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Concept for Renewable H2 Production

Please consider the following concept for renewable H2 production and distribution:
1) Applicable feedstocks include California sourced woody biomass, forest residues, agricultural-residues, and Refuse Derived Biomass (RDB) recovered form MSW (a renewable opportunity feedstock.)
2) Advanced thermal chemical conversion platform (employing pulse-detonation power for process intensification) and using oxygen enriched air to 70% O2 to accomplish partial oxidation.
3) The crude syngas product (H2 + CO) would include some N2 and other diluents; however, separation and recovery of high-purity H2 can be accomplished using membrane or adsorption technology; both are economic for H2 separation from medium-purity syngas, precluding the need for high-purity O2 for POx, which is costly.
4) High-purity H2 would be compressed and stored in tube-trailers -- skid-mounted horizontal cylinders which are traditionally used in California for cost-effective H2 distribution for industrial applications.
5) One fueling station would be established at UC Riverside, at CE-CERT, and several more locations would be established as needed to distribute at least 1,000 kg/day of gaseous H2.
6) The economics for this approach should be superior to all other competitive methods. Biomass residues are cost-effective, especially Refuse Derived Biomass, which has negative value. The gasification equipment would operate continuously for 8-hrs/day for 1000-kg output, and up to 24-hrs/day if greater H2 production is needed.
7) The advanced gasification technology is already being developed at pilot-scale at UC Riverside so that $1.5 million is probably enough to develop the H2-separation system and the tube-trailer distribution system.
8) The PI was trained at Airco-BOC and at Air Liquide in the production, use, and distribution of gaseous H2.
9) The up-side potential for the core gasification technology (POx methodology, intensified using pulse-detonation) is very attractive and in the near-term will enable significant process cost reductions.
10) A process description for biomass-to-RNG is attached. The RNG proposal is focused on catalytic methanation, including a novel cryogenic syngas cleaning process. However, it should be noted that H2 production is significantly less complex, partly because H2 separation from medium-purity syngas has been commercially available for more than 20-years; residual gases are suitable for renewable power generation.

We respectfully request that the H2 solicitation include broad enough language so that our production concept can compete with alternative methods. Thank you.

Additional submitted attachment is included below.

Pipeline Quality RNG Production
Using Syngas Methanation

Phase 1. Project Design, Systems Engineering

Team Member Organizations:

Taylor Energy
University of California Riverside

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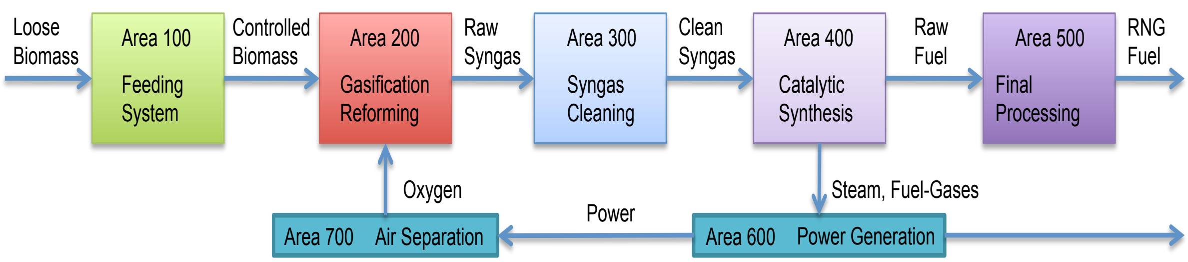
August 2017

Project Narrative

1.0 Objectives

The research team is developing Biomass-to-RNG technology designed for pipeline applications at community scale, using locally sourced renewable energy resources. Taylor Energy is developing novel gasification technology (Area 200), integrated with a catalytic synthesis module (Area 400) being developed by **Ceramatec Inc.**, for production of ultra-pure RNG. Technology development will include a cryogenic syngas cleaning system (Area 300) that employs liquid-CO2 as the scrubbing fluid.

Overall Process Flow Diagram – Biomass-to-RNG



1.1 Project Description

Taylor Energy's thermal gasification process employs a robust Jet Spouted Bed for 1st-stage gasification and a novel 2nd-stage Venturi-Reformer; both stages are powered using a proprietary Pulse-Detonation method. Unique to this embodiment, hot exhaust-gases discharged at supersonic velocity provide low-cost process intensification. This is significant because supersonic compression waves enhance the rate of chemical reactivity due to the repetitive shockwaves that course through the process at 4-cycles per second, pushing the molecules together, intensifying thermal chemical reactions at the molecular level.

The Taylor Energy gasification process operates up to 1150 °C -- below the ash-fusion temperature, but well above the 920 °C limit for typical circulating fluidized bed (CFB) gasifiers. Many process benefits are obtained by operating near -- but below -- the ash-fusion temperature. For example, a process goal is to reduce oxygen and steam consumption to minimize operating costs. The target feed rate for the test program is 3-tonne/day, feeding biomass, refuse derived biomass, and/or agricultural residues.

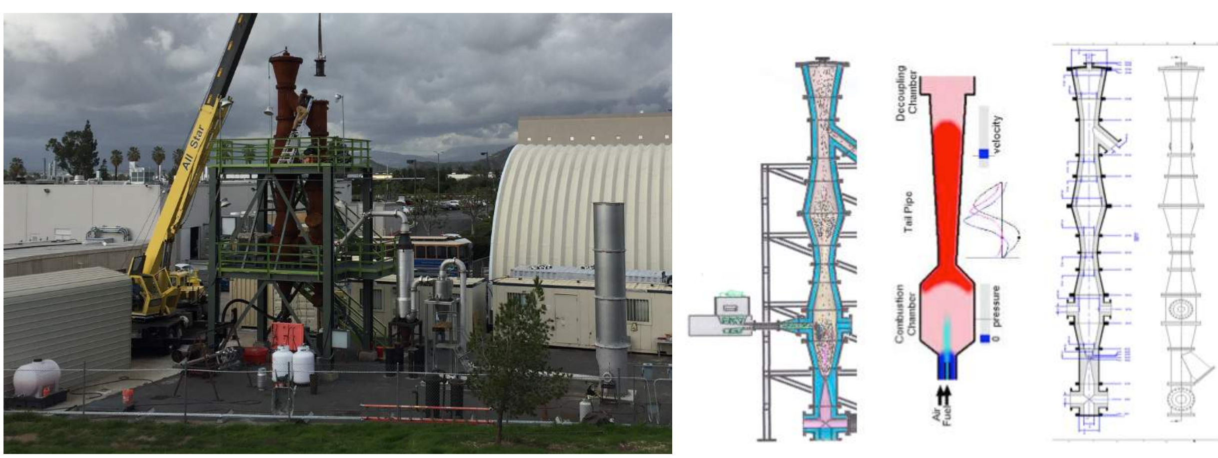


Figure 1.2. Taylor Energy's Modular Gasification / Reforming System located at UC Riverside

1.2 Potential Benefits

The gasification / reforming technology will integrate with a new modular synthesis process being developed by Ceramatec, Inc. The catalytic synthesis module shown below can be used for FT-liquids production with 2-bbl design capacity, or used for methanation of syngas to form CH4 at 10-scfm scale.

Methanation is the reaction of carbon oxides and hydrogen, making methane and water.

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$$
$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

Using methanation Biomass-to-RNG is potentially accomplished with 60% net conversion efficiency.

The successful integration of these key systems will advance the state-of-the-art leading to lower cost RNG, enabling a new embodiment that promises low capital & operating costs for community scale deployment of combined power and ultra-clean RNG production. Both the gasifier/reformer and the methanation module are designed for ease of fabrication, using mostly off-the-shelf components to minimize first-cost, and process intensification methods are employed to reduce operating costs.

Ceramatec's 10-scfm test module shown below will be shipped to UC Riverside's test-site in 2018, after completing tests at the Energy and Environmental Research Center, in North Dakota, feeding biomass and coal. We propose to use this module to test RNG production methods using nickel catalysts.

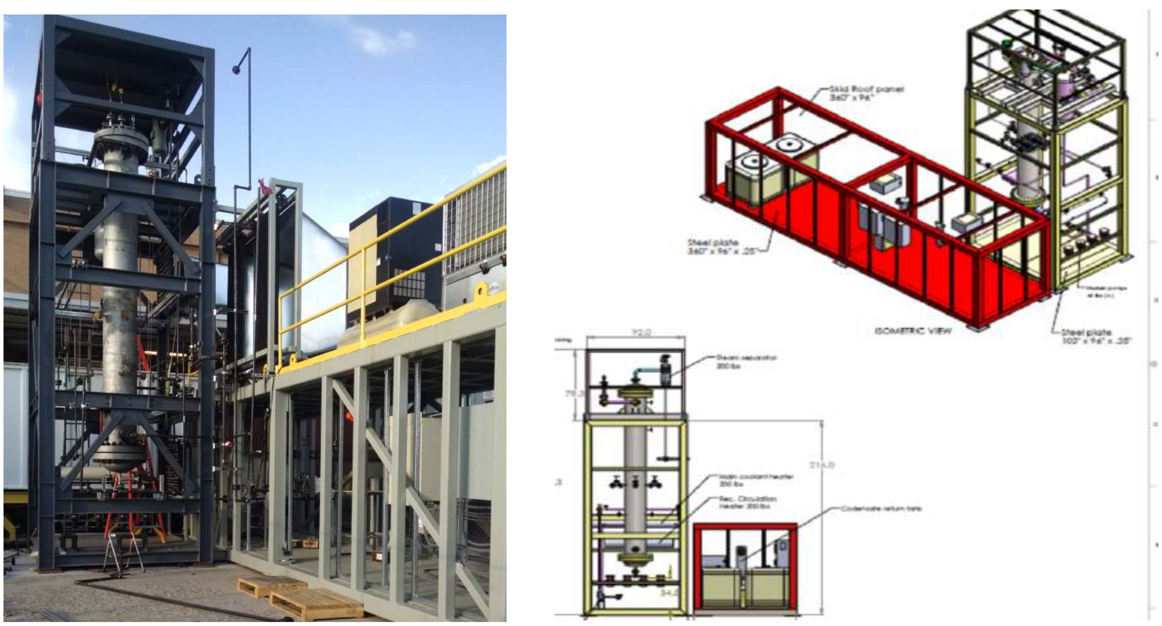


Figure 1.3. Ceramatec's 10-scfm synthesis modular

1.3 Syngas Cleaning

Fuels synthesis includes the need to develop a cryogenic syngas-cleaning module (Area 300), including syngas compression. Essentially all trace contaminants can be removed (<0.1 ppm for each contaminant) from the low molecular weight gases (H2, CO, CH4, N2) using cryogenic deep-cleaning methods that employ liquid-CO2 as the scrubbing solvent. The research team proposes to develop and test a modular cryogenic syngas cleaning method that is being employed by KBR and others for ammonia synthesis at refinery scale.

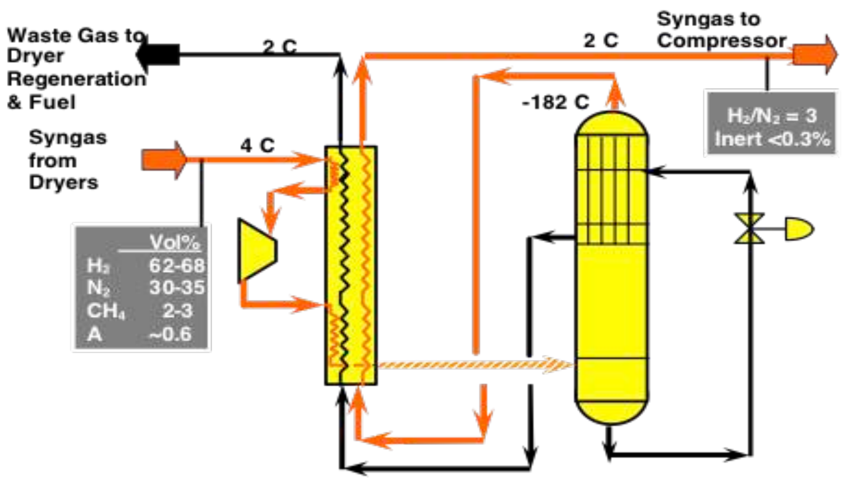


Figure 1.4. Cryogenic gas cleaning system used by KBR and others for ammonia synthesis

2.0 Technology Merits

2.1 Scientific and Technology -- Taylor Energy's shockwave gasification process employs a robust Jet Spouted Bed (JSB) primary. This is significant because shockwaves intensify the thermal-chemical reactions as a result of supersonic compression waves that pass through the reaction zone; and at the macro-level, rapid mixing and comminution of the feed enabling use of coarse feed materials.

Figure-2.1 shows a conical jet-spouted-bed; Figure-2.1 (d) shows the optimum configuration for rapid mixing and comminution of feed.

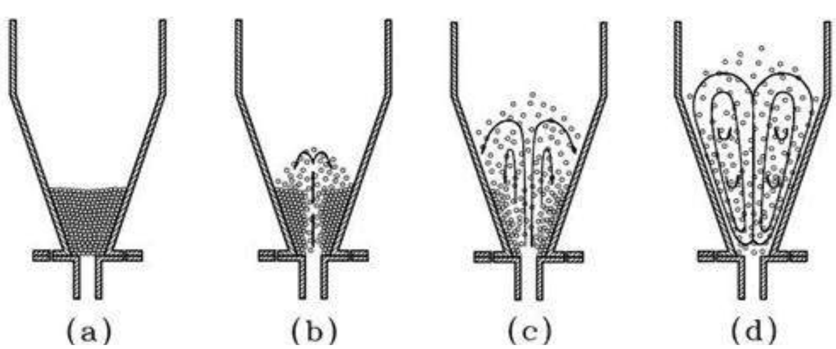


Figure-2.1. Conical Jet Spouted Bed

Unique to this embodiment, the JSB is powered by hot exhaust-gases discharged at supersonic velocity from a **Pulse-Detonation-Combustor**. This is significant because supersonic compression waves enhance comminution of the feed at the macro-level, and increase the rate of thermal chemical reactivity at the molecular level.

The gasifier configuration is shown below:

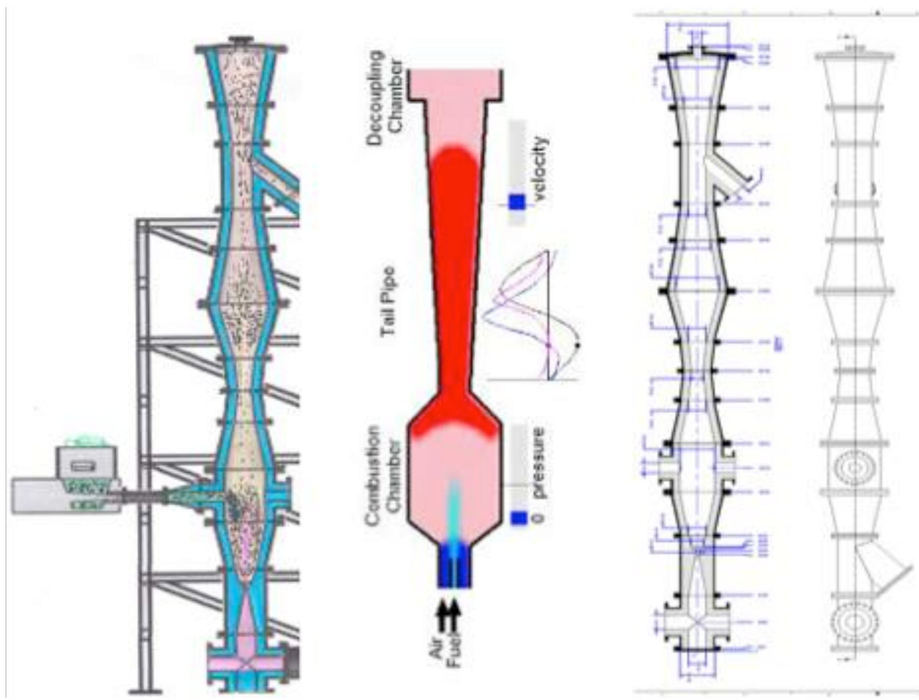


Figure-2.2. JSB type Biomass Gasification Reactor

The new gasification process is highly significant in that it uses pressure-gain-combustion methods. A problem with traditional gasification methods is that increasing process-intensity also increases parasitic-power. For example, employing high-temperature plasma for tar cracking or carbon-steam reforming increases process-intensity, but also increases the cost of parasitic power consumption; whereas our innovative pulse-detonation system increases process intensity and concurrently lowers parasitic-power consumption. Moreover, the pulse-combustion hardware is low-cost to fabricate and low-cost to operate when compared to competitive intensification methods. The power created by pulse-detonation is used to drive a Jet-Spouted Bed (JSB) receiver that serves as the devolatilization stage in the gasification process. Pulse-detonation experiments at OSU's combustion lab show the heat-output from a detonation burner.

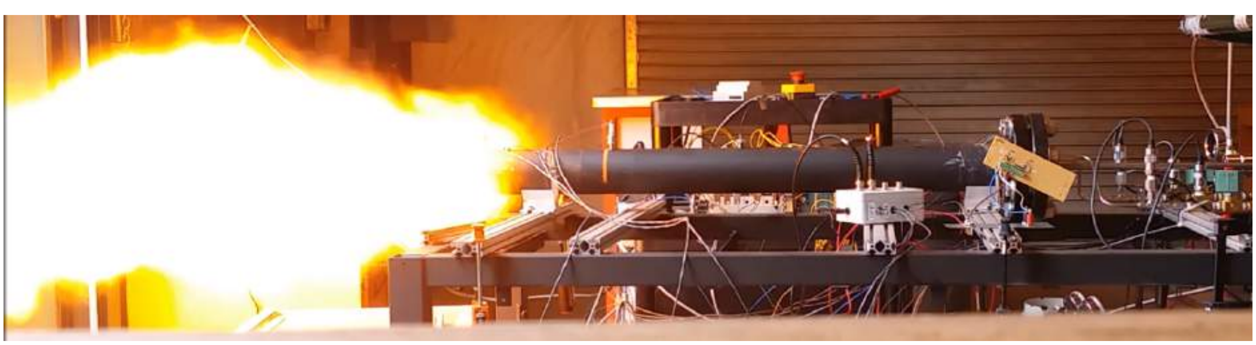


Figure-2.3. Pulse-Detonation Burner in operation at OSU's Combustion Laboratory

Although only limited testing has been performed to date, the research team has confirmed that the technology is highly significant. Pulse-detonation is a constant-volume process, and is the most efficient type of combustion. We use a small amount of propane to accomplish fuel-detonations that deliver supersonic shockwaves, following on the fundamental work performed by David L. Blunck at Oregon State University (OSU), where DOE-NETL is funding the development of Pulse-Detonation methods.

The gasification / reforming test facility shown below is located at the University of California Riverside. The pulse-detonation powered Jet-Spouted Bed operates in an expanded bed mode, and provides the environment for rapid heat and mass transfer between gases and solids.

Figure-2.4. Taylor Energy's Pulsejet burner being installed on top of Reformer; UC Riverside, CA

The 2nd-stage Reformer is likewise operated using pulse-detonation-power to increase mixing of particulate-solids with reactive gases; shown below in a horizontal arrangement, the reformer is fired in the downward direction, helping to draw product gases through the processing system. We prefer not to show the actual geometry of the Ventui-Reformer configuration, which is proprietary and confidential.

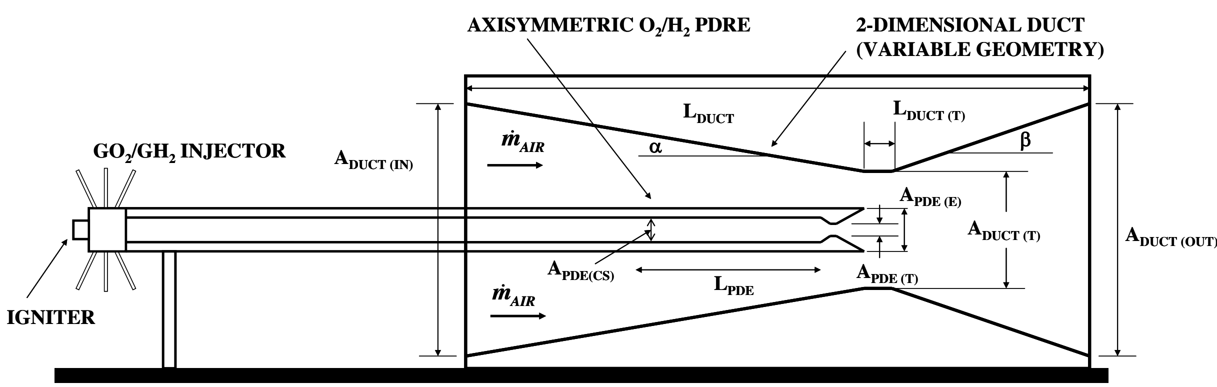


Figure-2.5. Configuration used for PDE-Venturi-Reformer; fired in the down-leg of the Syngas Process

The shockwave gasification/reforming technology will integrate with a new modular synthesis process being developed by Ceramatec, Inc. We will advance the state-of-the-art for community scale combined power and RNG production with the successful integration of these two sub-systems, along with a cryogenic gas-cleaning module.

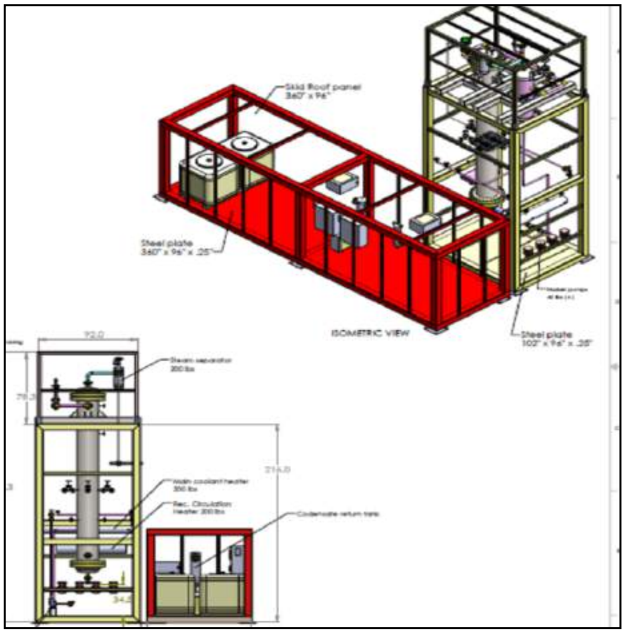


Figure-2.6. Ceramatec's Synthesis Test Module **Figure-2.7. Catalyst tubes**

The development of both the gasification module and synthesis module is based on REMS principles, using process intensification methods. Gasification employs pulse-detonation power, and the synthesis module employs enhanced heat transfer from the catalyst. These process intensification methods are intended to reduce operating costs at community scale to levels presently achieved at large refinery scale. The research team is presently funded by the California Energy Commission (CEC) to develop and test this technology for application to woody biomass for (storable) liquids production using forest residues derived from bark-beetle kill.

Ceramatec was selected by the US Department of Defense to develop modular FT-synthesis hardware intended for deployment at forward military base operations, to minimize the risk of transporting fuel through war zones. The DOE is funding Ceramatec to develop a modular syn-fuels skid in an effort to develop small-scale synthesis technology that is cost competitive with 40,000 bbl/day refinery methods when operating at 1,800 bbl/day. Ceramatec is using REMS methodology to accomplish these goals, employing mostly off-the-shelf materials, shop fabrication, and catalyst process intensification.

The methanation catalysis requires ultra-clean syngas for sustained economic operation. There are various proven syngas cleaning methods that include multiple methods, i.e., acid gases, HCN and ammonia. The process designer is typically required to implement several methods in series to purify syngas. For modular systems intended for medium-scale operation, a series of methods added process complexity that is burdensome, impacting both the capital and the operating cost.

What is wanted is a single method that removes essentially all the trace contaminates from syngas, including trace compounds that have not been anticipated in the design bases. There are surprises in the feed composition; the gas cleaning system has to be flexible, and applicable to the entire range of possible contaminants.

Cryogenic syngas cleaning methods that employ CO2 were first developed specifically for coal-derived syngas as a method to compete with the historic Rectisol process, which uses chilled methanol as the solvent; MeOH make-up costs are significant when MeOH is not the end-product; and there are some trace gases that can break through.

The PI first observed the operation of the Triple Point Crystallization (TPC) process, developed by Acrion in Cleveland, Ohio, in 1993. Food grade CO2 was a co-product of their cryo-scrubbing process. To date a CO2-wash version of their process has been commercialized for cleaning landfill gas at relatively large-scale in Brazil.

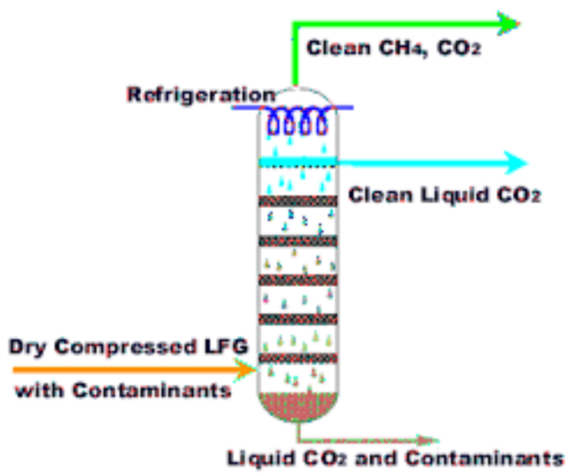


Figure 2.8. Acrion's CO2 wash process

CO2 gas-scrubbing technology has been proven to work successfully. What we want is a modular cryogenic syngas scrubbing methodology developed specifically for integration with RNG synthesis, with operating pressure in the 300 – 700 psig range, which is a good fit for cryo-scrubbing with liquid-CO2. The temperature for CO2 liquefaction is a function of pressure. Acrion was typically operating about 500 psig and -55 degrees C. whereas; KBR is operating at -182 degrees C.

The energetics for the cryo-scrubbing process are expected to be attractive compared to competitive multi-stage cleaning methods when heat-exchange is used effectively to recover most of the "cold." The cost of fabricating cold-box type heat exchanges has been reduced significantly in recent times due to robotic welding methods. Liquid-CO2 scrubbing is in the public domain; informed engineering practice can result in a custom modular design that uses mostly off-the-shelf components.

Gasification -- Background

One primary objective for the Taylor Energy Gasification / Reforming process is to produce high-quality synthesis gas while operating below the ash-fusion temperature. Many process benefits are obtained by operating very near -- but below -- the ash-fusion temperature. High-temperature gasifiers must operate well above the ash fusion temperature -- hot enough that molten ash flows at low viscosity at 1300 °C to 1450 °C, which incurs high oxygen cost and inherent refractory problems. From an energy and consumables perspective, high-temperature slagging-gasifiers should be disqualified for efficient operation at community scale.

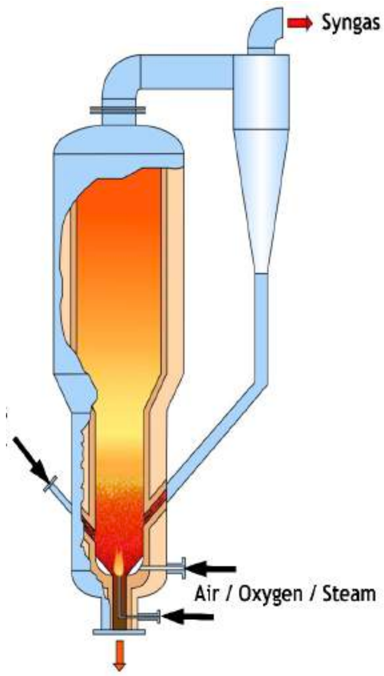


Figure-2.9. SES Gasifier

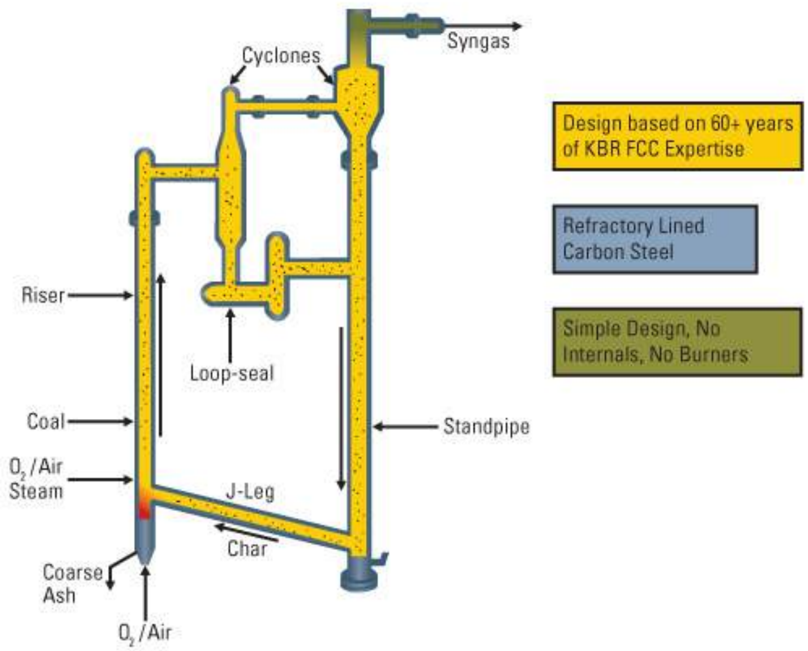


Figure-2.10. KBR Gasifier

The world's leading gasification systems are discussed below:

The Synthesis Energy Systems (SES) gasifier is the result of 50-years of development at the Gas Technology Institute (GTI), Des Planes, Illinois. SES has commercialized the technology in China, primarily for methanol synthesis using high-ash coal as the energy feed. The technology operates with relatively low downtime and is economic at large scale. However, one complete spare gasifier, available for parallel operation at all times, is still needed to handle unplanned outages. The KBR gasifier is the result of many years experience in Fluid Catalytic Cracking in the petroleum refining industry. The carbon conversion efficiency is high. However, the KBR technology is fairly complex (its tall, with expansion joints), and would be costly to construct and operate as a modular community scale system.

Both these state-of-the-art gasification technologies are applicable to various residual carbon feeds. However, both technologies are based on major innovations developed more than 50-years ago, and the core processes have not changed all that much in half a century. Employing pulse-detonation -- an emerging aerospace propulsion technology -- to drive a Jet Spouted Bed and to drive a Venturi-Reformer, offers significant improvements to the-state-of-the-art. Process intensification is the objective.

The Taylor Energy syngas process operates below the ash-fusion temperature, up to 1150 °C, but well above the 920°C limit for typical fluidized bed gasifiers. The goal is to reduce both capital and operating costs compared to existing systems, and to minimize oxygen and steam consumption.

Spouted Bed gasification by its self offers some improvements, but is not revolutionary. British Coal Corporation developed a spouted-fluidized bed gasification process in the late early 1990's. In fact, the GTI gasifier was operated as a spouted-fluidized bed during different phases of its development. The PI successfully developed an improved cast-refractory version of a traditional spouted bed during the 90's, at a time when GTI was using a costly metal alloy distributor to accomplish spouted-fluidization.

Incremental improvements are achieved using a Jet-Spouted Bed. A fully expanded conical bed, operating in the dilute phase, is very robust. For example, the JSB can handle the presence of a sticky liquid phase without slumping the bed; ash eutectics often form when operating near the ash fusion temperature that can create serious operational problems. The JSB offers improvements, especially considering the simplicity -- no distributor plate -- only a single central inlet nozzle, where high velocity gases enter the gasification system. Tsuji and Uemaki make use of a Jet Spouted Bed configuration to great benefit:

Typical Gasification Performance Data

Run No.	34	31	36	2023	2024	2025
Coal Feed Rate (kg dry coal/h)	6.51	6.45	6.47	10.4	10.4	10.4
Oxygen/Coal (kg/kg)	0.613	0.706	0.812	0.603	0.682	0.785
Steam/Coal (kg/kg)	0.676	0.930	0.943	0.712	0.750	0.786
Maximum Bed Temp. (°C)	1007	1033	1070	1034	1072	1120
Gas Yield (m^3(STP)/kg coal)	1.57	1.75	1.75	1.57	1.62	1.73
Gas Composition (Vol.%)						
H_2	41.1	39.0	36.5	40.3	38.4	35.5
CO	32.5	35.6	42.1	33.2	37.0	42.8
CO_2	22.7	22.1	18.4	22.9	21.3	18.8
CH_4	3.7	3.3	3.0	3.6	3.3	2.9
Gross Calorific Value of Product Gas (MJ/m^3(STP))	10.85	10.81	11.20	10.79	10.91	11.12
Carryover (Cyclone Catch) (kg/h)	1.83	1.27	1.16	2.63	2.23	1.62
Carbon Content in Carryover (mass%)	37.8	17.5	8.04	20.3	15.8	7.50
Carbon Conversion (−)	0.805	0.930	0.972	0.817	0.872	0.973
Cold Gas Thermal Efficiency (−)	0.665	0.739	0.769	0.662	0.693	0.752

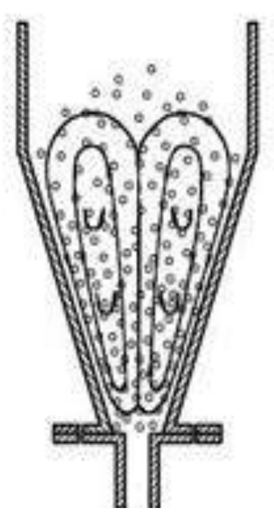


Figure-2.11. Jet Spouted Bed

Figure-2.12. Pilot-Scale JSB with Pulse-Detonation Burner

By incorporating Pulse-Detonation technology, revolutionary benefits are achieved. The JSB can use the shockwave power input efficiently; other gas distributors cannot recover the momentum.

A pulse-deflagration burner fires with velocity of 300-feet per second.
The pulse-detonation-burner discharges with velocities of 3,000 meters per second.

The pulse-detonation power cycle is shown below; notice the fundamental design simplicity. A pulse detonation burner is constructed using a tube, with fuel and O2 inputs, and a cyclic ignition system.

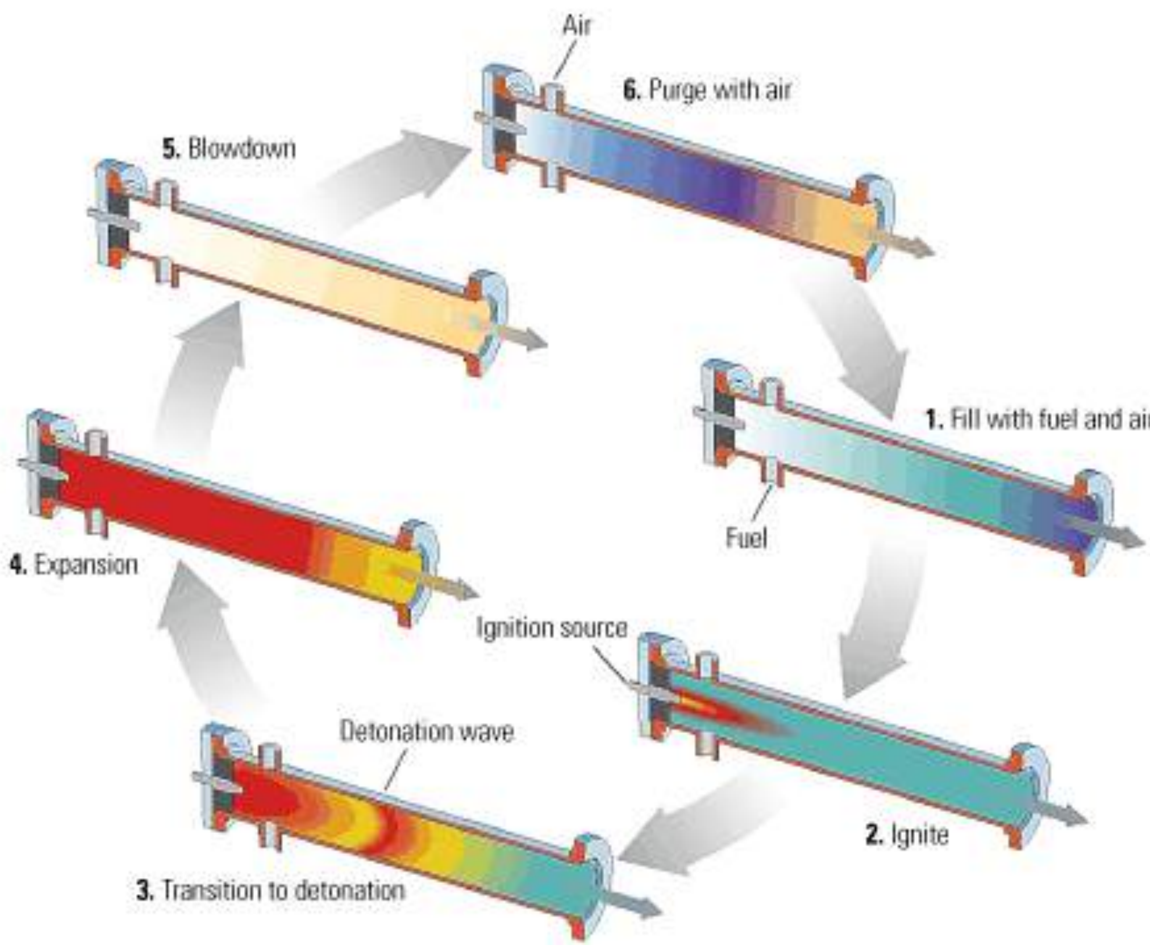


Figure 2.13 Pulse-Detonation -- Principal of operation

Regarding gasification, on the molecular level, passing supersonic compression waves through the process has the affect of operating at higher pressure because the molecules are pushed together periodically. The present embodiment operates near atmospheric pressure, which enables simplified construction and operation. Additionally, the mixing is intense, which serves to improve the kinetics, which are otherwise limited by heat and mass transfer between the gases and the solids.

Shockwave power input is highly significant; no one else is applying this emerging aerospace propulsion technology to gasification. We cannot prove exactly what we have yet because there is not enough data to make quantitative comparisons. We have a new methodology, that when fully exploited, will provide more than incremental improvements for modular energy conversion. During operational testing, one feels the power-snap from the shockwaves; ear protection is essential.

Figure 2.14 Pulse-Detonation Burner -- Designed by Taylor Energy and tested at UCR.

2.2 Technical Approach

The block diagram below shows the Biomass-to-RNG process, employing syngas methanation methods to produce high-purity methane. The proposed Phase-1 will focus on design and engineering of the systems identified in block flow-diagram below:

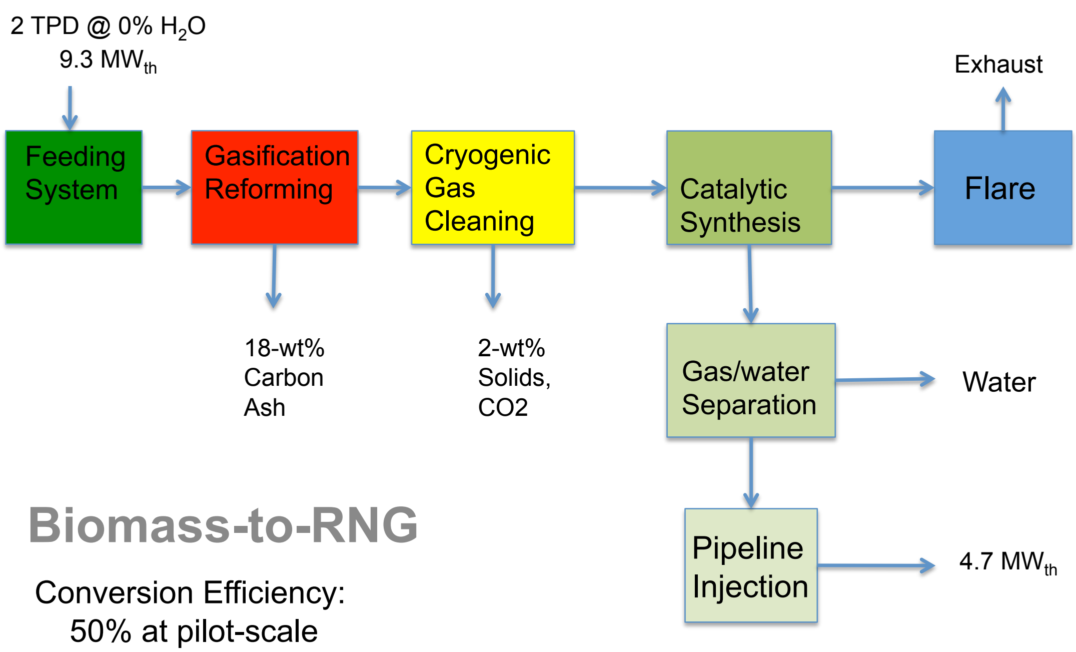


Figure-2.15. Process Flow Summary

The feed target is 3-tonne/day of biomass; the target output is 10-scfm CH4. For the purposes of this test program, the RNG product will be injected into the UCR pipeline, flared, or used for electric power generation. No effort will be made to up-grade the RNG products beyond pipeline quality.

The Phase-1 Statement of Work is summarized below:

Project Design Basis

Basic Site Characteristics
Basic Fuel Feedstock Characteristics
Identify biomass ratio, type of biomass, basic computational analysis of feed
Environmental Requirements

Basic Engineering Design Elements

Process Engineering
Process area descriptions
Block Flow Diagram (BFD)
Process Flow Diagram (PFD), and
Process & Instrumentation Diagram (P&ID)
Process simulation output and heat and material balances (H&MB)
Major Process Equipment specifications
Basic Equipment and instrumentation lists
Project Cost Estimate
Construction Cost Estimate
Operations Cost Estimate
Estimated Project Schedule

Other Items

Project execution and project management guidelines and procedures
Logistics
Material selection specifications and lists
Balance of Plant (including roads, buildings, site prep, rail layout)
Construction Planning

2.3 Technical and Management Capabilities

2.3.1 Background

Taylor Energy commenced developing gasification technology in the late 1980's by purchasing a modular Bubbling Fluidized Bed (BFB) from a defunct DOE-funded project intended to demonstrate gasification of cotton ginning waste. Tars that accumulated on a down-stream heat-exchanger resulted in a dramatic fireball, which terminated the project. Taylor Energy bought the equipment for $50k and moved the modular gasifier from Arizona to California to evaluate Auto Shredder Residue (ASR) as a gasification feedstock. Waste processors consider ASR one of the most difficult feedstocks for thermochemical gasification due to hazardous heavy metals content (*cadmium, mercury, lead*), high ash content (*glass, minerals*), and difficult plastics that result in trace toxic gases (*PVC and Nylon*).

Figure-2.16. Modular Bubbling Fluidized Bed

Figure-2.17. Cotton Crop resulting in Ag-residues

Since that time, Taylor Energy has designed and operated seven different pilot-scale gasification systems, with varying degrees of success, depending on the level of difficulty of the feed, the oxidant used for partial oxidation, the operating temperature (*slagging or non-slagging*), and the difficulty of product output (*hydrogen, syngas, fuel-gas.*) Two pilot-scale development projects are discussed in greater detail in the qualifications section, including early work using a spouted bed gasification system.

Figure 2.18. ASR Process patented by Taylor, circa '95

Figure 2.19. Auto Shredder Residue (ASR)

The technology proposed for research and development is based on 30-years experience in the thermochemical processing field, working to simplify and optimize gasification/reforming methods to achieve economic viability at industrial and community scale, as compared to refinery scale.

2.3.2 Team Qualifications, Capabilities, and Resources

Taylor Energy is a California nonprofit corporation currently funded by the California Energy Commission under EPC-14-045 to develop Advanced MSW gasification technology. Taylor Energy has operated as a consultancy since 1995, focusing on development of gasification technology at pilot-scale. Under the direction of the DOE project Manager, Donald Taylor will serve as the PI and will manage in-house research technicians, and the major subcontractors that include UC Riverside and Tech Fab. Donald Taylor, as Project Manager, has a successfully managed eight pilot-scale gasification projects listed below:

Company	**Technology**	**Type**	**Capacity**	**Completed**
PIER	JSB, Entrained	Air, direct	180 pound/her	2016
PWG	Pressed-Bed	Air, direct	720 pound/day	2014
West Biofuels	PYROX	Air, indirect	4 ton/day	2010
EPA	Transport Reactor	Air, direct	50 pound/hr	2006
DOE/WRI/Taylor	Draft-Tube	Air, direct	150 pound/hr	2004
Proler	Rotary-Retort	O2-CH4, direct	50 ton/day	1997
EER	Jet-Spouted Bed	O2-CH4-steam	20 ton/day	1993
Taylor Energy	Bubbling FB	Air, direct	2.5 ton/day	1987

Two of the gasification projects listed above are discussed as follows:

A 50-ton/day MSW gasification plant was designed and patented by Taylor Energy and assigned to Proler International, of Houston, Texas in 1995. The plant was successfully permitted to operate using MSW or ASR (Auto Shredder Waste). The syngas product was used for electric power generation. The unique feature of this plant was the ability to melt the residual ash and form a high-quality granular glass frit, employing TRW's cyclonic ash-melting technology: we used rocket-engine cooling methods to form a frozen slag-layer inside of the vitrification section.

Figure 2.20. Proler Syngas Process

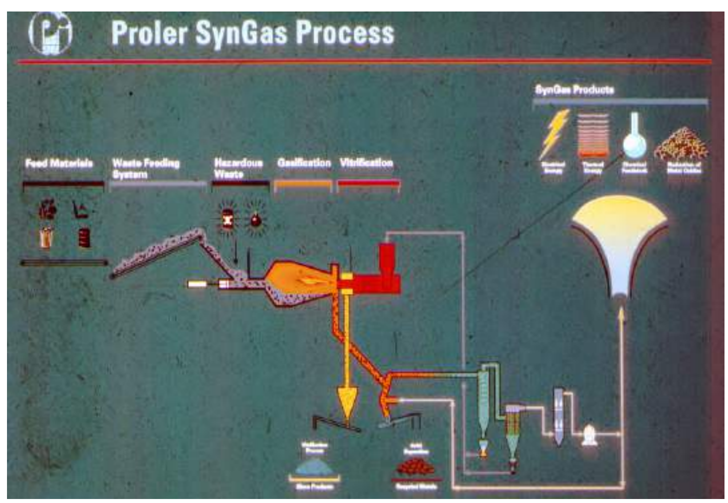


Figure 2.21. Process Fow Diagram; designed by Taylor Energy

Figure 2.22. Spouted Bed

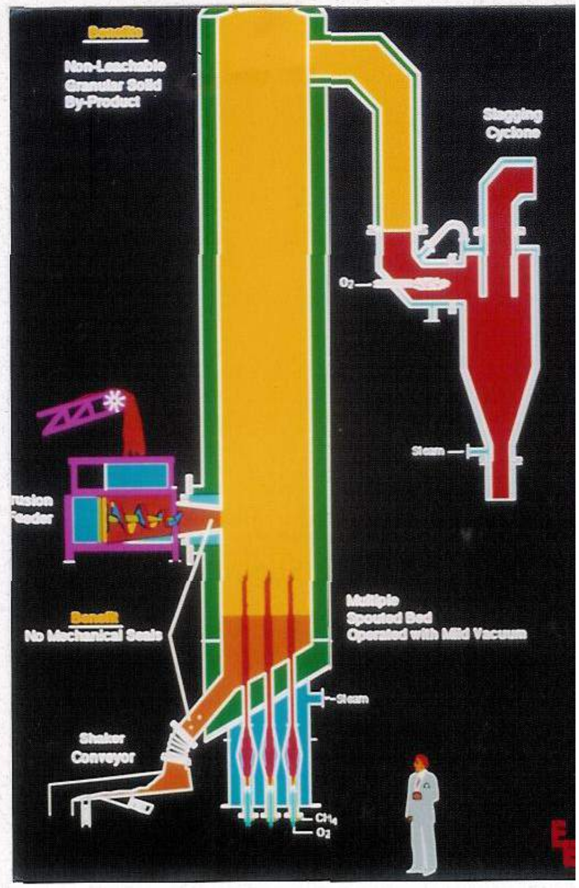


Figure 2.23. O2/H2O/CH4 Spouting alumina balls

This 20-ton/day MSW gasification plant was designed and patented by Taylor in 1993. Once located in Irvine, CA, the permits to operate were issued by the South Coast AQMD. The plant operated as a spouted-bed type POX reactor, firing oxygen-methane-steam to make hot syngas used to crack MSW into fuel-gases. A feature of the plant was the ability to process coarsely shredded MSW. The test-site was sold for housing in 1996 when General Electric bought Energy and Environmental Research Corp., which has become GE Global Research, Irvine.

Dr. Arun Raju has extensive experience in gasification of carbonaceous feeds, primarily operating and evaluating steam-hydrogasification methods at UCR; Arun served as the Chief Technology Officer for a coal hydrogasification project development effort funded by DOE and is the Director for the Center for Renewable Natural Gas at UC Riverside. He will serve as a Principal Investigator for UCR, managing the ASPEN modeling work that will be used to prepare the mass and energy balance, and perform an environmental analysis; his equilibrium models will be used to compare with experimental data. UCR's Bourns College of Engineering hosts the Alternative Fuels and Renewable Energy Research Program where integrated grid technology is being developed. These systems combine natural and renewable energy sources, such as biomass, solar, and wind, with lithium ion energy storage.

Ronald Meacham, General Manager of Tech Fab, a California Corporation, will manage hardware fabrication, construction activities, all modifications to the thermal feeding system, and acquisition of the feedstock to be used for testing. Mr. Meacham has successfully managed the pilot-plant fabrication and construction tasks that have been performed to date for EPC-14-045. The research and test facilities leased from UCR by Taylor Energy provide the infrastructure that is key to performance of the work.

A process flow diagram for the existing gasification pilot-plant is shown below:

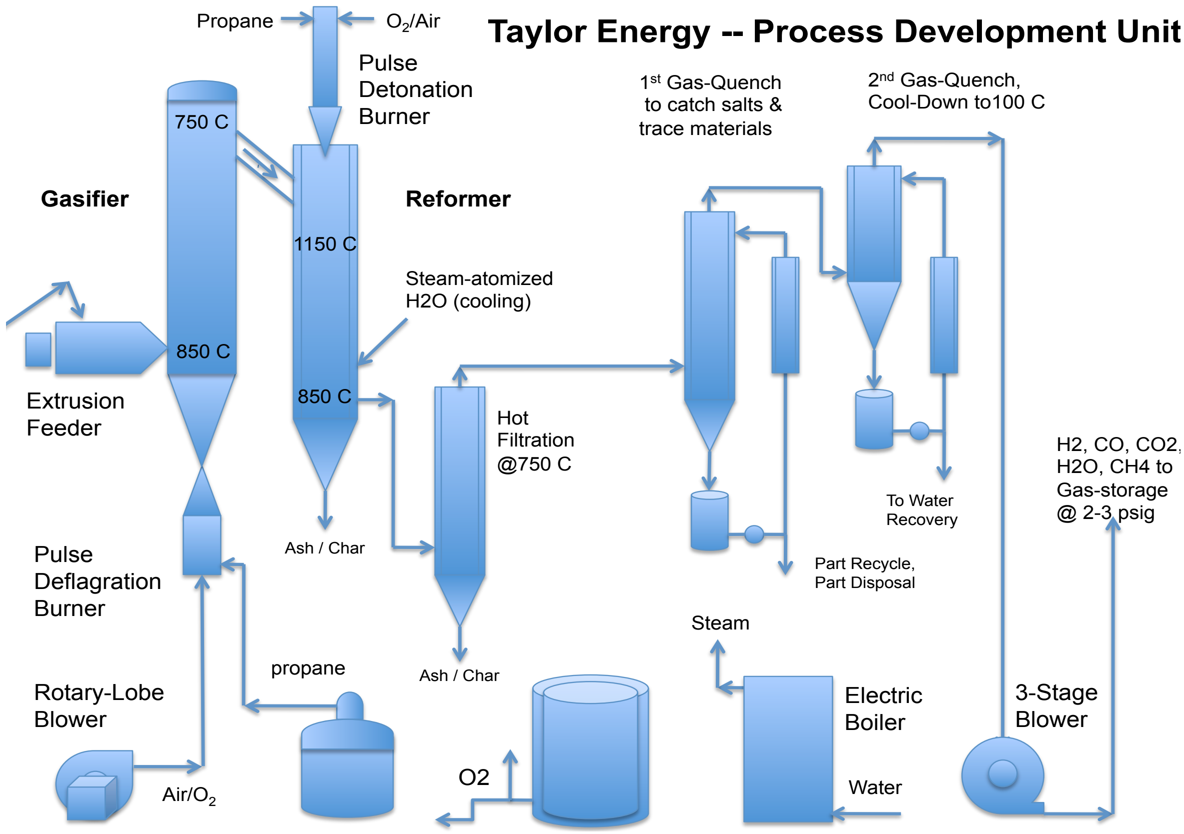


Figure 2.24. Existing Pilot-Plant Facilities located at UC Riverside used for process development

Figure 2.25 Gasification Test Facility at UCR

Figure 2.26 Modular reactor spool sections

3.0 Relevance and Outcomes/Impacts

Regarding the modular gasification system proposed for development, of the utmost importance is the need for process improvements that result in real cost savings. The gasification and reforming processes -- syngas production – require 60% of the installed capital cost when building a synthetic fuel facility. According to a techno-economic study performed by Splath, et al, "For all of the products examined in the economic analysis section (H2, SNG, MeOH, FT-Liquids, EtOH, mixed alcohols, olefins), *syngas production accounts for at least 50% of the product cost and in many cases it is more like 75%*." The study recommends that, "Overall, steps should be made to optimize the process in order to obtain the highest yield and least cost configuration. To reduce costs, efforts should be focused on minimizing the cost of clean syngas production." (Splath, P.L.)

A goal of the proposed research is to develop a gasifier/reformer embodiment that is low-cost compared to existing technologies. The Taylor Energy syngas process operates like an Entrained-Flow gasifier in many regards, but with improvements. The primary receiver is a JSB that retains oversized feed materials while fines are quickly elutriated by entrainment with process gases; the JSB serves to rapidly reduce the size of the feed in a high-temperature environment, which causes carbonaceous materials to become friable (more easily crumbled.) The intent of the 1st-stage JSB is to generate entrained-flow containing water vapor, volatiles, carbon-char, and particulate matter. A Spouted Bed is also created directly above the 1st-stage by using a reactor section composed of converging and diverging nozzles, which serve to hold-up larger carbon-char particles for further reaction. This JSB accomplishes a type of internal circulation, without the cost and complexity of an external circulation loop.

This two-stage design has been demonstrated at bench-scale by Tsuji, T., & Uemaki, O., who showed that coal could be gasified with greater efficiency by operating just below the ash fusion temperature, at significantly lower temperature compared to entrained-flow slagging type gasifiers. The proposed modular gasification process is a very flexible and enables converting diverse energy feeds into a syngas intermediate suitable for a variety of modular synthesis applications. The resulting syn-fuels can include jet fuel and renewable natural gas, and co-production electric power. The techno-economic objectives will be accomplished using process intensification methods; for example, higher carbon conversion at lower temperature compared to slagging-type gasification methods.

4.0 Roles Of Participants and Principal Investigators

Taylor Energy is the prime contractor. Donald Taylor will serve as the Project Manager and the Principal Investigator for Taylor Energy, which owns the intellectual properties for the gasification process, including trade secrets and patent applications for shockwave gasification. Taylor Energy will also own the resulting IP for the proposed cryo-syngas cleaning process.

Ceramatec owns their IP for the catalytic synthesis module; Ceramatec is presently forming a commercialization entity to exploit these various integrated technologies. Taylor Energy will license the gasification and reforming IP to Ceramatec's commercialization entity.

UC Riverside will provide the test-facility, which is located at the Bourns College of Engineering. The gasification test facility, constructed by Taylor Energy and by subcontractor Tech Fab, is presently leased to Taylor Energy for a 6-year term. UC Riverside personnel, faculty, and students will participate on a subcontract basis. Dr. Arun Raju will serve as the PI for UCR and has responsibility for managing their work tasks, including the evaluations and the analytical portions of the project.

The Organization Chart below shows the management structure; under the direction of the Research Manager, Taylor Energy will manage in-house research technicians, and the major subcontractors including UCR, and interface with key technology partners, including Ceramatec.

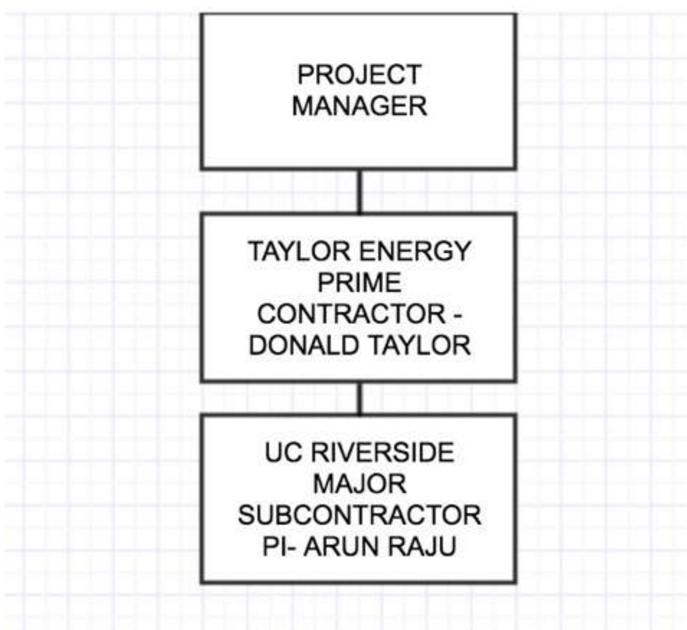
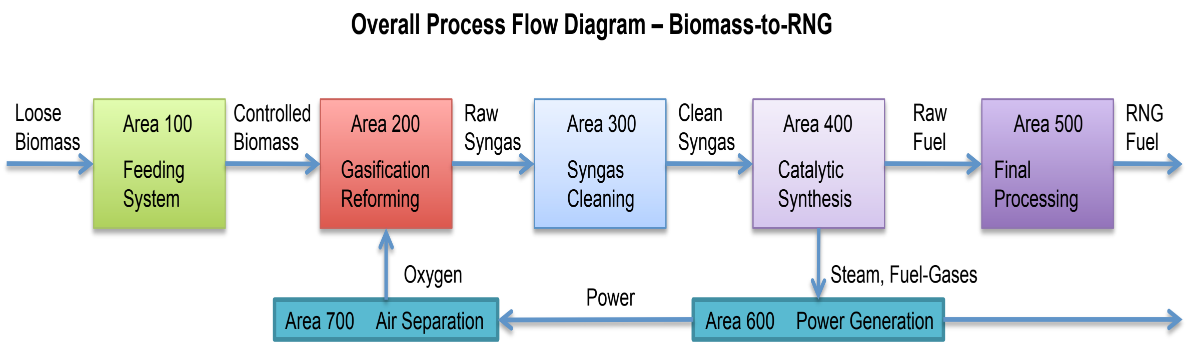


Figure 4.1. Project Management Structure/Responsibility Chart

Donald Taylor is PM/PI for Taylor Energy; Arun Raju is the PI for UCR. Taylor is responsible process for making decisions on scientific/technical direction; Taylor and Raju make decisions regarding publications jointly. Communication between members is typically by email which is archived to maintain a permanent records. Conflicts are solved one or one discussion until and consensus is achieved.

5.0 Statement of Project Objectives

The research team is developing Biomass-to-RNG technology designed for pipeline applications at community scale, using locally sourced renewable resources. Taylor Energy is developing novel gasification technology (Area 200), integrated with a catalytic synthesis module (Area 400) being developed by **Ceramatec Inc.**, for production of ultra-pure RNG. Technology development will include a cryogenic syngas cleaning system (Area 300) that employs CO2 as the self-scrubbing fluid.



SCOPE OF WORK

Phase 1 – Project **Preparation & Engineering Design**

Design and Engineer the Biomass-to-RNG system:
Feeding system, gasification, reforming, gas-clean-up, syngas purification, methanation, RNG delivery, producing 10-scfm CH4.

1.0 Project Design Basis

Basic Site Characteristics

Basic Fuel Feedstock Characteristics

Identify biomass types, basic computational analysis of feed

Environmental Requirements

Carbon cycle analysis

2.0 Basic Engineering Design Elements

Process Engineering

Process area descriptions
Block Flow Diagram (BFD)
Process Flow Diagram (PFD), and
Process & Instrumentation Diagram (P&ID)
Process simulation output and heat and material balances (H&MB)
Major Process Equipment specifications
Basic Equipment and instrumentation lists

Project Cost Estimate

Construction Cost Estimate
Operations Cost Estimate

Estimated Project Schedule

3.0 Other Items

Project execution and project management guidelines and procedures
Logistics
Material selection specifications and lists
Balance of Plant (including roads, buildings, site prep, rail layout)
Construction Planning

Future work:

Phase 2 -- Construction & Start-up Testing
The year-2 goal is successful evaluation of the Biomass-to-RNG system.

Phase 3 -- Testing Campaign & Evaluations
The program-end goal is operation of the Process Development Unit using oxygen enriched air and steam, feeding 3-tonne/day, producing clean dry syngas for 500-hours, producing 10-scfm pipeline quality RNG.

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Facilities & Other Resources Appendix

The gasification test facility located at UCR is described substantially in the Project Narrative.

In addition to gasification and reforming equipment, the UCR research site includes a full complement of ancillary facilities, including an electric boiler that provides steam, test-engines, a suite of analytical equipment, a machine shop, welding equipment, hand tools, fork lifts, labs, security services, offices, conferences rooms, a cafeteria, and experienced research personnel.

Syngas cleaning systems used to remove particulate mater and to wet-scrub the syngas with water are provided up-stream of the proposed cryogenic cleaning system.


In the South Coast Air Basin, an existing enclosed flare is used for fuel-gas combustion.


The Ceramatec FT-synthesis shown above skid will be shipped to UCR in 2018 for testing.

Equipment Appendix

Gasification Related Equipment Systems

- 20-HP Variable-speed extrusion-type feeding system
- 10-HP Roots type air-blower
- Ash Removal system
- High-Temperature Granular Filter
- Wet Scrubber
- Enclosed Fare
- Electric Steam Boiler
- Instrument air compressor
- Dedicated Infrared Gas Analyzer
- Temperature Monitoring and Recording System
- Two Pulse-detonation systems
- Oxygen flow control panel
- Propane flow control panel
- Infrared camera
- 350 kW Caterpillar Engine / Generator test engine
- Mobile emission test laboratory
- Cryogenic liquid storage
- Fuel storage facilities
- Laboratories with bench-scale gasification test facilities

Fabrication Equipment

- Refractory casting table with pneumatic-vibration
- Welding and oxy-actylene cutting systems
- Drill presses
- Machine tool lathe
- Power tools
- Storage containers
- Forklift with boom extension

Utilities

- 1,000-Ampere Electrical Service
- Pipeline Natural gas
- Propane Tanks
- Potable Water
- Contaminated Water storage