-deflagration (and/or pulse detonation) is broad, from lean to rich. The research program reports on testing the pulse-combustor operating rich, producing 30-volume-percent hydrogen.

The main focus of the statement-of-work was to operate the pulse-POx-combustor discharging hot-syngas into the Jet-Spouted-Bed (JSB) (the expansion chamber), intended for renewable methane production.

The researchers optimized pulse-combustor prototypes for hot-syngas production. The test program included the plan for a short series of preliminary tests integrated with a Jet-Spouted-Bed processing biomass feedstock to get some indication of the difference between operating with excess O2 (*autothermal gasification*) compared to *mild-steam-hydrogasification.*

The test program looked at *mild-steam-hydrogasification* according to the operating paradigm proposed by Hermann Feldman -- which offers many potential benefits. Hydrogasification typically requires operating pressure of 150-psig; the expectation (test objective) was to see if the integrated Pulse-Combustor/Jet Spouted Bed (JSB) could provide enough process intensification to enable hydrogasification under mild conditions, increasing the CH4 content in the product gases.

A key objective is to use sonic or ultrasonic compression waves to intensify thermal-chemical processes, to enhance carbon utilization within the process, while performing proof-of-concept testing of *mild-steam-hydrogasification*. The researchers intend to show that Pulse-Combustors integrated with a JSB offer special benefits based on simple proof-of-concept testing.

Essentially, the researches are using compression waves -- that pass through the process -- to increase thermal-chemical reactivity, rather than compressing the entire contents within the process. The prototype pulse-combustors served to increase the useful power output of the combustor-exhaust, and to discharge cyclic compression waves into the thermal-chemical process. A pulse-detonation combustor is shown below in Figure-3 and in Figure-4.

Figure-3. Pulse-Detonation-Combustor

Figure-4. Combustor w JSB

Project Objectives

The goal of this project was to determine the feasibility of an improved thermal-catalytic process using Refuse Derived Biomass as the energy feed for conversion into Renewable-Methane, employing a novel pulse-powered jet-spouted-bed, heated by H2-rich syngas produced in a pulse-type partial oxidation combustor.

1. Provide drawings showing key sub-components to be fabricated and installed on an existing Process Development Unit (PDU) located at UC Riverside, at the CE-CERT facility.
2. Demonstrate a pulse-POx-combustor with input greater than 60 kW-thermal per hour input capacity, based on propane input.
3. Demonstrate the test-systems are capable of measuring performance parameters within an error of +/- 5 percent.
4. Demonstrate a pulse-POx-combustor producing greater than 30-volume percent H2 output.
5. Demonstrate a pulse-POx-Combustor with pulse frequency greater than 7-Hz.
6. Demonstrate durability of the bed-material; demonstrate shattered or deformed balls are less than 10-percent after 48-hrs of operation.
7. Demonstrate zero significant *cracks* that could result in failure of the pulse-combustor.
8. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using steel balls greater than 1-mm diameter.
9. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using ceramic balls with less than 12-mm diameter.
10. Demonstrate RDB feed input greater than 0.5 lb/minute.
11. Demonstrate greater than 50-percent energy content as CH4 in fuel-gas products.
12. Demonstrate carbon-char product fractions are less than 25-weight percent of the dry-feed input.
13. Confirm from the project findings that a production cost of $8/mmBTU Renewable-Methane is supported.
14. Confirm from the project findings, using GREET Analysis, that the projected carbon footprint, using RNG for vehicle fuel, that WTW GHGs are less than 20-g CO2e/MJ, and <80 percent GHGs compared to gasoline.

Project Approach

1. Finalize design modifications and hardware sub-component additions to Process Development Unit at the College of Engineering, Center for Energy Research and Technology, Riverside, CA. (CE-CERT); complete design drawings.

The research team's initial approach was to finalize design modifications and prepare shop-drawings for the hardware needed as sub-components to be added to the Process Development Unit at UCR, the test facility located at the College of Engineering, Center for Energy Research and Technology, Riverside, CA.

The gasification system is shown below in Figure-5 and Figure-6.

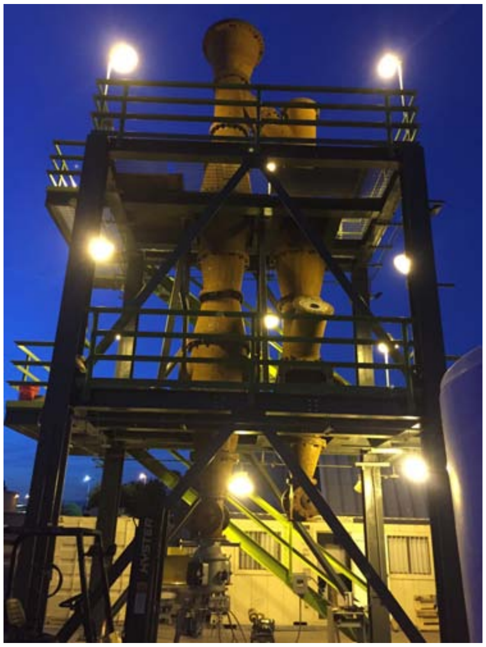


Figure-5. CE-CERT Test Facility

Figure-6. CE-CERT Test facility, Angle-2

Drawings were prepared to enable fabrication of multiple prototype Pulse-Detonation-Burners designed to integrate with an existing Jet-Spouted Bed (that serves as the expansion-stage for pulse-burner.) Initially, the researchers constructed a linear prototype using carbon steel, which was tested successfully. A shop drawing is shown in Figure-7 and the early prototype is shown in Figure-8.

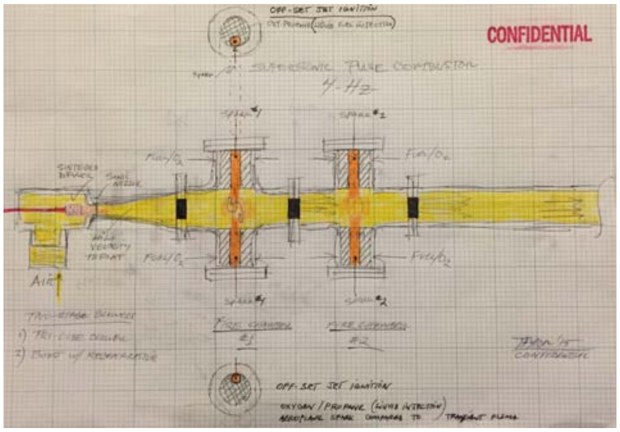


Figure-7. 3-stage combustor concept

Figure-8. Early hardware, 3-stage combustor

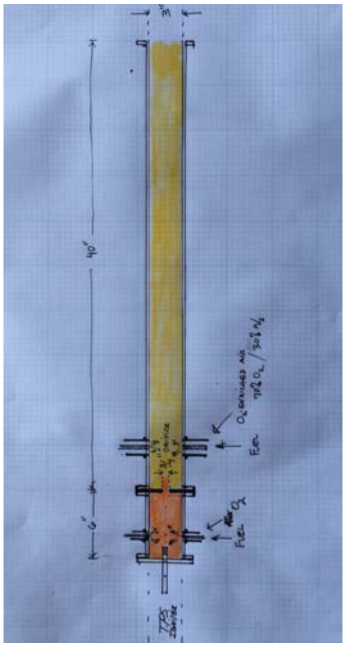


Figure-9. 2-stage combustor

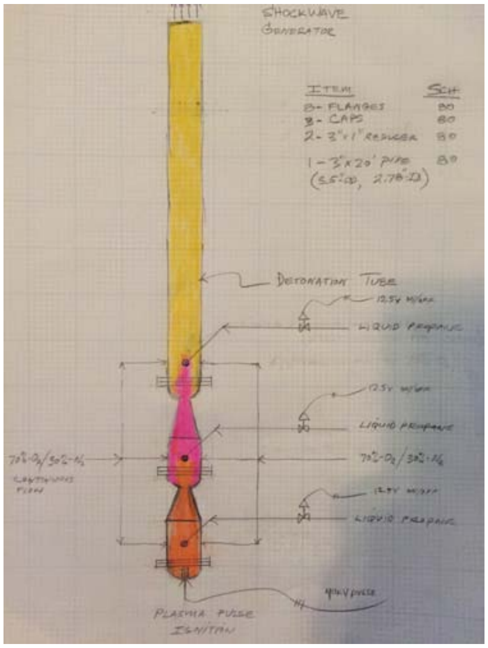


Figure-10. 3-stage pulse-combustor

Figure-11. Combustor

2. Fabricate one proof-of-concept Pulse-Deflagration-Burner integrated with the existing Jet-Spouted Bed (expansion stage). The initial results for a carbon steel pulse-combustor prototype were promising. The researchers then designed and fabricated a more sophisticated 3-stage prototype using stainless-steel, as shown in Figure-10 and Figure-11 above based on a California Institute of Technology propulsion design researched by J. E. Shepherd (2002). The approach used by the research team was to mount the pulse-combustor prototype on a horizontal test stand, shown below in Figure-12 and Figure-13, where preliminary testing was accomplished. The design uses two pre-combustion stages and one linear pulse-stage. The use of support-cables enabled the measurement of deflection during operation to measure thrust, following a procedure developed by Shepherd (2002), who performed similar work on a 2-stage pulse-detonation-engine employed for testing propulsion thrust.

Figure-12. A-Frame type Test-stand

Figure-13. Horizontal test-stand used to measure deflection

The research team initially experimented with a liquid propane fuel injection system composed of six automotive type fuel-injectors. High Pressure Solenoid Injectors, model HDEV5, made by Bosch for gasoline direct injection, were obtained from a Ferrari California, and were tested with some success. The fuel-injectors and the high-pressure manifold are integrated parts, both supplied to Ferrari by Bosch. A Bosch manifold was modified by the research team to fit the pulse-burner.

Figure 13a. Six Fuel-Injectors

Figure 13b. High-Pressure Solenoid Injector, HDEV5

Liquid fuel injection works with automotive engines and in rocket engines, etc., and is preferred in this application to maintain constant pressure in the propane storage tank. Withdrawing propane as a gas will always lower the temperature of the liquid in the tank due to evaporation, which reduces the vapor pressure, and therefore requires some adjustment from time to time during continuous operation. When testing the liquid fuel injectors, the liquid withdrawal valve on a 150-gallon propane tank was connected to the injector-manifold via a high-pressure propane hose, which was supplied at the tank vapor pressure. The vapor pressure in the propane storage tank varied from 60-psig to 120-psig, depending on the temperature.

The research team used ARDUINO, an open-source electrics platform based on easy-to-use hardware and software to control the fuel-injector timing and to control the spark-ignition timing.

The objective was to control the fuel and spark-ignition timing so as to initiate sonic detonations, and if possible to over-drive the detonation events, achieving supersonic pulses.

A pulse-detonation prototype combustor was tested using airflow input of 90-scfm at 3-psig, supplied by the rotary-lobe type blower operated at 3600-rpm. The spark-ignition timing was synchronized with the timing to open /close the solenoid fuel-injectors; the spark ignition was set to trigger at the end of the fuel-injection pulse. The timing sequence tested by the research team ranged from 2-Hz to 4-Hz. Forty test sequences were performed in this mode of operation.

The airflow was held constant at 90-scfm, while the timing for both fuel-injection and spark-ignition were varied from 2-Hz to 4-Hz, while concurrently testing the on-time/off-time sequence; the spark on-timing was tested in the range of 50-milliseconds to 200-milliseconds. Success is this case was defined by obtaining singular ignition events occurring in sequence.

The air pressure-drop -- through inlet nozzles that convert pressure into inlet velocity-- served as a type of backpressure valve. That is, momentum resulting from pulse-detonation events was maintained in the forward direction because the back-flow was largely prevented by the air-input flowing through sonic nozzles that prevented significant black-flow; because the air velocity, the momentum was in the direction of the air input; the same direction as the output products.

The power control sequence needed to operate the solenoid valve required delivery of 70-volts dc for 20-milliseconds; hold-open required 12.5-volts-dc for 50 to 200 milliseconds, and close-valve with zero voltage.

The pulse-detonation burner showed great potential in this mode of operation by producing some very significant detonations. However, precise control of the liquid fuel-injectors proved to be difficult, and as a consequence, the ignition events were irregular, and pulse-power was intermittent. Using this approach, the research team was not able to establish uniform pulse-combustion.

The operating pressure of the liquid system was only 160-psig; whereas, the injectors were designed for liquid pressure of 3000 psig. The fuel-injectors did not operate all that effectively at the lower pressure. In the context of the current proof-of-concept program, it was not possible to provide a high-pressure liquid supply system, which would have required transferring liquid propane to a nitrogen tank, then compressing the propane using nitrogen head pressure. Automotive fuel-injectors are intended for very high speed repetitive cycling (100-Hz), whereas the current program target was only 7-Hz.

Consequently, the decision was made to switch to a gaseous fuel injection manifold that was easier to control with a simple on/off power control signal used operating industrial solenoid valves that can operate at 4-Hz for 300,000 cycles.

Six gas injection nozzles were designed and fabricated, employing a nozzle orifice of 1.3-mm inside diameter. The necessary modifications were performed and then 24-tests were completed, achieving a pulse-detonation rate of 3-cycles per second. Using gaseous fuel, continuous pulse-ignition was achieved, and the system was deemed a preliminary success and moved to the JSB for further testing. Below in Figure-14 and Figure-15, the prototype pulse-detonation-burner is shown integrated with the Jet Spouted Bed, firing into the bottom of the JSB. The 3-stage pulse-detonation design was considered to be a high-risk and high-reward embodiment.


Figure-14. Pulse-Burner Integrated with JSB


Figure-15. Three-stage prototype installation

Program schedule and available funding were limiting factors that precluded further optimization. This system was operated successfully, producing shockwaves using air, not oxygen enriched air, which is a major accomplishment. A successful pulse-detonation burner generates the sound of a gunshot and creates a distinctive shockwave, which sounds like a bullet whizzing past.

According to Coleman (2001), cycling pulse-detonations are much easier to achieve using oxygen enriched air. Therefore, this 3-stage *pulse-detonation embodiment* was considered to be a major success that now provides the opportunity for future optimization by using oxygen enrichment, which is also more advantageous for performing mild-hydrogasification.

In parallel with the design & testing of the high-risk / high-reward pulse-detonation prototype, a more conventional *pulse-deflagration embodiment* was also developed by the research team. The second prototype was a single-chamber design; a pulse-deflagration-burner composed of a single flame-can employing a fuel/air mixer and a spark ignition system. The principle of operation is shown below in Figure-16. Initially, a stainless steel prototype, shown below in Figure-17, was tested successfully, achieving stable operation with a relatively high pulse-rate, on the order of 20-Hz. However, the potential for over-heating the flame-can (constructed of 316 alloy stainless steel) was considered problematic.

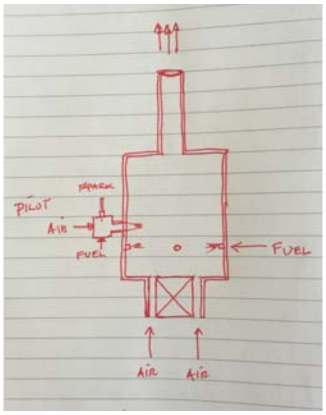


Figure-16. Design Principle

Figure-17. Early Stainless Steel Prototype

The research team concluded that the use of a cast-refractory type combustor would offer significant improvements and would enable high-temperature operation without the fear of rapid catastrophic failure due to high temperature excursions when transitioning from fuel-lean to fuel-rich operation. The internal shape of the pulse-deflagration burner is proprietary and is therefore not included in this report. Refractory was poured around molds that formed the internal shape of the rocket-type burner; stainless steel insertions were used to provide openings for fuel inputs and for instrumentation (temperature and pressure measurements), and to connect the spark-ignition system. Figures 18 and Figure 19 below show the burner housing and casting the refractory within that housing.

An iterative hardware development method was used -- in that multiple prototypes were built and tested in sequence, rather quickly, until a successful embodiment was obtained. For example, prototypes were constructed using carbon-steel, then stainless steel, and finally a cast-refractory embodiment was selected for integration and testing with the Jet Spouted Bed.

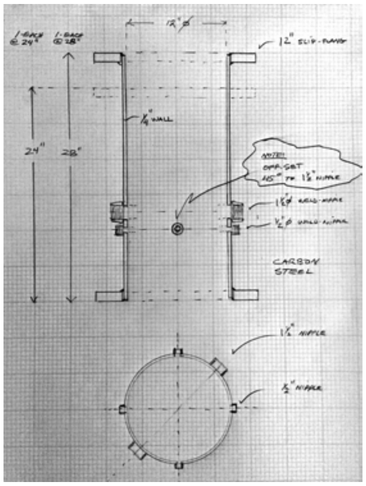


Figure-18. Burner Housing

Figure-19. Burner Casting

Figure-20. Integration with JSB

After curing the refractor and testing the pulse-deflagration burner at ground level to confirm the performance, the prototype pulse-burner was mounted on the bottom of the JSB. Figure-20 shows the integration of this embodiment with the JSB. The intent was to compare operation of a *pulse-deflagration burner* with a *pulse-detonation burner*.

3. Install connections to instrumentation to record input and output parameters.

The research team installed instrumentation, primarily including a dozen K-type thermocouples shown below in Figure-21 (the yellow leads), which were used to measure and record the temperature using a Yokogawa XL-100 temperature monitor shown in Figure-22. Pressure sensors used to measure the impulse frequency were also installed; two pressure sensors, model PX309-030AV, supplied by Omega, provided the pressure range needed; 0-30 psig absolute. Shown below in Figure-23, pressure gages with pressure range of 0-7 psig were also installed.

Three rotameters made by Dwyer, with flow ranges from 0-50 scfh, 0-200 scfh, and 0-10 scfm were used to control and measure the input of gaseous propane.

Figure-21.K-type Thermocouples

Figure-22. Yokogawa XL-100

Figure-23. Pressure monitoring

Air-flow input was measured indirectly using a Variable Frequency Drive (VFD) to control the RPM of a positive-displacement Roots Blower, shown below in Figure-24. The flow estimate was based on the performance-curve for the specific blower model with maximum out of 200-scfm at 1800-RPM. The Variable Frequency Drive was used to control the air-flow was follows: 60-Hz equates to 1800 RPM; 30-Hz is half the speed, 900-RPM. The performance curve for the blower indicates the air-flow at the specific RPM. The air-flow is not completely linear; however, at low back-pressure, half the RPM equates to half the flow volume: 30-Hz on the VFD equals approximately 100-scfm.

The optimum operating point for the *pulse-detonation prototype* was 43-Hz, equal to approximately 143-scfm air-input, operating with excess air. The pulse-detonation prototype was not operated successfully with excess fuel; that is, the fuel-rich mode of operation was not achieve using air. The pulse-detonation burner was too unstable in that mode of operation, with frequent misfires, and was determined to be too dangerous without using oxygen-enrichment to stabilize the ignition cycle. Therefore, the products of combustion were not tested for H2 content, and this prototype burner was not used to test its ability to form CH4, above the amounts predicted by modeling.

The operating range for the *pulse-deflagration prototype* was much broader. The burner was tested and operated successfully employing a range from 30-Hz to 60-Hz, testing both fuel-lean and fuel-rich operating modes.

Selecting the optimum operating point was a subjective process. For example, the operator listened to the sound of the system, listening for points of low-stress at high performance, particularly listening to the operation of the blower/motor combination. Above 52-Hz, there was back-pulse that was stressing the blower; whereas, in the range of 47-49 Hz, the sound of blower did not indicate any stressed at all. The procedure was subjective, but fairly obvious to an unskilled operator. For example, some operating frequencies would tend to develop a slight vibration in the drive-belt -- a cause to avoid that particular operating frequency.

Figure-24. Roots Blower – Powered by a Variable Frequency Drive

The adiabatic flame temperature for stoichiometric mixtures of air and propane is 1,977 C. The lowest temperature achieved during fuel-lean operation was approximately 380 C, which indicated that the *pulse-deflagration prototype* was very stable, being able to ignite and maintain stable operation with a very high rate of excess air. The lowest temperature achieved during fuel-rich operation was approximately 980 C, which likewise indicated that the *pulse-deflagration prototype* was relatively stable with excess fuel. A key to the approach was to avoid operating the burner using stoichiometric mixtures of air and propane because the resulting flame temperature of 1,977 C would have melted the refractory rather quickly. The approach was to fire the burner using fuel-lean conditions -- then turning up the fuel input rather quickly to fuel-rich operation, passing smoothly through the range where the highest temperatures would damage the prototype burner's refractory.

4. Finalize test-plan and test-matrix; obtain approval of test-plan and test-matrix.

A test-plan was finalized that included a test-matrix measuring the air-input as a function of propane input. A plan to obtain stakeholder approval of the test-plan and test matrix was included in the project plan.

5. Conduct proof-of-concept testing.

> (a) Conduct burner start-up, testing the pulse-deflagration-burner to evaluate H2 volume, & pulse frequency.

The pulse-deflagration combustor was operated in the fuel-rich mode (generating a reducing atmosphere) to measure the H2 content as a means of assessing the chemical reduction potential.

Tedlar sampling bags, 1-liter size made by Zefon, were used to obtain samples of output gases.

Researchers used pressure sensors to identify and measure the frequency of the pulse-combustor.

The test facility did not have the instrumentation capability to measure hydrogen content on-line.

One series of gas samples was obtained and analyzed while running through an air-fuel test matrix, operating from lean to rich. One test result showed suitable H2 content. Within the schedule, the turn-around time for external sample analysis precluded more than one test series. However, according to the preliminary screening, 900 C was the optimum temperature for H2 production firing air in the pulse-deflagration prototype. Testing of the gasification rector was carried out while the pulse-burner prototype was operated at 900 C, employing fuel-rich operating chemistry; in which case, the burner temperature sets the air-fuel mixture, which is repeatable with accuracy.

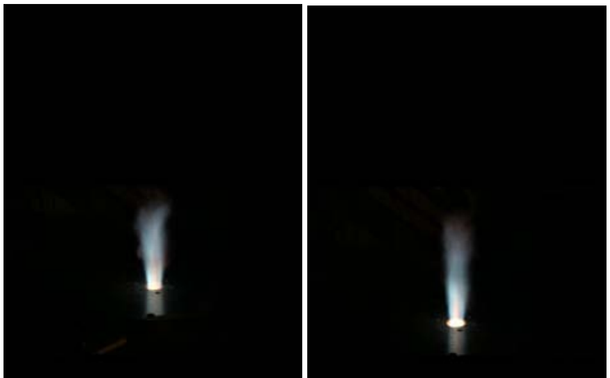


Figure 24a. Prototype Burner, fuel-rich

Figure 24b. Same Burner, Fuel-lean

The transition from fuel-lean-operation (excess air) to fuel-rich-operation (excess fuel) requires caution. In the middle of that transition (when the air-fuel stoichiometry is balanced) the propane flame temperature can reach 1,977 C, which is too hot for most materials of construction employed. The operator must pass smoothly through the highest temperature zone, and land in the cooler regions where endothermic fuel-reforming reactions serve to cool the products of combustion.

The researchers initially tested the pulse-burner prototype(s) using qualitative methods. For example, it was obvious when a burner was functioning properly because the pulse-deflagration creates a distinct "buzz," similar to the sound of the historic V-1 rockets of German design produced during WWII; an unsuccessful pulse-burner generates the continuous sound of hot-gases escaping from a nozzle, with no pulsing activity, and is similar to the sound of a rocket-nozzle.

(b) Test two types of bed material, less than 3-mm steel beads and less than 9-mm ceramic balls, to evaluate durability of balls and burner materials of construction.

The research team tested two types of bed materials; stainless steel beads and ceramic bed material; 0.5-mm and 1-mm stainless steel beads that were commercially available; 2-mm and 5-mm ceramic balls, also commercially available, were tested, to evaluate the stability and durability of bed materials, and to evaluate the materials of construction used to fabricate the burner and the Jet Spouted Bed. Smaller stainless steel beads were selected after very early testing showed that larger steel beads, with diameter greater than 1-mm, would not provide as many energetic collisions when compared to smaller diameter steel beads due to their very high density. Smaller diameter ceramic balls were selected partially for the same reason, and because the smaller diameter beads were expected to exhibit less tendency to break in halves due to thermal stress from rapid heating.

The Jet Spouted Bed gasification reactor located at UCR was tested using Refuse Derived Biomass (RDB) shredded to less than 1-inch. The proximate and ultimate analyses are shown below. The feed rate was set at 3-pounds per minute using an auger extruder made by Komar that was used to force the feed into the gasification reactor. The feed rate was established by operating a Variable Frequency Drive that powered the Komar feeder; the RPM of the drive was correlated with feed rate (in pounds per minute) by feeding then weighing the feed. The relatively dry feed (with some plastics content) contained approximately 8,300 BTU/pound, based on the Higher Heating Value.

RDB Proximate Analysis (percent)		**Ultimate Analysis (percent)**	
Moisture	3.65	C	46.45
Ash	13.37	H	5.91
Volatiles	72.75	N	0.41
Fixed Carbon	10.23	S	0.067
Total	100	O	30.14
		Cl	0.795

Table 1. RDB, Proximate and Ultimate Analysis

The test procedure used was to heat the gasification system to operating temperature using propane fired in the pulse-deflagration burner. The initial heat-up time was approximately 4-hours. Once the gasification reached 850 C, testing was commenced. Once the gasification reactor had been brought up to operating temperature (850 C) then it could be shutdown for several hours without substantial cooling, and could then be heated up again within about 1-hour prior to testing.

Testing was accomplished using the following sequence: the primary JSB gasification chamber was heated to 850 C, holding for approximately 30-minutes, operating the pulse-burner with excess air, using the fuel-lean mode of operation. The pulse-deflagration burner prototype was then adjusted to the desired stoichiometry – fuel-rich mode of operation at 900 C, and then RDB input was commenced for a period of 15-minutes to 20-miutes, while watching to see that reactor temperature remained stable at approximately 750 C, and was not diminishing below 750 C over time. The fuel-gas products were cleaned using cyclone separators and products were flared in an existing flare.

The above test procedure was performed 20-times over the course of a two-week testing period to obtain the test data. A gas sample port located down-stream of the gasification reactor was used to extract gas samples through a 1/2" stainless steel tube. The gas was conditioned by using one high-temperature filter, followed by chilling one ice baths to remove condensable fractions, and then directed to the CAI Analyzer; the sample gas is drawn through the system by a gas pump that is integrated into the CAI analytical system, which includes to pre-filters, a gas chiller, and a gas heater used to raise the sample gas temperature above a set dew-point.

After the operating and testing the gasification reactor at various conditions, the following shut-down procedure was followed: the RDB feeder is emptied, as much as possible, by operating the Gasifier until the extrusion feeder has pushed all the RDB feed into the extrusion tube. Then wood pellets are fed and extruded into the Gasifier so that no more RDB is present in the system. The gasification system is then shut-down by turning off the propane flow to the pulse-burner, while maintaining air flow through the burner to enable the reactor to cool slowly. The wood pellets continue to oxidize somewhat within the feed-tube; therefore, a small amount of water is sprayed onto the wood pellets to minimize the potential for sustaining a fire in the feeding tube.

After an initial cooling period of 30 minutes, the air blower is turned off, and all ports are immediately closed, and the feed hopper is sealed as much as possible. As long as air infiltration is minimized, then there is very little potential for reactions to continue internally.

Typically, a Jet Spouted Bed does not retain fuel inventory for more than a minute. However, the operator does not know if there has been any type of deposition, accumulation, or build-up of tar or carbon-char at some location within the system, that could ignite and burn after the system is shut-down (when air infiltration is present.) This is a well-known problem – the operator returns the next day to find that a pipe on the discharge end of the system has deformed due to excessive temperature resulting from over-night exothermic reactions.
Researchers observed wear on the deflagration burner nozzle, Figure-26, by looking closely at the nozzle, and measuring the diameter, Figure-27.

Figure-26. Pulse-deflagration Nozzle

Figure-27. Evaluating Nozzle Erosion

(c) After optimization, perform a short test-matrix, testing biomass conversion to CH4-rich fuel-gas products.

After developing optimum pulse-burner prototypes, the researchers performed a test-matrix with the intent of testing biomass conversion into CH4-rich fuel-gases. The gasification system was operated using Refuse Derived Biomass as the feed for testing integrate use of pulse-burner prototype. The research team tested two pulse-burner types integrated with the gasification system: a pulse-deflagration burner and a pulse-detonation burner.

Figure-28. Gasification Reactor during start-up

Figure-29. Open-Flare burning fuel-gas products

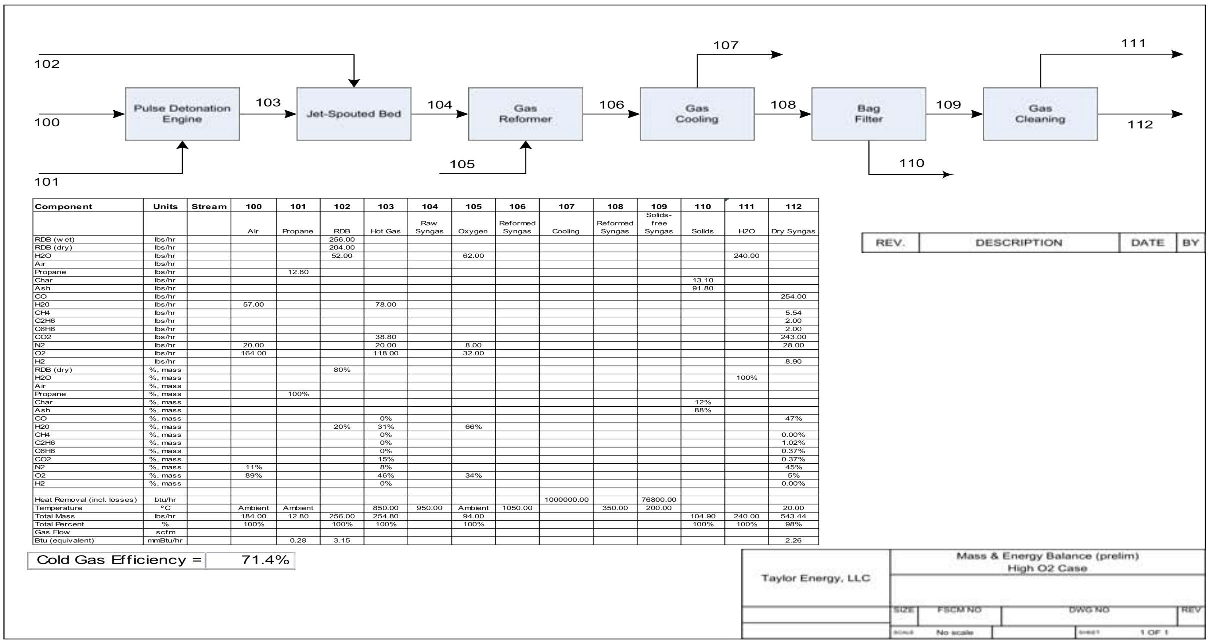
Thirty different tests were performed; to qualify as a test case, the operating conditions had to be distinct to the test-matrix, and the system had to exhibit stable temperature operation for 15-minutes at that conditions by staying within the range of 750-C, varying less than +/- 25-C. Performance of the text matrix resulted in obtaining sample data for 28-conditions; of that test series, two data points were discarded because the results showed too high a methane content; a calibration error was reasoned to be the cause.

The research team was able to perform very limited testing of the integrated system (pulse-burner prototypes firing into the Jet Spouted Bed) to obtain data in support of this report using refuse derive biomass as the energy feed.

Integrated testing of the pulse-burner prototypes with the Jet Spouted Bed was somewhat limited because the back-end of the gasification system employed an open-flare, which was permitted to operate for limited periods during the day; whereas, an enclosed-flare was being constructed, but was not operational during the reporting period. Fuel-gases were burned in an open-flare during continuous operation, and some fuel-gases were exhausted to atmosphere for short intervals during start-up, as shown above in Figures-28 and 29.

(d) Set up Process Heat & Mass Balance by Semi-empirical Method

The investigator prepared a preliminary Heat & Mass Balance, shown below in Figure-30. The Mass & Energy Balance is set up as a template; the outcomes are calculated, and are readily modified based on empirical data that can be input to the model. For example, below, nitrogen is shown to be 11-percent of the input composition, based on the assumption that a pilot-plant or commercial embodiment would use oxygen-enriched air; not pure oxygen, but significantly enriched, whereas the proof-of-concept testing was accomplished with air.



Component	Units	Stream	100	101	102	103	104	105	106	107	108	109	110	111	112
			Air	Propane	RDB	Hot Gas	Raw Syngas	Oxygen	Reformed Syngas	Cooling	Reformed Syngas	Solids-free Syngas	Solids	H2O	Dry Syngas
RDB (w et)	lbs/hr				256.00										
RDB (dry)	lbs/hr				204.00										
H2O	lbs/hr				52.00			62.00						240.00	
Air	lbs/hr														
Propane	lbs/hr			12.80											
Char	lbs/hr												13.10		
Ash	lbs/hr												91.80		
CO	lbs/hr														254.00
H20	lbs/hr		57.00			78.00									
CH4	lbs/hr														5.54
C2H6	lbs/hr														2.00
C6H6	lbs/hr														2.00
CO2	lbs/hr					38.80									243.00
N2	lbs/hr		20.00			20.00		8.00							28.00
O2	lbs/hr		164.00			118.00		32.00							
H2	lbs/hr														8.90
RDB (dry)	%, mass				80%										
H2O	%, mass													100%	
Air	%, mass														
Propane	%, mass			100%											
Char	%, mass												12%		
Ash	%, mass												88%		
CO	%, mass					0%									47%
H20	%, mass				20%	31%		66%							
CH4	%, mass					0%									0.00%
C2H6	%, mass					0%									1.02%
C6H6	%, mass					0%									0.37%
CO2	%, mass					15%									0.37%
N2	%, mass		11%			8%									45%
O2	%, mass		89%			46%		34%							5%
H2	%, mass					0%									0.00%
Heat Removal (incl. losses)	btu/hr									1000000.00		76800.00			
Temperature	°C		Ambient	Ambient		850.00	950.00	Ambient	1050.00		350.00	200.00			20.00
Total Mass	lbs/hr		184.00	12.80	256.00	254.80		94.00					104.90	240.00	543.44
Total Percent	%		100%		100%	100%		100%					100%	100%	98%
Gas Flow	scfm														
Btu (equivalent)	mmBtu/hr			0.28	3.15										2.26

Cold Gas Efficiency =	71.4%

REV.	DESCRIPTION	DATE	BY

Taylor Energy, LLC

Mass & Energy Balance (prelim)
High O2 Case

SIZE FSCM NO DWG NO REV
SCALE No scale SHEET 1 OF 1

Figure-30. Mass and Energy Balance

(e) Semi-empirical process model development.

UCR was also responsible for estimating the carbon footprint (CO2 emission / Energy produced) for the process and the products by using a Life Cycle Analysis thru GREET modeling. Using the Aspen Company Model, UCR researchers developed a semi-empirical model of the process.

The Aspen Model for the process has been developed by UCR; their report is included in the Appendix.

6. Perform analysis to determine cost for design, engineering, construction, and installation, with +/- 20% level of confidence, expressed as product cost.

This work has not been completed because the data does not indicate that methane production using this approach is a viable commercial path.

7. Estimation of Carbon footprint (CO2 emission / Energy produced) for the process and the products by Life Cycle Analysis thru GREET.

This work has not been completed because the data does not indicate that methane production using this approach is a viable commercial path.

Project Outcomes

1. Provide drawings showing key sub-components to be fabricated and installed on existing Process Development Unit (PDU).

The research team produced rudimentary shop-drawings suited for prototype fabrication; examples are shown below. Figure-31 shows the three-stage *pulse-detonation burner*. The layout is sufficient to identify and purchase the sub-components that are used to fabricate the device. Notice in the upper right hand corner of Figure 31 that off-the-self components are itemized. Those components, along with one shop drawing are sufficient guidance for the shop foreman to direct the hardware fabrication. For example, the location for spark, fuel, and air inputs are specified.

Figure-32 below shows the fabrication detail for the *pulse-deflagration burner*. Fewer off-the-shelf components were purchased and most of the materials were fabricated from pipe. Notice that the details are minimal, but sufficient to specify the location of input ports, and key dimensions, sufficient for a shop foreman to manage the fabrication work.

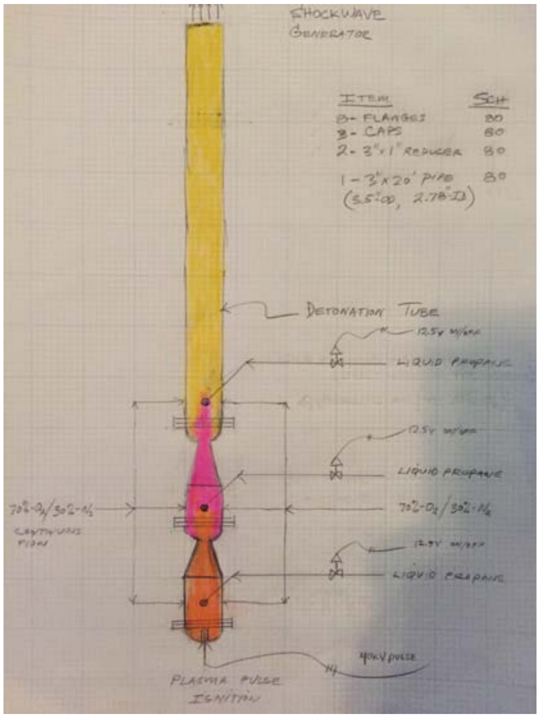


Figure-31. Pulse-Detonation Drawings

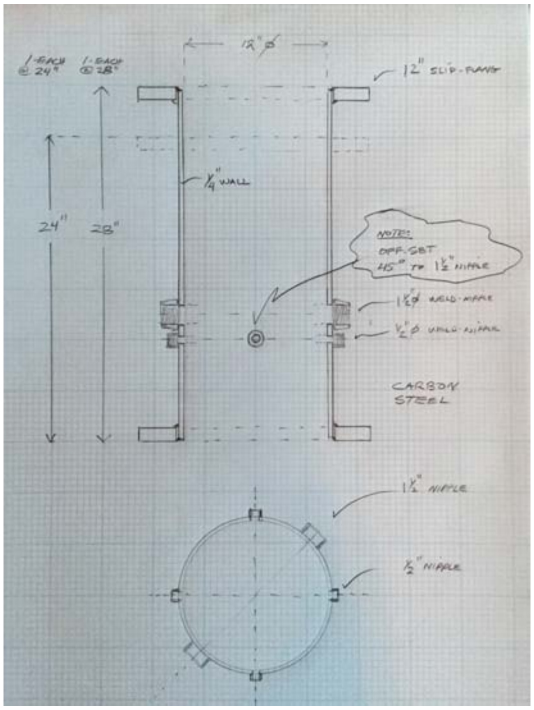


Figure-32. Pulse-Deflagration Drawings

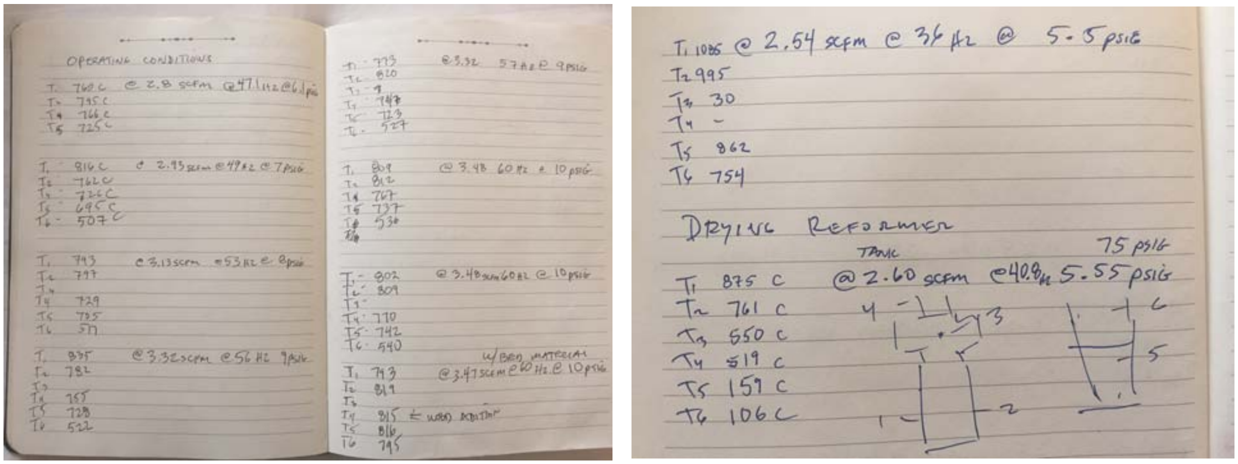
2. Demonstrate pulse-POx-combustor with input greater than 60 kWper hour input capacity, based on propane input.

The research team operated the pulse-burner prototype with an average firing capacity of 137-kW (thermal) per hour, based on a measured average flow of 3.1-scfm (186-scfh.)

186-scfh x 2,516 BTU propane/scf = 467,976 BTU/hr
467,976 BTU/hr / 3,412 BTU/kW = 137 kW

Liquids propane was delivered by truck to the test site and was stored in two 150-gallon high-pressure tanks. Diaphragm type pressure regulators were used to reduce and control the pressure; typically, the regulated pressure was maintained at 20-psig up-stream of the flow-meters. Propane input to the prototype burner was measured using three Dwyer flow-measuring devices -- three Rotameters --with capacities ranging from 0-50-scfh , 0-200-scfh, and 0-360-scfh, shown below in Figure-33.

Figure-33. **Fuel Measurements**



OPERATING CONDITIONS

T1 760 C @ 2.8 scfm @47.1Hz @6.1psi
T2 795 C
T4 766 C
T5 725 C

T1 816 C @ 2.93 scfm @49Hz @ 7psig
T2 762 C
T4 726 C
T5 695 C
T6 507 C

T1 793 @3.13scfm @53Hz @ 8psig
T2 797
T3
T4 729
T5 735
T6 577

T1 835 @3.32scfm @56Hz 9psig
T2 782
T3
T4 755
T5 728
T6 522

T1 773 @3.32 57Hz @ 9psig
T2 820
T3 -
T4 747
T5 723
T6 527

T1 809 @3.48 60Hz @ 10psig
T2 812
T4 767
T5 737
T6 530

T1 802 @3.48scfm 60Hz @ 10psig
T2 809
T3
T4 770
T5 742
T6 540

w/BED MATERIAL
T1 793 @3.47scfm @60Hz @ 10psig
T2 819
T3
T4 815 ← WOOD ADDITION
T5 816
T6 795

T1 1085 @ 2.54 scfm @ 36 Hz @ 5.5 psig
T2 995
T3 30
T4 -
T5 862
T6 754

DRYING REFORMER
TANK 75 psig
T1 875 C @2.60 scfm @40.8Hz 5.55 psig
T2 761 C
T3 550 C
T4 519 C
T5 159 C
T6 106 C

Figure-33a. Raw Test-data showing *Operating Conditions* used in the test matrix.

Note in the data above for 10 operating condition used in the test matrix; the specification for the fuel input ranges from 2.54 scfm to 3.48 scfm of propane input; the average fuel input is 3.1 scfm (186-scfh), equal to 137 kWh (468,000 BTU/hr.)

3. Demonstrate test-system is capable of measuring performance parameters within an error of +/- 5 percent.

Performance parameters testing included the following:

Air-flow input to the pulse-combustor prototype, acfm.
Air-flow measurement was achieved using a Variable Frequency Drive made by ABB. The selecting the drive frequency set the RPM of the blower; the blower RPM was directly proportional to the actual-flow. Optimum air-flow input was at 49-Hz, 163-scfm.

Gaseous propane input to the pulse-combustor prototype, scfm
A Rotameters (selected to measure the correct flow-range) was used to measure gaseous propane input. Average flow was 3.1-scfm; minimum flow was 2.4-scfm; maximum flow was 3.48 scfm.

Temperature of the pulse-combustor prototype and the gasification reactor, degrees C.
The performance of K-type thermocouples were measured against a reference hand-held thermocouple measuring device, and typically reported temperatures within +/- 10 percent, except in the case of thermocouple failure due to erosion when the thermocouples protruded too far into the path of pulsing bed materials. In key locations where the temperature must be measured with accuracy – two K-type thermocouples are used in each location for comparison.

For example, in Figure-35 below, the Yokogawa temperature monitor shows that T2 & T3, and T4 & T5, are measuring the temperature in the same location. Monitors T4 & T5 are located in the prototype pulse-burner; the temperature difference (609 C – 566 C = 43 C) is not due to the inaccuracy of the thermocouples, but is due to the difference in the flame impingement on the wall inside the burner resulting from a small irregularity in the air inlet orifice. This was determined by adjusting the air inlet orifice (by turning the nozzle slightly), which served to shift the higher temperature reading from T5 to T4, and then back again, from T4 to T5, depending on the angle of the inlet orifice. The temperature readings for monitors T2 & T3 (showing 410 C and 406 C respectively) are typical for the accuracy of redundant thermocouples.

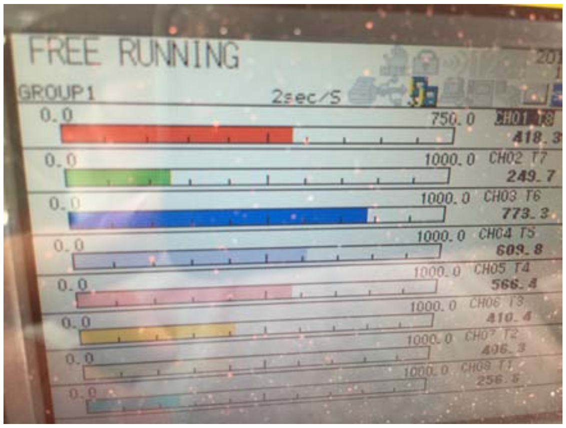


Figure-34.Yokogawa Temperature

Figure-35. Jet Spouted Bed during Operation

The JSB is shown during high-temperature start-up in Figure-34 above, looking into a view-port located opposite the extrusion feeder.

Pulse-pressure in the burner and in the gasification reactor, psi absolute
Pulse-frequency was measured using pressure sensors; the performance was very distinctive; pressure peaks showed an average pulse rise of 18.7-psig absolute; one pressure peak for each pulse; confirmation of the precision was done by evaluating two (2) sensors, one located in the pulse-combustor and one located down-stream in the gasification reactor; the resulting pressure peaks were accurate to within +/- 1 percent.

H2 content produced by the pulse-burner prototype, percent by volume
Gas samples containing H2 were collected using a pump to fill 1-liter Tedlar bags; the bag samples were sent out to a subcontractor to be analyzed by others for the H2 percent by volume. A method based on Thermal Conductivity Detection (TCD) is used to measure H2 content. The precision is claimed to be +/- 3-percent for this method. However, a comparative study performed by K. O'Connor for the US Army, July 2012, indicates the precision may by +/- 4.9-percent.

CH4 content in the product gases, post gasification of RDB, percent by volume
Methane, carbon monoxide, and carbon dioxide, were measured using an NDIR instrument made by California Analytical Instruments (CAI); specifically, the ZRE model was used for gas analysis. The precision is reported to be +/- 2 percent for methane; however, this level of performance was not achieved when higher hydrocarbons were present.

The best precision measured for methane (under actual operating conditions, when the product gases included additional low-molecular-weight hydrocarbon gases) was +/- 6.46 percent, and the worst was +/- 42 percent. The precision of the methane analysis was observed to decrease roughly in proportion with the increasing presence of other low-molecular-weight hydrocarbon gases. Real-time measurement of methane -- using an NDIR type analyzer -- is somewhat more difficult than is purported by the instrument supplier.

4. Demonstrate pulse-POx-combustor greater than 30-volume percent H2 output.

One series of gas samples was obtained and analyzed while running through an air-fuel test matrix, operating from lean to rich, recording the fuel and air input while measuring the temperature of the burner. One test result showed with suitable H2 content, reported in the table below:

Component	**Gas Fraction, volume-percent, including N2**
N2	42.7
H2	17.4
CH4	9.4
CO	8.7
CO2	21.3
C2H6	0.5

Table 2. Optimum Hydrogen Content Produced by Pulse-Deflagration Burner Firing Propane

Within the schedule, the turn-around time for external sample-analysis precluded more than one test series. However, according to the preliminary test, 900 C was the optimum temperature for H2 production firing air in the pulse-deflagration prototype.

Therefore, testing of the gasification rector was carried out while the pulse-burner prototype was operated at 900 C, employing fuel-rich operating chemistry; in which case, the burner temperature sets the air-fuel mixture, which is repeatable with high accuracy.

The research team performed the tests using air, rather than employing oxygen enriched air. The data is also reported for the pulse-deflagration prototype with the N_2 removed, assuming the use of oxygen rather than air.

Component	Gas Fraction, volume-percent, with N_2 removed
H_2	30.3
CH_4	16.4
CO	15.1
CO_2	37.3
C_2H_6	0.9

Table 3. Hydrogen Content Produced by Pulse-Deflagration Burner Firing Propane

5. Demonstrate pulse-POx-Combustor frequency greater than 7-Hz.

The maximum *pulse-deflagration burner* frequency measured using a low-pressure monitor. The peaks were recorded over time and used to calculate that the pulse-frequency was equal to 21-Hz. The integration of pulse-deflagration burner with the JSB is shown in Figure-37 below.

Figure-36. Pulse-Deflagration burner

Figure-37. Pulse-Detonation Burner

Maximum *pulse-detonation burner* frequency was 3-Hz; the pulse-detonation frequency can likely be increased to 4-Hz when using oxygen enriched air input to the pulse-detonation burner.

6. Demonstrate durability of bed-material -- shattered or deformed balls less than 10-percent after 48-hrs operation. The researchers measured the performance of the ceramic bed materials by counting the number of beads in a 1-cup sample, and counting the number of broken beads in

the same random sample. The research team found that 1-percent of the balls shattered after 48-hours of operation. Bed materials are shown in Figure-38 and Figure-39 below. The 1-percent shattered beads may result from manufacturing flaws that show up after the first time the beads are fired at high temperature, and that after the initial high rate of breakage, the loss of bed material is not thought to be problematic. Metal beads can replace ceramic beads if shattering of the bed material was to become a significant issue.

Figure-38. Steel Beads

Figure-39. Ceramic Balls

7. Demonstrate zero significant *cracks* that could result in failure of pulse-combustor.

When refractory is cured, it is typical for some small cracks to appear on the surface. Small cracks were observed in the refractory that resulted from high-temperature curing, but not a result of pulse-combustion. If the small cracks were due to pulse combustion, the cracks would have increased over time with operation, which was not the case. The small cracks that were observed in the combustor seemed to result from the casting process these cracks were not seen to grow over time during operation. However, the researchers did observe excessive erosion of the refractory lining in the base of the Jet Spouted Bed. The refractory employed was a high-density material, but not a refractory type that is particularly resistant to erosion.

8. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using steel balls greater than 1-mm diameter.

The pulse-deflagration burner was set at an optimum operating condition. The stainless steel bed materials were added one at a time. The expanded bed height was measured by looking into the hot gasification reactor, using a mirror employed at the level of the feed port to look at the height of the fountain created by the expanded particles. The research team operated with an expanded bed height of 60-inches when operating with a bed composed of 0.5-mm stainless steel beads. 1-mm steel beads were observed to form a fountain higher than 24-inches, but the performance (as a means of ablation) was not as robust compared to smaller (lighter) bed materials.

9. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using ceramic balls less than 12-mm diameter.

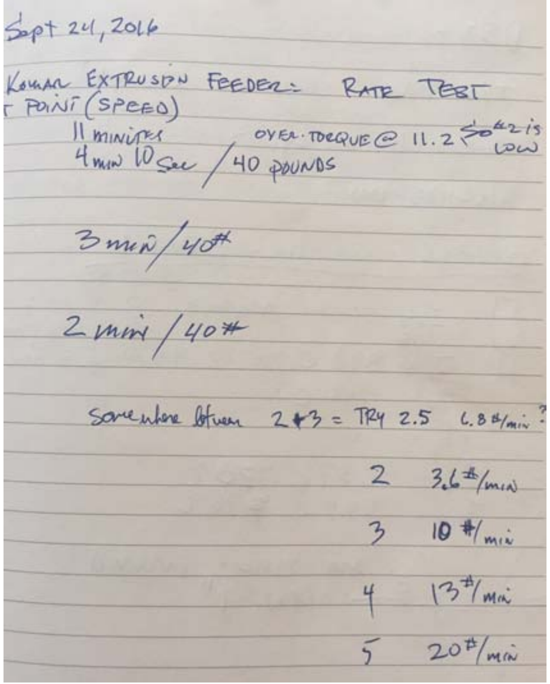
The pulse-deflagration burner was set at an optimum firing condition. The ceramic bed materials were added one at a time. The expanded bed height was measured by looking into the hot gasification reactor, using a mirror employed at the level of the feed port to look at the height of the fountain created by the expanded particle bed. A fountain height of 80-inches and 60-inches respectively was observed when operating with ceramic beads, with diameter of 2-

mm and diameter of 5-mm. The performance of the ceramic bed materials was observed to provide the most robust environment for gasification service due to greater number of collisions that should correlate with more rapid ablation of the feed materials.

10. Demonstrate RDB feed input of greater than 0.5 lb/min.

This objective was completed successfully; the minimum feed rate was measured to be 3.6-pounds per minute, based on measuring the weight of feed material inputs over time. The extrusion type feeding system is shown in Figure-40 below and raw-data showing weight and time measurements.

Figure-40. Biomass Feeding System



Sept 24, 2016

KOMAR EXTRUSION FEEDER: RATE TEST
T POINT (SPEED)
11 MINUTES
4 min 10 Sec / 40 POUNDS
OVER-TORQUE @ 11.2 So #2 is LOW

3 min / 40#

2 min / 40#

Somewhere between 2 + 3 = TRY 2.5 6.8#/min ?

2	3.6#/min
3	10 #/min
4	13#/min
5	20#/min

Figure-41. Komar Rate Test Notes

11. Demonstrate greater than 50-percent energy content as CH4 in fuel-gas products.

The syngas composition shows the best three data points taken at 20-minutes intervals during a 1-hour operating period with stable operating conditions with the pulse burner operating at 900 C to optimize H2 output to the gasification reactor. The average methane content was 7.46 percent by volume based on the data reported below:

Component (vol-%)	Sample-1	Sample-2	Sample-3	Average
H2	8.14	8.38	8.57	8.36
CO	8.99	8.88	8.60	8.82
CH4	7.36	7.52	7.50	7.46
CO2	14.9	15.45	14.93	15.09
N2	47.7	47.17	46.94	47.28
H2O	10.91	10.60	11.46	10.99

Table 4. Analysis of fuel-gas products: Methane content (wet basis with 12% H20-vapor)

12. Demonstrate carbon-char product fractions are less than 25-weight percent of the dry-feed input.

The data below shows that the average carbon-char content is approximately 9.47-wt% of the gasification products. The products -- the outputs -- can be viewed as a measure of the total inputs; based on conservation of matter, the mass that goes in is the same as the mass that goes out. The data shows that the carbon-char fraction, when measured on a dry-basis, is 10.77-wt percent of the dry-feed.

Products (wt-%)	Sample 1	Sample 2	Average
Gases	64.00	59.77	61.89
Tar	4.50	4.20	4.35
Char	9.80	9.15	9.47
Ash	12.39	18.18	15.29
Pyrolysis water	9.31	8.69	9.0
Total	100	100	100

Table 5. Analysis of product fractions: Carbon-char content

13. Confirm from the project findings that a production cost of $8/mmBTU Renewable-Methane is supported.

This work was not done because the methane content in the syngas product was not thought to be sufficient to warrant further analysis as a stand-alone process, and requires further integration to achieve economic viability.

14. Confirm from the project findings, using GREET Analysis, that the projected carbon footprint, using RNG for vehicle fuel, that WTW GHGs are less than 20 g CO2e/MJ, and -80 percent GHGs compared to gasoline.

This work was not done because the methane content was not thought to be sufficient to warrant further analysis as a stand-alone process, and requires further integration.

Conclusions

1. Provide drawings showing key sub-components to be fabricated and installed on existing Process Development Unit (PDU).

The requisite drawings to construct a prototype *pulse-detonation burner* and a *pulse-deflagration burner* prototype were prepared and used successfully to fabricate the hardware employed for project testing.

2. Demonstrate pulse-POx-combustor with input greater than 60-kW per hour input capacity, based on propane input.

The *pulse-deflagration burner* was tested at a firing rate of 137-kWh, based on thermal input as propane

3. Demonstrate test-system is capable of measuring performance parameters within an error of +/- 5 percent.

The parameters that required measuring are listed:

Air-flow input to the pulse-combustor prototype, acfm.
Gaseous propane input to the pulse-combustor prototype, scfm
Temperature of the pulse-combustor prototype and the gasification reactor, degrees C.
Pulse-pressure in the burner and in the gasification reactor, psi absolute
H2 content produced by the pulse-burner prototype, percent by volume
CH4 content in the product gases, post-gasification of RDB, percent by volume

The methods used to measure the six key performance parameters above were sufficient for the project needs, if not always accurate to +/- 5 percent.

4. Demonstrate pulse-POx-combustor greater than 30-volume percent H2 output.

It was determined that 900 C was the optimum temperature for H2 production when firing air/propane mixture in the pulse-deflagration prototype. One test-series was used to identify an operating point suitable for generating 30-volume-percent H2.

5. Demonstrate pulse-POx-Combustor frequency greater than 7-Hz.

The pressure peaks were measured over time and used to demonstrate operating frequency of 21-Hz.

6. Demonstrate durability of bed-material -- shattered or deformed balls less than 10-percent after 48-hrs operation.

The research team found that 1-percent of the balls shattered after 48-hours of operation.

7. Demonstrate zero significant *cracks* that could result in failure of pulse-combustor.

The researchers did observe excessive erosion of the refractory lining in the base of the Jet Spouted Bed, but no stress-cracking resulting from thermal or mechanical shock. The refractory employed was a high-density material, but not a refractory type that is particularly resistant to erosion. An abrasion resistant refractory must be selected and employed for casting the section the houses the Jet Spouted nozzle on the discharge site. Alternatively, an abrasion resistant refractory brick material may be used to construct the bottom section of the Jet Spouted Bed.

8. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using steel balls greater than 1-mm diameter.

The research team operated with an expanded bed height of 60-inches when operating with a bed composed of 0.5-mm stainless steel beads. When using 1-mm steel beads the bed was observed to form a fountain higher than 24-inches, but the performance (as a means of ablation) was not as robust when compared to smaller size bed materials.

9. Demonstrate maximum expanded bed height greater than 24-inches during jet-spouting using ceramic balls less than 12-mm diameter.

Fountain heights of 80-inches and 60-inches respectively were observed when operating with ceramic beads, with diameter of 2-mm and diameter of 5-mm. The performance of the ceramic bed materials was observed to provide the most robust environment for gasification service due to greater number of collisions that should correlate with more rapid ablation of the feed materials.

10. Demonstrate RDB feed input of greater than 0.5 lb/min.

The capacity of the Komar feeder was tested and it was determined that the minimum feed rate was 3.6-pounds per minute. Therefore, in some cases the feeder would need to be operated intermittently to lower the feed rate below 3.6-pounds per minute, for example, by selecting a 50-percent duty cycle so that feeder is on 20-seconds and off 20-seconds. The Komar feed controller has the ability to adjust the duty cycle.

11. Demonstrate greater than 50-percent energy content as CH4 in fuel-gas products.

The maximum CH4 content measured for methane was 43.69-percent by volume, when measured as a fraction of the total chemical energy content in the product gases. The project goal was 50-percent of gas-phase energy in the form of methane. The 50%-content goal was not accomplished. However, the methane molecule contains so much energy that a mere 7.46-percent by volume in the products contains 43.7-percent of energy in the product gases.

There is combined cycle that could make economic sense, even with this low CH4 content: Assume that syngas -- containing a 1:1 ratio of H2:CO -- is the desired co-product to be used in a Fischer-Tropsch synthesis to make jet fuel; assume a once-through F-T synthesis process that would produce a high-value liquid stream, and more CH4, which is an unavoidable co-product made during F-T synthesis of hydrocarbons. The initial 7.5-percent methane would pass through an F-T synthesis reactor with minimal impact on the process, except slightly diminishing the partial pressure of reactants H2 and CO. Down-stream of an idealized F-T synthesis reactor, after recovery of the hydrocarbon liquids, gaseous methane would become the majority product, diluted with CO2, water vapor, light hydrocarbons, and nitrogen.

The process tested herein may have strong appeal in a scenario where hydrocarbon liquids are produced using an F-T topping cycle, followed by renewable methane recovery from the high-energy tail gases.

12. Demonstrate carbon-char products fractions are less than 25-weight percent of the dry-feed input.

The data show that the carbon-char fraction, when measured on a dry-basis, is 10.77-wt percent of the dry-feed. A successful commercial process would necessarily use carbon-char as the primary fuel to provide hot-reducing gases to accomplish gasification within a H2-rich processing environment.

However, ASPEN modeling has shown that carbon is not as reactive as propane when used as a source of reducing gas, i.e., hydrogen. The model has a rate limit based on the difficulty of contacting solid carbon with gaseous reactants, which makes sense because there are physical limits, carbon is not a free-floating element; issues arise: gas-solids mixing, laminar-flow barriers to gas/solids contact, porosity, sorption, diffusion; lots of limiting interactions to consider. Probably recycling a relatively large amount of potassium salts, along with the recycle of carbonaceous-ash would help increase the conversion rate of carbon into carbon monoxide.

13. Confirm from the project findings that a production cost of $8/mmBtu Renewable-Methane is supported.

This work was not completed because the methane content in the syngas product was not thought to be sufficient to warrant further analysis based on the project concept of a stand-alone renewable methane production facility. An economic analysis of the co-production of F-T liquids and renewable methane (as described above in item 12) was too complex, considering the scope of the project and the schedule constraints.

14. Confirm from the project findings, using GREET Analysis, that the projected carbon footprint, using RNG for vehicle fuel, that WTW GHGs are less than 20 g CO2e/MJ, and -80 percent GHGs compared to gasoline.

This work was not completed because the methane content in the syngas product was not thought to be sufficient to warrant further analysis based on the project concept of a stand-alone renewable methane production facility. The GREET Analysis for the co-production of F-T liquids and renewable methane was too complex, considering the scope of the project and the schedule constraints.

There are indications that through continuing efforts the process may be improved; the remaining quantitative goals could then be demonstrated with favorable results if the analysis included the co-production of F-T liquids and renewable methane.

Not enough favorable data has not been generated to support the key project goal, renewable methane with greater than 50% of the energy content in the form of CH4, and a new process cannot be commercialized without more substantive performance data.

However, both the pulse-deflagration and pulse-detonation burner technology, integrated with Jet Spouted Bed operation, have been reduced to practice; further developments will constitute refinements of the technology approach and may lead to the demonstration of a new co-production process that generates both hydrocarbon liquids and renewable methane.

Recommendations

A successful commercial process would necessarily use the carbon-char as the primary fuel to provide hot-reducing gases to accomplish gasification and methane formation within an H2-rich processing environment. The ASPEN modeling work has identified a key processing issue; that is, carbon-char (used in a POx reaction with oxygen and steam) may not be as good a source of reducing gases as propane.

According to the model, carbon-char does not reach chemical equilibrium; probably, a catalyzed means of increasing the rate of carbon conversion into carbon monoxide needs to be demonstrated; probably using potassium salts and, and possibly including a low-cost source of iron oxide as a minor component of the feed would help catalyze the carbon reactions.

The additional proof-of-concept testing is need to demonstrate *nearly* 50-percent of the energy content can be produced as CH4 content in fuel-gas products. The present work shows the methane formation rate can be 43.7 percent of the energy content; *nearly* 50-percent. Increasing the number to 45-percent or 47-percent would be likely be significant to the over all process economics.

The GREET analysis is expected to be favorable because the feedstock is renewable. Carbon-char can be recycled to the front-end of the thermal process and consequently the carbon-char content in the ash is not too significant to the process economics.

Additional proof-of-concept testing is needed to show that mile steam-hydrogasification reactions that produce renewable methane can be intensified using supersonic shockwaves that result from pulse-detonations emanating from a high-temperature syngas-generator. Great potential still exists to deploy a high-risk / high-reward methodology that uses a pulse-detonation burner to generate high-energy low-cost shockwaves -- that compress and mix the reactor contents when passing through, rather than compressing the entire contents of the reactor externally.

Public Benefits to California

Based on the results of this research, the process was able to convert 44-percent of the energy content in the energy feed into CH4. The potential annual economic benefits to California is $ 2.13-billion per year, based on the following analysis: In California, the resource potential is 4.7-pounds of Municipal Solid Waste (MSW) per person per day. Approximately 70-percent of MSW can be recoverable as Refuse Derived Biomass (RDB), the energy feed, which is a low-density, high surface area feedstock well suited for thermal chemical conversion into renewable methane. Gasification typically converts 70-percent of RDB into synthetic gas. The results indicate that 44-percent of the net energy contained in RDB can be converted into 465-mmscfd Renewable-Methane, resulting in energy value benefits using the following assumptions and conversion factors:

<u>Conversion Factors</u>

- There are 39 million people in California
- Per capita MSW generation is 4.7-pound per day
- The MSW disposal cost is $45/ton
- RDB is recovered from MSW with 70-percent recovery
- Thermal Gasification converts RDB into synthetic gases with 70-percent efficiency
- After drying, RDB contains approximately 7,500 BTUs per pound
- 44-percent net conversion into Renewable Methane (CH4)
- CH4 contains 910 Btu per standard cubic foot (Btu/scf)
- Renewable Methane is valued at $10/mmBtu

<u>The daily volume of Renewable Methane is calculated as follows</u>:
39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB = 128, 310,000 pounds per day of RDB
128,310,000 pounds per day of RDB x 7,500 Btu/lb = 962,325 mmBTU per day as RDB
962,325 mmBTU/day as RDB x 0.70 gasification efficiency = 673,627 mmBTU per day as synthetic gas
673,627 mmBTU/day / 910 Btu/scf CH4 x 0.44 net conversion efficiency = 325 mmscfd.

<u>The daily economic value is calculated as follows</u>:
39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB = 128, 310,000 pounds per day of RDB
128,310,000 pounds per day of RDB x 7,500 Btu/lb = 962,325 mmBTU per day as RDB
962,325 mmBTU/day as RDB x 0.70 gasification efficiency = 673,627 mmBTU per day as synthetic gas
673,627 mmBTU/day x 0.44 net conversion efficiency x $10/mmBtu = $ 2,963,950 per day

<u>The daily disposal cost savings is calculated as follows</u>:
MSW also has an associated disposal cost of $45/ton.
39 mm people x 4.7 lbs. MSW/person/day x 0.70 MSW->RDB/2000 lbs/ton x $45/ton = $2,886,975/day

<u>Potential annual economic benefits are summarized below</u>:		**Annual Benefits**
<u>Methane Value</u>:		
$ 2,963,950 per day x 365 days/year =		$ 1,081,841,000 /year
<u>Disposal Savings</u>:		
$ 2,886,975/day x 365 days/year =		<u>$ 1,053,745,000 / year</u>
Cumulative value (methane value plus disposal savings):	=	$ 2,135,586,000 /year

Sustainable communities benefit from increased reliability when more distributed sources of renewable-methane are input to the pipeline distribution system. Moreover, renewable methane production facilities would be available to operate as stand-along fuel source in times of emergency.

Glossary

MSW	Municipal Solid Waste
RDB	Refuse Derived Biomass
PDU	Process Development Unit
POx	Partial Oxidation
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
RNG	Renewable Natural Gas
WTW	Well to Wheel
GHG	Green House Gases
PDE	Pulse Detonation Engine
JSB	Jet Spouted Bed
UCR	University of California Riverside
RM	Renewable Methane
AD	Anaerobic Digestion
CE-CERT	College of Engineering - Center for Environmental Research and Technology
RPM	Revolutions Per Minute
WRI	Western Research Institute

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Conversion Factors

There are 39 million people in California
http://www.census.gov/quickfacts/table/PST045215/06

Per capita MSW generation is 4.7-pound per day
http://www.calrecycle.ca.gov/lgcentral/goalmeasure/DisposalRate/MostRecent/default.htm

The MSW disposal cost is $45/ton
http://www.calrecycle.ca.gov/publications/Documents/1520%5C20151520.pdf

RDB is recovered from MSW with 70-percent recovery
Waste-to-Energy Feasibility Study: Gasification & Melting Integrated with a Gas-to-Liquid Process and Power Generation. Prepared for Kobelco Eco Solutions, Ltd., by Taylor Energy

Thermal Gasification converts RDB into synthetic gases with 70-percent efficiency
Technical Report NREL/TP-6A20-46587 November 2010

After drying, RDB contains approximately 7,500 Btu’s per pound
Waste-to-Energy Feasibility Study: Gasification & Melting Integrated with a Gas-to-Liquid Process and Power Generation. Prepared for Kobelco Eco Solutions, Ltd., by Taylor Energy

44-percent net conversion into Renewable Methane (CH4)
Preliminary data generated by this study

CH4 contains 910 Btu per standard cubic foot (scf)
http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html

Renewable Methane is valued at $10/mmBtu
https://www.socalgas.com/for-your-business/power-generation/biogas-biomethane

Appendix

Submitted to: Donald G. Taylor, Taylor Energy
Submitted by: UCR

Project Title:
Contract Number: EISG 14-17G

Task:

Semi-empirical ASPEN Process Model Development

A detailed and two step Aspen Plus process model is developed and used to predict the process equilibrium performance and to compare the equilibrium data with the experimental data from the Feldman report[1]. Aspen Plus is a well-known simulation tool that has the ability to handle non-conventional feedstocks and process streams using built-in process units and physical/chemical property databases.

The 2-step Aspen Plus model includes:

- Step-1: The biomass feedstock is mixed with moisture and syngas produced form the Step-2 in a Methane production reactor (MPR) to the gas mixture containing H_2, CO and CH_4 with other components.
- The unreacted char from MPR is mixed with steam and oxygen in a Steam Oxygen Gasifier (SOG) for syngas production.

Process Description

Figure 1 shows the simplified Process Block Diagram (PBD) of the syngas production process from biomass[1]. The process consists of a two- stage reactor system. In first stage, the solid waste feed and moisture mixed with a hydrogen-rich synthesis gas generated from the gasification of residual carbonaceous char in steam oxygen gassifier (SOG) reactor. In this first stage, the incoming waste is devolatilized and hydrogasified and the residual char is then gasified in the SOG reactor to produce the hot synthesis gas.

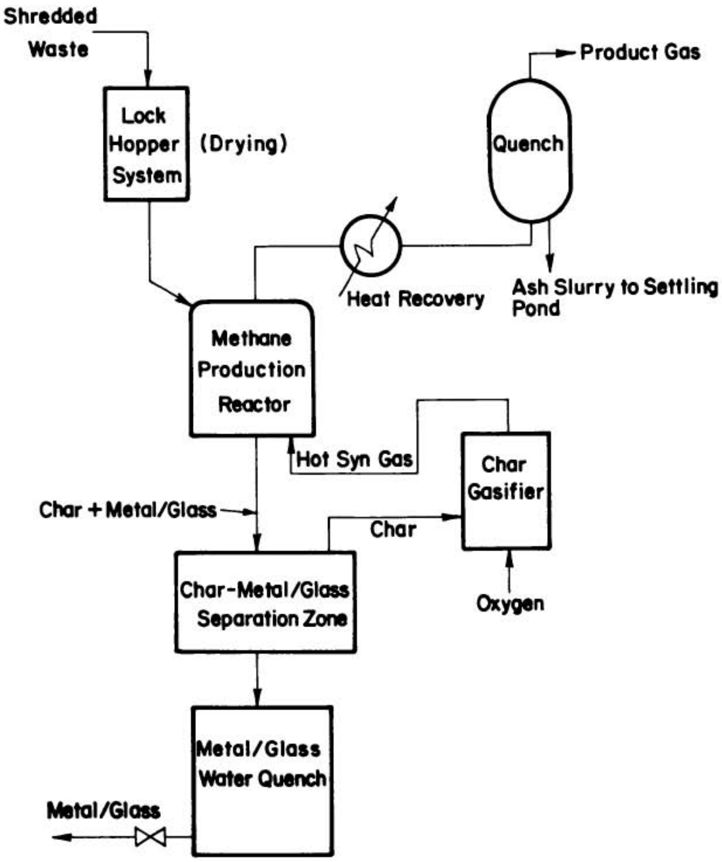

Figure 1 Process Flow Diagram of the Gasification System[1]

The proposed feedstock is Refuse Derived Biomass (RDB). The key properties include[2]:
Proximate analysis:
Fixed carbon: 10.61% (lb/lb-dry-feed)
Volatile matter: 75.51% (lb/lb-dry-feed)
Moisture content: 0%
Ash: 13.88% (lb/lb-dry-feed)
Calorific Value: 8681 Btu/lb-dry-feed (HHV)

Ultimate analysis (wt%): Ash-13.055; Carbon- 48.21; Hydrogen- 6.14; Nitrogen- 0.43; Chlorine- 0.825; Sulfur- 0.07; Oxygen- 31.27

The operating condition of the reactor system is chosen from the existing literature data to compare with the equilibrium data that obtained from Aspen Plus process simulator. The outlet syngas composition from the report is used in the simulation instead of the composition from Aspen Plus. This allows comparison of the experimental data in the report with Aspen predictions.

The operating conditions of the process include[2]:
MPR:
Temperature: 750 °C
Pressure: 1 bar
RDB feed rate (dry basis): 70 lb/hr
Moisture feed rate: 30 lb/hr
Syngas feed rate: 2.449 lb-moles/hr

SOG:

Temperature: 1482 °C
Pressure: 1 bar
Char input flow rate: 17.8 b/hr
Oxygen feed rate: 13.24 lb/hr
Steam feed rate: 23.8 lb/hr

Process details are shown in Figure 2.

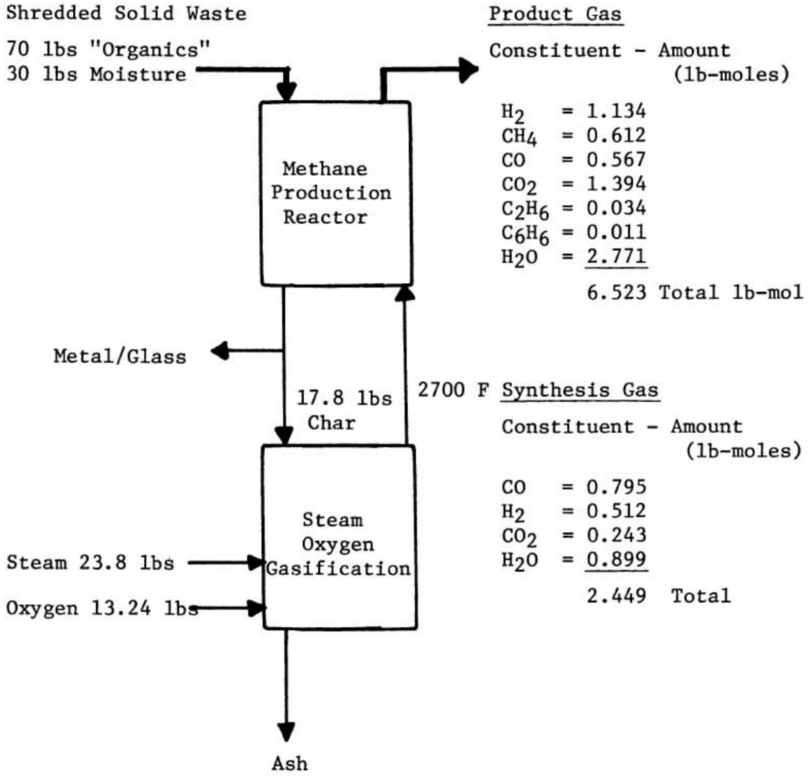

Figure 2 Syngas Production Process with Operating Conditions and Material Balance[1]

<u>Description of Aspen Plus Simulation</u>

The feedstock is fed into the MPR on a steady basis at predetermined feed/moisture/syngas ratios. The model simulates the MPR using decomposition and gasification units. These units are based on built-in Aspen reactor blocks and calculate the equilibrium composition in the reactor under the given conditions by means of Gibbs free energy minimization. The model uses the Peng-Robinson equation of state for thermodynamic calculations. The decomposition block converts the non-conventional feedstock such as RDB into its basic elements on the basis of yield information using the RYIELD block and the gasification block calculates the equilibrium product gas composition using the RGIBBS block.

The carbon conversion information, feed flow rates and compositions, and the reactor operating conditions are supplied by the user based on existing experimental data. The decomposed components get mixed with water and syngas, and heated up before entering to the MPR. The product of MPR is contains ash, metal/glass and unreacted char. Ash metal/glass are removed (not shown in the figure) from the product gas and sent to the SOG reactor as feed. Oxygen and steam are also feed to the SOG reactor. The product syngas is used as the feed for MP reactor. Figure 3 shows the gasifier model in the Aspen Plus user interface.

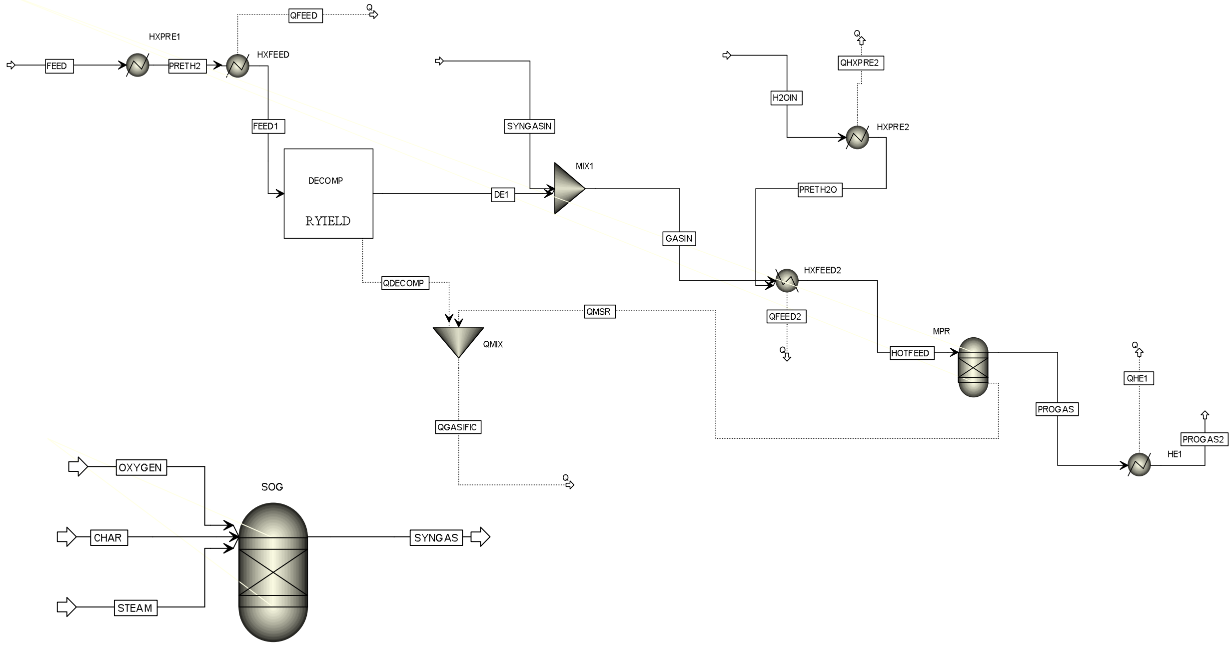

Figure 3 MPR and Gasifier Model in the Aspen Plus User Interface

Table 1 Comparison of the simulation data with the experimental data

Product Gas	MPR			SOG	
	Experimental[1]	Aspen Plus simulation	With simulated SOG product*	Experimental[1]	Aspen Plus simulation
Pressure bar	-	1	1	-	1
Temperature °C	-	850	850	1482	1482
Total Flow lb-moles/hr	6.523	7.592	7.937	2.803	2.449
H_2 (lb-moles/hr)	1.134	3.177	3.600	0.852	0.512
CO (lb-moles/hr)	0.567	1.546	1.934	1.285	0.795
CO_2 (lb-moles/hr)	1.394	0.819	0.870	0.197	0.243
H_2O (lb-moles/hr)	2.771	2.029	1.507	0.469	0.899
CH_4 (lb-moles/hr)	0.612	0.000	0.005		

C_2H_6 (lb-moles/hr)	0.034	0.000	0.000		
C_6H_6 (lb-moles/hr)	0.011	0.000	0.000		

* Syngas feed to the MPR is same as the product syngas from simulation results. For all other case the syngas feed to the MPR is taken from the experimental results obtained by using the SOG reported by Fledmann[1]

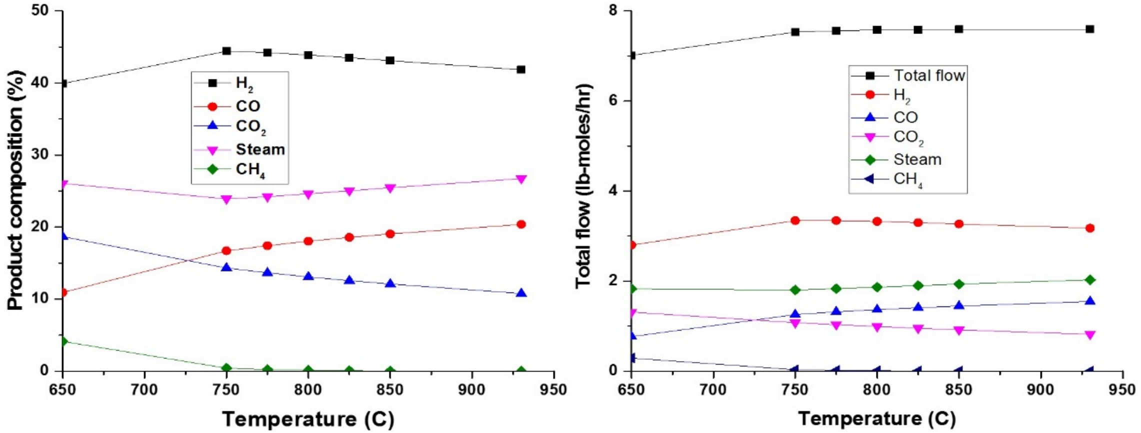

Figure 4: Product syngas composition and flow rate for the MPR reactor

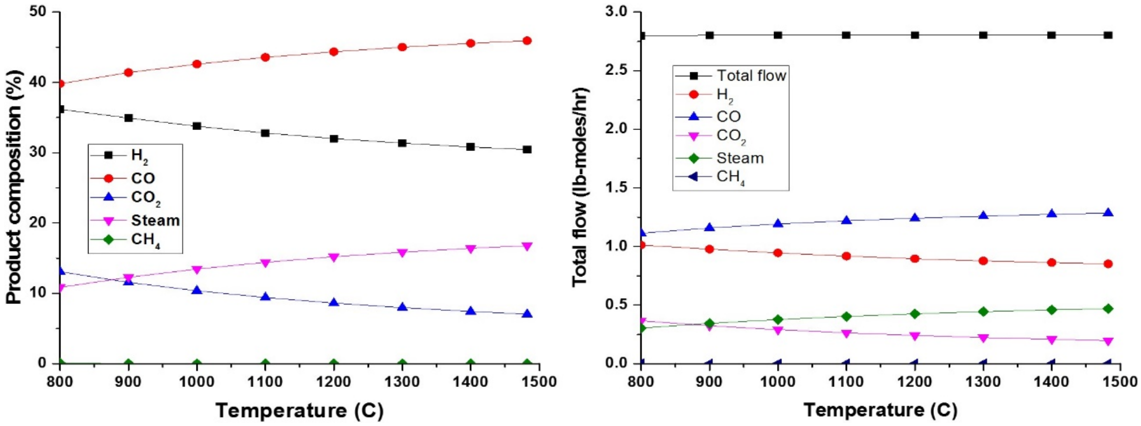

Figure 5: Product syngas composition and flow rate for the SOG reactor

Table 1 shows the product distribution comparison for both MPR and SOG reactor for Aspen plus simulation and the experimental data available in literature. The goal is to lower the methane production whereas the methane production is significantly high as found in the experimental data. Temperature plays an important role for the methane composition in the outlet gas from MPR as shown in Figure 4. Increasing temperature decrease the methane composition as well as increase the CO production. CH_4 and CO_2 production at 650 °C operating temperature is close to the experimental data whereas equilibrium H_2 and CO production is much lower for the experimental condition.

References

Feldmann, HERMAN F., and J. Alderstein. "Syngas process." *Prepr. Pap. Natl. Meet., Div. Environ. Chem., Am. Chem. Soc.;(United States)* 18.1 (1978)[2] RDF pilot gasification test report 2010 06 RevA

Development Status Questionnaire

California Energy Commission
Energy Innovations Small Grant (EISG) Program
PROJECT DEVELOPMENT STATUS

Questionnai

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Please Identify yourself, and your project: **PI Name**: Donald G. Taylor **Grant #** 14-17G

Overall Status

Questions	Comments:
1) Do you consider that this research project proved the feasibility of your concept?	*No. The concept is "direct" thermal-chemical production of renewable methane.*
2) Do you intend to continue this development effort towards commercialization?	*We built and tested a prototype pulse-combustion system, but did not make the connection with the use o the prototype burner to generate methane rich gases.*

Engineering/Technical

3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	*The prototype pulse-burner has to be integrated with a biomass gasification system, which system is not completed at yet; But will be ready for integrated testin in early 2017.*
4) Have you defined a development path from where you are to product demonstration?	*Yes, we have a clear development path.*
5) How many years are required to complete product development and demonstration?	*Two years.*
6) How much money is required to complete engineering development and demonstration?	*Probably $1.5 million in CEC funding, potentially obtain from a grant for testing woody-biomass processing.*
7) Do you have an engineering requirements specification for your potential product?	*No. We do not have specification details.*

Marketing

8) What market does your concept serve?	*Industrial, waste-to-energy*
9) What is the market need?	*Use societal wastes as a renewable energy feedstock.*
10) Have you surveyed potential customers for interest in your product?	*YES. However, the discussions are confidential at this time.*
11) Have you performed a market analysis that takes external factors into consideration?	*Yes, we are aware of external factors: competitors, and other new technologies, and regulations that impact.*

12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*No.*
13) What is the size of the potential market in California for your proposed technology?	*The market is based on 4-pounds per person per day o organic waste going to landfill, multiplied by 39-million people in California. The source is the CA Integrated Waste Board.*
14) Have you clearly identified the technology that can be patented?	*Yes. We have specific technology that has been reduce to practice, but not patented as yet. We are waiting to b closer to commercialization to apply for patents.*
15) Have you performed a patent search?	*YES, we are very active in this IP area, supporting a professional patent attorney in searching prior art.*
16) Have you applied for patents?	*No.*
17) Have you secured any patents?	*No.*
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*No.*
Commercialization Path	
19) Can your organization commercialize your product without partnering with another organization?	*NO. We intend to joint-venture or license with commercial companies in the waste recycling business.*
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*YES. We are in communication with a large regional waste hauling company, and the with the leading nation company in the same business.*
21) Have you developed a commercialization plan?	*Yes. We have several possible paths to commercialization, depending on continuing interest expressed by the various parties.*
22) What are the commercialization risks?	*Waste gasification technology as a whole has been the greatest risk; the capital and operating costs are at risk.*
Financial Plan	
23) If you plan to continue development of your concept, do you have a plan for the required funding?	*Yes. Apply for CEC grant funding for woody-biomass. If unsuccessful, we will seek private funding.*
24) Have you identified funding requirements for each of the development and commercialization phases?	*Yes. Our next phase is long-term testing to accumulate 500 hours of operation, prior to pursuing a demonstratio*
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*YES. The EISG program is a sub-set of a larger CEC program, discussed in some detail in the Introduction.*
26) What are the go/no-go milestones in your commercialization plan?	*The only "no-go" would be in the case of some catastrophic failure experienced during development.*
27) How would you assess the financial risk of bringing this product/service to the market?	*Zero risk, really. The process will work. There is always "execution risk," in the case something goes wrong.*

28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*No. We do not have a current business plan in written form. Although, we have several written plans that need up-dating with current information.*

Public Benefits

29) What sectors will receive the greatest benefits as a result of your concept?	*Residential.*
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*The cumulative value is calculated to be $2.1 billion. Please see the Public Benefits section of the Final Report, where the calculations are presented.*
31) Does the proposed technology reduce emissions from power generation?	*YES. But more work is required to assert firm numbers.*
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*No. The technology is win-win for all. However, any thermal process will have detractors looking for faults.*

Competitive Analysis

33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	*Low initial capital cost. Low operating cost. High conversion efficiency. Cost effectiveness is the key to penetrating the waste-to-energy market.*
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	*The technical approach is new, so to speak. Historically waste gasification has had problems. There have been huge failures. Most recently, Air Produce lost $1.2 billion by shutting down two parallel MSW gasification trains in England; a major blow to the waste-to-energy industry, the opinion of this author.*

Development Assistance

The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.

35) If selected, would you be interested in receiving development assistance?	*YES. Cooperating with DOE on a demonstration scale project would be very helpful.*