Energy Research and Development Division

FINAL PROJECT REPORT

Advanced Recycling of MSW

Shockwave Gasification of Refuse Derived Biomass (RDB)

California Energy Commission

Edmund G. Brown Jr., Governor

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PREPARED BY:
Primary Authors:

Donald G. Taylor
Arun SK Raju, Ph.D.

Taylor Energy
P.O. Box 523
Verdugo City, CA 91046
Phone: (714) 832-9526
https://TaylorEnergy.org

Contract Number: EPC-14-045

Prepared for:
California Energy Commission

Prab Sethi

Laurie Hope
Deputy Director
Energy Research and Development Division

Robert P. Oglesby
Executive Director

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Advanced Recycling of MSW is the final report for the project, EPC-14-045, conducted by Taylor Energy. The information from this project contributes to Energy Research and Development Division's EPIC Program. All figures and tables are the work of the authors of this project unless otherwise credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

During the past decade, pulse detonation engines have emerged as a high-priority technology for development of various aerospace propulsion methods. The Taylor Energy shockwave gasification technology uses pulse-detonation to intensify gasification performance. This state-of-the-art propulsion method enhances biomass gasification and fuel-gas reforming. Using societal wastes as the energy feed, Taylor Energy demonstrated an enhanced method of producing renewable energy. The project goal was to design, construct, and start-up a pilot-scale system located at the University of California Riverside with 3-ton/day capacity. The researchers tested the system performance using post-sorted Municipal Solid Waste (MSW) as the renewable energy feed. Advancing this novel gasification technology intended for waste processing and biopower generation helps California achieve near-term goals, converting 30-million tons/year of municipal waste into usable biopower. Using ASPEN modeling to perform the economic analysis, the research team showed that shockwave gasification has up-side potential. Results indicate that fuel-gas production capacity can be increased by 100 percent compared to existing technology for the same total installed cost. The pilot-scale system can operate at 6-tons/day, whereas the initial design was only for half that capacity. As a result of preliminary testing, the Levelized Cost of Power (LCOP) is expected to be reduced by 30 percent to $118/MW when compared to commercial-scale MSW combustion systems that use Rankine cycle steam systems to generate electric power. Subsequent testing and optimization of key subsystems during on-going project development will confirm the benefits and report quantitative results in terms of LCOP. This project development effort fulfills an important California market-need for MSW utilization at community scale.

Keywords: waste gasification, shockwave gasification, renewable power, MSW reforming

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EXECUTIVE SUMMARY

Introduction

In California, waste-haulers dump 30-million tons per year of organic materials into existing landfills -- the equivalent of throwing-away 60-million barrels of oil per year.[1] In the United States, waste-haulers landfill more than 137-million tons per year of Municipal Solid Waste (MSW). Waste-to-energy projects could recover 75-percent of all MSW as Refuse Derived Biomass (RDB). This is a significant source of energy since the per capita disposal rate of refuse derive biomass in the U.S. is 4.4-pounds per person per day, or about 1-ton per person per year.

Currently, California and the U.S. can benefit from the economic use of MSW as a gasification feed, particularly in the 2-MWe to 40-MWe net power output range. Industry has overlooked this size range because the business opportunity is too small for companies the size of General Electric and Shell, while the R&D effort is complex and costly for smaller business entities. There is a real market need to address MSW as an "opportunity feedstock" and to address the equipment size range needed for distributed power generation in California communities. There is also substantial interest worldwide in the development of modular cost-effective waste-to-energy plants; an export opportunity for California. Taylor Energy is developing shockwave-powered gasification technology intended for community scale power generation. The system-cost projection is $3,750/kWh of installed capacity at 300-ton/day scale (10-MWe).

The objective of this project was the design, construction, and start-up testing of the pilot-scale waste-to-energy system shown in **Figure 1,** located at University of California Riverside (UCR).

Figure 1: Taylor Energy's Pilot-scale Gasification Test-Facility at UC Riverside

Photo Credit: Taylor Energy

[1] CalRecycle, State of California, Publication #DRRR 2015-1524.
https://www2.calrecycle.ca.gov/publications/download/1150.

The Taylor Energy gasification technology, currently at TRL 3-4, uses pulse-detonation to intensify gasification performance. The research team is applying state-of-the-art pulse-detonation methods to gasification and reforming. The thermal conversion technology proposed for further research and development is based on Taylor Energy's 30-years of experience in thermo-chemical processing, working to optimize gasification/reforming methods intended to achieve economic viability at community scale.

Project Purpose

Advancing this novel gasification technology intended for waste processing and biopower generation will help California achieve near-term goals by potentially converting a portion of the 30-million tons/year of MSW into useful biopower and other energy products. The novel gasification technology is projected to reduce the Levelized Cost of Power (LCOP) by 30 percent compared to commercial-scale MSW combustion systems that use Rankine steam-cycle systems for electric power generation, thereby addressing the availability of millions of tons of MSW derived fuels that are presently disposed by burial in California landfills.

The California Energy Commission funded Taylor Energy to test the gasification of Refuse Derived Biomass (RDB) recovered from Municipal Solid Waste (MSW). Applying pulse-detonation technology to waste biomass gasification will significantly improve the state-of-the-art relative to existing thermochemical conversion methods. With no moving parts, pressure-gain combustion produces gas momentum in the form of shockwaves that micronize the feed, increasing the reaction rate through both size-reduction and enhanced-mixing, which serves to lower the system-cost for RDB gasification used for distributed power generation.

Taylor Energy has designed the gasification process -- including the internal shape of the reactors -- to efficiently use the characteristics of shockwave-derived momentum. The project has significantly advanced shockwave technology applied to gasification and reforming methods. In addition to clean power, industry will use this technology to convert MSW residues into renewable methane and ethylene/propylene fractions used to make renewable plastics.

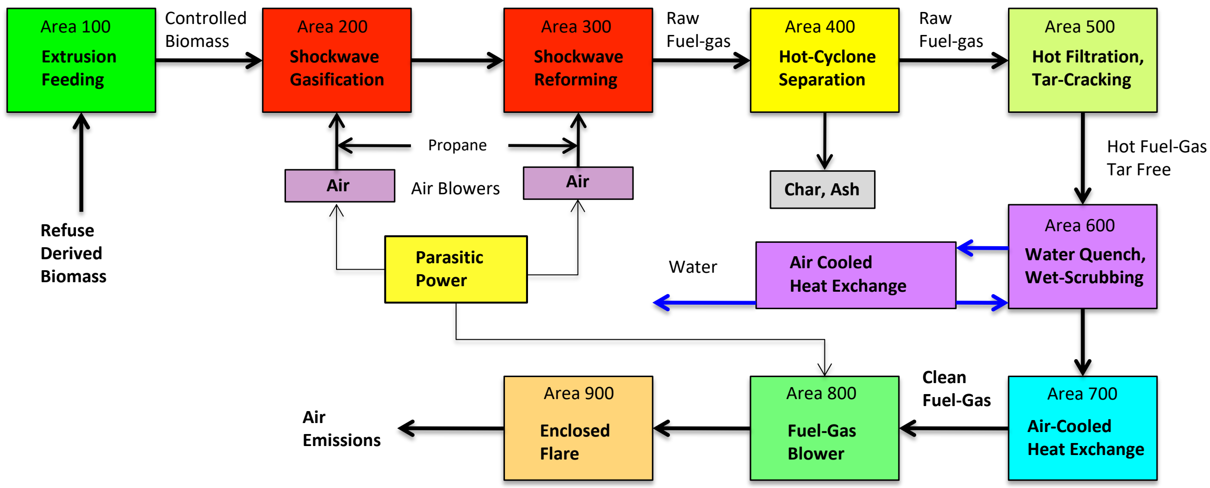
Shockwave-powered gasification shows significant up-side potential to enable system-wide cost reductions; the specific benefits relative to biopower will be quantified in terms of lowering the LCOP. This project will fulfill the market-need for MSW utilization as a sustainable resource at community scale and will thereby lower the ratepayer's cost for renewable power.

Project Approach

Taylor Energy designed and constructed the pilot-scale test facility located at UC Riverside. The gasification process shown in **Figure 2** below, includes three key stages to accomplish thermal chemical conversion. A first-stage Jet-Spouted Bed devolatilizes the feed (Area 200) and a second-stage Venturi-Reformer cracks 97-percent of the tar-vapors into low-molecular weight gases (Area 300).

These two stages convert the feed into gases and into friable materials that are size-reduced, entrained, and elutriated with the fuel-gases. Two cyclone separators remove carbon-char with the mineral ash; char recycle is employed as needed. A third-stage moving-bed tar-cracker removes trace aerosols (Area 500). For testing purposes, fuel-gas cleaning was accomplished using wet-scrubbers (Area 600 & Area 700).

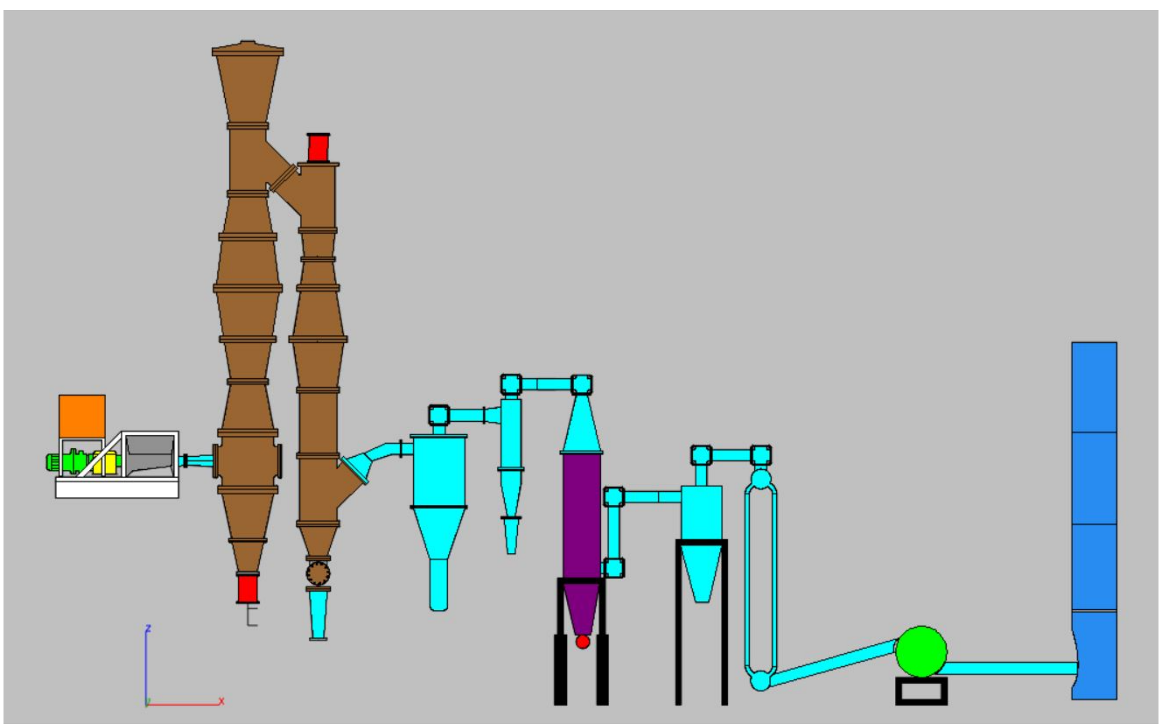
Figure 2: Block Flow Diagram Showing Project Approach



Source: Taylor Energy

Figure 3 below shows the modular construction we used for the gasification reactor and the reformer. Note in **Figure 4** that the reactor spool-sections are bolted together using custom made graphite-gaskets for the seal. This modular construction method served to reduce the overall installation cost.

Figure 3: Taylor Energy's Modular Construction of Gasification/Reforming System at UCR



Source: Taylor Energy

Figure 4: Graphite Gaskets Form the Seal Between Spool-Sections Bolted Together

Photo Credit: Taylor Energy

One of the goals was to reduce costs when compared to existing MSW combustion systems. For example, we minimize the parasitic utility costs by reducing the air input pressure to 3-psig, using pressure-gain combustion (pulse-detonation.) Currently, no other fluid-bed or entrained-flow gasification system can operate with such a low pressure-drop budget. Our process maximizes the system-capacity relative to the reactor-volume.

Three process parameters: *time, temperature,* and *turbulence*, control the gasification rate, along with the *particle size* -- which controls the rate of heat and mass transfer between gases and solids. The ash-fusion temperature is the upper temperature limit for the gasification/reforming processes. Both the gasifier and the reformer operate just below the ash-fusion temperature, at 1150 ˚C, well above the 950 ˚C limit for typical fluidized bed gasifiers. Whereas, increasing turbulence reduces the retention time required, and the retention time is also reduced by rapid size-reduction of the feed using aggressive shockwave-powered ablation methods. Thus, shockwaves are used to increase gas/solids mixing and reduce particle size.

Project Results

The feeding system was designed to input 3-pounds per minute, 180-pounds per hour, nominally at 2-ton/day test facility. Thus far, we have performed proof-of-concept testing, operating the gasification system at equilibrium conditions for approximately 4-hour to 8-hour test periods. It takes about 1-hour to heat and reach thermal equilibrium conditions. Typically, we heated the gasification system using wood shavings (see **Figure-5** below), then switched to feeding the RDB as shown below in **Figure 6**.

Figure 5: RDF Feeding System

Figure 6: Komar Feeder -- Extruding RDB

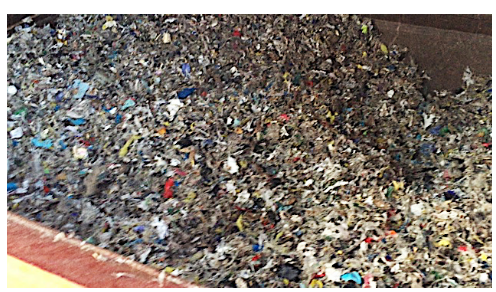


Photo Credits: Taylor Energy

Pulse Deflagration Burner – Initially, we installed and tested pulse-deflagration burners on the bottom of the jet-spouted-bed; see for example, **Figure 7,** which shows a commercially available pulse-jet burner. The jet-spouted bed can be seen during operation in **Figure 8,** looking into a side-port located opposite the feeder. We measured the pulse-deflagration frequency using pressure sensors that showed an average peak pressure rise to 18.7-psia and average pulse-frequency of 21-Hz.

Figure 7: Pulse-deflagration Burner

Figure 8: Jet Spouted Bed During Start-up Testing

Photo Credits: Taylor Energy

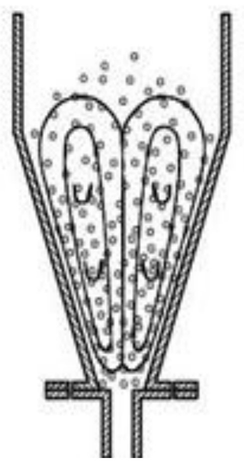
Pulse-Detonation Burner – Next, we performed start-up tests using a pulse-detonation burner designed by Taylor Energy. **Figure 9** below shows the pulse-detonation burner being test-fired at 2.5-Hz, which we conducted before integrating it into the gasification system. The pulse-detonation-burner generates powerful repetitive shockwaves. During the external testing of the detonation-burner we measured the power of compression waves at continuous readings of 110-decibels, 25-yards from the pulse-power source firing at 2.5 detonations per second.

Figure 9: Testing the Pulse-Detonation Burner (Externally)

Photo Credit: Taylor Energy

The interior mechanics of a Jet-Spouted Bed is illustrated in **Figure 10**. In **Figure 11**, the pulse-detonation burner is installed on the bottom of the jet-spouted bed gasification reactor. We operated this burner with excess air; the maximum pulse-detonation frequency was 2.5-Hz.

Figure 10: Jet-Spouted Bed



Source: D. Kunii

Figure 11: Detonation-Burner Firing into Jet Spouted Bed

Photo Credits: Taylor Energy

We measured the performance of the gasification system parameters using the pulse-detonation burner, performing proof-of-concept testing and early-stage development. During initial testing, we adjusted the pulse-detonation burner to achieve optimum firing conditions, while testing different bed materials.

The expanded bed-height was measured by looking into the hot gasification reactor -- at the level of the feed-port -- to look at the height of the fountain created by the expanded particle bed. Fountain heights of 80-inches and 60-inches were observed when operating with ceramic beads with diameters of 3-mm and of 5-mm, respectively. **Figure 12** below shows the ceramic beads that provided the most robust environment for gasification due to the greater number of collisions correlating with more rapid ablation of the feed materials. The steel beads shown in **Figure 13** are indestructible; but because of their higher density the spouting action and the resulting fountain was subdued when compared with ceramic beads.

Figure 12: Ceramic Beads

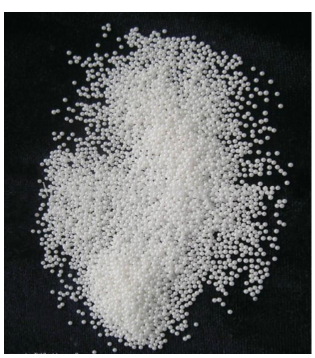


Figure 13: Steel Beads

Photo Credits: Taylor Energy

We performed gasification testing using 3-mm ceramic beads, feeding RDB at 3-lbs/minute, which feed was provided by a waste management company. The outputs were measured as fractions of the total inputs. The feedstock is supplied to the entrained-flow gasifier (employing a primary spouted bed receiver) through an extruder feeder and the gasification process is enhanced through a pulse-detonation burner. The gasifier products are sent to the reformer that also includes a pulse-detonation burner. The product gas stream from the reformer goes through conventional gas clean-up steps including ash/char separation, filtration, and gas cooling.

We used an infrared analyzer to measure four key gases in order to control the process: CO, CO_2, CH_4, and O_2. Tedlar-bags were used to sample and analyze the gas to evaluate trace components and to verify that the gas compositions is suitable for power generation. The fuel-gas composition data is summarized in Chapter 3, Project Results. The energy content of the fuel-gas product was typically 190 to 227 BTU/standard cubic foot, with the CO content ranging from 10 to 22 percent by volume, the H_2 content was 8 to 14 volume-percent; CH4 was typically 4 to 6 volume-percent, and CxHy content was found to be 2 to 5 percent by volume dry-gas.

Technology/Knowledge Transfer/Market Adoption

The technology being developed at pilot-scale is designed for scale-up to single-trains with 1200 ton/day RDB thermal-processing capacity producing 40-MW of net power to the grid. This technology is intended for deployment at community scale and replicated at multiple locations. The knowledge gained from this project is used by the thermochemical conversion community to increase understanding of new conversion pathways, new methods of using shockwave power to intensify thermal-chemical processes.

We intend to establish a demonstration-scale project that generates 1.7 MWe processing about 40-ton/day RDB. The opportunity is technology driven in the sense that the conversion process must be proven at some reasonable scale to gain momentum. Concepts are easily promoted; but in the waste-to-energy business, there have been past failures; technology-success at some modest scale is needed to verify the any advanced gasification concept. A 1.7 MW plant is an economic scale for various venues around the world. Catalina for example has the need for a 40 ton/day waste to energy project. We consider the small-size plants to be semi-commercial endeavors because the economics require some unique constraint to make sense; for example, a small island community imports liquid fuels for power generation, and therefore, already pays a high cost for baseload power.

The commercial module we plan to market is a 427-ton/day plant exporting 10-MWe. For permitting purposes in California, 500-ton/day is the optimum size for early deployments. The value proposition is that MSW can be used economically as a sustainable energy resource. However, as we understand the market, the opportunity is present within certain performance parameters, driven by the ability to guarantee throughput, and adequate return on investment, when operating with reasonable feedstock contracts and modest revenue contracts for the renewable energy products. MSW is a significant source of renewable energy: the per capita disposal rate of refuse derive biomass in the U.S. is 4.4-pounds per person per day, about 1-ton per person per year. In California, waste-haulers dump 30-million tons per year of organic materials into 80 existing landfills. New waste-to-energy projects could utilize 75-percent of all MSW landfilled to generate more than 3,300 MWe. At least 50,000 ton/day RDB is certainly obtainable, controlled by long-term contracts that are dedicated to advanced recycling type energy projects.

Benefits to California

This project will result in the ratepayer benefits of rural and urban economic development, lowered environmental impact, and increased security. Economic benefits are lower electric bills, achieved by lowering the cost of renewable power which makes up a portion of the energy mix. Environmental benefits include decreased impacts from global climate change by using renewable feedstocks instead of fossil fuels. They also include reduced health risks due to reduced landfill operations. Security benefits include reduced reliance on natural gas delivered via interstate pipelines used for power imports compared to using an instate resource.

According to the Black & Veatch screening model used to analyze biomass gasification technology, at 300-dry-ton/day 10-MWe scale, the LCOP would be $118/MWh, based on our process cost projections and operating cost estimates. **Figure 14** shows Taylor Energy's concept for a 427-wet-ton/day waste-to-energy facility using gasification integrated electric power generation.

Figure 14: Proposed Commercial-Scale MSW Receiving & Processing

Source: City of Kona, HI

One measure of the project value is the projected cost-savings when compared to the cost of power generated using existing waste-to-energy conversion methods. The competitive cost for large commercial waste-to-energy power is about $142/MWh in 2018, increasing to about $158/MWh in 2024. Assuming a mean power price of $158/MWh for existing waste-to-energy derived power, the measurable cost savings is estimated to be $40/MWe for every megawatt of power generated using the proposed new shockwave gasification/reforming technology.

Future work includes a subsequent Taylor Energy/UCR project funded by the California Energy Commission to compare several different power generation cycles using forest residues. And then, using an optimum process configuration, accumulate 500-hours of operating data in preparation for a 1.7 MWe demonstration project. We have also requested funding from the USDA to perform a series of tests, converting forest biomass into light-olefins and methane.

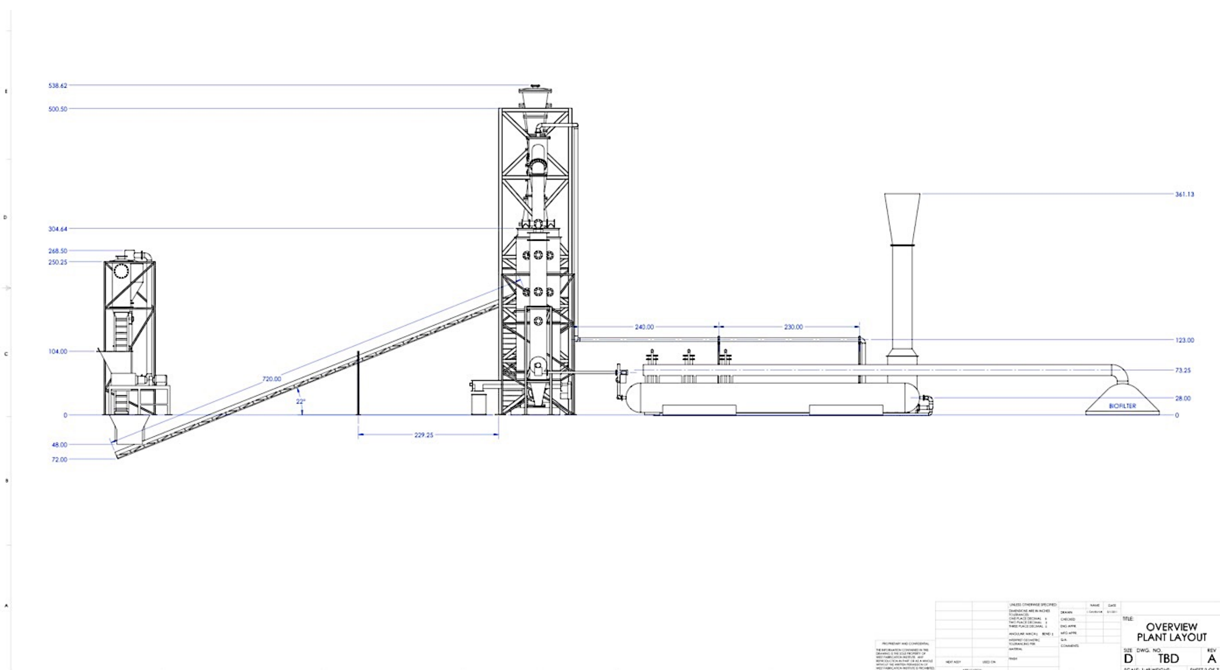
Recommendations

Waste biomass gasification is well known and is efficient, but the cost of sustainable power derived from societal wastes is higher than for power from fossil derived natural gas, for example. In order to generate renewable power from California's abundant municipal waste residues, the thermal gasification and fuel-gas utilization processes must be improved. To enable the economic use of the State's organic waste residues, to build an advanced recycling industry that employing thousands of people, we need advanced waste-to-energy conversion methods that are economical. Breakthroughs are needed that enable techno-economic advances.

However, the business and technology-development risks are significant. The resources and the barriers to develop waste gasification and related synthetic-fuels production technology are too great for most small businesses, and too developmental at this stage for the majors to allocate significant R&D funds. Refinery-scale utilization of residual petrol-carbons is well-known and not considered high-risk; although, the capital investments are large for the refinery-scale embodiments. Production of community scale renewable power made from waste biomass is not being developed aggressively by industry leaders in the fossil fuel and petrochemical industries at this time.

Allocation of Energy Commission funs to the accomplishment of multiple demonstrations-scale waste conversion projects is highly desirable to overcome barriers that otherwise prevent commercialization of waste utilization technologies that will help California achieve multiple environmental, economic, and security goals. **Figure 15** below shows the preliminary design for construction of a modular type 40-ton/day waste gasification system used to generate 1.7 MWe.

Figure 15: RDB Gasification/Reforming System Designed for 40-TPD Demonstration-Scale



Source: Taylor Energy

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CHAPTER 1: Project Justification

Background

In California, waste-haulers dump 30-million tons per year of organic materials into existing landfills -- the equivalent of throwing-away 60-million barrels of oil per year. In the United States, waste-haulers landfill more than 137-million tons per year of Municipal Solid Waste (MSW).[2] Future waste-to-energy projects could utilize 55-percent of all MSW generated yearly. This is a significant source of energy since the per capita disposal rate of refuse derive biomass in the U.S. is 4.4-pounds per person per day, or about 1-ton per person per year.

Currently, California and the U.S. can benefit from the economic use of MSW as a gasification feed, particularly in the 1-MWe to 20-MWe net power output range. Industry has overlooked this size range because the business opportunity is too small for companies the size of General Electric and Shell, while the R&D effort is complex and costly for smaller business entities. There is a real market need to address MSW as an "opportunity feedstock" and to address the equipment size range needed for distributed power generation in California communities. There is also substantial interest worldwide in the development of modular cost-effective waste-to-energy plants; an export opportunity for California bases businesses.

Overview

Taylor Energy is developing a modular type of shockwave-powered gasification technology intended for community scale power generation. The system-cost projection is $3,750/kWh of installed capacity at 300-ton/day scale (10-MWe). The Commission funded Taylor Energy to design, construct, and test a pilot-scale gasification system intended to process refuse derived biomass recovered from Municipal Solid Waste (MSW).

The Taylor Energy gasification technology, currently at TRL 3-4, uses pulse-detonations to intensify the gasification system performance. Applying pulse-detonation technology to waste gasification will improve the state-of-the-art relative to existing thermochemical conversion methods. The technology is based on Taylor Energy's 30-years' experience in thermo-chemical processing, working to optimize gasification/reforming methods for use at community scale.

Agreement Goals

The goals of this agreement are to:

- Validate the technical performance of a two-stage thermal-catalytic gasification process operating with experimental data described in the agreement objectives.
- Verify the economic viability of the integrated waste gasification and reforming process from the project findings as described in the agreement objectives.

This Agreement will result in the ratepayer benefits of greater electricity reliability and lower costs by developing distributed generation capacity that uses a renewable resource otherwise disposed in landfills; 1-ton of MSW contains the energy equivalent of 2-barrels of oil. Assume 30% net conversion to electric power; about 1-ton-MSW is consumed to make 1-MWh of electric

[2] Ibid.

power. The Levelized Cost of Power (LCOP) is estimated to be $118/MWh for 10-MW scale, which results in ratepayer savings of $32/MWh compared to grid supplier power that will likely average $150/MWh through 2024.

This Agreement will lead to technological advancements and breakthroughs that overcome barriers to achieve the State's energy goals by developing a Pulse-Jet-Spouted-Bed integrated with a Draft-tube Reforming system. Preliminary engineering, resulting in equipment costs estimates based on projected mass & energy balances anticipate system cost is <$3750/kWh of installed capacity. Design, construction, and start-up testing will provide necessary research and verification of this breakthrough in waste processing.

Agreement Objectives

The objectives of this Agreement are to:

- Operate the gasification/reforming process continuously for 8-hours, with RDB input of 3-pounds per minute (1.08-mmBTU per hour, based on energy content of 6,000 Btu/lb for RDB), with average fuel-gas output of 0.80-mmBTU/hr, having energy content of 230 BTU/scf, demonstrating 74% net conversion efficiency of feed into fuel-gas.
- Operate the thermal-chemical gasification process with over-all Stoichiometric Ratio (SR) =0.28, using oxygen enriched air to 33%-O2 to achieve carbon conversion >90% as measured by Feedstock /Products/Char analysis.
- Operate pulse-deflagration burner(s) that heat and power both the gasification and the reforming process with frequency >7-Hz using Transient Plasma ignition, firing the pulse burners with excess air.
- Establish the durability of stainless-steel pulse-combustor(s) with no observable failures due to high-temperature and pulse detonation operation during proof-of-concept testing.
- Establish Process Heat & Mass Balance by Semi-empirical Method and Semi-empirical ASPEN process model development.
- Confirm from the project findings that a cost of $3,750 per kWh of installed-capacity is supported, based on a 300-ton/day modular system.
- Confirm from the project findings that the LCOP of $118/MWh, including 10% return on equity, is supported based on a 300-ton/day modular system.
- Estimate Carbon footprint for the process and the products by Life Cycle Analysis through GREET.

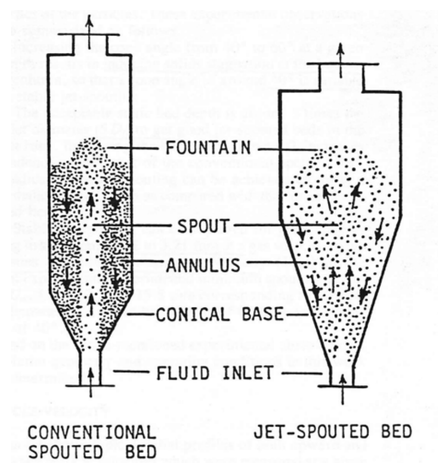
Objective

Our objective was to research and develop thermal-catalytic recycling technology that promises to overcome the technical and economic barriers preventing the use of Municipal Solid Waste (MSW) as an energy resource in California. Our goal was to verify key subsystems for advanced recycling of MSW, producing clean fuel-gas for electric power generation by constructing a pilot-scale process development facility and verify pilot-scale subsystems that would enable the use of MSW as a renewable energy resource, cost-competitive with fossil fuel products by 2020. The pilot-scale facility expanded on proof-of-concept testing we had previously performed at large bench-scale, using the jet-spouted bed gasification reactor, shown below in **Figure 16.** The fluid-bed dynamics of our jet-spouted bed gasification reactor are illustrated and compared to conventional spouted-bed in **Figure 17.**

Figure 16: Proof-of-Concept Site

Photo Credit: Taylor Energy

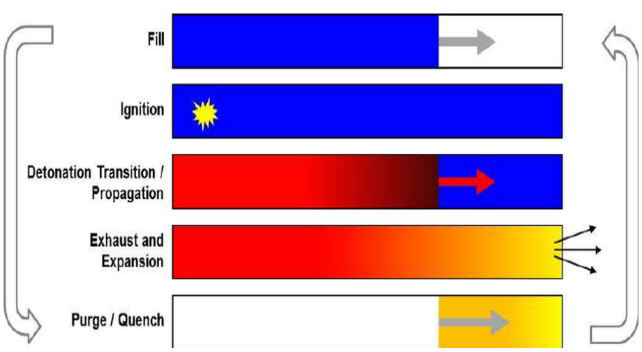
Figure 17: Conventional Bed vs Jet-Spouted Bed



Source: D. Kunni

With an Energy Innovations Small Grant (EISG) we compared a pulse-detonation-burner with a pulse-deflagration-burner. Pulse-detonation burners operate by igniting an air-fuel mixture in a tube as illustrated below in **Figure 18**.

Figure 18: Pulse-Detonation Burner



Source: Researchgate, University of Cincinnati

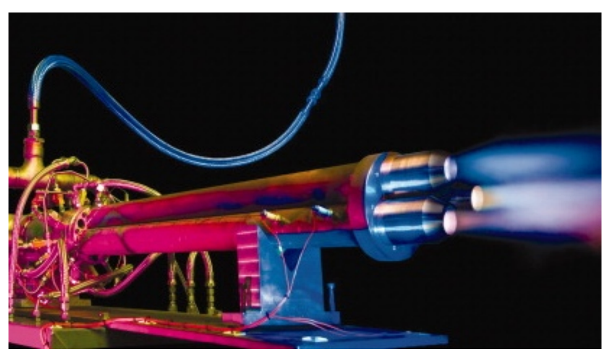
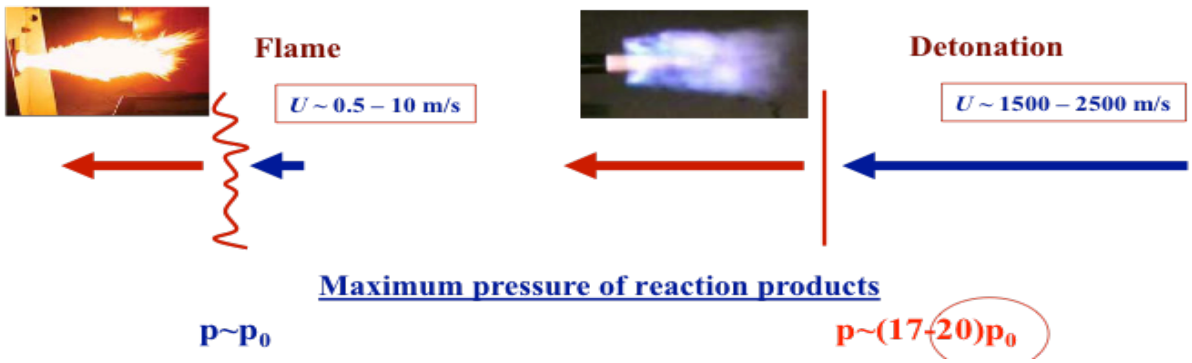


Photo Credit: FlugRevue.de

Figure 19 below shows the flame front velocity of "detonation" compared to "deflagration." The discharge velocity from a pulse-detonation burner is reported to reach 2,000 m/sec, and the pressure-gain can be 20-times the input pressure.

Figure 19: Velocity of "Deflagration" Compared to "Detonation"

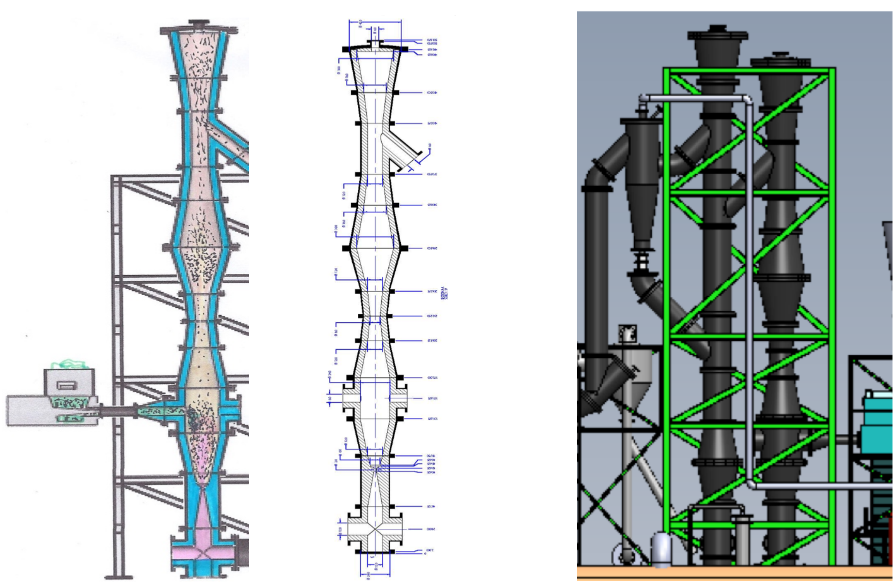


Source: Sergey M. Frolov, ECM-2013, Lund, Sweden

Taylor Energy designed, constructed, and tested the pilot-scale system to prove that ultrasonic-shockwaves generated by pulse-detonation can power a JSB to provide a unique thermal processing environment where heat and mass transfer are increased by supersonic compression waves, creating intense reaction zones where hot-gases mix and react vigorously with carbon-char. Shown below in **Figure 20**, the jet-spouted-bed gasification system offers the following benefits:

- Ability to use gas inputs at high-temperature with extremely high-velocity
- Insensitive to sticky-particles, or molten ash eutectics; no fluidization problems.
- Simple to operate
- Low-cost to construct

Figure 20: Jet-Spouted-Bed Gasification Reactor, 2-D and 3-D Models



Source: Taylor Energy

A second stage tar-reformer also powered by a pulse-detonation-burner enabled conversion of tars and some residual carbon into low-molecular weight gases. The tar-reformer is expected to produce fuel-gases containing seven times less tar compounds compared to plasma-torch technology used by others for second stage tar-reforming. Pulse-detonation-combustors can be operated ultra-lean, so that input of oxygen-rich product gases at 1,800 m/s can be used to enhance turbulence and mixing within the tar-reformer. Effective fuel-gas reforming enables simple gas cleaning methods. Once tars are removed, fine-particles are filtered at medium-temperature; the fuel-gases are cooled and cleaned at ambient temperature.

We tested the ultrasonic process intensification in conjunction with the use of a low-cost mineral catalyst, activated by a small quantity of alkali. The goal was to generate clean fuel-gases with up to 230-Btu/scf, intended for economic production of renewable electric power.

Existing Waste Gasification Technology

Waste-to-energy plants are generating 0.84 Quads per year, or 2.2% of US electric power. As of 2018, 85 plants employ thermal technology to process MSW in 23 US-states.[3]

- 70 waste-to-energy plants use mass-burn technology
- 14 plants burn refuse derived fuel
- 1 pyrolysis/gasification plant
- 85 plants process 97,000 tons of MSW per day
- 85 plants process 26 million tons of MSW per year
- 2,572 megawatt-hours power
- Recycling has peaked at 34.7%
- Only 10.4% of MSW in the USA is used for waste-to-energy.

In California, about 0.9 million tons of MSW were burned (transformed) at 3-permitted MSW mass burn facilities. Provisions in the Public Resources Code, sections 40201 and 41783 allow limited diversion credit for transformation. MSW-powered generating plants typically operate 90-percent of the time, providing base-load electric power.

There are many successful WTE facilities operating in North America and a few failures. Several different technologies are in use and more technologies are in development. In the past, economics for new MSW projects have typically favored the larger facilities that burn 3,000 tons per day. Yet not all communities generate that much MSW or have interest in teaming with neighboring communities to aggregate waste volumes.

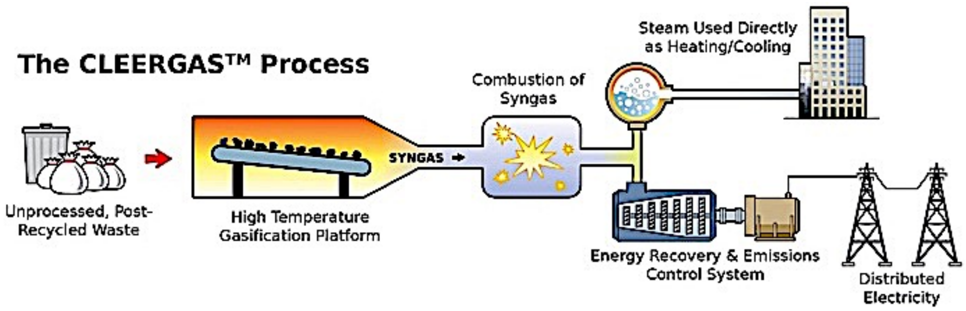
Existing modular facilities do not seem to meet the demand requirements. Smaller facilities with new designs would potentially fill this gap. For example, Covanta has developed a 300-ton/day modular (2-stage) combustion technology -- marketed as “gasification.” The Covanta process uses "staged-combustion," adding combustion-air in two-stages, which they call gasification. However, the power generation cycle uses the heat of combustion for steam power generation. Whereas, a true gasification process generates a fuel-gas product (or a synthesis gas) that is cooled and cleaned prior to use in advanced power generation cycles.

The new Covanta “gasification” technology shown in **Figure 21** below is not a true gasification process as defined by the Gasification Technology Council because the process employs a 2-

[3] American Gas Association, Full-Fuel-Cycle Energy and Emission Factors for Building Energy Consumption- 2018 Update. Jan. 2019. https://www.aga.org/globalassets/research--insights/reports/22433-ffc-final-report-2019-01-14.pdf

stage combustion method followed by a heat-recover-steam-generator used to power a steam turbine.

Figure 21: Covanta Waste Gasification Module



Source: Covanta

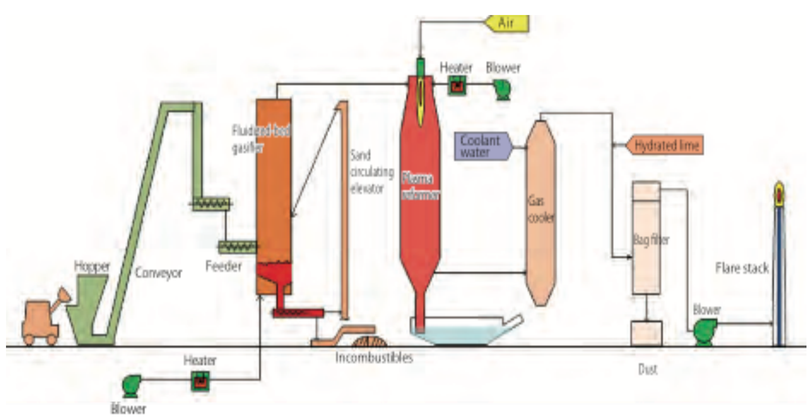
New waste-to-energy (WTE) projects are in the pipeline in several states and provinces, including Florida, Maryland, Puerto Rico, and Ontario, Canada; but it is not easy to locate, permit, and finance, large mass burn facilities. The permitting process is especially arduous for large WTE facilities. Public opposition is often a significant factor; environmental groups often raise questions about large new projects.

Advantages of Modular Technology

Private ownership is more feasible for projects with a lower capital cost, and with a shorter time-line to completion. Air permits are less burdensome, and less time consuming for projects with a lower volume of pollutants, resulting in more favorable modeling. Smaller projects are less likely to attract opposition from neighbors or environmental groups. And smaller projects have less impact on local roads due to truck traffic.

There is substantial interest worldwide in the development of smaller waste-to-energy plants. Smaller plants are designed to process MSW as the sole energy input, potentially generating near-zero residue by employing ash-melting technology. **Figure 22** below shows a modular MSW gasification process that is being developed in France by Kobelco-Eco Solutions, a subsidiary of Kobe Steel. This technology may be intended for future deployment in the USA.

Figure 22: Kobe Steel's Modular MSW Gasification Process



Source: Kobe Steel

New projects are enabled by multiple factors:

- A site that is acceptable to the community -- connected to a vibrant road network
- Landfill available for waste not suitable for the WTE process
- Strong political support
- Ability to raise capital
- Adequate energy revenue (electricity, or renewable fuels)

Gasification Technology – State-of-the-Art

There are about 420 large industrial gasification systems operating in the world today, most using coal, coke, or heavy residues. The scale is 10,000 -- 100,000 ton/day feed input. Community-scale needed for distributed power generation is 300 – 1,200 ton/day, using refuse derived biomass recovered from MSW. [4]

There are many village-scale gasifiers with less than100 kWh capacity. The up-draft or down-draft gasifiers, exemplified by Ankor, Community Power, and others, have demonstrated small-scale systems that operate continuously and provide some benefits. This type of technology is said to scale-up to about 1-MWe; however, only when using uniform (ideal) biomass feed materials. The up-draft & down-draft systems require a uniform feed. For example, during WWII, when “a million” vehicles operated on producer gas, a huge cottage industry was also required to make uniform feed needed to fuel these gasifiers. There certainly are “opportunity” biomass feeds in California, such as almond hulls, rice hulls, and forest residues, that are suitable for up-draft and down-draft type gasification system. Nevertheless, these systems cannot handle garbage unless it is pelletized; and the cost of producing RDF-pellets is considered prohibitive.

Fluid-bed gasification systems (both BFB & CFB types) are applicable to RDB feeds; however, when applied to MSW-derived fuels, the traditional BFB and CFB systems have been costly to build and costly to operate; especially at community scale. Persistent metallurgical issues associated with bubble-caps, and all other alloy-air-distribution hardware that typically cause unplanned outages (due to the cyclic oxidation-reduction of metal at points where oxidizing-air first mixes with feed), which reduces on-line availability to less-than 80 percent.

The dual-fluid-bed being tested by West Biofuels LLC (based on the Guessing DFB design) is technically sound, but the system complexity is too great for application to power generation at the modest scale required for distributed power generation in California. The Guessing DFB technology was derived from refinery technology, used extensively for fluid catalytic cracking, not typically used for production of fuel-gas intended for electric power generation. Likewise, the Battelle/FERCO effort in Burlington, Vermont, based on the DFB designed by the BCL, has also been proven too costly to construct and to operate when applied to medium-scale power generation. According to Taylor, “We studied these issues carefully. Dr. Diazo Kunii, author of the textbook, *Fluidization Engineering,* performed the comparative study for our team. When electric power is the objective, a single fluid-bed, that is air-blown, offers superior performance compared to any type of dual-fluid-bed.”

Figure 23 below shows a PYROX type dual-fluid-bed designed by Kunii & Taylor, built by Taylor Energy for West Biofuels. PYROX is a third example of a dual-fluid-bed gasification system that

[4] The Gasification Industry, Global Syngas Technologies Council. 2018. https://www.globalsyngas.org/resources/the-gasification-industry/

is too costly to deploy for electric power generation.

Figure 23: Pilot-Scale PYROX Dual-Fluid-Bed Gasification System (5-ton/day)

Photo Credits: Taylor Energy

Sierra Energy is developing an O2-slagging system designed specifically to gasify MSW. However, that type of gasifier is “upside-down,” in the sense that exceeding the ash-fusion temperature may be necessary for secondary tar-reforming, but not in the primary stages where drying, pyrolysis, and gasification occur. The oxygen cost is necessarily high because an oxygen fired tar-reforming stage is still required down-stream from the high-temperature primary.

Large-scale coal gasification is well proven, but modular scale waste-gasification still has issues. The knowledge base in biomass gasification has come a long way during the past 25-years. However, little has been done to fundamentally improve on the economics of biomass gasification through process simplification, and through process intensification.

There is a broad gap in the available technology and scientific knowledge required for economic use of MSW as a gasification feed, particularly in the 1-MWe to 20-MWe power output range appropriate for community scale project. This size range is overlooked by industry because the business opportunity is small for large companies the size of General Electric and Shell, while the R&D effort is complex and costly for smaller business entities. There is a real market need to address refuse derived biomass as an “opportunity” feedstock recovered from MSW; and to optimize the economic returns for the plant sizes needed for distributed power generation in California communities.

Economic Benefits

In California, 30-million tons of organic materials are being added to landfills each year; equivalent to disposing 60-million barrels of oil per year in 80 California landfills. The project goal for the system cost is $3,750 per kWh of capacity at 300-ton/day (10-MWe). According to the Black & Veatch screening model developed for biomass gasification, the Levelized Cost of Power (LCOP) would be $118/MWh, based on the project assumptions. One direct measure of the value is the cost savings when compared to grid purchased power. The cost for commercial power in PG&E territory is increasing to about $158/MWh in 2024. The measurable cost savings is estimated to be $40/MWh for every megawatt of power generated using refuse derived feeds.

The resource potential provided to IOU ratepayers – based on 31.6 percent net energy conversion of MSW derived biomass into electric power – will produce 3,300-MWe of renewable power. These projections are presented in **Table 1** below and the potential energy cost saving are shown in **Table 2** below.

Table 1: MSW Feedstock Available & Potential Distributer Power

Mass	30-million ton/yr MSW / 8,760 hrs/yr = 3,424 ton/hr MSW 3,424 ton/hr x 75% recovery as RDB = 2,568 ton/hr RDB 2,568 ton/hr RDB x 14 mmBTU/ton = 35,958 mmBTU/hr
Energy Content	35,960 mmBtu/hr (10,539 MWth)
Distributed Power	10,359 MWth x 0.316 net to power = 3,330 MWe

Source: Taylor Energy

Table 2: Measurable Value -- Potential Energy Cost Savings

3,330 MWh x $40/MWh x 8760 h/y x 0.90 availability	= $ 1.05 Billion per year

Source: Taylor Energy

We estimated the costs for design, engineering, construction, and installation, with +/- 15 percent level of confidence for a commercial scale system, expressed as the levelized cost of power. We expect to confirm from the project findings that the production cost of renewable power using RDB as the feed will provide cost savings benefits of $40/MWh.

The research team designed, constructed and completed start-up tests of the pilot-scale system to develop this breakthrough MSW thermal recycling method. The pilot-scale system brings together key subsystems for integrated testing that are needed to accomplish this overall improvement. Waste gasification engineering fundamentals are evaluated relative to the MSW feedstock basis.

Technical Advisory Committee

A Technical Advisory Committee meeting was held on January 23, 2017. The participants are listed below:

- Mr. Bob Bradley, Biomass Power Plant Developer
- Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy
- Dr. Sam Young, Retired Naval Captain
- Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering
- Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology

Meeting comments and the subsequent discussion are listed below:

Mr. Bob Bradley, Business Man, Biomass Power Plant Development

Data should be in a form that is comprehensible to the non-scientist; simple graphic output images. He would we like to know the permitting constraints; the permit values for emissions for the Imperial Valley? My response: yes.

The 160-acre site owned by his company, ML Energy, located in the Imperial County, is permitted for thermal processing of biomass and refuse derived biomass. A natural gas pipeline is at the foot of the property; transformers and power connections exist to export 30-MWe of power to the grid.

Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy

Concern about any waste water treatment issues; organics in the waste water.

My response: Nitrogen compound sin the feed form ammonia NH3 during gasification, which reacts with HCl (also formed during gasification), forming ammonium chloride that precipitates as a salt in the final water scrubbing system. However, for successful operation, heavy organic fractions must be removed from the fuel-gas up-stream from the aqueous scrubbing system to preclude a water treatment issue. The Reformer and High-Temperature-Granular-Filter are intended to remove heavy organics from the products gases by thermal cracking. A favorable market response can be expected ("I would be excited…") if pulse-jet burner is "as good as" a plasma burner – without the high initial cost and the high operating cost.

Dr. Sam Young, Retired Naval Captain

Requested information about the schedule; and about the environmental performance. My response: The testing will be completed by the end of June and the draft -reports will be submitted by the end of the year. Environmental issues will certainly need to be addressed thoroughly during demonstration scale operation, running extended test campaign. After this program, next step is to achieve 500 hours of operation, in preparation for demonstration scale.

Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering

Discussed the ASPEN modeling and analytical work that will be performed as project deliverables.

Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology

Requested information about scale-up program; we responded with information about the CEC's demonstration programs.

Appendix D, Technical Advisory Committee Documents, includes the notifications, and invitations.

CHAPTER 2: Project Approach

Introduction

This chapter discusses the design, construction, and start-up-testing of a pilot-scale waste biomass gasification system being developed for community scale biopower generation. In addition, subsystem development goals included comparing operation of a *pulse-deflagration burner* with a *pulse-detonation burner*. An iterative hardware development approach was used; multiple prototypes were built and tested in sequence, rather quickly. For example, prototype pulse-burners were constructed using carbon-steel, then stainless steel, and finally cast-refractory embodiments were selected for integration and testing with the Jet Spouted Bed.

Pilot-Scale System Design and Installation Plan

Introduction -- The syngas process being developed by Taylor Energy is designed to handle difficult waste materials, including Municipal Solid Waste (MSW) that has been recovered as Refuse Derived Biomass (RDB-fluff). RDB-fluff is the combustible fractions within MSW that are recovered by shredding and size reducing MSW, then using air classification and screening to separate the light fractions that include 90 percent of useful energy content found in MSW.

The Taylor Syngas Process integrates several novel subsystems to accomplish economic conversion of RDB-fluff into clean fuel-gases suitable for electricity generation. The system employs an atmospheric-pressure gasification reactor designed to convert refuse derived biomass into low-molecular weight gases using partial oxidation methodology, also known as autothermal gasification.

The process consists of feeding RDB-fluff into a first stage autothermal gasification reactor using an extrusion process, forming an air-tight plug that prevents air infiltration. RDB-fluff is gasified in a robust jet spouted bed type of fluidized bed that is powered by a pulse detonation burner that imparts both heat and momentum to the input gases. The input gas power is used to comminute the feed materials through ablation within the first-stage JSB, and to increase the thermal chemical reaction rates at the molecular level my increasing the gas-solids mixing rate. A secondary tar-reforming stage is used to crack hydrocarbons and convert carbon-char into fuel gases suitable for electric power generation (after gas clean-up.) A detailed description of the process is included in subsequent sections; the completed pilot-scale gasification/reforming system is shown below in **Figure 24.**

Figure 24: Waste/Biomass Gasification Test Facility, UC Riverside

Photo Credit: Taylor Energy

System Operation Overview

The system is operated using three-psig blower-air for partial oxidation. A future program contemplates the use of steam/oxygen as the oxidant for production of synthesis gases intended for integration with a 25-scfm renewable methane synthesis process.

The current program produces low-BTU fuel-gases that are flared on site. RDB design input is 3-pounds per minute (1.08-mmBTU per hour, based on energy content of 6,000 Btu/lb for RDB), with average fuel-gas output of 0.80-mmBTU/hr, having energy content up to 230 BTU/scf, demonstrating 74 percent net conversion efficiency of feed into fuel-gas. Air emissions are discussed in detail in subsequent sections.

No hazardous liquids or solids are generated. Acid gases are 'self-neutralized" within the process; for example, ammonia formed within the process reacts with hydrogen chloride, also formed within the process; the result is the formation of ammonium chloride, a neutral salt. Similarly, heavy metals react with hydrogen sulfide to form insoluble metal sulfides. For example, trace amounts of lead typically report to the ash as lead(ll) sulfide, PbS, also known as the mineral galena, which is nearly insoluble in water and dilute acid.

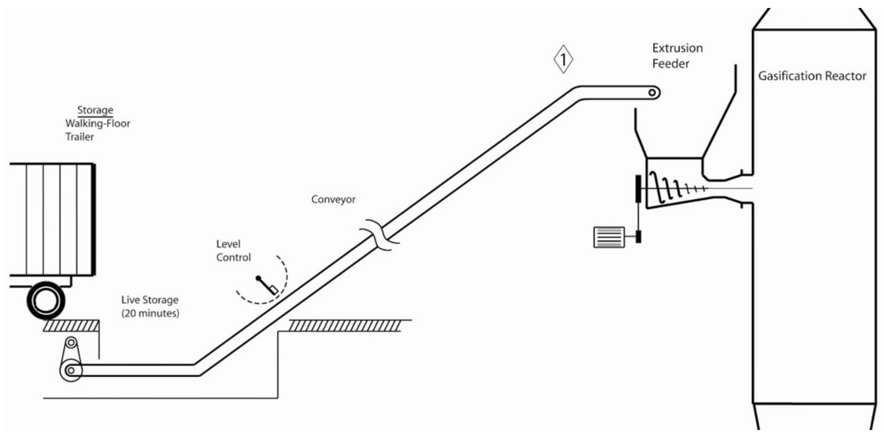
The program objective was to quantify the system inputs and outputs; to develop a reliable mass & energy balance; and to identify any operating difficulties that would prevent commercialization of the technology at large-scale. For example, the program sought to identify erosion, corrosion, or deposition problems that can be detected during short-term operational testing; deposition of sticky solids is a particularly worrisome problem that shows right away. An endurance test-campaign was not proposed at this time. The current test program culminated in two (2) 8-hour continuous runs that established equilibrium conditions for the process.

System Design -- How the system works

Feeding RDF into the Gasification Reactor

A commercial-scale feeding system is shown in **Figure 25** below; RDF-fluff is conveyed by belt-conveyor (@35-degrees from the horizon) into a Komar type extrusion-auger feeder, located well above grade. The pilot-scale system uses a simplified version of a commercial feeding system, using the Komar feeder, but not the belt.

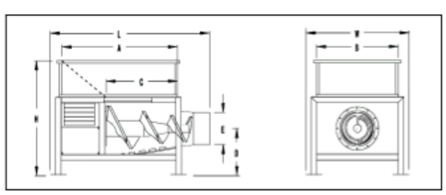
Figure 25: RDB Commercial Feeding System



Source: Taylor Energy

The Komar extrusion-feeder is a high-torque augar-feeder that forces RDF-fluff into the gasification reactor, forming a feed-plug that seals the gasification reactor from ambient-air infiltration. The Komar extrusion-feeder shown in **Figure 26** below is effective for feeding RDF-fluff into an atmospheric pressure gasification reactor; however, this type of feeder does not work well with feeds that do not form an air-tight plug when compressed. The RDF plug, formed by the extrusion-auger feeder, allows the escape of some fuel-gas from time to time, and the feeder includes a containment hood under induced-draft to capture any “smoke.” A fire suppression system that directs CO_2 into the feeder is also provided. Feeding RDF-fluff is simplified by using the extrusion-auger feeder. For large capacity commercial systems, two or three extrusion-feeders would be located around the periphery of the reactor.

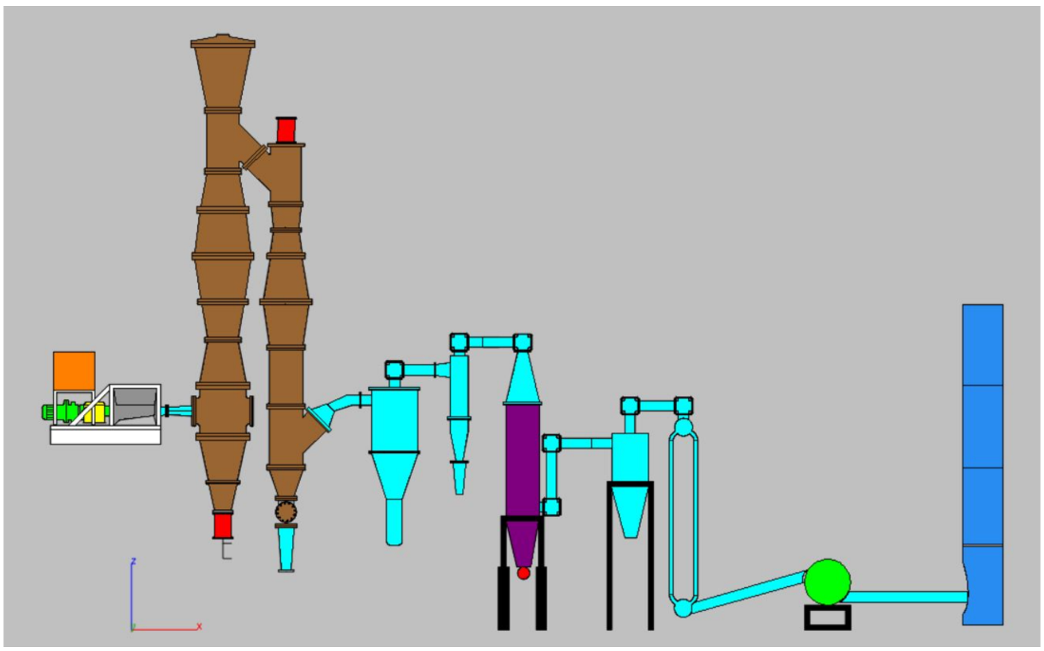
Figure 26: Komar Extrusion-Feeder, 20 HP gear drive



Source: Komar

Gasification Process -- The fundamental engineering approach was to design the process for time, temperature, and turbulence requirements within the gasification reactor and within the reformer. Autothermal gasification chemistry was employed to drive the process; 25-28 percent of the energy in the feed was combusted within the process to generate heat and products of combustion. The heat thus released was sufficient to crack or otherwise reform the remaining organic compounds into low molecular weight gases, carbon-char, and organic tar-vapors that are typically 5-wt percent of the products. The new technology shown in **Figure 27** focuses on the internal operation of the gasification reactor and improves conversion of tar fractions into low-molecular weight fuel-gases.

Figure 27: Existing Gasification Test Facility



Source: Taylor Energy

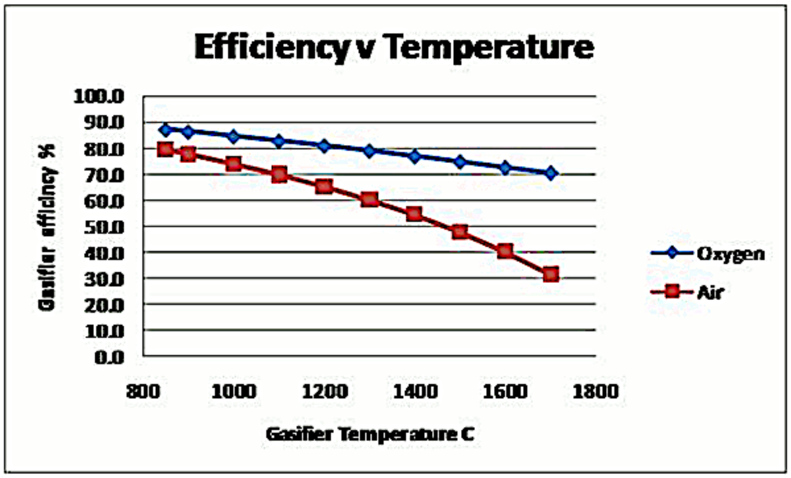
Looking at the over-all stoichiometry, the thermal-chemical process operates with a Stoichiometric Ratio (S.R.) of 0.28, using oxygen enriched air to 33 percent oxygen to achieve carbon conversion less than 90 percent as measured by feedstock/products/char analysis.

High-temperature operation is favored

High-temperature favors equilibrium in the direction of low-molecular weight gases. Therefore, the subject gasification system operates better at higher-temperature, producing more syngas and fewer tar compounds; however, with significant limits: The trade-off is that higher operating temperature results in lower efficiency. Although, the efficiency decrease due to heat-loss is hidden because much un-reacted carbon is present (about 5-15 percent of the energy input can appear as carbon-char when gasification is accomplished at 750 C).

Therefore, operating at higher temperature results in greater carbon conversion to carbon monoxide (CO, fuel-gas), and the negative effect of higher operating temperature is less noticeable. Increasing the operating temperature begins to improve net conversion efficiency (by causing more carbon to react to form more syngas), but ultimately all factors being equal, employing higher temperature is less efficient – primarily because more fuel is consumed to generate the extra heat -- and partly because the heat loss is greater. See **Figure 28** below, which plots the gasification efficiency verses the operating temperature.

Figure 28: Gasification Efficiency versus Temperature



Source: Air Products

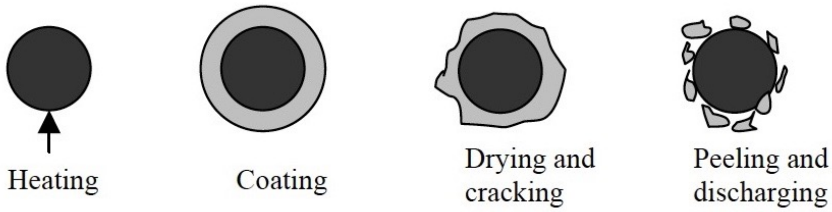
Higher operating temperature also results in more difficult constraints on the physical hardware used to construct the gasification reactor (especially refractory, steel, etc.). For example, molten-bath type gasification systems tend to be expensive to construct due to the refractory cost.

For fluid-bed systems, the greatest constraint on maximum high-temperature operation is that above a certain point, ash-fusion becomes the limitation. During fluid-bed operation, the formation of sticky-ashes (eutectics) can result in bed agglomeration that "freezes" the bed and shuts down the system. On the other hand, deposition of sticky ash particles in the discharge duct exiting the gasification reactor does not shutdown the process instantly but will increase system backpressure until shutdown is inevitable.

Kinetics are primarily related to particle size – In this case, process kinetics are primarily related to the particle size of the waste feed because gasification reactions are (mostly) all rapid, but are constrained by heat and mass transfer limitations, both of which are a function of particle size. Therefore, the subject gasification reactor operates more efficiently with small particles.

The reaction between gases and solids occurs at the surface of the particle and work their way into the center as shown in **Figure 29** below. That is, the rate of heat and mass transfer continue to increase when the outside of the particle is ablated to allow the inside of the particle to be heated, and by concurrently exposing more of the particle surface to reactive gases. Size-reduction of the feedstock is intended to improve the kinetics by improving the rate of heat and mass transfer. Feedstock size reduction is essential.

Figure 29: Particle Ablations increases the rate of thermal chemical reactivity



Source: Marzouk Benali and Tadeusz Kudra, CANMET-Energy Diversification Research Lab

Gasification Chemistry -- The thermal chemistry is mostly fixed by the feedstock composition, the moisture content, and the stoichiometry of the process, which sets the operating temperature. The objective is to react the residual carbon-char (formed in sequence, following devolatilization and gasification) with oxygen that is input as superheated air.

The thermal chemistry can be improved by adding a gasification catalyst. RDF-fluff includes ash components that contribute catalytic properties to the process. Carbon does not begin to react with H_2O vapor until about 850 C without a catalyst present. The moisture content in RDF-fluff is sufficient to provide the H_2O needed to react with carbon; addition of steam is usually unnecessary, and drying the feed excessively is usually undesirable.

The configuration of the gasification reactor is designed to circulate carbon-char into a high-temperature zone at the base of the reactor, where superheated air mixes instantaneously with carbon-char and some fraction of the feedstock, creating carbon-rich stoichiometry. No flame-front is established, nor maintained in the gasification reactor. Carbon reacts with three oxidizing gases: O_2, CO_2, and H_2O.

Oxygen (present in the air input) is the most highly oxidizing of these three gases; however, in a well-designed gasification reactor, CO_2 and H_2O are almost as likely to react with carbon, as is oxygen. By the end of the process, not all the carbon is consumed, and not all the CO_2 and H_2O are reacted with carbon. However, the objective when trying to improve the centuries old gasification process is to move in the direction of 100% carbon utilization through greater reactivity with both CO_2 and H_2O.

Gasification Reactor—Configuration Accomplishes Methodology

The gasification reactor was designed specifically to implement the desired gasification methodology. The construction is of carbon steel, lined with castable cement refractory.

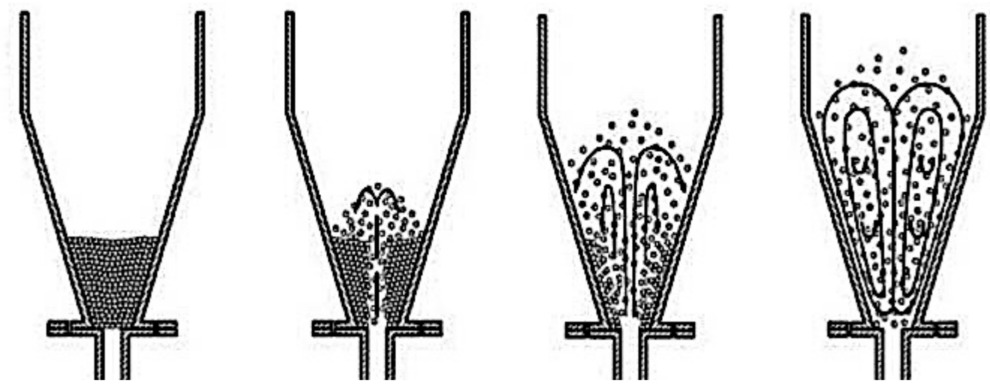
Jet-Spouted Bed (JSB)

A typical circulating fluid bed (CFB), used successfully for RDF gasification, provides high rates of heat and mass transfer. The JSB is a type of fluid-bed reactor used commercially for coal gasification, drying sticky materials, coating solids with powders or liquids, and for drying materials that are impossible to fluidize using any other means of fluidization. The JSB shown in **Figure 30** below has been tested extensively for thermal processing applications and particularly used for gasification of coal and other carbonaceous feedstocks. However, the JSB has not received much attention for commercial applications and is under-utilized, considering the benefits when compared to traditional CFB and BFB gasification technology.

The primary benefits of the jet-spouted-bed applied to RDB-gasification are the following:

- Least sensitive to high-temperature fluidization problems
- Less operation complexity
- Lower cost to construct
- Rapid ablation of the feed material (size reduction by comminution of the feed)

Figure 30: Jet-Spouted-Bed Circulation Patterns

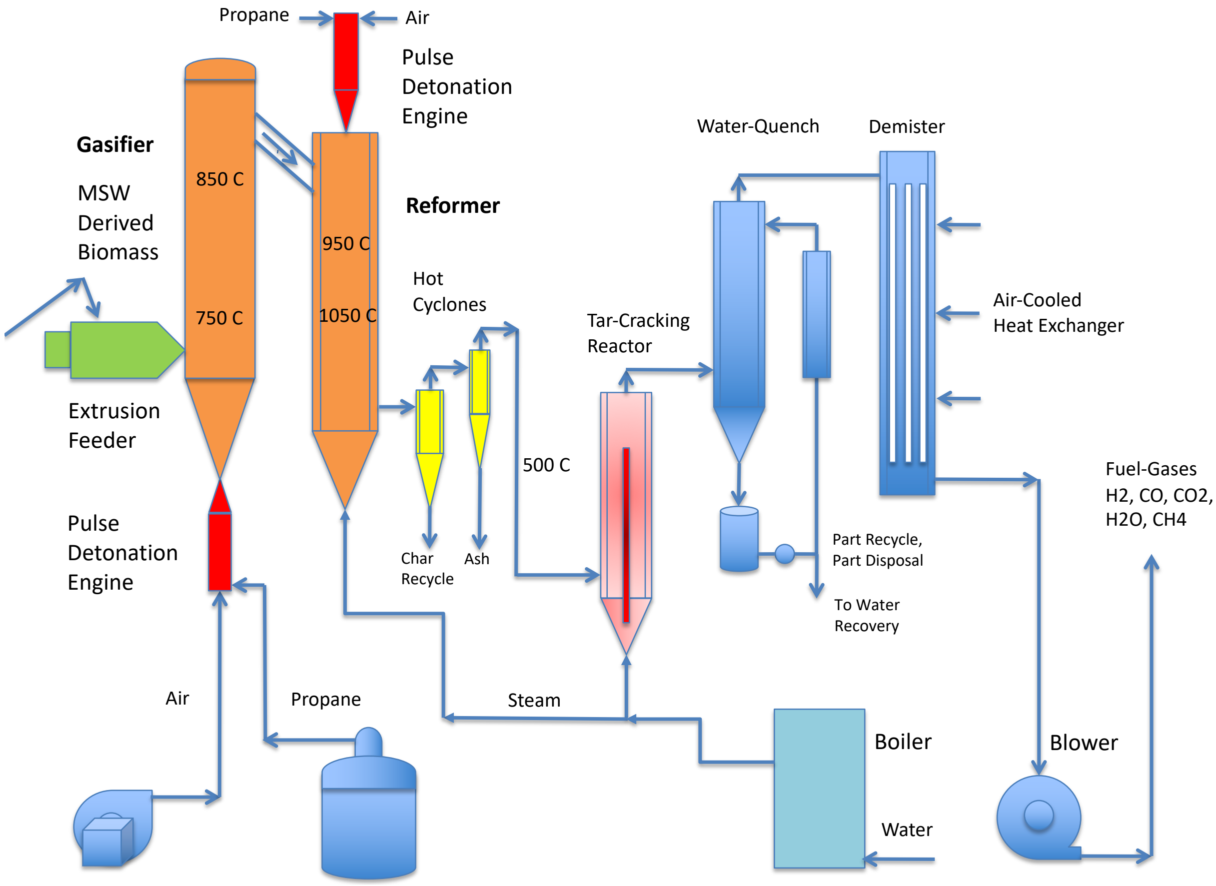


Source: D. Kunni

The JSB is a type of fluidization regime with operating properties that are most favorable for RDB-fluff gasification, which contains difficult materials that are not gasified quickly in a typical BFB or CFB -- because the size of the waste material prevents heat and mass transfer. Employing the JSB for gasification provides a unique thermal processing environment where heat and mass transfer are enhanced by the rapid size-reduction of the feedstock. The supersonic shockwaves used for fluidization enter the bottom of the (inverted) conical reactor at a velocity greater than 1,000 feet per second.

In the JSB, the pressure-drop that is typically used to enable uniform distribution of input gases (through a CFB type gas distributor) is recovered as momentum, in the form of high-velocity gases which micronize the RDB feedstock. An analogy would be the placement of a superheated sandblasting nozzle in the bottom of a conical fluid-bed gasification reactor. The result is an increase in the gasification rate compared to a typical CFB. Large materials (contained within the feedstock) are held in the thermal-comminution zone, where they are continuously milled into fine-particles; whereas, the fine-particles are quickly elutriated, flowing out with the product gases, entering the reformer for further up-grading. A summary process flow diagram is show below in **Figure 31.** Note that an air/propane mixture is provided to power the pulse detonation burners.

Figure 31: Gasification/Reforming System -- Process Flow Diagram



Source: Taylor Energy

Control of the Gasification Process

Control of the process is accomplished by adjusting both the feed input and the air input. For fine adjustments, the air-input is held constant and the feed input is varied slightly. Small adjustments to the feed input alter the direction of temperature change. The reactor temperature is monitored and recorded at 12-key locations; alarms warn the operator when temperature excursions occur. The control functions are implemented by using a computer-controlled output signal (4-20 milliamp) that adjusts a variable frequency drive, used to control all the major rotating equipment.

It is essential that the RDB feed input continue uninterrupted during gasification, because loss of feed input causes the reactor temperature to increase. This is because the feed input is used to cool the gasification reactor (through endothermic reactions), and loss of feed causes the reactor to heat up quickly -- opposite the effect during combustion; halting the feed to a combustion process lowers the temperature. Therefore, an important control function for any gasification system is to employ robust continuous feeding equipment.

The feedstock preparation (RDB-fluff) is also important to insure consistent fuel properties for thermal gasification, and consistent moisture being the most important single property. The control system adjusts the feed input rate primarily to adjust the variable moisture content in the feed, which impacts the reactor temperature. Higher moisture content cools the reactor.

Reforming -- Similar to the leading CFB gasification process, the Taylor Syngas Process employs a tar-cracking reactor that closely follows the gasification reactor. However, in the Taylor Process, the tar-cracking reactor is more closely integrated with the gasification reactor—there is no cyclone separating the two reactors. This is possible because the solids processed in the JSB gasification reactor are circulated internally using the high-velocity jet-spouted-bed; not circulated externally, as is done when employing a typical CFB design. The circulating structure (in the upper portion of the gasifier) is formed by a low-velocity/high-velocity section, where the superficial velocity is less than 40-feet per second, and the pressure drop is less-than 6" water column vacuum

Partial Cracking in the Gasification Reactor --The top portion of the gasification reactor is constructed to establish an internal circulation zone where carbonaceous solids are held-up and circulated to increase the retention-time. Tar products (that result from gasification in the lower portion of the reactor) are also circulated along with the carbon-char to provide the conditions for polyaromatic hydrocarbons to crack into lower molecular weight organic compounds. In the top portion of the gasification reactor, some of the heavier hydrocarbons are cracked into benzene, toluene, and xylene (BTX) and carbon char.

Tar-Reformer -- To be effective, the tar cracking process must be carried to completion. Tar content is routinely reduced to less-than 5-wt% of the syngas product. The Taylor Syngas Process anticipates cracking the final 5%-tar fraction in a catalytic reactor composed of a down-leg that operates as a reformer. Calcined dolomite is used as a catalyst for destruction of tar in the gasification of waste residues at high temperature.

Dolomite is an anhydrous carbonate mineral composed of calcium magnesium carbonate, ideally $CaMg(CO_3)_2$. Using dolomite as a catalyst, the tars are sufficiently cracked at about 950 C, and if necessary, the down-leg reformer can operate up to 1,100 C. Dolomite is typically used as the cracking catalyst because it is low-cost and plentiful and serves to capture sulfur with the ash as calcium sulfide. Other minerals, including potassium, iron, and calcium, are active catalysts for carbon gasification and have a favorable impact by minimizing the residual carbon-char in the ash. The high-temperature tar-reformer provides the environment to increase the carbon conversion, particularly by including alkali salts; potassium is especially effective at catalyzing carbon gasification.

Syngas Cooling -- After the tar has been converted by thermal-catalytic-cracking at 950-1100 C, the syngas can be cooled using steam and/or atomized water injection without experiencing excessive fouling due to deposition of stick tar-char particles.

Gas Suction, Gas Compression & Gas Storage -- Gas suction is used to keep the gasification reactor's internal pressure near atmospheric. The gas-flow volume created during gasification tends to fluctuate highly because syngas is produced in large puffs. It is necessary to use a Phase-1 centrifugal blower that provides constant suction with variable-flow, thereby providing relatively constant pressure in the gasification reactor even though the gas-flow is fluctuating.

Standard Operating Procedure

Air Input -- The pulse-detonation blower-air is powered by a variable frequency drive; the air-input to the system is controlled by adjusting the RPM of the blower drive motor. Typically, the blower will be operated at 90 percent capacity -- 80-scfm.

Air-fuel Ignition -- The blower-air input is super-heated using a small amount of propane that is combusted inline using pulse detonation burners, employing lean combustion, resulting in air pre-heat to an average temperature of about 950 C. The instantaneous temperature of the pulse-detonations has not been measured yet. A spark-ignition provides a 20-kV spark. The ignition firing frequency is adjustable from 1-10 Hz.

Establish near-stoichiometric combustion feeding biomass -- Propane input is controlled by a regulator that modulates the pressure. Typically, the pulse-detonation-burners would be initially fired using 14-psig gas pressure, then turned back to about 12-psig for continuous operation. With the pulse-detonation-burners operating in stable lean-fire mode, the biomass feed input is commenced at a rate that results in near-stoichiometric combustion; with S.R.=1, the reactor is heated to operating temperature rather quickly; typically, within 60-minutes.

Initiate Gasification by increasing feed input -- When the base on the reactor reaches 850 C, the feed rate is increased to four times the feed rate used for combustion. For example, start-up would be accomplished feeding one-half to one pound per minute for biomass combustion; then increased up to two to three pounds per minute for gasification service.

Continuous operation -- Typically, the air input rate is held constant, while the feed input is modified to increase or decrease the reactor temperature. Increasing the feed results in lowering the reactor temperature; reducing the feed results in increasing the reactor temperature.

Fuel-gas products -- The low-molecular weight fuel-gases are directed to the emergency flare or to the process gas clean-up train. Typically, during operation, some portion of the fuel gases will be flared during start-up and shutdown; the fuel-gases not pulled through the gas scrubbing train are directed to the flare station.

Air Emissions – Typically, an operating sequence would not last longer than about eight hours because the reactor heats up quickly, and likewise the shutdown sequence is rapid. The net CO_2 emissions from propane combustion will impact the over-all CO_2 emissions for the combined CE-CERT/Bourns facility. The emergency flare employs a pilot flame, which consumes about 10,000 BTU/hr, resulting in an additional emissions source equal to one-half pound per hour, or two pounds of propane consumption during each four-hour operating session. The feedstock is CO_2 neutral. The maximum feedstock input for the gasification reactor is three pounds per minute, equal to 180 pounds per hour; about 1-mmBTU/hr.

Standard Shutdown Procedure -- Turning off both the propane and the biomass feed commences the system shutdown, while monitoring the reactor temperature; the temperature will rise initially when the feed input to the gasifier is halted. The air is allowed to remain "on" during the standard shut-down procedure, allowing time for the biomass (fuel) inventory to be depleted.

Emergency Shutdown -- The system can be shut-down immediately by turning off the main electrical power at the local panel, or at the main electrical panel; turning off the power serves to shut-down all inputs, including propane, air, and biomass. Likewise, an unplanned power outage will safely shut down the system. Depending on the amount of biomass fuel inventory in the gasification reactor, the system will continue to produce "smoke" while it remains hot; the smoke is directed to the flare stack, where the smoke will dissipate harmlessly.

Hazardous Materials -- No hazardous materials are generated during operation of the gasification system. The carbonaceous ash is non-toxic. No liquids are collected or recovered.

Fabrication & Construction of Pilot-Scale System

Introduction -- The syngas process being developed by Taylor Energy is designed to handle difficult waste materials, including municipal solid waste (MSW) that has been recovered as refuse derived biomass (RDB-fluff.) RDB-fluff is the combustible fractions within MSW that are recovered by shredding and size reducing MSW, then using air classification and screening to separate the light fractions that include 90 percent of useful energy content found in MSW.

The Taylor syngas process integrates several novel subsystems to accomplish economic conversion of RDB-fluff into clean fuel-gases suitable for electric power generation. The proposed system will employ an atmospheric-pressure gasification reactor designed to convert refuse derived biomass into low-molecular weight gases using partial oxidation methodology, also known as autothermal gasification. The gasification reactor and tar-reformer are shown in **Figure 32** below.

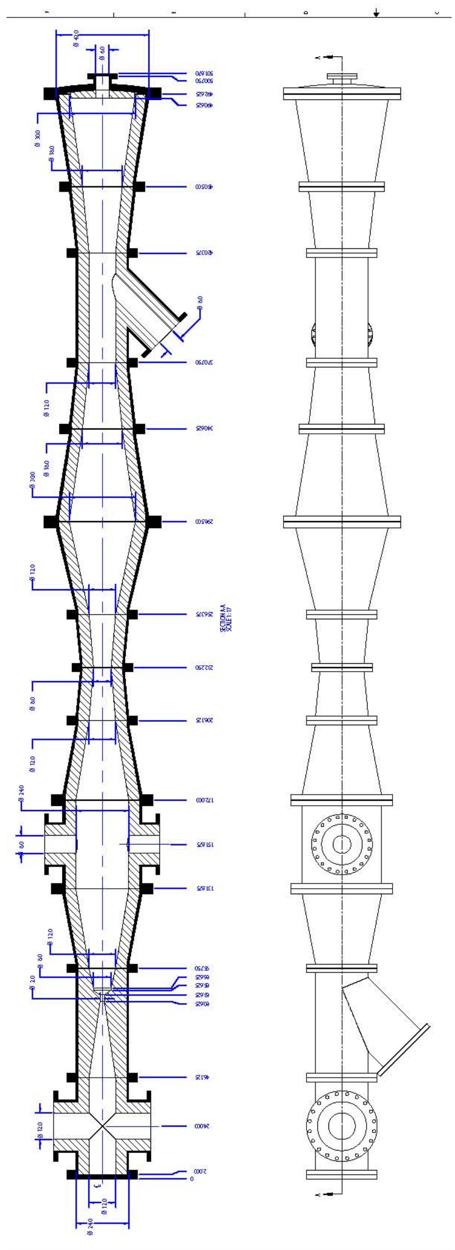
Figure 32: Gasifier (right), Tar-Reformer (left)

Photo Credit: Taylor Energy

The process consists of feeding RDB-fluff into a first stage autothermal gasification reactor using an extrusion process, forming an air-tight plug that prevents air infiltration. RDB-fluff is gasified in a robust jet spouted bed (JSB) type of fluidized bed that is powered by a pulse detonation burner that imparts both heat and momentum to the input gases. The input gas power is used to comminute the feed materials through ablation within the first stage JSB, and to increase the thermal chemical reaction rates at the molecular level by increasing the gas-solids mixing rate. A secondary tar-reforming stage, employing an "entrained flow" reactor in a down-leg configuration, is used to crack tars and convert carbon-char into fuel gases suitable for electric power generation after gas clean-up.

The Fabrication & Construction Report summarizes pertinent elements of the engineering, design, construction, and fabrication relative to the gasification and reforming systems. The gasification reactor is shown below in **Figure 33**. Each section of the reactor has been drawn separately with details sufficient for fabrication. The flanged sections are cast from graphitic ductile iron that is well suited for high-temperature processing needs.

Figure 33: Jet-Spouted Gasification Reactor, 2-D Solids-Works Drawing



Source: Taylor Energy

Flanged pipe sections provided by US Pipe shown below in **Figure 34** are fastened together to form both the thermo-catalytic gasification reactor and the POx reformer (not shown).

Figure 34: Carbon-steel "spool sections"

Photo Credit: Taylor Energy

Refractory -- The reactor sections are lined with refractory; cast using five inches to six inches thick layers of refractory on all the reactor internals, employing two layers: one, an inner insulating refractor lining, and two, a hard-face lining that contains the process. An alumina/silica refractory formula was tested for gasification service and found suitable, and even more stable compared to a high-purity alumina formula.

Refractory was costly to purchase and install; the refractory lining thickness was minimized to reduce costs during pilot-scale testing; heat-loss is a concern because dense refractor is not insulating, but much high-density material is needed to provide a strong hard-face for the internal reactor surface, which must withstand abrasion from high velocity particles. The refractory materials were supplied by Harbison-Walker Refractory, Santa Fe Springs, CA.

Refractory cement was mixed with water and poured into molds. Castable refractory is composed of special materials suitable for high temperature operations. We used relatively high-density cement (140-lbs/ft3) for the internal hard-face, and low-density cement (70-lbs/ft3) for the insulating layer (backing). The refractory inside linings were cast carefully using two layers of refractory cement. Internal molds were made from 12-gage steel, forming the inside shape. The steel molds used for casting the internal shape were purchased from Gerlinger Steel & Supply.

Shown below in **Figure 35** is a conical reactor section with the mold in place, ready for filling with refractory.

Figure 35: Casting Reactor Sections with Internal Mold

Photo Credit: Taylor Energy

After casting, the team removed the steel molds using an oxy-acetylene torch as shown below in **Figure 36.** When the team used cardboard tubes to cast straight sections, they burned them out using a light-oil starting fluid as shown in **Figure 37.**

Figures 36: Removing Steel Molds

Figure 37: Burning out Cardboard Molds

Photo Credits: Taylor Energy

Fabrication and construction required casting 20 individual sections; two layers each. Forty separate casting operations were performed; the spool sections are shown below, **Figure-38.**

Figure 38: Spool-Section with two-layers of cast refractory

Photo Credit: Taylor Energy

High Temperature Gasket Material – A high-temperature gasket material shown below in **Figure 39,** composed of two different layers of a special graphite material firmly compressed together, was used to construct high-temperature seals placed between each of the sections during construction.

Fasteners -- Grade-5 carbon-steel fasteners shown in **Figure 40** below were used to hold the sections together. Grade-5 steel is heat treated to impart strength and reduce the brittle nature of steel -- so that bolts will stretch rather than break in the event of an internal pressure spike. Threads are individually coated with zinc or copper based anti-oxidant in preparation for high-temperature oxidative service.

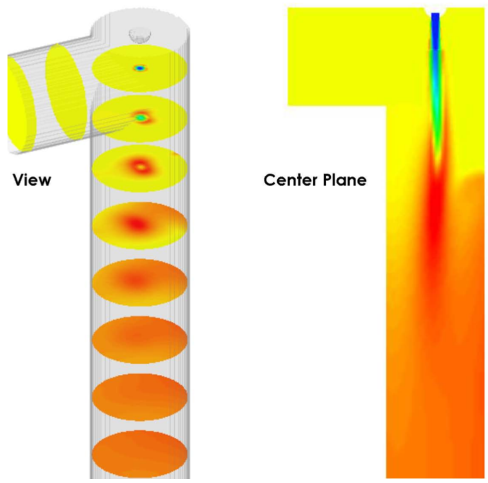
Figure 39: High-temperature Gasket Material

Figure 40: Grade-5 Carbon Steel Bolts

Photo Credits: Taylor Energy

Reforming --The Taylor syngas process employs a tar-cracking reactor that is integrated with the gasification reactor. The principle of operation is shown in **Figure 41** below. Carbon-char is not removed up-stream of the reformer; direct-coupling with the reformer is desirable because carbon-char produced in the JSB gasification reactor is intended to react with O_2, CO_2 & H_2O in the tar-reforming stage.

Figure 41: Tar-Reformer, Principle of Operation

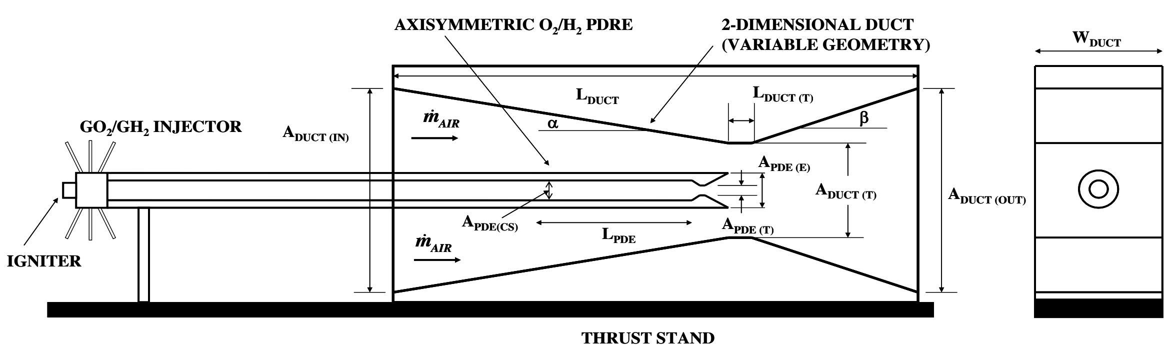


Source: Air Products

Tar-Reformer --Tar content in gasification products is routinely 5 to 15-wt percent of the products. The Taylor Energy process is intended to crack the tar fraction in the down-leg that operates as an entrained-flow type reformer. This configuration provides sufficient time, temperature, and turbulence to accomplish partial-oxidation reactions.

We added a converging – diverging nozzle section (used to enhance mixing) to the reformer, positioned in the center of the down-leg, (see **Figure 42**) as an alternative to the draft-tube configuration that was originally planned.

Figure 42: Pulse-Detonation Powered Venturi-Reformer, Fired in the Down-leg



Source: AIAA 2010-6882

Start-up Planning and Preliminary Start-up Testing

Safety review and safety training – We conducted a safety review and training meeting for the gasifier/reformer system. Shown below in **Figure 43,** a pulse-detonation-burner is installed on top of the reformer section. **Figure 44** shows the installation of the pulse-deflagration burner on the bottom section of the gasifier. Safe-operating procedures were developed, and technicians were trained in the start-up, operation, and shut-down procedures.

Figure 43: Installing the Detonation Burner on top of the Reformer

Photo Credit: Taylor Energy

Figure 44: Pulse Deflagration Burner Located at the Bottom of the Gasifier

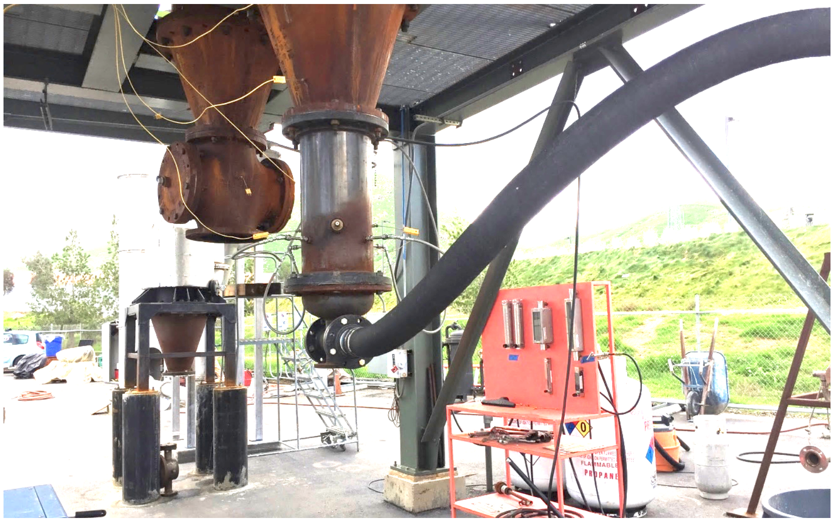


Photo Credit: Taylor Energy

Taylor Energy used a Komar extrusion feeder with a variable frequency driver to control the feed rate as shown in **Figure 45**. The extrusion feeder forms a plug-seal with atmosphere.

Figure 45: Komar Extrusion Feeder and Variable Frequency Drive that controls the feed-rate

Photo Credit: Taylor Energy

Preliminary start-up – Taylor Energy performed a preliminary start-up using the pilot-scale test system shown below in **Figure 46.** The fuel-gas product was flared using the enclosed flare shown below in **Figure 47**.

Figure 46: Pilot-scale Facility

Figure 47: Flare used to burn fuel-gas products

Photo Credits: Taylor Energy

Start-up Testing

The purpose of this project was to test a new method for producing Renewable-Fuel-Gases using a high-intensity thermal processing method. Using Taylor Energy's test facility at UCR shown in **Figure 48** below, we tested a mild-gasification process using Refuse Derived Biomass

(RDB) as the energy feed. Pilot-scale pulse-detonation-burners were integrated with both the gasifier and the reformer to accomplish process intensification.

Figure 48: Taylor Energy's Gasification Test Facility located at UC Riverside

Photo Credit: Taylor Energy

The energy feedstock tested is an RDB-fluff that is recovered from MSW by shredding in two stages using rotary-shear type shredders; size-classification to less than one inch, then air-stripped to remove glass, sand, grit, and debris, from the light fractions.

The resulting *RDB-fluff* shown in **Figure 49** contains most of the chemical energy available in MSW, including the plastic fractions. RDB is dried 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.

Figure 49: RDB-fluff

Photo Credit: Taylor Energy

Test Objectives -- This test program looked at gasification according to the operating paradigm proposed by Tsuji & Uemaki, employing partial-oxidation in two-stages, which offers many benefits. The test objective was to see if the integrated pulse-detonation burners could provide enough process intensification to enable gasification under mild conditions, and concurrently increase the gas-phase energy content in the fuel-gas product when compared to traditional gasification methods that co-produce significant quantities of tars and carbon-char.

This program is intended to prove that a pulse-detonation-combustor generating hot-exhaust gases can be used to drive a jet spouted bed. Note that the input to the pulse-combustor includes propane and air and can also include oxygen/steam. An initial objective was to generate hot product gases that are directed into bottom of the jet spouted bed, and to provide both heat and power a tar-reformer fired as the down-leg of gasification system. The over-all objective was to produce *energy-rich fuel gas suitable for electric power generation.*

According to Melaina & Eichman (2015), the operating range for a pulse-detonation burner is broad, ranging from lean to rich – with little change in the power output. The focus of the statement-of-work was to operate the pulse-detonation-combustor discharging hot-syngas into the jet-spouted-bed (JSB) (the expansion chamber), producing fuel-gases intended for renewable power production. The pulse-combustor was operated with excess-O2 in the exhaust-gases.

We optimized pulse-combustor prototypes based on obtaining the maximum discharge velocity for the combustion products. A key objective is to use supersonic compression waves to intensify thermal-chemical processes, to enhance carbon utilization within the process. We have shown that a pulse-detonation combustor integrated with a JSB offers special benefits based on simple proof-of-concept testing. We are using compression waves -- that pass through the process -- to increase thermal-chemical reactivity.

The pilot-scale pulse-detonation combustor served to increase the useful power output of the combustor-exhaust, creating cyclic compression waves passing through the thermal-gasification process. A pulse-detonation combustor is shown below in **Figure 50**.

Figure 50: Pulse-Detonation Installed on the bottom of the JSB

Photo Credit: Taylor Energy

Planning, design, engineering and construction phases were performed in order to build the gasification system shown below in **Figure 51**. The program test plan included a short series of preliminary tests integrated with the jet-spouted-bed processing refuse derived biomass to verify the performance of the system when operating in the *autothermal gasification* mode.

Figure 51: Taylor Energy's Test Facility located at UC Riverside

Photo Credit: Taylor Energy

For initial testing of the pilot-scale burners, the approach used by the research team was to mount the pulse-combustor prototype(s) on a horizontal test stand, shown below in **Figure 52**, where preliminary testing was accomplished. The design uses one pre-combustion stages and one linear run-up stage. The use of support-cables enabled the measurement of deflection to measure thrust, following a procedure developed by Shepherd (2002), who performed similar work on a pulse-detonation-engine employed for propulsion.

Figure 52: Taylor Energy's Pulse-Detonation Test-Stand located at UC Riverside

Photo Credit: Taylor Energy

The initial results for a carbon steel and cast refractory type pulse-detonation-burner (PDB) prototype were promising. We also designed and fabricated a prototype using stainless-steel, based on a California Institute of Technology propulsion design developed by Shepherd (2002), using pre-ignition stages. A pulse-detonation flame is shown in **Figure 53**.

Figure 53: Horizontal Operation; Firing at night using the Pulse-detonation Test-stand

Photo Credit: Taylor Energy

We made the decision to use a gaseous fuel injection manifold that is easy to control with a simple on/off power control signal used for operating industrial solenoid valves that can operate at 10-Hz for 6,000,000 cycles. Gas injection nozzles were designed and fabricated, each employing a nozzle orifice of less than five mm inside diameter. Using gaseous fuel, continuous pulse-ignition was achieved, and the system was deemed a preliminary success and moved to the JSB for further testing.

Next, we tested the pulse-detonation prototype using airflow input of 70-scfm at 3-psig, supplied by the rotary-lobe type blower operated at 2,600-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 we tested ranged from 1-Hz to 2.5-Hz. We performed 25 test sequences in this mode of operation. Concurrently, we operated the gasification reactor and produced fuel-gas, which was combusted in an enclosed flare; the fuel-gas flame is shown in **Figure 54** below.

Figure 54: MSW derived fuel-gases being combusted within an enclosed flare

Photo Credit: Taylor Energy

The airflow was held constant at 70-scfm, while the timing for both fuel-injection and spark-ignition were varied from 1-Hz to 2.5-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 in 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 a sonic nozzle that prevented significant black-flow.

The pulse-detonation burner showed great potential in this mode of operation by producing some significant detonations. However, precise control of the fuel-injection and the spark timing have proved to be more difficult than anticipated; and therefore, thus far, the ignition events have been limited to 2.5 ignitions per second. Nevertheless, using this approach, we were able to establish uniform pulse-combustion.

We performed the necessary modifications and completed 12-tests, achieving a pulse-detonation rate of 2.5-cycles per second. Below in **Figure 55** the prototype pulse-detonation-burner is shown integrated with the Jet Spouted Bed, firing into the bottom of the JSB. The pulse-detonation design was considered a high-reward embodiment

Figure 55: Pulse-Detonation-Burner Integrated with Jet Spouted Bed

Photo Credits: Taylor Energy

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

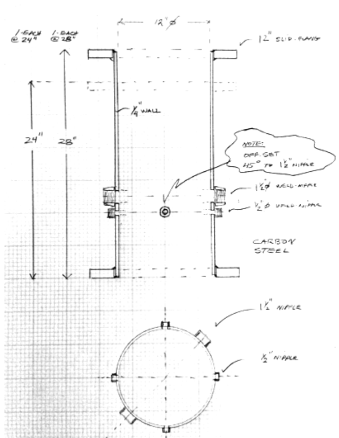
In parallel with the design & testing of the pulse-detonation prototype, the research team also developed a more conventional pulse-deflagration embodiment. The second prototype was a single-chamber design; a pulse-deflagration-burner composed of a single flame-can employing a fuel/air mixer and a spark ignition system. Initially, the team tested a stainless-steel prototype, shown below in **Figure 56**, 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 56: Early Stainless-Steel Pulse-Jet Burner Prototype

Photo Credit: Taylor Energy

Taylor Energy concluded that the use of a cast-refractory type combustor would offer significant improvements and 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 team poured refractory around molds that formed the internal shape of the rocket-type burner and used stainless-steel insertions to provide openings for fuel inputs and for instrumentation (temperature and pressure measurements), and to connect the spark-ignition system. **Figure 57** and **Figure 58** below show the pulse-jet burner housing and the refractory casting within that housing. **Figure 59** shows the pulse-jet deflagration burner attached to the bottom of the Jet-Spout-Bed. Taylor Energy's goal was to compare operation of a *pulse-deflagration burner* with a *pulse-detonation burner*.

Figure 57: Burner Housing



Source: Taylor Energy

Figure 58: Burner Casting

Figure 59: Integration with JSB

The optimum operating point for the *pulse-deflagration prototype* was 43-Hz, equal to 143-scfm air-input, operating with excess air. The operating range for the *pulse-deflagration prototype* was much broader. We successfully tested and operated the burner, employing a range from 30-Hz to 60-Hz, testing the fuel-lean operating mode.

The adiabatic flame temperature for stoichiometric mixtures of air and propane is 1,977 C. The lowest temperature achieved during fuel-lean operation was 780 C, which indicated that the *pulse-deflagration prototype* was stable, being able to ignite and maintain stable operation with a high rate of excess air. 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 as shown in **Figure 60** – avoiding the range where the highest temperatures would damage the prototype burner's refractory. **Figure 61** shown fuel-rich burner,

A test-plan was finalized that included a test-matrix measuring the air-fuel input as a function of RDB input. The team carried out start-up testing of the gasification rector with the pulse-burner operating at 900 C, employing fuel-lean operating chemistry. The burner temperature set the air-fuel mixture, which was repeatable with accuracy.

Figure 60: Burner, fuel-rich

Figure 61: Burner, fuel-lean

Photo Credits: Taylor Energy

The research team tested three types of ceramic bed materials; 0.5-mm, 1-mm, 3-mm 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 JSB. We selected smaller beads after early testing showed that larger beads, with diameter greater than 1-mm, would not provide as many energetic collisions when compared to smaller diameter steel beads. 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.

Test Results

Taylor Energy tested the jet spouted bed gasification reactor using refuse derived biomass (RDB) shredded to less than 1-inch. The proximate and ultimate analyses are shown below in **Table 3**. 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 dry feed (with some plastics content) contained 8,300 BTU/pound, based on the higher heating value.

Table 3: RDB, Proximate and Ultimate Analysis

RDB Proximate Analysis (%)		Ultimate Analysis (%)	
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

Source: Taylor Energy

Once the gasification reached 850° C, we commenced testing. The start-up and test procedures were performed 10-times over the course of a four-week period to obtain the test data. We used the gas sample port located down-stream of the gasification reactor to extract gas samples through a one-half inch stainless steel tube. The gas was conditioned by using a high-temperature filter, followed by chilling in an ice bath to remove condensable fractions. It was then analyzed with a CAI Analyzer; the sample gas is drawn through the system by a gas pump that is integrated into the CAI analytical system, which includes two pre-filters, a gas chiller, and a gas heater used to raise the sample gas temperature above the dew-point.

After developing optimum pulse-burner prototypes, the team performed a test-matrix testing RDB conversion into fuel-rich gases. The research team tested two pulse-burner types integrated with the gasification system: a pulse-deflagration burner and a pulse-detonation burner. Performance of the text matrix resulted in obtaining sample data for 21-conditions.

The team tested the integrated system to obtain data in support of this report using refuse derive biomass as the energy feed. Fuel-gases were burned in an enclosed-flare shown in **Figure 62**, which was constructed for this project. RDB derived fuel-gas can be seen burning within the flare during continuous operation in **Figure 63** below.

Figure 62: Enclosed-Flare

Photo Credits: Taylor Energy

Figure 63: Flare burning MSW-derived fuel-gases

The syngas composition shows the best three data points taken at 20-minutes intervals during 1-hour operating period with stable operating conditions with the pulse-burner operating at 900 C to optimize power output to the gasification reactor. The average methane content was 7.46 percent by volume based on the data reported below in **Table 4**.

Table 4: Analysis of fuel-gas products

Component (vol%)	Sample 1	Sample 2	Sample 3	Average
CO	7.8	8.4	7.20	6.92
CH4	7.6	7.8	7.0	6.46
CO2	12.1	14.6	15.3	14.0
N2	46.7	43.4	45.47	44.2
H2O	10.1	10.0	10.9	9.9

Source: Taylor Energy

The data below in **Table 5**, shows that the average carbon-char content is 9.47-wt percent 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.

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

Products (wt%)	Sample 1	Sample 2	Average
Gases	**64.0**	**59.77**	**61.89**
Tar	**4.50**	**4.20**	**4.35**
Char	**9.80**	**9.15**	**9.47**
Ash	**12.39**	**18.18**	**15.291**
Pyrolysis water	**9.31**	**8.69**	**9.0**
Total	**100**	**100**	**100**

Source: Taylor Energy

CHAPTER 3: Project Results

Introduction

The results are based on testing waste gasification technology at 3-ton/day scale. Project results are used to develop a conceptual and preliminary engineering design for a demonstration-scale project that will convert 40-ton/day of refuse derived biomass into fuel-gases sufficient to generate power with 1.7-MWe net output. The project results also include the preliminary design of two commercial-scale gasification plants:

- 300-dry-ton/day waste-to-energy facility using atmospheric-pressure gasification integrated with a steam-injected gas turbine to generate 9.5-MWe and achieve 31.6-percent net conversion efficiency for the waste-to-energy process.
- 500-dry-ton/day waste-to-energy facility using an advanced gasification cycle operating at 400-psia that is integrated with a high-efficiency gas turbine to generate 46.6 MWe that enables 45-percent net conversion efficiency for the waste-to-energy process.

The three reports that are attached as appendices A, B, and C, and summarized in this chapter.

Table 6: Goals, Objectives, and Achievements

Agreement Goals and Objectives	**Achievements**	**Comments**
Validate the technical performance of a two-stage thermal-catalytic gasification process operating with experimental data described in the agreement objectives.	Achieved	The two-stage thermal-catalytic gasification process operates successfully within parameters established in the project objectives.
Verify the economic viability of the integrated waste gasification and reforming process from the project findings as described in the agreement objectives.	Achieved based on the project results	Project findings were used to evaluate the economic viability of the technology, which is projected to provide an attractive rate of return at community scale >10-MWe scale.
Operate gasification reforming process continuously for 8-hours, with RDB input of 3-pounds per minute (1.08-mmBTU per hour, based on energy content of 6,000 Btu/lb for RDB), with average fuel-gas output of 0.80-mmBTU/hr, having energy content of 230 BTU/scf, demonstrating 74%	Continuous operation >8-hrs. RDB input of >3-lbs/minute. Firing input >1 mmBTU/hr. Output >0.8 mmBTU/hr. Average BTU content was less than 230 BTU/scf.	Average BTU content was greater than 127 BTU/scf to 190 BTU/scf because N_2 and CO_2 dilution were higher than projected.

net conversion efficiency of feed into fuel-gas.	The net efficiency was less than 74% conversion to gas because due to more carbon content in the ash, which may require increasing the retention time for the solids	The net efficiency was calculated to be 68%; the carbon conversion needs improvement to increase net efficiency.
Operate the thermal-chemical gasification process with over-all Stoichiometric Ratio (SR) =0.28, using oxygen enriched air to 33%-O2 to achieve carbon conversion >90% as measured by Feedstock /Products/Char analysis.	The system has not been operated with oxygen enrichment to 33%. The carbon conversion was less than 90%.	The system has not been operated with oxygen enriched air achieved to 33% oxygen content, due to the cost O_2 relative to other budget constraints; therefore, the carbon conversion was lower than projected.
Operate pulse-deflagration burner(s) that heat and power both the gasification and the reforming process with frequency >7-Hz using Transient Plasma ignition, firing the pulse burners with excess air.	Pulse-deflagration burners operated at >21-Hz with excess air. Transient Plasma Systems (TPS) ignition was not used successfully.	The TPS ignition system
Establish the durability of stainless-steel pulse-combustor(s) with no observable failures due to high-temperature and pulse detonation operation during proof-of-concept testing.	Not achieved	Stainless-steel is not an ideal material for pulse-combustion. Cast-refractory pulse-burners were proven durable. Water-cooled copper used for fabrication was also proven durable.
Establish Process Heat & Mass Balance by Semi-empirical Method and Semi-empirical ASPEN process model development.	Achieved	A semi-empirical process heat and mass balance was prepared; and ASPEN modeling was performed.
Confirm from the project findings that a cost of $3,750 per kWh of installed-capacity is supported, based on a 300-ton/day modular system.	Achieved based on project results	Cost projections support the $3,750 per kWh of installed-capacity, based on the projections for a 300-ton/day modular system.

Confirm from the project findings that the LCOP of $118/MWh, including 10% return on equity, is supported based on a 300-ton/day modular system.	Achieved based on projections.	Modeling the use of refuse derived biomass as a low-cost energy source results in lowering the LCOP according to projections.
Estimate Carbon footprint for the process and the products by Life Cycle Analysis through GREET.	Achieved	Carbon Life Cycle Analysis modeling using GREET is attractive.

Source: Taylor Energy

Specific Advancements During this Agreement

Pulse-Detonation Methods

Pulse-Detonation methods applied to waste biomass gasification were first reduced to practice by Taylor Energy with Commission funds through the successful performance of EISG-14-04G, completed in July 2016; the final report titled is: "Syngas Process Development for Renewable-Methane Production."

Proof-of-concept testing was accomplished using a 3"-ID Pulse-Detonation-Burner, employing oxygen-enrichment and pre-combustion stages to accomplish the deflagration-to-detonation transition (DDT.) Whereas, the present project embodiment uses a 4" ID burner, 48" in length, constructed of water-cooled concentric metal tubes. The DDT is accomplished using a Shchelkin coil, [a spiral coil named after Kirill Ivanovich Shchelkin, a Russian physicist who described it in his 1965 book Gas Dynamics of Combustion.]

The improvements in performance are significant when an understanding of the applied science is used to manage the operational issues; the technical performance issues were informed by Afthon, LLC, a California based consultancy that specializes in the design and the development of detonation technology.

The key advancements in technical knowledge are summarized below:

- The detonation cell-size is of critical importance; according to DDT-modeling performed by Afthon, the air/propane mixture needs a cell-size larger than 3"; therefore, the use of a 4" ID burner-tube is a key operating parameter that does not scale down. The technology is expected to scale-up very nicely; however, the minimum cell-size required for air/propane detonations is >3.5" diameter.
- The materials selected for the burner fabrication are extremely important because a strategy must be employed that eliminates the formation of any hot-spots within the burner interior -- no glowing red edges that ignite the fuel/air mixture prematurely. Ignition timing is critical; a timed sequential spark must ignite the air/fuel mixture; any hot-spots within the burner interior (even those that develop during extended operation) will prevent proper operation of the detonation cycle.

- Previous work resulted in pulse detonation burners able to fire at 1-2 Hz. Improved methods enabling firing at 5-Hz. The pulse-detonation power output increases in proportion to the detonation rate.
- When designed, constructed, and operated with an understanding of the applied science, pulse-detonation methods are extremely powerful. We found that a 4" ID x 48" long DDT-type burner provides about 3-times more power than we are able to fully utilize in the present gasification reactor and reformer configuration. For the tests performed, we turned down the burner output significantly by filling the detonation tube to 37% of full capacity, operating with about 30-scfm air input to the burner, rather than using 90-scfm as called for in the original burner specifications.
- Significant power -- in the form of supersonic shockwaves -- is made available from stoichiometric air/fuel detonations. We are only beginning to understand how to employ this new technology to enhance gasification and reforming methods; all the thermochemical reactions that convert organic polymers into low-molecular weight gases are potentially enhanced.

Waste-to-Energy Evaluation, 40-ton/day, 1.7 MW (Appendix A)

Report Summary

An objective was to evaluate a 40-ton/day gasification facility employing advanced MSW recycling technology integrated with electric power generation, using refuse derived biomass (RDB) as the feedstock in an environmentally responsible manner at demonstration Scale.

Based on the project feasibility study, a 40-ton/day scale (36-tonne/day) -- using an average of two (2) tractor-trailer loads per day, each carrying 20-tons -- has been determined to be the optimum capacity for a Demonstration Scale facility, based partially on the transportation logistics. **Figure 64** shows the Walking-floor Tractor-Trailer used to transport the RDB.

Figure 64: Walking-Floor Type Tractor-Trailer to Transport RDB

Photo Credit: Havago Transport

At design capacity, no more than five trucks per day will deliver shredded-RDB to a covered storage facility between the hours of 7 AM and 4 PM Monday through Saturday. Once in the receiving area, the feed will be visually inspected, then unloaded in the receiving and storage area. The conversion technology is accomplished with the steps below:

- Receive an average of 40-ton/day of shredded-RDB at the Renewable Energy Facility.
- Taylor Energy Gasification technology is used to convert RDB into a fuel-gas product;
- Clean the fuel-gas by removing all impurities through filtration and wet-scrubbing; and
- Generate Electricity using Medium-Speed IC Engine-Generators

Figure 65: Refuse Derived Biomass (RDB) recovered from Shredded-MSW

Photo Credit: Taylor Energy

The feedstock basis used for the waste-to-energy demonstration facility is an RDB-fluff produced from the light-fractions of commingled paper, organics, and plastics, that are separated from shredded MSW as shown in **Figure 65**. RDB contains a high volatile-fraction with relatively low fixed-carbon, thus offering a feedstock with excellent properties for thermal gasification. The plastic fractions and high-surface-area paper are gasified quickly in a high-temperature entrained-flow type gasification environment. The rapid formation of volatiles derived from paper and plastic serve to enhance the gasification of more resistant woody-biomass (when compared to wood alone).

The Feed Basis used to define Refuse Derived Biomass for this evaluation is listed below as Rev 1, compared to other feeds in **Table 7**.

Table 7: RDB Ultimate Analysis in Rev 1 compared to MSW and other feeds.

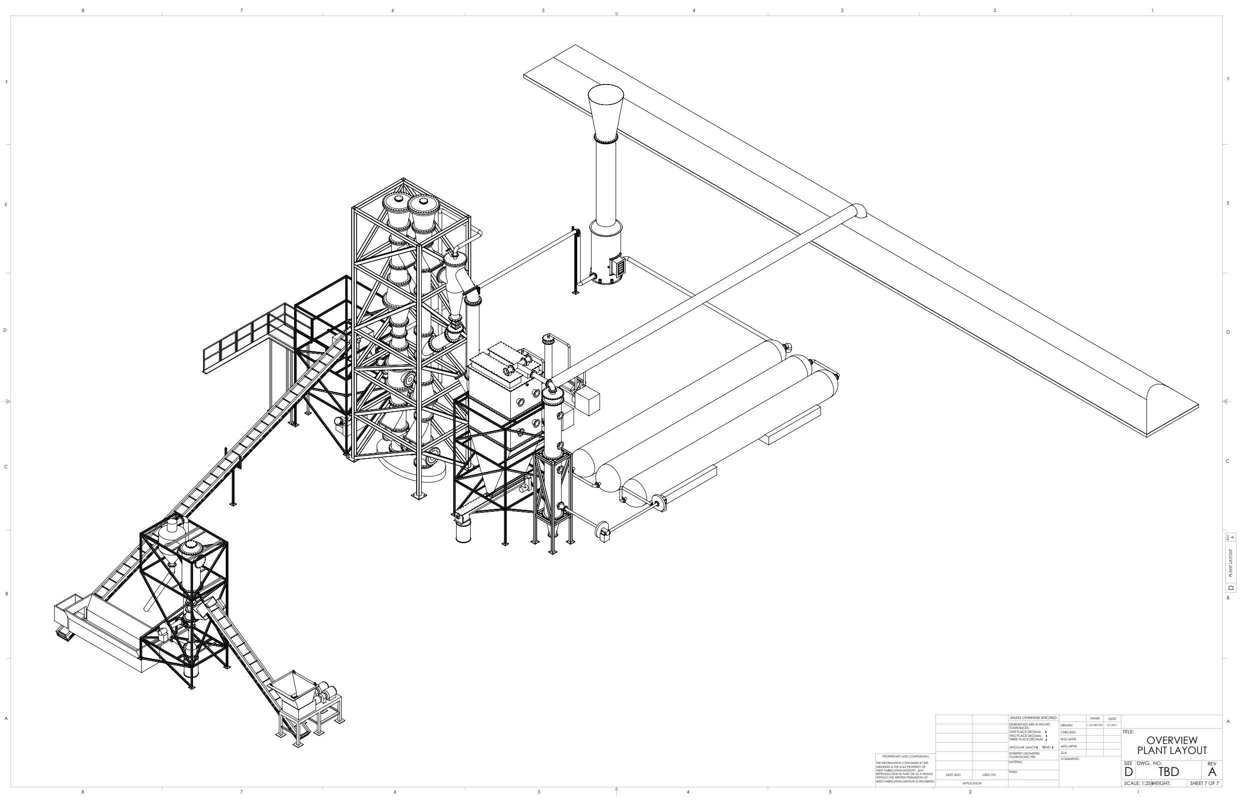
										Rev 1
		Pilot	Pilot	Pilot	Demo					Proposed
					40t/d		Pap+Plas		Battelle	Design
		700 °C					Mixed	Raw		
	HHV,	MunWast	MunWast	Plastic	MW	Pulp	Waste	MSW	RDF	
	Btu/scf	Mol%	Mol%		Mol%					
C		37.74	37.74	75.4	33.4	37.5	55.1	48.43	47.31	47.6-31
H		5.01	4.93	12.2	4.42	4.88	8.6	7.06	6.61	6-4.5
N		1.79	1.61		1.26	1.28	0.2	0.99	0.68	1.2-1
S		0.5	0.7	0.1	0.47	4.63	0.3	0.15	0.14	0.4-0.3
Cl		0.7	0.43	2.1	1	0.29	1.2	0.64	0	1.5-1.0
O		26.9	30.6	9.7	28.05	28.1	20.8	29.92	34.71	34-27.2
ASH		27.4	23.8	0.5	31.1	23.2	13.8	13.31		20-12

Source: Taylor Energy

Taylor Energy developed the preliminary design for a 1.7 MWe demonstration scale RDB gasification facility. The 3-D drawings were performed using SolidWorks; one image is shown below in **Figure 66**. The design includes a front-end shear-shredder, and a pneumatic classification system used to recover RDB from MRF residues. Note also that a portion of the fuel-gas product is stored at low-pressure (3-5 psig) in the three storage tanks shown below. Three engine-generators designed to burn low-BTU gas are used for power. The demonstration system includes a large enclosed flare to be used during system-starts, before the engine-generators are engaged.

The engine-exhaust is directed to a large biofilter used for final polishing of trace emissions. A biofilter consists of an engine-exhaust distribution manifold covered with moist shredded wood that is operated as a living aerobic filter. Taylor Energy designed the world's largest biofilter in Orange County, California for CR&R Waste Services; the biofilter design calls for a superficial velocity of 5-feet/second.

Figure 66: Proposed Gasification Facility; feeding system through bio-filtration



Source: Taylor Energy

Demonstration-Scale Project Input and Outputs

The system is designed to process a total of 13,140 tonnes per year of RDF; 36-metric tonnes per day (40-short tons/day) RDF containing up to 21% moisture, which equates to 1,650 pounds per hour. Two parallel power trains will each generate net output of 854 kW per hour, operating 8,760 hours per year at 100% on-line availability, which is accomplished by providing one complete spare engine, resulting in a combined output from two engines of 1,708 kWh.

Waste-to-Energy Evaluation, 425-wet-ton/day, 9.5 MWe (Appendix B)

Report Summary

The objective is to evaluate a 300-dry-ton/day commercial waste-to-energy facility, using Refuse Derived Biomass (RDB) as the energy feedstock in an environmentally responsible manner, and to utilize this renewable energy source to produce electricity on or near a California Landfill, providing 9.5-MWe of base load electrical output for delivery to the grid and fulfilling the economic requirements of project developers.

The facility will utilize MSW otherwise delivered to the County landfill. To encourage private haulers and the County to take advantage of the RDB production facility, the gate fee or tipping fee at the landfill will be unchanged. This pricing will not increase the operating expenses for the commercial haulers, and will insure adequate feedstock for RDF production, provide environmental benefits, and secure a low-cost renewable fuel source for the Waste-to-Energy Facility.

Figure 67: Conceptual Design for a Nominal 432-wet-ton/day Waste-Biomass Gasification Facility

Source: City of Kona HI

At design capacity, trucks will deliver MSW inside of an enclosed facility between 7 AM and 4 PM Monday through Saturday. Once inside the receiving area, MSW will be visually inspected and pre-sorted to remove non-combustible, and other unsuitable materials. After tipping and sorting, the conversion to electric power is accomplished with these steps below:

- Convert 432 wet-ton/day MSW into 300 ton/day RDB (at or near the landfill site)
- Transport 300 ton/day RDF to the Renewable Power Generation Facility.
- Using Taylor Energy’s Gasification Process, convert RDB into a fuel-gas product;

- Clean the fuel-gas by Reforming tars and by removing all impurities; and
- Generate Electricity using Steam Injected Gas Turbine Technology (STIG cycle)

RDF is received and stored in a sixty thousand (60,000) square foot, clear-span metal building. The building will be approximately forty-nine (49) feet high at its roof eave and rises to fifty-eight (58) feet high at its roof peak. This building contains the receiving area, material-handling equipment and the Walking-Floor type storage bunkers, which hold the processed RDF until it is conveyed to the gasifiers. Adjacent to the RDF receiving and storage building, shown in Figure 1.2, is an uncovered, exterior screened area of approximately sixty thousand (60,000) square feet, which contains most of the gasification and power generation equipment, which includes two parallel gasification trains, each sized to process 150-ton/day RDB, providing a total RDB gasification capacity of 300-ton/day.

The perimeter screening fence is thirty (30) feet high along the West side and twenty (20) feet high along the North side with an enhanced screening element in the Northwest corner, which rises to approximately forty-eight (48) feet, serving to shield conversion equipment somewhat from view. The area also contains a ten thousand (10,000) square-foot sound insulated building, which will house the power generation equipment, composed to one power train, with gross power output of 11.25-MWe, resulting in name-plate capacity of 9.5-MWe net output. When operating with 85% availability, the pro-forma output is projected to be 8,075 kW/hr, based on 8760 hours per year. Immediately to the east of an exterior screened area is the maintenance and water treatment facility. It will be a two-story metal building enclosing approximately sixteen thousand (16,000) square feet.

RDF Facility, Operational Summary

The conversion technology proposed to transform MSW into RDB is accomplished as follows:

- Waste receiving
- Separation of recyclable materials
- Waste sorting, shredding, followed by air-classification.
- RDF is transported to the Energy Facility using walking floor tractor-trailers.

The conversion process commences when MSW arrives at the landfill in waste collection vehicles, such as front loaders, roll-off trucks, transfer trailers, and a public tipping floor, as in **Figure 68.** A landfill facility will typically be open approximately three hundred twelve (312) days per year.

When operating at full capacity, the system is slated to receive at least five hundred (500) tons of MSW per day, Monday through Saturday, for a total of up to three thousand (3,000) tons of MSW per week; 156,000 wet-ton/year is the minimum design capacity for the receiving facility.

Figure 68: MSW on the Tipping Floor

Photo Credit: Taylor Energy

It is anticipated that the facility will receive no more than five (5) waste collection vehicles per hour between the hours of 7 a.m. and 4 p.m. Monday through Saturday. MSW is processed within an enclosed building. No waste materials will be visible to persons outside the building and fugitive litter, such as paper or plastic waste, will not be released once inside the building. Visual waste-inspection for hazardous materials by the tipping floor operators will be done for each load entering the tipping floor.

RDB Production

The proposed RDB facility will employ one 500-ton/day processing line, intended to operate seven (7) hours per day (one work shift per day). Using a bucket type front-loader, MSW is pushed into the primary shredder (**Figure 69**), operated by one person seated inside an air-conditioned cab.

Figure 69: Primary Shear-Shredder used for 1-stage MSW Size Reduction

Source: SSI

After primary shredding, the coarse-shredded feedstock is sent to the secondary shredder for final size reduction, reducing the size to less than two-inch (<2"), as shown in **Figure 70**. A belt-conveyor delivers this produce to the air classification systems, to separate the heavy fractions, resulting in the production of a homogeneous RDF-fluff, which is directed to storage piles located adjacent to load-out holes.

Figure 70: Rotary-Shear shredder used 2-stage Size-Reduction and for RDB production

Source: SSI

RDB-Fluff Storage

The RDB is transported in walking floor tractor-trailers to the Renewable Energy Facility, and delivered to the storage area, constructed of steel reinforced concrete floor with two push-walls constructed of steel reinforced concrete, where the RDB-fluff is piled and moved about with a front-loader. The storage capacity of the facility is large enough to contain two-days of RDF-fluff. Periodically, RDB is pushed into live-bottom storage bunkers, where it is stored on a walking-floor conveyor, which controls the feed-rate to the gasifier. The storage bunkers are 10' wide x 10' deep x 60" long, providing at least 2-hours of storage capacity, so that the RDB-feedstock is continuously withdrawn by the means of a Rate Control System that feeds the gasification process, as shown in **Figure 71**.

Figure 71: Walking Floor Storage Controls RDB Feed Rate to Gasifier

Photo Credit: Taylor Energy

The fuel-gas analysis is listed in **Table 8** below.

Table 8: Analysis of Fuel-gas products

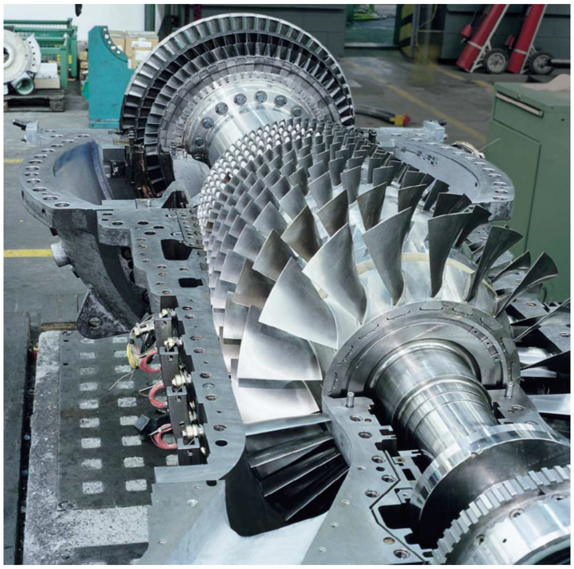
Item	Gasifier	Reformer	Post Gas Clean-up
CO	8.82	10.0	10-22
H2	7.36	8.61	8-14
CH4	5.46	6.51	4-6
CxHy	3.24	4.88	2-5
NH3	0.26	0.25	0.05-0.1
CO2	14.09	15.65	15-18
H2O	13.66	9.48	10
N2+Ar	46.83	46.48	40-45
C10H8	0.25	0.023	0.01-0.02
H2S	78 PPMv	48 PPMv	20-40 PPMv
HCl	139 PPMv	90 PPMv	25-35 PPMv
HCN	30 PPMv	20 PPMv	20-30 PPMv
HHV	184 BTU/scf	230 BTU/scf	227 BTU/scf
Tars	13.8 g/Nm3	1.2 g/Nm3	0.5 g/Nm3
M.W.	26.7	26.5	26
Density	0.074 lb/ft3	0.071 lb/ft3	0.070 lb/ft3

Source: Taylor Energy

Power Island - Steam Injected Gas Turbine for Electric Power Generation

Electric power will be generated using the fuel-gas to fire a well-proven gas turbine engine. The proposed Energy Facility will employ one GE10-1 Industrial Gas Turbine (**Figure 72**). The engine has output capacity of 11,250 kWh, with 31% simple cycle efficiency. The GE10-1 gas turbine is selected for use with low-BTU fuel-gas derived from RDF gasification. A heat recovery steam generation (HRSG) is added to the system; the steam produced is injected into the gas turbine to increase mass flow and reduce emissions, while increasing the power cycle efficiency to 42%. The power cycle is called a “Steam Injected Gas Turbine;” and know in the industry as a STIG Cycle or Cheng Cycle Gas Turbine, which increases the power output.

Figure 72: GE10-1 Gas Turbine Engine for operation with Low-BTU fuel-gas



Source: General Electric

The gas turbine is to be provided by General Electric (GE) and packaged by a company with experience designing and fabricating skid mounted power generation equipment for industrial applications. The power island supplier provides complete services for the power production modules, including the skid design, fabrication of the power plant skids, and includes the installation and start-up of the turbine engines. They also provide a long-term maintenance sub-contract that includes periodically rebuilding the turbines and other moving parts.

Figure 73: Steam Injected Gas Turbine (STIG) used to Increase Efficiency

Source: General Electric

The over-all thermal efficiency for the process is improved by employing the advanced STIG Cycle shown above**, Figure 73**, where Heat Recovery Steam Generation (HRSG) is used to produce steam that is injected into the gas turbine, reducing air emission and increasing the power output. The gas turbine provides gross power output of 11.25 MWe at 42% efficiency by employing the STIG Cycle.

Design Capacity

The nominal design basis (at the MRF or landfill) calls for receiving and processing 432-wet-ton/day MSW, assuming 25% debris, glass, grit, and recyclables, including metals. Therefore, removing 25% non-energy materials will result in 324-wet-ton/day feedstock is available for energy use. The design basis assumes 25% moisture; preliminary processing removes 2% moisture. Therefore, the nominal RDB design basis is 317-wet-ton/day MSW with 23-wt% moisture and assumes that RDF is dried during production to result in 300-ton/day of RDB-fluff with 17.5-wt% moisture, containing approximately 5,000 Btu/lb, LHV.

Feed rate: 300 wet-ton/day RDB, containing 5,000 Btu/lb-wet @ 17.5-wt% moisture

300 ton/day x 2,000 pound/ton = 600,000 pounds per day	
600,000 pounds/day / 24 hours per day = 25,000 pound per hour	
5,000 Btu/pound-dry LHV x 72% (net gasification eff.) = 3,600 Btu/pound as fuel-gas	
3,600 Btu/pound as fuel-gas x 25,000 lb/hr = 90,00,000 Btu/hr (90 mm Btu/hr)	
90 mm Btu/hr x 42% (net STIG-cycle eff.) = 37.8 mm Btu/hr (as electricity)	
37.8 mm Btu/hr (as electricity) x (1 kWe / 3,412 Btu) =	**11,075 kWh** (gross power output)
Parasitic Power Uses	**(**1,575 kWh)
Net	**9,500 kWh**

Projections—Budgetary

Available Energy as Heat: 25,000 pounds per hour x 5,000 Btu/pound = 125 mm Btu/hr
Each of the two (2) lines, feeding 150 ton/day of RDB, with a total capacity of 300-ton/day.
Each of the two (2) gasification reactors, processing 150-ton/day RDB, which equates to an input capacity of 300-ton/day RDF, produced (at the MRF or landfill) from a total of 432-ton/day MSW. Input: 300-ton/day RDB, producing 90 mm Btu/hr fuel-gas output

Gasification System	
11,075 kWh (gross) x $1,430/kWh=	$ 15,837,250.00
Power Generation Island	
11,075 kWh (gross) x $1,270/kWh=	$ 14,065,250.00
Engineering Design	$ 1,175,000.00
Commissioning, start-up management	$ 1,500,000.00
Total	$ 32,577,500.00
Cost per kW Installed ($ 32,577,500 / 9,500 kW) =	**$ 3,429 / kW (installed capacity)**

This budgetary price does not include the facility for converting MSW into RDB at the MRF or landfill, or the buildings proposed to house the Maui Renewable Power Facility. This price does not include the cost of interconnecting to the power grid, i.e., the cost for step-down transformers, or the payment of taxes, and does not include the payment of fees, events, or operations that are unique to the project site.

Systems Modeling and Analysis, 600 wet-ton/day MSW Feed

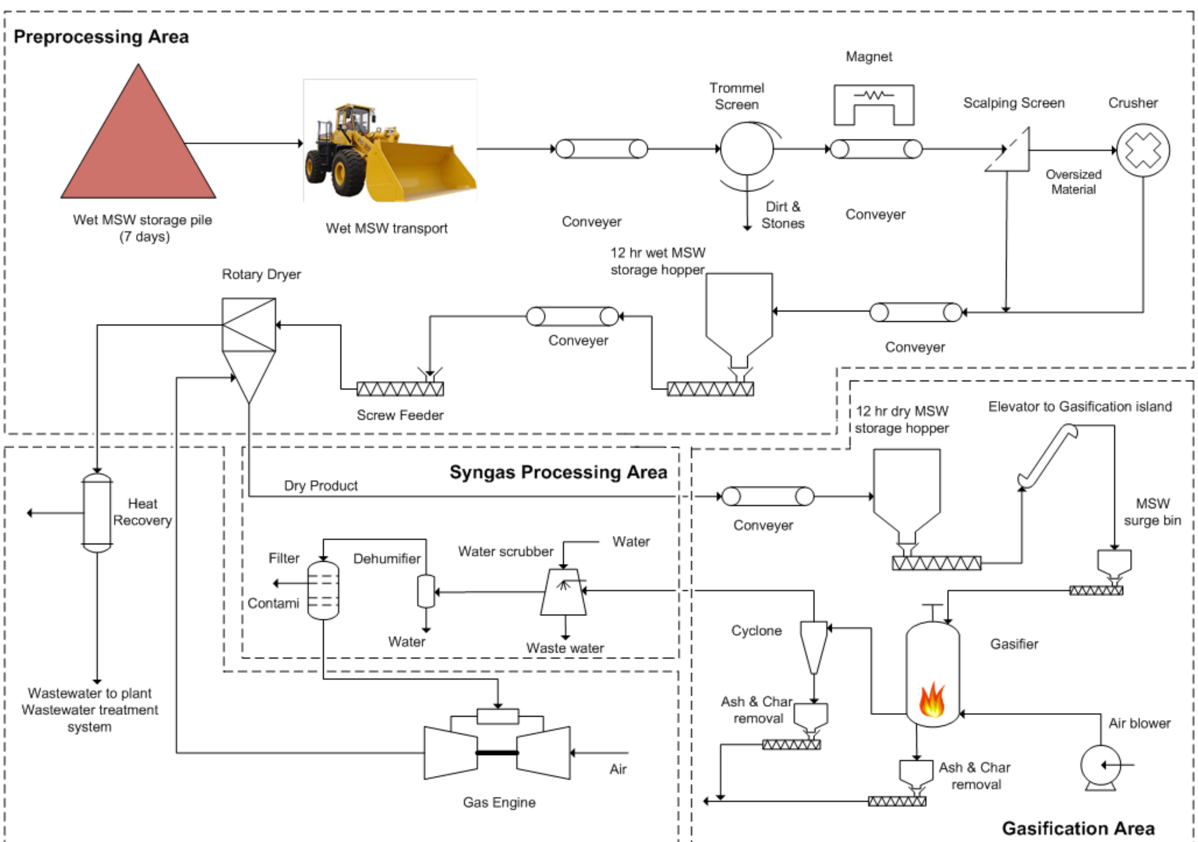
Dr. Arun Raju, UC Riverside (Appendix C)

Report Summary

The plant is assumed to be located near a landfill or a waste processing facility and the waste material is composed of both organic and inorganic residues. Cost of MSW gathering, loading and unloading and transportation is included in the analysis. The power generation plant process diagram is shown in **Figure 74**. The plant includes a feedstock preprocessing area where wet-MSW is dried and shear-shredded according to the gasifier requirements. The MSW is then gasified in the gasification area to produce a medium/high energy content syngas. The raw syngas is cooled and cleaned to remove contaminants and undesired components in the syngas processing area.

The power island converts the syngas into electricity using a combined cycle gas turbine or an internal combustion engine depending on the configuration. The plant size is 500 dry metric tons per day of MSW throughput. Except for the gasifier, all technology components such as the feed pretreatment system, syngas cleanup system, and gas turbine/engine are considered mature, and commercially available.

Figure 74: Flow diagram of the waste to power conversion facility



Source: UCRiverside

Projected System Performance is summarized below in **Table 9.**

Table 9: Projected System Performance

Cold gas efficiency	85.7%
Syngas energy content (MMBtu/SCF)	151.1
Power generated	49.1
Auxiliary load	2.5
Net power export	46.6
Plant electric efficiency	45%

Source: UCRiverside

Total Plant Cost (TPC) and Total Required Capital (TRC) for a nominal 600-wet-TPD plant MSW-to-Power plant (500 TPD dry basis) were estimated with project life of 20-years excluding construction period. TPC was evaluated by determining equipment and installation cost adding indirect cost and project contingency. TRC was estimated by adding financial cost and working capital on the TPC. Operation and maintenance cost were also determined to calculate Internal Rate of Return (IRR) with 10% discount rate in the cash flow analysis. Major inputs in the financial model are listed in **Table 10.**

Table 10: Major financial model inputs

Project economic life (yr)	20
Debt (%)	55
Equity (%)	45
Payment term (yr)	10
Interest (%)	8
MSW gate fee ($/ wet ton)	30
Discount rate (%)	10
Tax rate (%)	38
Electricity sale price ($/Mw)	90

Source: UCRiverside

A debt/equity financial structure of 55/45 is set with 8% loan interest rate and 38% income tax in the cash flow analysis. The lifetime of the plant was assumed to be 20 years in addition with two-year construction period and first six-month 70% production capacity ramp-up period. Straight line depreciation method is used in the whole plant through project lifetime with plant salvage value of zero. Working capital was applied before plant operation and recovered at the end of the project life. A 10-year repayment term was used in the loan period with one-year grace period on principal repayment.

MSW feedstock cost is assumed to be zero since it is considered as waste. A 30 $ per wet ton MSW was given as payback from MSW tipping fee and disposal cost. A first-year construction price of 90 $/Mwh for electricity is used. Escalation factors of 3% is employed in power sale price to reflect inflation factor within plant lifetime. Variable operation costs including all consumable chemicals and waste disposal were assumed to be 2% of EPC cost with a 2% yearly escalation factor. The economic analysis results are shown in **Table 11**.

Table 11: Financial model outputs

IRR (%)	18.64
NPV (MM$)	45.80
Payback time (yr)	10.1
LCOE ($/Mwh)	41.01

Source: UCRiverside

The financial model shows an 18.64% IRR with LCOE of 41.01 $/kw. The payback period of the plant is 10.1 years excluding the two-year construction period with an NPV of 41.01 MM$.

Sensitivity Analysis

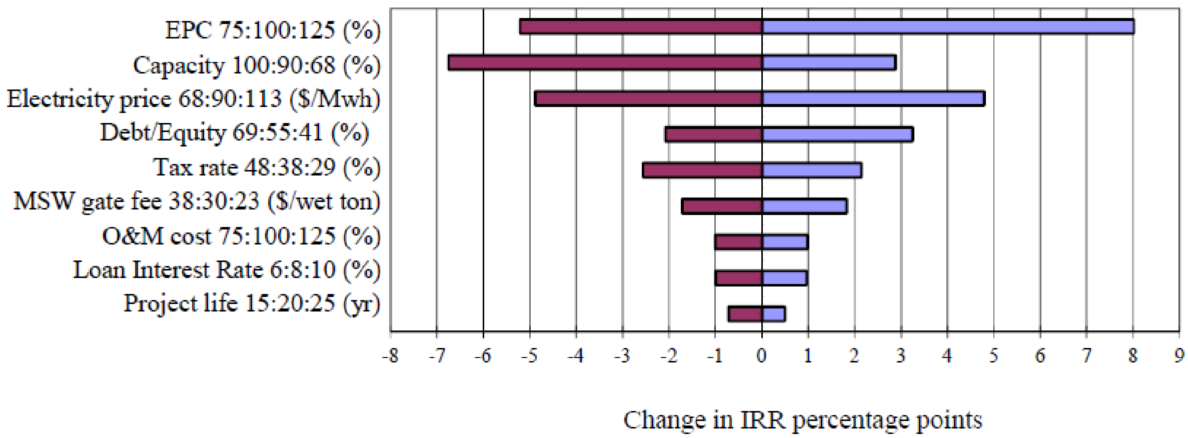
Except for plant feed and output rates, all financial model inputs were varied to determine the project financial sensitivities. The range of model input variables used in the sensitivity analysis is listed in **Table 12**. Input changes for the model were based on previous IRR calculation inputs. IRR sensitivity was evaluated using a ±25% change in the unit input. The variables and their impact on the financial outputs were then ranked to determine the model inputs of highest sensitivity, as shown in **Figure 73.**

Table 12: Range of values used in the sensitivity analysis

Model input	Baseline	(+25%) High Range	(-25%) Low Range
EPC cost ($MM)	96.4	120.5	72.3
Capacity (%)	90	100	68
Electricity sale price ($/Mwh)	90	113	68
Payback of MSW gate fee ($/ wet ton)	30	38	23
O&M Cost ($MM)	4	5	3
Project life (Yrs)	20	25	15
Debt (%)	55	69	41
Tax rate (%)	38	48	29
Loan Interest Rate (%)	8	10	6

Source: UCRiverside

Table 13: Relative sensitivities of major plant inputs, +/-25%



Source: UCRiverside

Based on IRR sensitivity analysis results, the most influential factor is EPC since it dominates the project contingency, capital depreciation and total amount of loan capital. Because other model inputs are based on a percentage of the plant EPC cost, changes in this variable has a multiplier impact on the overall economic results. Plant capacity is the second most important factor that determines the amount of power generation.

The IRR decreases by 6.8% if the plant capacity drops from 90% to 68%. Electricity sale price is the third important factor that affects the plant revenue directly and IRR varies ±4.9% while electricity sale price changed by ±25%. Debt/Equity, tax rate and payback of MSW gate fee also have important effect on IRR range from ±1.7% to ±3.2%. O&M cost, loan interest and project life have less impact on IRR within ± 1.0%.

Conclusions

The 500-dry-ton/day embodiment modeled and analyzed by UC Riverside represents an advanced version of the gasification process that operates at 400-psi, which serves to boost the over-all plant efficiency to 45%, compared to 31.5% efficiency for a near-atmospheric pressure gasification cycle integrated with a steam-injected gas turbine used for power generation.

A demonstration-scale project is based on a 40-ton/day embodiment, that will receive two tractor-trailers loads per day, each containing about 20-ton of refuse derived biomass. Power output would be 1.7 MW based on using IC engines designed for operation on low-BTU gases. Permitting a 1.7 MW demonstration scale MSW-to-Power project would not be problematic because the environmental impacts are minimal and would allow for a negative declaration.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Technology Transfer Plan

A primary benefit of the EPIC program is the technology and knowledge-sharing that occurs both internally within the renewable energy community and across the other IOUs, CEC, and the industry. To facilitate this knowledge-sharing, Taylor Energy and UC Riverside will share the results of this project in industry workshops and through public reports published on the Taylor Energy website.

UC Riverside has already started sharing the knowledge internally via meetings and presentations and will continue to do so targeting groups that deal with related renewable energy and biopower generation issues such as Clean Energy Programs, and Grid Integration and Innovation. External outreach will target the utilities as end users and industry as service providers. Additional stakeholder outreach will include policymakers and companies in the collection and waste recycling business; the distributed energy sector and municipal jurisdictions could also benefit by being informed about emerging waste-to-energy systems.

Taylor Energy has already shared project results at a symposium sponsored by UC Riverside's Center for Renewable Natural Gas, which symposium included diverse interested parties. The Center will continue to facilitate meetings with interested stakeholders. In addition, Taylor Energy plans to present the project to audiences at the thermochemical knowledge sharing conventions listed below in **Table 14**.

Table 14: Planned Knowledge Sharing Venues

Name	Description	Time/Location
TC Biomass	The International conference on thermochemical conversion science	Q3 2019
TC Biomass	The International conference on thermochemical conversion science	Q3 2020

Source: Taylor Energy

Market Adoption

The technology being developed at pilot-scale is designed for scale-up to single-trains with 1200 ton/day RDB thermal-processing capacity producing 40-MW of net power to the grid. This technology is intended for deployment at community scale and replicated at multiple locations.

The knowledge gained from this project is used by the thermochemical conversion community to increase understanding of new conversion pathways, new methods of using shockwave power to intensify thermal-chemical processes.

Taylor Energy intends to establish a demonstration-scale project that generates 1.7 MWe processing about 40-ton/day RDB. The opportunity is technology driven in the sense that the conversion process must be proven at some reasonable scale to gain momentum. Concepts are easily promoted; but in the waste-to-energy business, there have been past failures; technology-success at some modest scale is needed to verify the any advanced gasification concept. A 1.7 MW plant is an economic scale for various venues around the world. Catalina for example has the need for a 40 ton/day waste to energy project. The team considers the small-size plants to be semi-commercial endeavors because the economics require some unique constraint to make sense; for example, a small island community imports liquid fuels for power generation, and therefore, already pays a high cost for baseload power.

The commercial module plan to market is a 427-ton/day plant exporting 10-MWe. For permitting purposes in California, 500-ton/day is the optimum size for early deployments. The value proposition is that MSW can be used economically as a sustainable energy resource. However, the opportunity is present within certain performance parameters, driven by the ability to guarantee throughput, and adequate return on investment, when operating with reasonable feedstock contracts and modest revenue contracts for the renewable energy products.

MSW is a significant source of renewable energy: the per capita disposal rate of refuse derive biomass in the U.S. is 4.4-pounds per person per day, or about 1-ton per person per year. In California, waste-haulers dump 30-million tons per year of organic materials into 80 existing landfills. New waste-to-energy projects could utilize 75-percent of all MSW landfilled to generate more than 3,300 MWe. At least 50,000 ton/day RDB is certainly obtainable, controlled by long-term contracts that are dedicated to advanced recycling type energy projects.

Data Access

Upon request, Taylor Energy will provide access to data collected that is consistent with the CPUC's data access requirements for EPIC data and results.

Knowledge management is now the common term used to express knowledge in different ways by researchers. Knowledge management is defined by Stuhlman (2007) as a conscious, hopefully consistent, strategy implementation to gather, store and retrieve knowledge and then help distribute the information and knowledge to those who need it in a timely manner.

Technical Advisory Committee

A Technical Advisory Committee meeting was held on January 23, 2017. The participants are listed below:

- Mr. Bob Bradley, Biomass Power Plant Developer
- Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy
- Dr. Sam Young, Retired Naval Captain
- Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering
- Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology

Meeting comments and the subsequent discussion are listed below:

Mr. Bob Bradley, Business Man, Biomass Power Plant Development
Data should be in a form that is comprehensible to the non-scientist; simple graphic output images. He would we like to know the permitting constraints; the permit values for emissions for the Imperial Valley? My response: yes.
The 160-acre site owned by his company, ML Energy, located in the Imperial County, is permitted for thermal processing of biomass and refuse derived biomass. A natural gas pipeline is at the foot of the property; transformers and power connections exist to export 30-MWe of power to the grid.

Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy
Concern about any waste water treatment issues; organics in the waste water.
My response: Nitrogen compound sin the feed form ammonia NH3 during gasification, which reacts with HCl (also formed during gasification), forming ammonium chloride that precipitates as a salt in the final water scrubbing system. However, for successful operation, heavy organic fractions must be removed from the fuel-gas up-stream from the aqueous scrubbing system to preclude a water treatment issue. The Reformer and High-Temperature-Granular-Filter are intended to remove heavy organics from the products gases by thermal cracking. A favorable market response can be expected ("I would be excited…") if pulse-jet burner is "as good as" a plasma burner – without the high initial cost and the high operating cost.

Dr. Sam Young, Retired Naval Captain
Requested information about the schedule; and about the environmental performance. My response: The testing will be completed by the end of June and the draft -reports will be submitted by the end of the year. Environmental issues will certainly need to be addressed thoroughly during demonstration scale operation, running extended test campaign. After this program, next step is to achieve 500 hours of operation, in preparation for demonstration scale.

Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering
Discussed the ASPEN modeling and analytical work that will be performed as project deliverables.

Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology
Requested information about scale-up program; we responded with information about the CEC's demonstration programs.

Appendix D, Technical Advisory Committee Documents, includes the notifications, and invitations.

CHAPTER 5: Conclusions/Recommendations

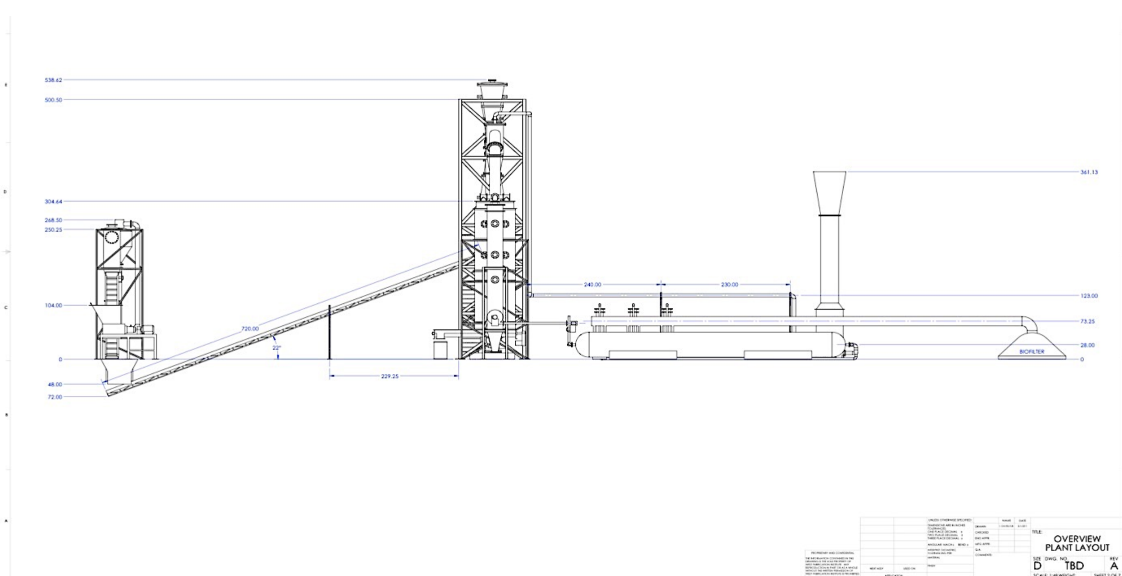
Introduction

Waste biomass gasification is well known and efficient, but the cost of sustainable power derived from societal wastes is higher than for power from fossil derived natural gas. In order to generate renewable power from California's abundant municipal waste residues, the thermal gasification and fuel-gas utilization processes must be improved. The State's organic waste residues can be used to build an advanced recycling industry that employs thousands of people, by advancing waste-to-energy conversion methods that are economical. Breakthroughs are needed that enable techno-economic advances to bring cleaner energy to the state.

However, the business and technology-development risks are significant. The resources and the barriers to develop waste gasification and related synthetic-fuels production are too great for most small businesses, and too developmental for the majors to allocate significant R&D funds. Refinery-scale utilization of residual petrol-carbons is well-known and not considered high-risk; although, the capital investments are large for the refinery-scale embodiments. Production of community scale renewable power made from waste biomass is not being developed aggressively by industry leaders in the fossil fuel and petrochemical industries at this time.

Allocation of Energy Commission funs to the accomplishment of multiple demonstrations-scale waste conversion projects is highly desirable to overcome barriers that otherwise prevent commercialization of waste utilization technologies that will help California achieve multiple environmental, economic, and security goals. **Figure 75** below shows the preliminary design for construction of a modular type 40-ton/day waste gasification system used to generate 1.7 MWe.

Figure 75: RDB Gasification/Reforming System Designed for 40-TPD Demonstration-Scale



Source: Taylor Energy

Recommended Improvements

Improve pulse-detonation burner – The team can fire the pulse-detonation burner (**Figure 76**) at 2.5 Hz. The optimum firing rate may be around five to seven Hz.

Figure 76: Pulse-Detonation Burner

Photo Credit: Taylor Energy

Improve carbon-char conversion -- During start-up testing the team produced a significant amount of carbon-char. This is a typical result considering the operating conditions. The team will move to increase the rate of carbon-char conversion. The team have designed a bluff-body to insert into the top section of the gasifier, which will serve to retain char particles in the gasification zone, enabling internal circulation of carbon-char and thereby allowing for more carbon conversion to low-molecular weight gases. The technical literature indicates that carbon-char production can be reduced by 80 percent (under some conditions) by enabling internal recirculation within the gasification zone by inserting a bluff-body.

The team has had difficulty achieving high operating temperature in the venturi-reformer. The venturi portion of the reformer is working well -- in that the venturi creates suction which is taking pressure off the feeding system; however, the team have not been able to operate at a sufficiently high temperature to demonstrate effective carbon-char reforming. The researchers need to reach 1000° C to 1200° C. Increasing the pulse-detonation rate to 2.5-Hz increases the heat out-put to the reforming zone. Also, a preheat burner has been designed for use in pre-heating the back-end of the reformer so that the system can reach operating temperature sooner.

Improve carbon-char removal -- Two hot-cyclones operating in series are used for removal or carbon-char. A roughing hot-cyclone is used to separate 70 percent of the carbon-char particles from the gaseous product stream. Leaving the fine carbon particles in the syngas provides another chance to react the carbon with CO_2 and H_2O vapor to make more syngas.

CHAPTER 6:
Benefits to Ratepayers

California Renewable Energy Incentives

EPIC Program

The California Public Utilities Commission established the purposes and governance for the Electric Program Investment Charge on May 24, 2012. In this decision, the CPUC designated the Energy Commission as one of four administrators of the program.

The portion of the EPIC Program administered by the Energy Commission provides funding for applied research and development, technology demonstration and deployment, and market facilitation for clean energy technologies and approaches for the benefit of ratepayers of Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company through a competitive grant solicitation process. Projects must address strategic objectives and funding initiatives as detailed in the appropriate EPIC Investment Plan.

In December 2016, the Energy Commission adopted a target for 25 percent of EPIC Technology Demonstration and Deployment (TD&D) funding to be allocated to projects sited in disadvantaged communities, under Senate Bill 350 (De León, 2015). Additionally, on October 7, 2017, Governor Jerry Brown signed Assembly Bill 523 (Reyes, 2017) into law, adding an additional requirement of EPIC's technology demonstration and deployment funds to be allocated to projects located in and benefitting low-income communities. The bill also requires the Commission to consider the adverse localized health impacts of proposed projects to the greatest extent possible, when applicable.

Renewable Electric Power

California Gov. Jerry Brown signed Senate Bill 100 (SB100) into law, setting the fifth largest economy in the world on a path to 100 percent renewable energy by 2045. SB100 builds on California's clean energy leadership by establishing bold new clean energy targets for the state. California is now the largest global economy to commit to 100 percent renewable energy.

The bill–now law–authored by Senator Kevin de León (D-Los Angeles), revises goals for clean energy, moving them up by several years. It requires California to get fifty percent of its energy from renewable resources by 2026, and sixty percent by 2030. The goal of the bill is to achieve 100 percent renewable electricity by 2045.

SB100, includes an amendment to California's Renewable Portfolio Standard (RPS). An RPS is a regulatory standard requiring a certain amount of energy to come from renewable sources like solar and wind. Currently, the California's RPS requires half of all electricity delivered by utilities to come from renewable sources of energy by 2030. SB100 builds on California's clean energy leadership by establishing bold new targets for the state. SB100 creates a new RPS target of 60 percent of the electricity in our state generated by from renewable sources by 2030. It also establishes that the remaining 40 percent come from zero-carbon sources by 2045. The legislation creates flexibility for California between 2030 and 2045 for new clean, renewable technologies to emerge as the state pursues 100 percent clean energy by 2045.

Renewable Natural Gas

California Governor Jerry Brown signed SB 1440 (Sen. Ben Hueso), a bill sponsored by the Sacramento-based Coalition for Renewable Natural Gas (RNG Coalition) that authorizes the California Public Utilities Commission (CPUC) to adopt a biomethane procurement program that benefits ratepayers, is cost-effective, and advances the state's environmental and energy policies.

"The signing of SB 1440 into law is an important next step towards realizing increased development, deployment and utilization of renewable natural gas from a variety of feedstocks in the State," said Johannes Escudero, CEO of the RNG Coalition. "The bill creates a proceeding where Taylor Energy will have the opportunity to make the case for why and how an RNG procurement program will create market certainty that the industry needs in order to access the investment capital required to build RNG production facilities in California."

"Over the past couple of years, we have passed groundbreaking legislation to address climate change and reduce the emissions of dangerous greenhouse gases and short-lived climate pollutants," said Senator Hueso. "With the efficacy of the RNG Coalition and the signing of SB 1440 into law, we have taken a step further to advance the state's methane emissions' reduction goal, while decarbonizing the natural gas pipeline system in California."

Signing of SB 1440 follows Brown's signing of another RNG Coalition-sponsored bill last week. AB 3187 (Asm. Tim Grayson) requires the CPUC, by no later than July 1, 2019, to open a proceeding to consider funding biomethane interconnection infrastructure through a gas corporation's utility rates.

"Renewable natural gas has many environmental advantages because it can replace fossil sources of natural gas in homes and businesses," said Assembly member Grayson. "This legislation will help equip biomethane producers and utilities to further integrate this clean energy technology in order to meet California's greenhouse gas reduction goals."

AB 3187 directs the CPUC to consider addressing the single largest cost barrier – interconnection costs - and enables the industry to invest in and construct RNG facilities to lead the state to meet its climate change goals. The RNG Coalition looks forward to the opportunity to advocate for increased interconnection incentives before the California Public Utilities Commission next year.

"With California's organic waste diversion and methane reduction mandates fast approaching, it is critical that we consider policies now to enable the development of renewable natural gas facilities in California," said Nina Kapoor, RNG Coalition Director of State Government Affairs.

Ratepayer Benefits From this Project

This project will result in the ratepayer benefits of rural and urban economic development, lowered environmental impact, and increased security. Economic benefits are lower electric bills, achieved by lowering the cost of renewable power which makes up a portion of the energy mix. Environmental benefits include decreased impacts from global climate change by using renewable feedstocks instead of fossil fuels. They also include reduced health risks due to reduced landfill operations. Security benefits include reduced reliance on natural gas delivered via interstate pipelines used for power imports compared to using an instate resource.

According to the Black & Veatch screening model used to analyze biomass gasification technology, at 300-ton/day scale, the LCOP would be $118/MWh, based on our process cost projections and operating cost estimates. **Figure 13** shows our concept for a 300-dry-ton/day waste-to-energy facility using gasification integrated electric power generation.

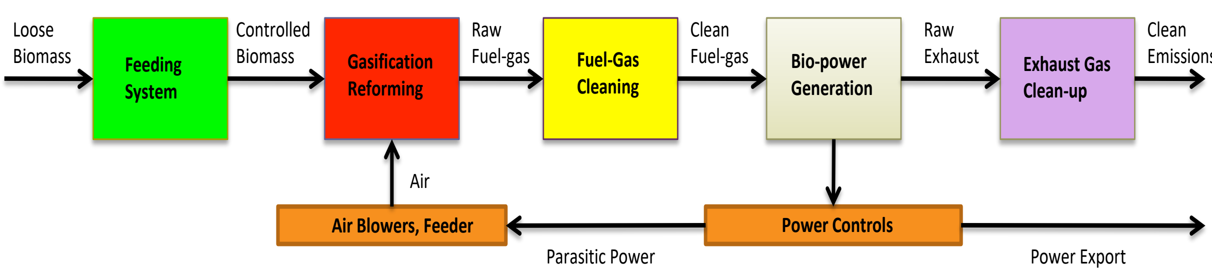
Figure 13: Proposed Commercial-Scale MSW Receiving & Processing

Source: City of Kona, HI

One measure of the project value is the projected cost-savings when compared to the cost of power generated using existing waste-to-energy conversion methods. The competitive cost for large commercial waste-to-energy power is about $142/MWh in 2018, increasing to about $158/MWh in 2024. Assuming a mean power price of $158/MWh for existing waste-to-energy derived power, the measurable cost savings is estimated to be $40/MWe for every megawatt of power generated using the proposed new shockwave gasification/reforming technology.

Future work includes a subsequent Taylor Energy/UCR project funded by the California Energy Commission to compare several different power generation cycles using forest residues. And then, using an optimum process configuration, accumulate 500-hours of operating data in preparation for the scale-up design of a 1.7 MWe demonstration project.

Overall Process Flow Diagram – Biomass-to-Power



Source: Taylor Energy

GLOSSARY

MSW	Municipal Solid Waste
RDB	Refuse Derived Biomass
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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APPENDIX A:
Waste-to-Energy Evaluation, 40-ton/day, 1.7 MWe renewable electricity, Taylor Energy

Analysis and Evaluations

1.0 Technology Description--Introduction

An objective was to evaluate a 40-ton/day gasification facility employing advanced MSW recycling technology integrated with electric power generation, using refuse derived biomass (RDB) as the feedstock in an environmentally responsible manner at demonstration Scale. Based on the study that follows, a 40-ton/day scale (36-tonne/day) -- using an average of two (2) tractor-trailer loads per day, each carrying 20-tons -- has been determined to be the optimum capacity for a Demonstration Scale facility, based partially on the transportation logistics.

Figure 1.1: Walking-Floor Type Tractor-Trailer to Transport RDB

Photo Credit: Havagotransport

At design capacity, no more than five trucks per day will deliver shredded-RDB to a covered storage facility between the hours of 7 AM and 4 PM Monday through Saturday. Once in the receiving area, the feed will be visually inspected, then unloaded in the receiving and storage area. The conversion technology is accomplished with the steps below:

- Receive an average of 40-ton/day of shredded-RDB at the Renewable Energy Facility.
- Taylor Energy Gasification technology is used to convert RDB into a fuel-gas product;
- Clean the fuel-gas by removing all impurities through filtration and wet-scrubbing; and
- Generate Electricity using Medium-Speed IC Engine-Generators

Figure 1.2: Shredded-MSW produces Refuse Derived Biomass (RDB)

Photo Credit: Taylor Energy

The feedstock basis used for the waste-to-energy demonstration facility is an RDB-fluff produced from the light-fractions of commingled paper, organics, and plastics, that are separated from shredded MSW.

RDB contains a relatively high volatile-fraction with relatively low fixed-carbon, thus offering a feedstock with excellent properties for thermal gasification. The plastic fractions and high-surface-area paper are gasified quickly in a high-temperature entrained-flow type gasification environment. The rapid formation of volatiles derived from paper and plastic serve to enhance the gasification of more resistant woody-biomass (when compared to wood alone). The Feed Basis used to define Refuse Derived Biomass for this evaluation is listed below as Rev 1, compared to other feeds:

Table 1.1: RDB Ultimate Analysis in Rev 1 compared to MSW and other feeds.

										Rev 1
		Pilot	Pilot	Pilot	Demo					Proposed
					40t/d		Pap+Plas		Battelle	Design
		700 °C					Mixed	Raw		
	HHV,	MunWast	MunWast	Plastic	MW	Pulp	Waste	MSW	RDF	
	Btu/scf	Mol%	Mol%		Mol%					
C		37.74	37.74	75.4	33.4	37.5	55.1	48.43	47.31	47.6-31
H		5.01	4.93	12.2	4.42	4.88	8.6	7.06	6.61	6-4.5
N		1.79	1.61		1.26	1.28	0.2	0.99	0.68	1.2-1
S		0.5	0.7	0.1	0.47	4.63	0.3	0.15	0.14	0.4-0.3
Cl		0.7	0.43	2.1	1	0.29	1.2	0.64	0	1.5-1.0
O		26.9	30.6	9.7	28.05	28.1	20.8	29.92	34.71	34-27.2
ASH		27.4	23.8	0.5	31.1	23.2	13.8	13.31		20-12

Source: Taylor Energy

1.1 Bulk Properties of RDB

The feedstock specification call for RDB shredded to one-inch-minus (<1") to be used for gasification at demonstration scale. In the laboratory, it is possible to produce RDB with up to about 8,000 Btu/lb. Air-dried RDB, containing 12% moisture, with 6,930 Btu/pound is probably a realistic number to use for the engineering basis (at demonstrations scale) because the RDB production quality is controlled and the paper and plastics content tends to be relatively high.

However, for commercial scale projections, note that a more realistic number is about 5,000 Btu/lb because much more green waste is typically present, the mineral-ash content is generally higher, and there are more refractory components in the feed, such as tree-bark, which results in more fixed carbon reporting to the solid residues.

1.2 RDB Storage and Feeding

Shredded-RDB is transported in a walking floor tractor-trailer to the renewable energy facility, and delivered to the storage area, constructed of a concrete steel-reinforced floor with two perpendicular push-walls also constructed of steel-reinforced concrete, where the RDB is piled and moved about with a front-loader. Periodically, RDB is pushed into a live-bottom storage bunker, where it is stored on a walking-floor conveyor, which controls the feed-rate to the gasifier. The storage bunkers are 10' wide x 10' deep x 60' long, providing 24-hours of storage capacity, so that the feedstock is continuously withdrawn by the means of a Rate Control System that feeds the gasification process.

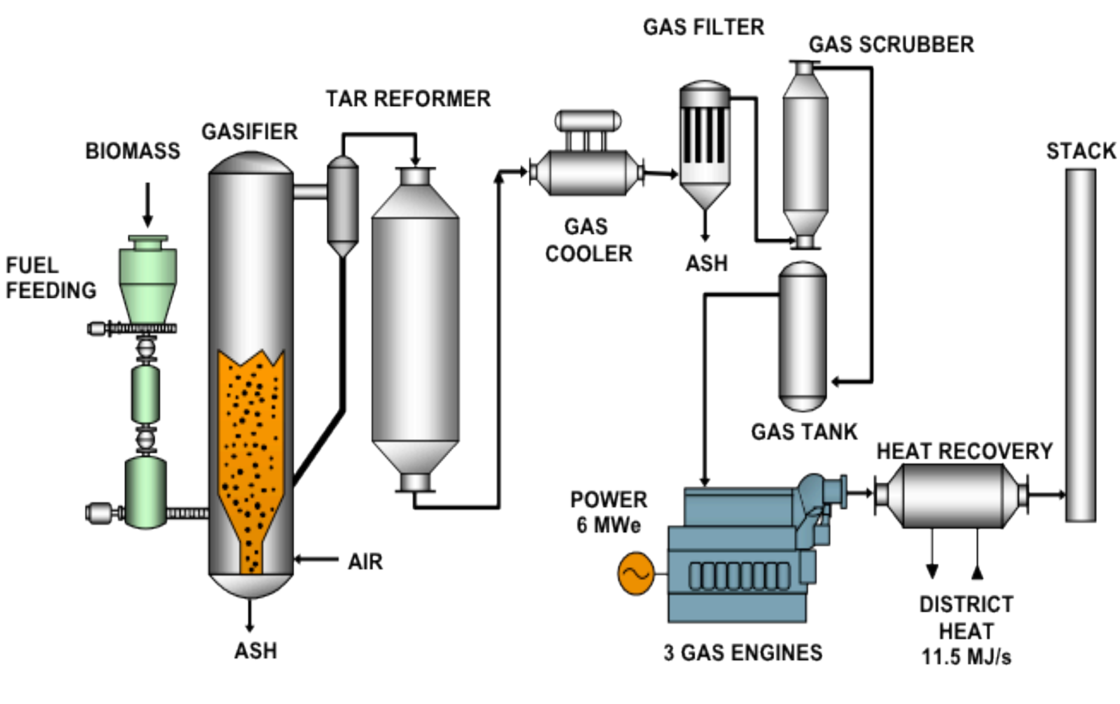
Figure 1.3: Walking Floor Bunker Storage, Discharging onto Screw Conveyor

Photo Credit: Taylor Energy

2.0 Gasification Integrated with Power Generation

The product of RDB gasification is a fuel-gas that consists primarily of hydrogen, light hydrocarbons including methane, carbon dioxide, carbon monoxide, nitrogen, and water vapor. This fuel-gas product has a low-energy-density compared to natural gas but can be used very effectively for electric power generation when fired in medium-speed reciprocating engines at demonstration scale (40-ton/day), whereas, a STIG-cycle gas turbine may be a more desirable alternative at Commercial Scale.

Figure 2.1: Graphic Representation: Entrained-Flow Gasification used for Power Generation



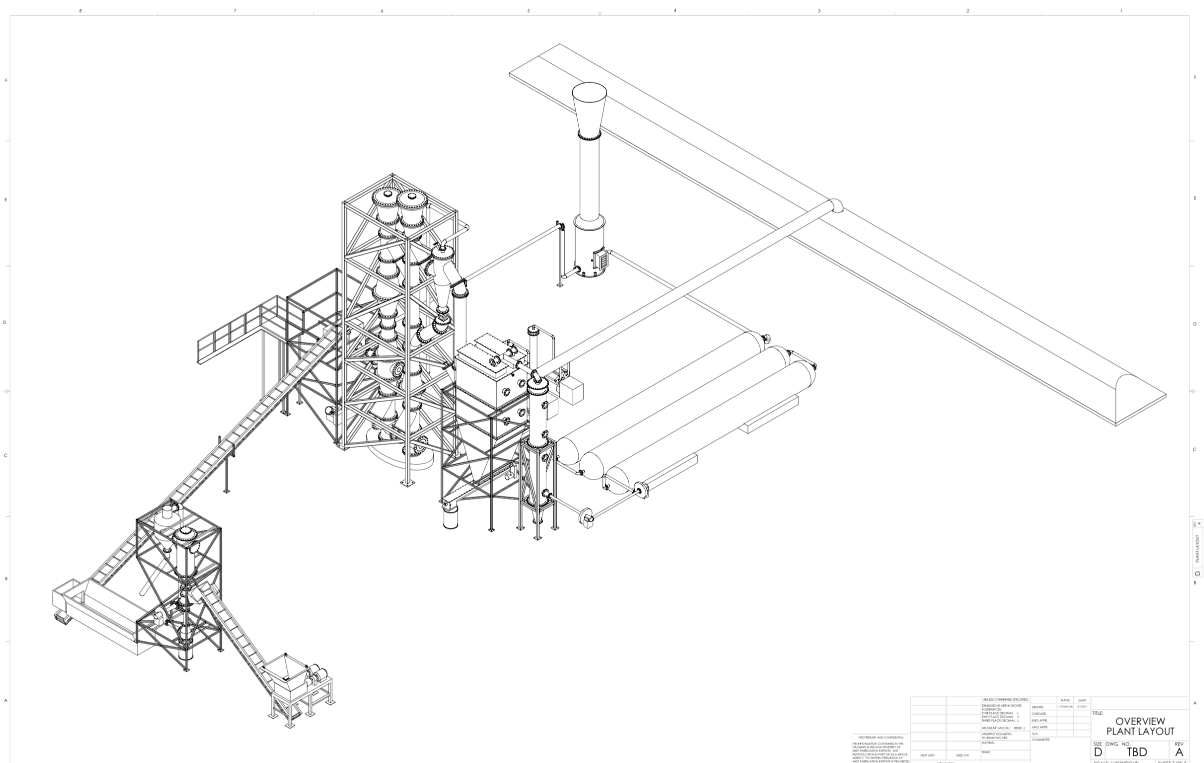
Source: Carbona GTI

Autothermal gasification is generic process type. Entrained-flow gasification technology (employing a spouted bed primary receiver), followed by a pulse-detonation powered tar-reformer is proposed for demonstration. RDB is metered into the gasifier operated near atmospheric pressure, using an extrusion-screw type auger-feeder that forms a seal with atmosphere, minimizing the infiltration of ambient air.

Low-pressure air (less than 3-psig) enriched to 33% O2 is input to the reactor to enable partial oxidation of about 30% of RDB energy content, which generates the heat necessary to gasify and reform RDB, converting the organic fractions into low-BTU fuel-gases and carbon-char.

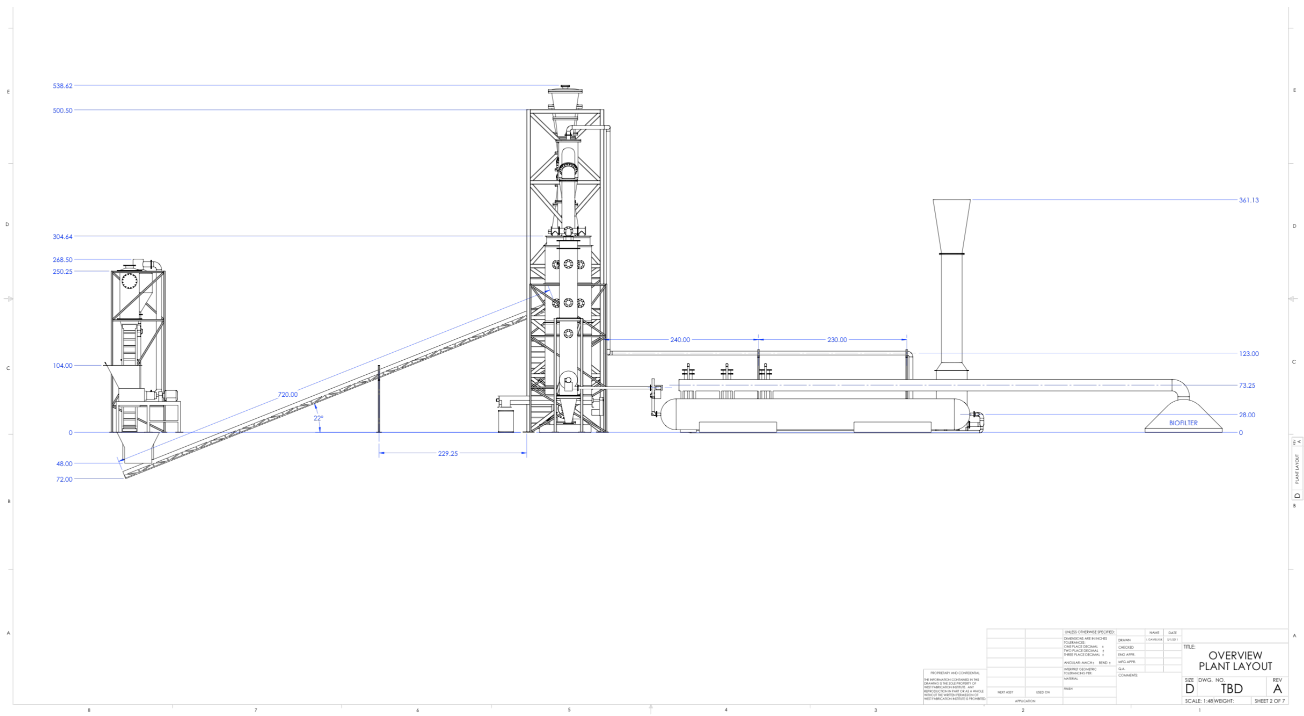
Compared with other existing gasification technologies, the Taylor Energy process is simple to operate, and is very robust for continuous power generation applications. Moreover, diverse fuel types can be used as the energy feedstock. For example, sawdust, leafy biomass, or refuse derived biomass, are all acceptable energy sources for the gasification/reforming system that is shown below.

Figure 2.2: RDB Gasification / Reforming System Designed for Demonstration-Scale



Source: Taylor Energy

Figure 2.2: RDB Gasification / Reforming System Designed for Demonstration-Scale

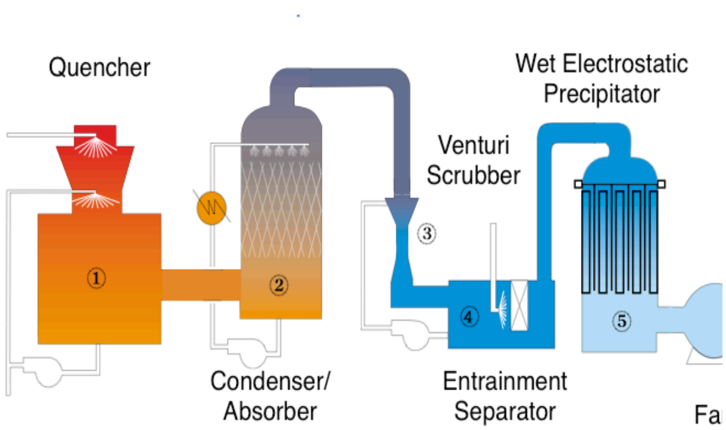


Source: Taylor Energy

2.2 Gas Cleaning System

Multiple cleaning stages that separate solids, then cool and scrub the product gases are designed to remove fly ash, acid gases, volatile salts, and reduce the moisture content of the fuel-gas product. The cleaning system is composed of cyclone-separators, special filters, and wet-scrubbers that have been designed for this type of fuel-gas cleaning application. Envitech, Inc. of San Diego, California, has provided the specific design of the Demonstration Scale fuel-gas cleaning system shown below.

Figure 2.4: Fuel-gas cleaning system



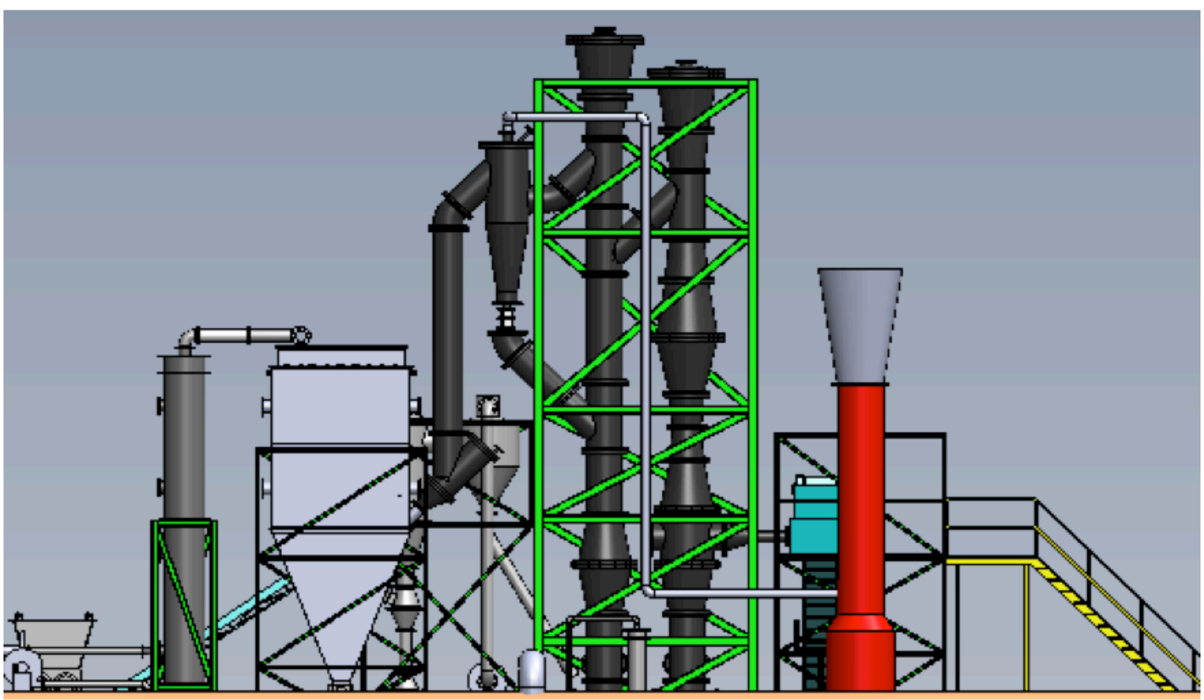
Source: Envirotec

Fly ash, which includes a significant carbon-char fraction, is composed of light particulate-matter that is entrained in the fuel-gas stream and is first removed using hot-cyclone separators followed by filtration. Carbon-char combined with mineral ashes will be disposed in a near-by Class-I Sanitary Landfill.

The final wet-scrubber is a water-based system that reacts ammonia with acid gasses present, providing the water-environment where trace amounts of ammonia (NH3, produced during gasification) react with trace amounts of hydrogen chloride (HCl, liberated from polyvinylchloride during gasification) to form ammonium chloride, a harmless salt that can be precipitated from the scrubber-water brine.

The fuel-gas leaving the aqueous scrubbing system will flow through a demister to remove moisture entrained as a fine aerosol mist. At this point, the gas purification process is complete. The gas is compressed to less than five pounds (<5-psig), using a multi-stage centrifugal blower, and delivers the fuel-gas to buffer-storage tanks used to manage the fluctuations in gas production volume that are inherent in the gasification process. The buffer-storage capacity is used to dampen the variations in flow. The storage tanks hold less-than 30-seconds of production gas volume, but this minimal storage is nevertheless essential to enable fuel-gas to be is withdrawn continuously on demand by the engine generating equipment. After passing over a three-way catalyst to minimize the NOx, CO, and HC content, the engine exhaust is cooled and humidified and delivered to the bio-filtration for final polishing where any trace contaminants that may have passed through the system are moved.

Figure 2.5: RDF Gasification System



Source: Taylor Energy

The gasification system will be equipped with an emergency flare designed to burn fuel-gas during start-up and during any emergency off-specification conditions. The flare is shielded from view.

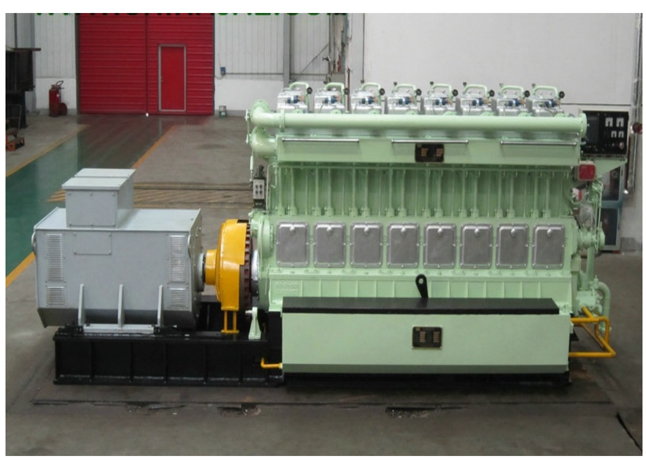
Figure 2.2: The Demonstration Facility will employ an enclosed flare

Photo Credit: Taylor Energy

2.3 Electric Power Generation

At demonstration scale, electric power will be generated by combusting clean fuel-gas in well-proven reciprocating type engines. The power generation-island will employ three medium-speed engines. Each engine has a maximum power capacity of 1000 kWh, with 42% simple cycle efficiency. Five-hundred RMP engines (500-RPM) made by JAE are selected for use with low-BTU fuel-gas that are far superior to 1,500-RPM engines typically provided by other engine suppliers in the smaller size ranges. These are superior engines for operation with low-BTU fuel-gas because (at 500-RPM) the time available to complete in-cylinder combustion is 3-times longer when compared to time available when operating at 1,500 RPM (that is, period of crank-angle is 3-times longer). While this may seem like a small detail, an inherent property of low-BTU fuel-gas is that the combustion kinetics are limited by the inert fractions present, that get in way and slow the reactivity. More time in the combustion chamber is essential. High-speed engines fail, where medium and low-speed engine can succeed.

Figure 27: Medium-Speed IC Engine, designed for operation with Low-BTU fuel-gas



Source: Shendong Diesel

JAE, the largest engine manufacturer in China, is the proposed engine manufacturer, supplying low and medium-speed ship engines, and engines designed for continuous stationary power generation. Ship-engines of this similar type are routinely serviced in port cities throughout the Pacific region.

2.4 Bio-filtration of Engine Exhaust

Bio-filtration is a gas purification method that can serve as a final cleaning process, whereby trace contaminants are removed from exhaust gases that would otherwise be released into the environment. Taylor Energy performed the preliminary design of a bio-filtration system constructed by CR&R and is considered one of the largest bio-filtration systems in the world. The bio-filter, shown below, is capable of processing 300,000-scfm of air discharged from a Materials Recycling Facility (MRF). The exhaust is passed through moist shredded wood that serves as the final (biological) filtration media.

Figure 2.8 Bio-filter designed Taylor Energy

Photo Credit: Taylor Energy

While bio-filtration has rarely been used to purify engine-exhaust, the data are very promising. The compost serves as a fixed bed filtration system. The superficial velocity of the exhaust gases to be purified must be maintained below 15-feet/second, and preferable less-than 5-feet/second. The aerobic microbes present in moist shredded can metabolize trace compounds, and reduce the oxidation state of trace heavy metals, incorporating some trace elements into the cell structure, i.e. sulfur up-take is typically 80% of any trace amounts present in the exhaust gases.

Based on the experience and testing gained at CR&R, the bio-filter can also be used to “show” the harmless character of the engine-exhaust. For example, flowering plants and shrubs are planted on the surface of the bio-filter. Moisture and excess air (>11% excess O2) are controlled to provide optimum growing conditions. When the plants are healthy, the bio-filter is healthy, which demonstrates the harmless quality of the engine-exhaust discharged to atmosphere. The costs to construct and to operate a bio-filter are modest when compared to the benefits.

3.0 Environmental Benefits

Accomplishing the conversion of waste-to-energy using gasification technology is presently the cleanest method available for using RDB that includes up to 25% plastics content as an energy resource. The historic method of burning MSW with excess air is technically feasible; modern methods used to control air emissions have proven to be reliable and work well enough so that traditional boiler/steam cycle incineration plants can be permitted for operation within the most jurisdictions.

However, relative to the environmental performance, gasification is always cleaner than incineration. Why? Because incineration methods mix excess-air with the waste-fuel to enable combustion—and thereafter, the exhaust gases are cleaned; whereas, gasification methods heat the waste to make fuel-gas first, then the gases are cleaned prior to combustion with excess air; that is, the gas is cleaned prior to combustion. Consequently, the fuel-gas volume that is subject to cleaning is one-fifth the volume of the combustion exhaust resulting from incineration.

The ability to clean a gas is a function of the volume and the partial pressure of the contaminants. Smaller gas volume results in cleaner gas and lower air emissions. Therefore, gasification has emerged as the cleanest method for using solid fuels for power generation. For example, coal-gasification is always cleaner when compared to coal-combustion. Biomass-gasification is always cleaner when compared to biomass-combustion. RDB gasification is only recently emerging as the best alternative for optimum environmental performance when used to convert MSW into fuel-gas that is comparable in purity to pipeline natural gas.

3.1 Air Emissions

Prior to use, fuel-gas is cleaned and scrubbed to achieve a purity level comparable to pipeline natural gas. At Demonstration Scale, the clean-gas is then used as fuel in medium-speed engine-generators. The proposed facility will include three engines; two engines operating continuously; one on stand-by.

Combustion of clean fuel-gas in two engines will be the primary source of emissions from the waste-to-energy conversion equipment. The power generating equipment will utilize lean-combustion methods to reduce air emissions to levels that are below the regulatory limits. Oxides of nitrogen (NOx), carbon monoxide (CO), and minor component, such as volatile organic compounds (VOC), are anticipated to be below the established regulatory limits.

If necessary, the same catalytic converters used to control automobile exhaust can also be used to purify the engine exhaust. Ninety percent (90%) NOx reduction can be achieved using this catalytic reduction technology, which relies on a 3-way catalyst to convert NOx into inert nitrogen (N2) returned to the atmosphere. Carbon monoxide (CO) and minor component, such as volatile organic compounds (VOC), generated by the engines are anticipated to be below the statutory limits.

Emission of greenhouse gases (GHG) from the proposed waste-to-energy facility using RDB gasification technology are projected to be far less than those that result from burying MSW in the landfill.

3.2 Fuel-gas Output (percent by volume)

The power generation system includes the gasifier/reformer, gas cooling, filtration, wet-scrubbing, engines, and exhaust treatment, all used to meet or exceed European and U.S. emissions standards.

	Gasifier	**Tar-cracker**	**Gas Clean-up** (typical)
CO	8.82	10.0	10-22
H2	7.36	8.61	8-14
CH4	5.46	6.51	4-6

CxHy	3.24	4.88	1-2
NH3	0.26	0.25	0.05-0.1
CO2	14.09	15.65	15-18
H2O	13.66	9.48	0.82 (saturated at 40° F)
N2+Ar	46.83	46.48	40-45
C10H8	0.25	0.023	0.01-0.02
H2S, PPmv	78	48	20-40
HCL, PPMv	139	90	25-35
HCN, PPMv	30	20	20-30
HHV,BTU/scf	184	250	302
Tars, g/Nm3	13.8	1.2	0.5
M.W.	26.7	26.5	26
Density, lb/ft3	0.074	0.071	0.070
Char, wt-&%	15	5	0.01
Ash, wt-%	7	7	0.08

Source: Taylor Energy

3.3 Exhaust Emissions (adjusted to 11% O2)

	Design Limit	Nominal
CO, mg/Nm3	2.5-5	1.8-3.6
Particulates, mg/Nm3	3-7	2-5
HCl, mg/Nm3	0.5-2	0.4-1.4
HF + HBr, mg/Nm3	<0.1	<0.1
SO2, mg/Nm3	5-15	<3.6
Heavy Metals, mg/Nm3	2.2	<1.5
NOx, mg/Nm3	200	40

PCB, ng/Nm3	163.0	<0.1
PCDD/PCDF, ng/Nm3	13.1	<5.0
Specific Heavy Metals		
Lead (Pb), mg/Nm3	<0.005	Nil
Cadmium (Cd), mg/Nm3	<0.0004	Nil
Mercury (Hg) , mg/Nm3	0.008-0.05	Nil

3.4 Residues from the Renewable Energy Facility

All processing of RDF will be performed inside the materials handling area, which will be covered for rain and sun protection, and sheltered from the prevailing winds.

Waste products generated by the facility include:

Liquid waste:

- Domestic wastewater from staff bathrooms,
- Wash water from cleaning the RDF receiving floor,
- Cooling water discharge.

Gaseous waste:

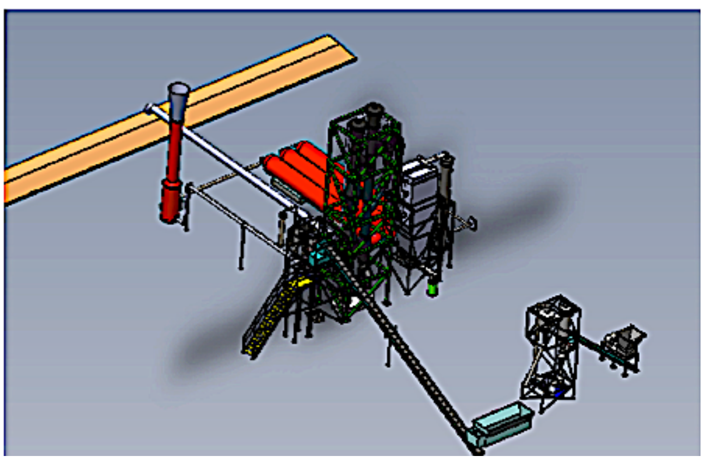
- Steam and carbon dioxide and minor air emission components

Solid waste:

- Fly ash that is captured by the emissions control equipment.

Fly-ash combined with 5% to 10% carbon-char is to be disposed in the landfill.

Figure 3. Proposed Gasification Facility; feeding through bio-filtration



Source: Taylor Energy

4.0 Project Input and Outputs

The system is composed of two parallel trains, and one complete spare process train, designed to process a total of 13,140 tonnes per year of RDF; 36-metric tonnes per day (40-short tons/day.) Each gasification train is design to process 18-tonne per day of RDF containing up to 21% moisture, which equates to 1,650 pounds per hour. Two power trains will each generate net output of 854 kW per hour, operating 8,760 hours per year at 100% on-line availability, which is accomplished by providing one complete spare, resulting in a combined output of 1,708 kWh. Detailed projections and capacity calculations are discussed below and in Sections 4.1 and 4.2 below.

4.1 Single Train Design Capacity

Feed rate: 18 wet-tonne/day RDF, containing 6,930 Btu/lb-wet @ 20-wt% moisture

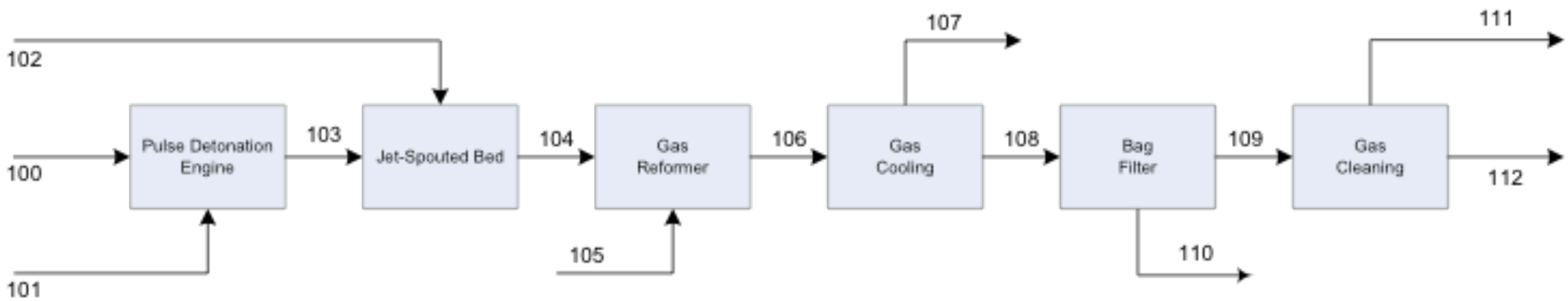
Gasification efficiency 72%,

Engine-Generator Efficiency 42% (0.72 x 0.42 =	30% efficiency
6,930 Btu/pound-dry LHV x 30% (net output eff.) =	2,079 Btu/pound (as electricity)
2,079 Btu/pound x (1 kWe / 3,413 Btu) =	0.609 kWe per pound (shredded wood)
18 tonne/day x 2,200 pound/ton =	39,600 pounds per day
39,600 pounds/day / 24 hours per day =	1,650 pound per hour
1,650 pounds per hour x 0.609 kWe per pound =	1004 kWh (gross output)
Parasitic Power Uses (air, gas compression)	(150 kWh)
Net	854 kWh

4.2 Two parallel Trains Online (One Complete Spare)

Two process trains, each designed for 18-tonne/day capacity, operating at 100% capacity.

Two Train--Name Plate Capacity	**36 tonne/day RDF**
Operating Hours at 100% online	8,760 hours/year
3300 #/hr x 8,760 hr/yr / 2200 #/ton	13,140 tonne/year RDF
3300 pounds per hour x 0.609 kWe per pound =	2008 kWh (gross output)
Parasitic Power Uses (air, gas compression)	(300 kWh)
Net	1708 kWh
Net output, 100% (8,760 hr/yr)	1.7 MWe
Pro-forma (average output for 8,760 hr/yr)	1,708 kWh
Complete Spare Engine Capacity	854 kWh



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 (wet)	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
H2O	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%
H2O	%, 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

5.0 Projections—Budgetary

Each of the two (2) lines, feeding 18-tonne/day of RDF, with a total capacity of 36-tonne/day.

Each of the two (2) gasification reactors, processing 18-tonne/day of RDF, which equates to an input capacity of 36-tonne/day shredded RDF (with 20% moisture). One complete spare.

Input:	36-tonne/day RDF
Available Energy: (3300 #/hr x 6,930 Btu/#)	22.87 mm Btu/hr
Output: (as fuel-gas @ 72% efficiency):	16.47 mm Btu/hr
Gasification system	
2562 kWh x $1,400/kWh=	$ 3,586,800.00
Power Generation Island	
2562 kWh x $1,200/kWh=	$ 3,074,400.00
Preliminary Technical Design Analysis:	$ 575,000.00
Start-Up, Commissioning and staff training,	
and initial the management of the plant	$ 500,000.00
Total	$ 7,736,200.00
Total Installed Cost ($7.74 mm /1.7 MWe)	$ 4,529/kW (of installed capacity)

This price does not include the cost of interconnecting to the power grid, the cost for step-down transformers, or the payment of duties and taxes generated by the import of equipment and does not include the payment of fees or taxes, or other events or operations that are unique to the customer's site. If there are site constraints that limit the size to a single train, or two trains, then the proposal will be revised to fit the site.

6.0 Analysis and Evaluations

The material/energy balances of the overall process proposed for Demonstration have been analyzed using Aspen Plus process simulation software.

6.1 Background

There is significant literature available on gasification of carbonaceous matter that can be used to design the process model approach. It is well established that the high temperature decomposition of carbonaceous feed occurs in two stages. At lower temperatures (400-600 ºC), devolatilization takes place, resulting primarily in chars and liquid products and at higher temperatures (600-1000 ºC), gaseous products occur because of several series-parallel reactions. Presence of a gasifying agent significantly influences these stages, and the overall process can be summarized as follows, with the pyrolysis step much faster than the gasification.

Devolatilization (pyrolysis, thermal decomposition):

Feed + Heat (400-1200 ºC) → Coke (char) + Liquids (tar) + gases

Gasification:

Feed + Gasifying agent + Heat (700-1400 ºC) → Gases (H_2, CO…)
+ Minerals (ash)

The key reactions involved are listed below[11].

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H_{1000K} = -89.9\ kJ/mol \quad (1)$$

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H_{1000K} = 170.7\ kJ/mol \quad (2)$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H_{1000K} = 136.0\ kJ/mol \quad (3)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_{1000K} = -34.7\ kJ/mol \quad (4)$$

$$C + O_2 \leftrightarrow CO_2 \qquad \Delta H_{1000K} = -394.5\ kJ/mol \quad (5)$$

$$2C + O_2 \leftrightarrow 2CO \qquad \Delta H_{1000K} = -222.0\ kJ/mol \quad (6)$$

Reaction 1 is the hydrogasification reaction, which essentially accounts for the methane production. Reactions 5 and 6 are combustion reactions, traditionally employed for generating the required process heat by supplying oxygen or air into the gasifier. Reactions 2, 3 and 4 are the steam gasification reactions. The equilibrium trends for the C-H-O system are shown below[1].

Table 6.1. Equilibrium trends for the C-H-O system

	Temperature ↑	**Pressure ↑**	**H/O ratio ↑**
X_{H2O}	↓	↑	↷
X_{H2}	↑	↓	↑
X_{CO}	↑	↓	↓
X_{CO2}	↷	**1**	↓
X_{CH4}	↷	↑ **2**	↑

[1] Carbon and Coal Gasification, NATO ASI Series, eds., J.L. Figueiredo and J.A. Moulijn, Martin Nijhoff Publishers, 1986

1 – Maximum constant, but shifts to higher temperature

2 – Maximum shifts to higher temperatures

The system is also influenced by the reactivity of carbon with various species, as shown below (1073 K and 0.1 atm)[2].

$$\begin{array}{ccccccc} r_{O_2} & >> & r_{H_2O} & > & r_{CO_2} & > & r_{H_2} \\ 10^5 & & 3 & & 1 & & 3.1^{-3} \end{array}$$

However, the actual product gas composition depends on the rate at which equilibrium is attained, i.e., reaction velocity and this information can only be obtained through experimental work. The reaction velocity depends on various parameters such as the flow rate (residence time), reactor volume and type, T, P and the feedstock composition. For all the gasification reactions, the rate is slow at lower temperatures and increases exponentially with temperature[3]. However, even at very high temperatures, the rate of gasification is considerably slower than that of the oxidation reactions and traditionally, a catalyst is employed in the absence of oxygen.

Industrial processes have been designed to carry out individual gasification reactions in different temperature ranges by using multiple stages and to optimize the reactions separately. The optimal feed composition and process parameters such as the feed rate and temperature in these two stages need to be evaluated in order to obtain maximum efficiency and desired product composition. The main purpose of the process simulation is to perform such optimization work effectively in order to help support the experimental work and to perform analysis and evaluation for technology development.

6.2 Aspen Plus Simulation Development

A detailed Aspen Plus process model has been developed and can be used to predict process behavior, and material and energy balances. Aspen Plus is a well-known simulation tool that can handle non-conventional feedstocks and process streams using built-in process units and physical/chemical property databases. A brief description of the process model used to perform the simulations is given below.

<u>Process Description</u>

Figure 1 shows the Process Flow Diagram (PFD) of the Aspen model under development. A detailed description of the technology including unique advantages is discussed in the original proposal. The

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[2] P.L. Walker jr, F. Ruskino jr and L.G. Austin, Adv. Catalysis XI, 133, 1959

[3] H.D. Schilling, B. Bonn and U. Krauss, Coal Gasification-Existing processes and new developments, Graham & Trotman Ltd, 1981

feedstock is supplied to the entrained-flow gasifier (employing a primary spouted bed receiver) through an extruder feeder and the gasification process is enhanced through a Pulse Deflagration Burner. The product stream from the gasifier is then sent to the reformer that includes a Pulse Detonation Burner. The product gas stream from the reformer goes through conventional gas cleanup/upgrading steps including ash/char separation, filtration, and gas cooling.

The proposed feedstock is Refuse Derived Biomass (RDB). The key properties include:

Fixed carbon: 8.0% (0.0970 lb/lb-dry-feed

Volatile matter: 57.0% (0.6909 lb/lb-dry-feed)

Moisture content: 17.5% wet basis

Mineral ash: 17.5%

Calorific Value: 6,000 – 6,900 Btu/lb-dry-feed

The basic parameters of the proposed Jet Spouted Bed followed by an entrained-flow section, integrated with Pulse-Detonation-Reformer include[4]:

Temperature: 800 ˚C (1472 ˚F)

Air input: 29.8 scf/lb-wet-feed

Power for compression of primary air: 15.8 kWh/ton-dry-feed

Power for oxygen production (enrichment to 33%): 41.6 kWh/ton-dry-feed

Fuel-gas heating value: 227 Btu/scf

Fuel-gas density: 20.3 scf/lb

Fuel-gas production: 26.9 scf/lb-wet-feed

Efficiency (gasification and reforming): 72.9%

Description of Aspen Plus Simulation

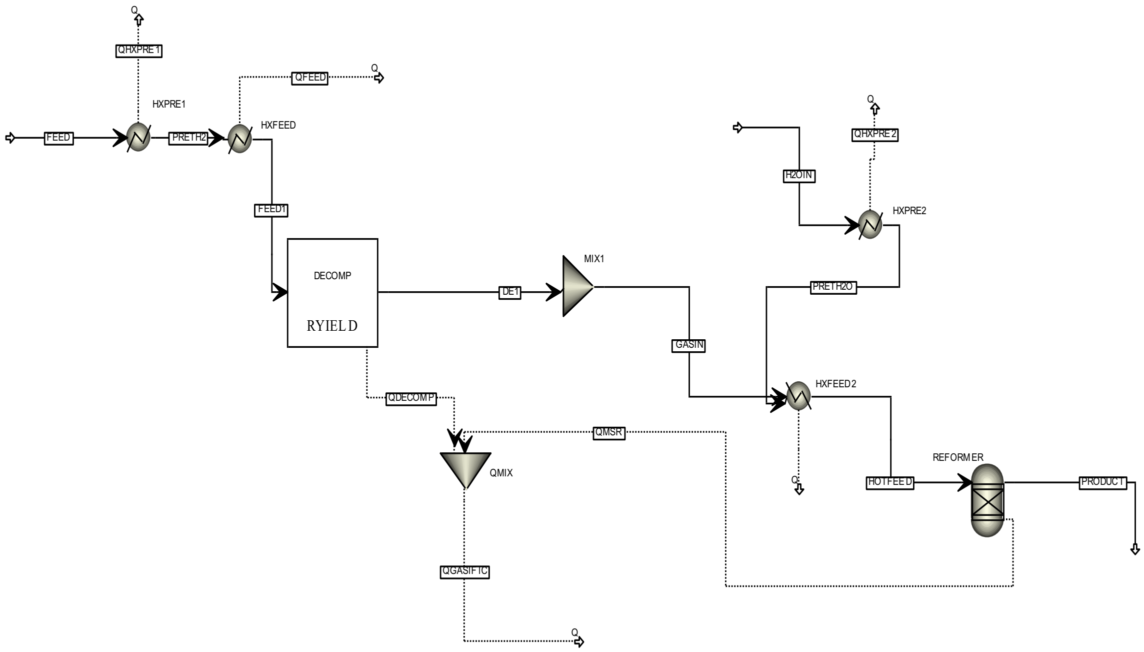
The solid feedstock is fed into the gasifier on a steady basis at predetermined feed/air ratios. The model simulates the gasifier using decomposition and gasification units. These units are based on built-in Aspen reactor blocks and calculate the equilibrium composition in the reactor under the given 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 biomass or coal into its basic elements based on yield information using the RYIELD block. The components are then sent to the gasification block (RGIBBS), which calculates the equilibrium product gas composition using the Gibbs free energy minimization approach.

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 ash and unreacted char

[4] Taylor Energy technical reports DK-99-2 & DK-98-3

are removed from the reactor as a solids-stream and the product gas is subjected to gas cleanup in order to remove trace contaminants that can include ammonia, hydrogen chloride, and hydrogen sulfide. The clean gas stream is then cooled down in two quench steps and is sent to gas storage.

Figure 6.2 below shows the gasifier model in the Aspen Plus user interface.



Source: UCR

Downstream Processes

Downstream processes such as methane reforming for fuel production or combustion-based power generation are simulated using specific versions of the model. The fuel production module is discussed below.

The clean product gas then enters the Steam Methane Reformer (SMR). The SMR is simulated using a built-in REQUIL equilibrium block. The reactions considered in the SMR are given below.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2, \quad \Delta H = 206 \text{ kJ/mol}$$
$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2, \quad \Delta H = 165 \text{ kJ/mol}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2, \quad \Delta H = 247 \text{ kJ/mol}$$
$$CO + H_2O \leftrightarrow CO_2 + H_2, \quad \Delta H = -40 \text{ kJ/mol}$$

The product gas from the SMR is then sent through a separator where the excess H_2 is removed for recycle to the SHR. The gas is cooled sufficiently in order to be used in the Fischer-Tropsch reactor. The Fischer-Tropsch reactor block used an external model, which is called by the Aspen Plus through FORTRAN module. This external model was empirically developed by Hamelinck et al.[5] to predict the selectivity of the Fischer-Tropsch process and can be expressed as below.

[5] C.N. Hamelinck, A.P.C. Faaij, H. Uil and H. Boerrigter, Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential, Energy, 29, 2004

$$S_{C_{5+}} = a_1 + a_2.T + a_3.\frac{[H_2]}{[CO]} + a_4.([H_2]+[CO]) + a_5.P_{Total}$$

Where,

Sc_{5+} – Mass fraction of hydrocarbons in the product with 5 or more carbon atoms

a_i – Empirical parameters

$[H_2]$ and [CO] - Concentrations of H_2 and CO expressed as fraction of the feed gas

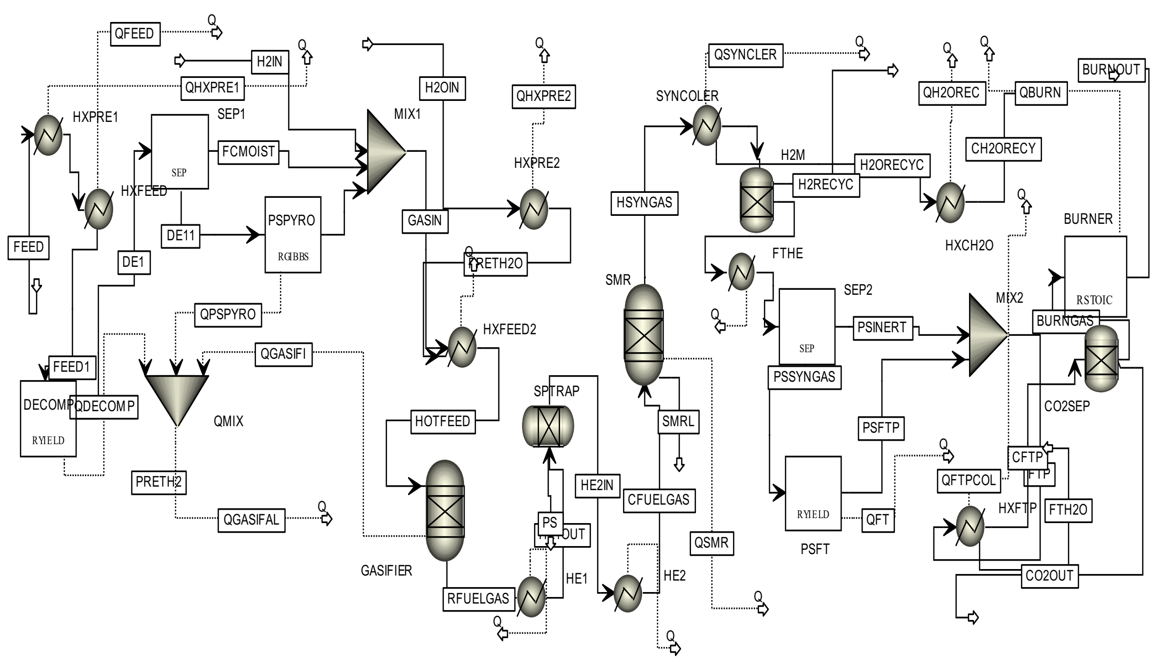
T – Temperature (K)

P – Pressure (bar)

According to Hamelinck et al., a least sum of squares fit of the above model with proprietary data resulted in the following equation, which was also found to be in accord with experimental results using a cobalt catalyst reported by Dry[6]. This equation is used to simulate the FT reactor.

$$S_{C_{5+}} = 1.7 + 0.0024T + 0.088\frac{[H_2]}{[CO]} + 0.18([H_2]+[CO]) + 0.0078p_{Total}$$

Figure 6.3 Integrated Aspen-Plus simulation Process Flow Diagram



Source: UCRiverside

6 M.E. Dry, The Fischer–Tropsch synthesis, Catalysis: science and technology, edited by J.R. Anderson and M. Boudart, Berlin, Germany, Springer; 1981, 160–253

The Aspen Plus simulations of SHR and SMR are based on equilibrium assumptions whereas the FTR is simulated by means of an empirical expression. While the simulation results can be used to perform heat and mass balances, to design experiments and to understand process behavior, it must be noted that experiments conducted in laboratory or pilot scale reactors may not be under equilibrium. Figure 6.3 shows the process flow diagram for fuel production from the Aspen simulation user interface.

The different efficiency values calculated using the simulation results are listed below.

CCE = Chemical Conversion Efficiency based on the number of moles of carbon converted into product gases. CCE is defined for each reactor separately

OCE = Overall Conversion Efficiency of the process based on the number of moles of carbon converted into product gases excluding CO_2

OCE HHV = Overall Conversion Efficiency of the process based on the HHV (Higher Heating Value) of the feed and the final product

Power Generation Module

The power generation module involves gas cleanup followed by a combustion block that simulates the stoichiometric combustion of the gas in an engine. The combustion efficiencies and electric output are based on the engine performance specifications.

Preliminary Results

Based on the equilibrium predictions, the net thermal efficiency of the process varies significantly, from 38% to 70% for fuel production and 35% to 70% for power generation. The values are highly sensitive to the process parameters including operating temperature, feed composition, and pressure. Experimental data on carbon conversion, product gas composition, yield, and energy use will be used to update the model in order to evaluate process performance for the specific feedstock/product combinations and further optimization.

6.3 Life Cycle Assessment

Two of the most important criteria used for the technological evaluation of industrial systems are the total energy consumption and the net emissions of the desired pathway. Conventional methods of evaluation often focus on a limited number of steps in a production pathway and are inadequate in their ability to quantify the “cradle-to-grave” energy use and emissions. LCA models iteratively calculate the energy use and emissions associated with specific pathways using large databases consisting of information on various stages of the pathways and some user-specified input values. An LCA of the gasification process for fuel production was conducted and the results are given below.

Greenhouse gases. The key GHGs considered by the LCA and their global warming potential (GWP) compared to CO_2 are given in the Table below. The GWPs are the 100-year warming potential values published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and are often referred to as the IPCC 2007 GWPs[7]. The GHG emissions for each pathway are calculated for each GHG and are reported on a carbon dioxide equivalent (CO_2e) basis using the GWPs.

[7] IPCC 2007, Climate Change 2007: Working Group I: The Physical Science Basis, from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html.

Table 6.2. Global Warming Potentials of the key GHGs

GHG Name	100 Year GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Chlorofluorocarbons(CFC-12)	10,900
Hydrofluorocarbons (HFC-134a)	1,430

Source: UCRiverside

Energy use. The categories of energy use are listed below.

- Total and fossil energy used per unit of energy produced for each stage of the fuel production steps
- Total energy used per kilometer driven for the fuel used in vehicles
- Fossil energy used per kilometer driven for the fuel used in vehicles
- The proportions of types of energy used for each stage of the fuel production cycle

A number of software packages are available that include extensive databases and 'pathways' that can be used to evaluate most of the existing technology/pathway options. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is one such model that is widely used in academic studies, especially in the United States. This study is conducted using the CA-GREET 2.0 Tier 2 model (CA-GREET 2017). The CA-GREET model is a modified version of the GREET model consisting of California specific assumptions.

The basic assumptions used in model are listed below:

- Analysis year: 2015
- Feedstock: Baseline pathway-petroleum oil; Biomass gasification pathway- forest residue
- CAMX grid (California-Mexico grid) mix is considered as regional electricity mix for utility supply for all the cases except solar or wind.
- CA Crude is selected for regional crude oil use
- Natural gas (NG) feedstock is considered as North American (NA) NG
- Final product FT Diesel use: passenger car with 24.81 MPGGE
- Baseline case uses Conventional low sulfur diesel refining process for fuel production
- Process efficiency: Baseline case- 89.3% (Conventional low sulfur diesel refining); Biomass gasification to FT Diesel- 49%
- Co-product credits: none
- Steam/electricity export credits: none

The Well to Tank (WTT) results of the FT-Diesel production life cycle analysis are presented in Table 6.3 below. The total and fossil energy use are listed including specific petroleum, coal and natural gas use information. The fuel production process relies on natural gas and petroleum whereas the Biomass gasification to FTD process uses some natural gas and petroleum along with the renewable resource.

The table also presents the GHG emissions in CO_2 equivalent values. The GHG emission for the baseline case is 29.8 kg CO_2e/mmBtu fuel, while the GHG emission for the biomass gasification process is -69.9 kg CO_2e/mmBtu fuel.

Table 6.3. WTT analysis of FT-Diesel production from biomass

	Energy usage or emission (Btu/mmBtu or g/mmBtu)	
Item	Baseline conventional Diesel	Biomass gasification to FTD
Total Energy	313,163	1,124,378
Fossil Fuels	309,598	82,299
Coal	3,791	816
Natural Gas	245,588	13,580
Petroleum	60,219	67,903
CO_2 (w/ C in VOC & CO)	25,823	-69,883
CH_4	139.80	9.10
N_2O	0.49	0.24
GHGs	29,464	-69,585
VOC: Total	9.85	3.55
CO: Total	20.69	12.96
NOx: Total	43.15	32.87
PM10: Total	4.03	2.60
PM2.5: Total	3.49	1.88
SOx: Total	26.16	7.84

Source: UCRiverside

The Well to Wheel (WTW) results is presented in Table 6.4 below. The results include the total energy use per mile driven using the specified fuel and the GHG emissions. The WTW analysis shows that the biomass gasification pathways use significantly higher amounts of energy per mile of the vehicles driven. The GHG emission from vehicle using the baseline fuel production process is 392 gCO_2e/mile driven, while it is 24 gCO_2e/mile driven for the biomass gasification pathway.

Table 6.4. WTW analysis of FT-Diesel production from biomass

Item	Energy usage or emissions (Btu/mile or g/mile)							
	Baseline conventional Diesel				Biomass gasification to FTD			
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	478	702	3,769	4,949	130	4,107	3,769	8,006
Fossil Fuels	470	697	3,769	4,935	130	180	0	310
Coal	8.25	6.04	0.00	14.29	0.41	2.67	0.00	3.08
Natural Gas	427	498	0	926	14	37	0	51
Petroleum	34	193	3,769	3,996	115	141	0	256
CO_2 (w/ C in VOC & CO)	39	59	294	392	-277	14	287	24
CH_4	0.41	0.11	0.09	0.62	0.01	0.02	0.09	0.13
N_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHGs	49	62	297	408	-277	15	290	28
VOC: Total	0	0	0	0	0.00	0.01	0.08	0.09
CO: Total	0.03	0.05	2.73	2.81	0.02	0.03	2.73	2.78
NOx: Total	0.09	0.07	0.23	0.40	0.04	0.09	0.23	0.36
PM10: Total	0.01	0.01	0.02	0.04	0.00	0.01	0.02	0.03
PM2.5: Total	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.02
SOx: Total	0.03	0.07	0.00	0.10	0.00	0.03	0.00	0.03
VOC: Urban	0.01	0.01	0.05	0.07	0.00	0.00	0.05	0.06
CO: Urban	0.00	0.02	1.91	1.94	0.00	0.00	1.91	1.91
NOx: Urban	0.01	0.03	0.16	0.21	0.00	0.00	0.16	0.17
PM10: Urban	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.02
PM2.5: Urban	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01

SOx: Urban	0.00	0.0 5	0.00	0.05	0.00	0.00	0.00	0.00

Source: UCRiverside

7.0 Engineering Design Calculations for Gasification Process

This section uses an empirical based design/calculation approach that can be compared with the ASPEN modeling approach presented in Section 6.0.

A key issue is the net energy conversion efficiency for the thermal gasification process. The following calculations show the engineering design basis that is likewise used to project the net RDB gasification efficiency for thermal conversion of RDB into fuel-gas, which projected at 72.9% when deployed at commercial scale.

The efficiency for the much smaller demonstration scale system is projected to be somewhat less than 68%, due to higher heat losses. The process will employ low-pressure air enriched to 33% O2 input in order to increase the BTU content of the fuel-gas product to 270 BTU/scf, which enables the fuel-gas to be used for combustion in existing engine generating equipment, and in gas turbines.

7.1 RDB to be gasified and product pattern in a gasification reactor

[Necessary data are adopted from Technical Report DK-84-4]

- RDB to be gasified (note d.f. = dry feed)
  - Gross heating value 3839 kcal/kgd.f. = 6909 Btu/lb d.f.
  - Water content 18.0% wet basis
  - Mineral/metal 17.5%
  - Based on 1 kg of d.f.
    - Volatile matter 0.691 kg
    - Fixed carbon 0.134 kg
    - Mineral/metal 0.175 kg
    - Water 0.215 kg
- Product pattern in the circulating (gasification at 720C = 1328F)
  - Volume of dry gas 0.4913 Nm^3/kgd.f. = 7.87 scf/lb d.f.
  - Gross heating value 5204 kcal/Nm^3 = 585 Btu/scf
  - Mass of tar 0.0504 kg/kgd.f. = 0.0504 lb/lb d.f.
  - Mass of char 0.1176 kg/kgd.f. = 0.1176 lb/lb d.f.
  - Water formed 0.174 kg/kgd.f. = 0.174 lb/lb d.f.

7.2 Necessary heat for gasification

Necessary heat = $Fs(0.24)(Ts_2 - 750) = 613.38 + 275.0\ Wp + L_1$ [kcal/kgd.f.]

Wp is the ratio of water vapor used for fluidization

In the Modified Fluid Bed Pyrox, steam is not used, then Wp = 0

The approximate value of heat loss L_1 is estimated in technical report DK-98-4 for 300 tons per day plant.

Surface Area

π(3m)(6m) + π(5m)(10m) + π(7.2m)(13m) + π(5m)(3m) + [π(2.4m)(4.5m) + π(1.6m)(8m)](4) = 851.4m^2

Thermal insulation is made to keep surface temperature of the reactor at 80C = 176F.

Heat transfer coefficient at the outer surface is estimated as:

Natural convection h_c = 5.9 kcal/m^2hr°C

Radiant heat h_r = 5.8 kcal/m^2hr°C

$h_c + h_r$ = 11.7 kcal/m^2hr°C = 2.396 Btu/ft^2hr°F

Assume 20% more heat loss through the support structure of the reactor.

[(851.4 m^2)(11.7 kcal/m^2hr°C)(80°C – 20°C)(1 + 0.2)] / [(1,000,000 kg feed/24hr)(1 – 0.175)kg d.f./kg feed] = 20.9 kcal/kg d.f.

Thus, necessary heat for gasification in the Modified Single-Fluid-Bed is calculated to be:

613.38 + 20.9 = 634.2 kcal/kgd.f. = 1142 Btu/lb d.f.

7.3 Amount of the air to burn carbon completely

(0.1172 kg/kg d.f.)(22.4 Nm^3/12 kg)(1/0.21) = 1.042 Nm^3 air/kg d.f.

7.4 Heat balance for combustion of carbon in the bed

Letting 0.1172 kg carbon/kg d.f. to be burnt in the bed to give necessary heat for gasification, heat balance in the bed should be checked.

[Heat Input]

Combustion heat of carbon

(7838 kcal/kg c)(0.1172 kg c/kg d.f.) = 918.6 kcal/kg d.f.

[Heat Output]

Necessary heat for gasification = 634.2 kcal/kg d.f.

Apparent heat of combustion gas

(0.1172 kg c/kg d.f.)([22.4 Nm^3/(12 kg c)(0.21)])(0.34 kcal/Nm^3°C)(720°C-20°C) = 247.9 kcal/kg d.f.

Heat output = 634.2 + 247.9 = 882.1 < 918.6 kcal/kg d.f.

Heat balance can be achieved by slight adjustment of air-flow rate.

7.5 Estimation of heating value

From Table 3, page 32, in technical report DK-98-1, density of gas produced from MSW, c.a. 4600~5000 kcal/Nm^3 (517~562 Btu/scf) is found to be 1.0 kg/Nm^3. Thus, volume of cracked gas from recycled tar stream is estimated as:

(0.0302 kg/kgd.f.)(1/1.0 kg/Nm^3) = 0.0302 Nm^3/kgd.f.

Volume of combustion gas is given by:

(0.1172 kg c/kgd.f.)(22.4 Nm^3/[(12kg C)(0.21)] = 1.042 Nm^3/kgd.f.

Thus, low heating value of product gas from the Modified Fluid Bed PYROX is estimated to be:

1790 kcal/Nm^3

7.6 Gasification efficiency

η = [(5402)(0.4913) + (0.0302)(0.6)(8000) kcal/kgd.f.] / 3839 kcal/kgd.f. = 0.729 = 72.9%

7.7 Heating Value of fuel-gas product

Gasification efficiency is high in the Autothermal Fluid-Bed; however, heating value of product gas is low, 1790 kcal/Nm^3 = 201.2 Btu/scf. It goes without saying that the higher the heating value, the safer it is to burn, and therefore we prefer to increase its heating value, for example, up to 2500 kcal/Nm^3 = 281 Btu/scf. In order to increase the heating value of the product gas, we have the following three options:

- Feeding of dry RDB
- Pre-heat of the partial oxidation air
- Enrichment of O_2 in the air, using O_2 unit

7.8 Heating Value of product gas increased by drying the feedstock

[(5402 kcal/ Nm^3)(0.4913 Nm^3/kgd.f.) + (0.0302 kg tar/kg d.f.)(0.6)(8000 kcal/kg tar)] / (0.4913 Nm^3/kg d.f. + 0.0302 Nm^3/kgd.f. + 0.730 Nm^3/kg d.f.) = 2236 kcal/Nm^3

Dry feed is extremely effective to increase the heating value of product gas.

Water content	0.175 kg/kg d.f. $\rightarrow$ 0
Heating value	1790 kcal/Nm^3 $\rightarrow$ 2236 kcal/Nm^3
	(25% increase using dry-RDF)

Oxygen Enrichment to 33% O2 has the impact of increasing the BTU content to 270 BTU/scf, which is the approach employed and is preferable to additional drying of the shredded feed.

APPENDIX B:
Waste-to-Energy Evaluation, 300-ton/day, 9.5 MWe renewable electricity, Taylor Energy

T1.0 Technology Description--Introduction

The objective is to evaluate a 300-ton/day commercial waste-to-energy facility, using Refuse Derived Biomass (RDB) as the energy feedstock in an environmentally responsible manner, and to utilize this renewable energy source to produce electricity on or near a California Landfill, providing 9.5-MWe of base load electrical output for delivery to the grid, and fulfilling the economic requirements of project developers.

The facility will utilize MSW otherwise delivered to the County landfill. To encourage private haulers and the County to take advantage of the RDB production facility, the gate fee or tipping fee at the landfill will be unchanged. This pricing will not increase the operating expenses for the commercial haulers, and will insure adequate feedstock for RDF production, provide environmental benefits, and secure a low-cost renewable fuel source for the Waste-to-Energy Facility.

At design capacity, trucks will deliver MSW inside of an enclosed facility between the hours of 7 AM and 4 PM Monday through Saturday. Once inside the receiving area, MSW will be visually inspected and pre-sorted to remove non-combustible, and other unsuitable materials. After tipping and sorting, the conversion to electric power is accomplished with these steps below:

- Convert 432 wet-ton/day MSW into 300 ton/day RDB (at or near the landfill site)
- Transport 300 ton/day RDF to the Renewable Power Generation Facility.
- Using Taylor Energy's Gasification Process, convert RDB into a fuel-gas product;
- Clean the fuel-gas by Reforming tars and by removing all impurities; and
- Generate Electricity using Steam Injected Gas Turbine Technology (STIG cycle)

1.1 Appearance of the proposed Waste-to-Energy Facility

RDF is received and stored in a sixty thousand (60,000) square foot, clear-span metal building. The building will be approximately forty-nine (49) feet high at its roof eave and rises to fifty-eight (58) feet high at its roof peak. This building contains the receiving area, material-handling equipment and the Walking-Floor type storage bunkers, which hold the processed RDF until it is conveyed to the gasifiers.

Adjacent to the RDF receiving and storage building, shown in Figure 1.2, is an uncovered, exterior screened area of approximately sixty thousand (60,000) square feet, which contains most of the gasification and power generation equipment, which includes two parallel gasification trains, each sized to process 150-ton/day RDB, providing a total RDB gasification capacity of 300-ton/day.

The perimeter screening fence is thirty (30) feet high along the West side and twenty (20) feet high along the North side with an enhanced screening element in the Northwest corner, which rises to approximately forty-eight (48) feet, serving to shield conversion equipment somewhat from view.

The area also contains a ten thousand (10,000) square-foot sound insulated building, which will house the power generation equipment, composed to one power train, with gross power output of 11.25-MWe, resulting in name-plate capacity of 9.5-MWe net output. When operating with 85% availability, the pro-forma output is projected to be 8,075 kW/hr, based on 8760 hours per year. Immediately to the east of an exterior screened area is the maintenance and water treatment facility. It will be a two-story metal building enclosing approximately sixteen thousand (16,000) square feet.

1.2 RDF Facility, Operational Summary

The conversion technology proposed to transform MSW into RDB is accomplished as follows:

1) Waste receiving
2) Separation of recyclable materials
3) Waste sorting, shredding, followed by air-classification.
4) RDF is transported to the Energy Facility using walking floor tractor-trailers.

The conversion process commences when MSW arrives at the landfill in waste collection vehicles, such as front loaders, roll-off trucks, transfer trailers, and a public tipping floor. A landfill facility will typically be open approximately three hundred twelve (312) days per year.

When operating at full capacity, the system is slated to receive at least five hundred (500) tons of MSW per day, Monday through Saturday, for a total of up to three thousand (3,000) tons of MSW per week; 156,000 wet-ton/year is the minimum design capacity for the receiving facility.

Figure 1.3 MSW on the Tipping Floor

Photo Credit: Taylor Energy

It is anticipated that the facility will receive no more than five (5) waste collection vehicles per hour between the hours of 7 a.m. and 4 p.m. Monday through Saturday. MSW is processed within an enclosed building. No waste materials will be visible to persons outside the building and fugitive litter, such as paper or plastic waste, will not be released once inside the building. Visual waste-inspection for hazardous materials by the tipping floor operators will be done for each load entering the tipping floor.

1.3 MSW--Bulk Properties of RDB

The Feedstock to be used for the proposed Renewable Energy facility is an RDB-fluff produced from the light-fractions of commingled C&D, wood, biomass, paper, organics, and plastics, separated from shredded-MSW. Refuse Derived Biomass (RDB) contains a relatively high volatile-fraction with relatively low fixed-carbon, thus offering a feedstock with excellent properties for thermal gasification.

The plastic fractions and high-surface-area paper are gasified quickly in an entrained-flow type gasification reactor. The rapid formation of volatiles derived from paper and plastic serve to enhance the gasification of C&D, wood, and landscape clippings (when compared to wood alone). The basis used to define Refuse Derived Biomass for the Proposed Project is listed below as Rev 1, compared to other feeds:

Table 1.1 Ultimate Analysis of MSW and RDB

										Rev 1
		Pilot	Pilot	Pilot	Demo					Proposed
					40t/d		Pap+Plas		Battelle	Design
		700 °C					Mixed	Raw		
	HHV,	MunWast	MunWast	Plastic	MW	Pulp	Waste	MSW	RDF	
	Btu/scf	Mol%	Mol%		Mol%					
C		37.74	37.74	75.4	33.4	37.5	55.1	48.43	47.31	47.6-31
H		5.01	4.93	12.2	4.42	4.88	8.6	7.06	6.61	6-4.5
N		1.79	1.61		1.26	1.28	0.2	0.99	0.68	1.2-1
S		0.5	0.7	0.1	0.47	4.63	0.3	0.15	0.14	0.4-0.3
Cl		0.7	0.43	2.1	1	0.29	1.2	0.64	0	1.5-1.0
O		26.9	30.6	9.7	28.05	28.1	20.8	29.92	34.71	34-27.2
ASH		27.4	23.8	0.5	31.1	23.2	13.8	13.31		20-12

Source: Taylor Energy

Figure 1.4 Shredded MSW1.4

Photo Credit: Taylor Energy

RDB Production

The proposed RDB facility will employ one 500-ton/day processing line, intended to operate seven (7) hours per day (one work shift per day). Using a bucket type front-loader, MSW is pushed into the primary shredder, operated by one person seated inside an air-conditioned cab.

Figure 1.5 Primary size reduction

Photo Credit: SSI

After primary shredding, the coarse-shredded feedstock is sent to the secondary shredder for final size reduction, reducing the size to less than two-inch (<2"). A belt-conveyor delivers this produce to the air classification systems, to separate the heavy fractions, resulting in the production of a homogeneous RDF-fluff, which is directed to storage piles located adjacent to load-out holes.

Figure 1.6 Rotary-Shear shredder used for RDB production

Photo Credit: SSI

1.8 RDB-Fluff Storage

The RDB is transported in walking floor tractor-trailers to the Renewable Energy Facility, and delivered to the storage area, constructed of steel reinforced concrete floor with two push-walls constructed of steel reinforced concrete, where the RDB-fluff is piled and moved about with a front-loader. The storage capacity of the facility is large enough to contain two days of RDF-fluff. Periodically, RDB is pushed into live-bottom storage bunkers, where it is stored on a walking-floor conveyor, which controls the feed-rate to the gasifier. The storage bunkers are 10' wide x 10' deep x 60" long, providing at least 2-hours of storage capacity, so that the RDB-feedstock is continuously withdrawn by the means of a Rate Control System that feeds the gasification process

Figure 1.7 Walking Floor Storage Controls RDB Feed Rate to Gasifier

Photo Credit: Taylor Energy

2.0 Introduction to Gasification Technology

Gasification is a well-established method for converting solid fuels into gaseous clean-fuels. Gasification was used to make clean-fuel-gases during the war years to power transportation vehicles.

Figure 2.1 Cars and Buses all used Solid Fuels During WWII

Source: Public Domain

Every vehicle above has a gasification reactor attached to the back to provide fuel-gas for transportation. During the 1930's several hundred thousand vehicles in Europe used shredded wood as a fuel.

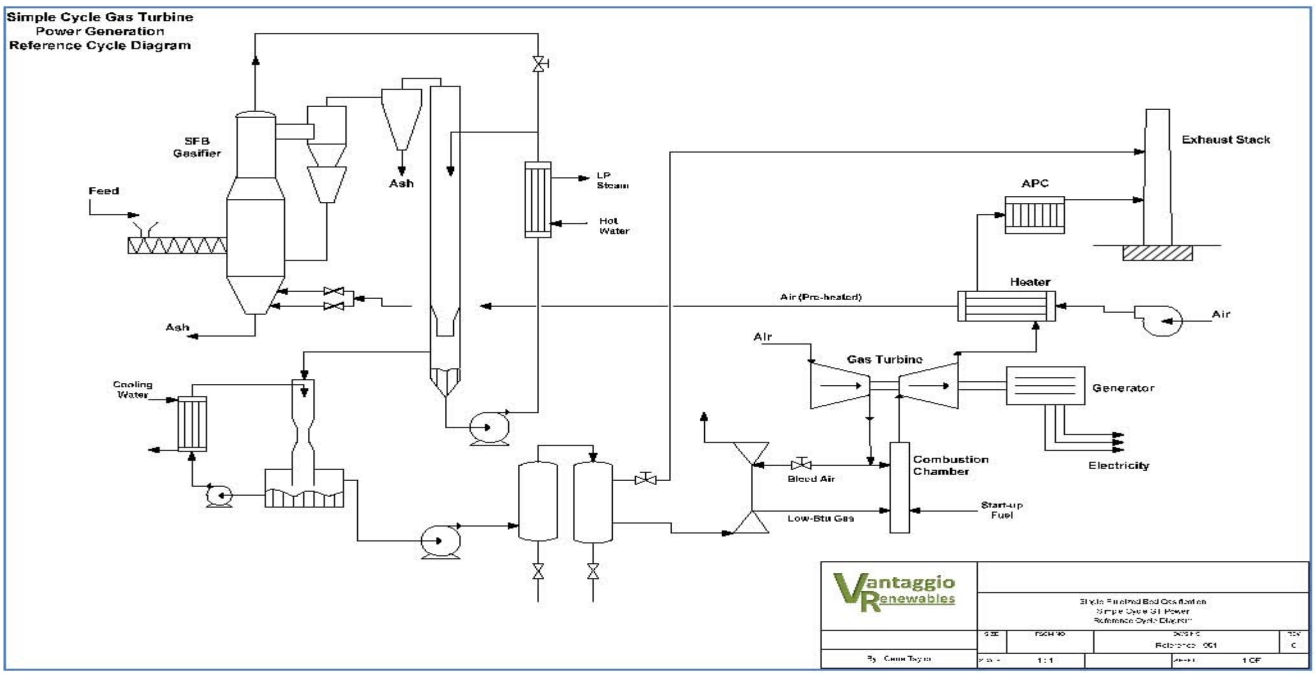
Figure 2.2 Mercedes Benz with wood-gasifier mounted on the back

Source: Public Domain

2.2 RDB Gasification Integrated with Power Generation

The product of RDB gasification is a fuel-gas that consists primarily of hydrogen, methane, carbon dioxide, carbon monoxide, nitrogen, and water vapor. This fuel-gas product has a low-energy-density compared to natural gas but can be used for electric power generation when fired in a gas turbine.

Figure 2.3 Gasification Process integrated with STIG Gas Turbine Power Generation



Source: Vantaggio

The RDF is metered into an entrained-flow gasifier, operated near atmospheric, using an extrusion-screw type auger-feeder that forms a seal, isolating the gasification system from the ambient air. Oxygen-enriched air is provided to oxidize 25% of fuel input, which generates the heat necessary to heat RDB, converting the biomass and plastic residues into low-BTU fuel-gas and carbon-char.

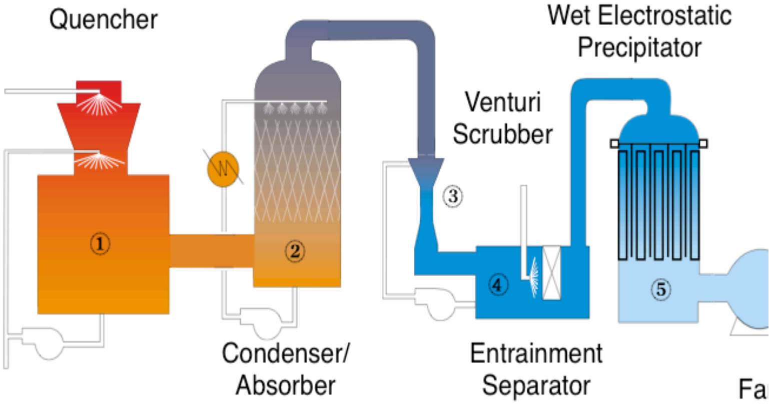
Figure 2.4 Taylor Energy Gasification Reactor and Reformer

Photo Credit: Taylor Energy

2.3 Gas Cleaning System

The fuel-gas product is quenched and cooled and cleaned using specialized filter equipment; multiple cleaning stages that cool and scrub the product gas are designed to remove fly-ash, acid gases, trace volatile metal vapors, and reduce the moisture content. This cleaning system is composed of special filters and scrubbers that have been designed specifically for this type of application.

Figure 2.5 Fuel-gas cleaning system



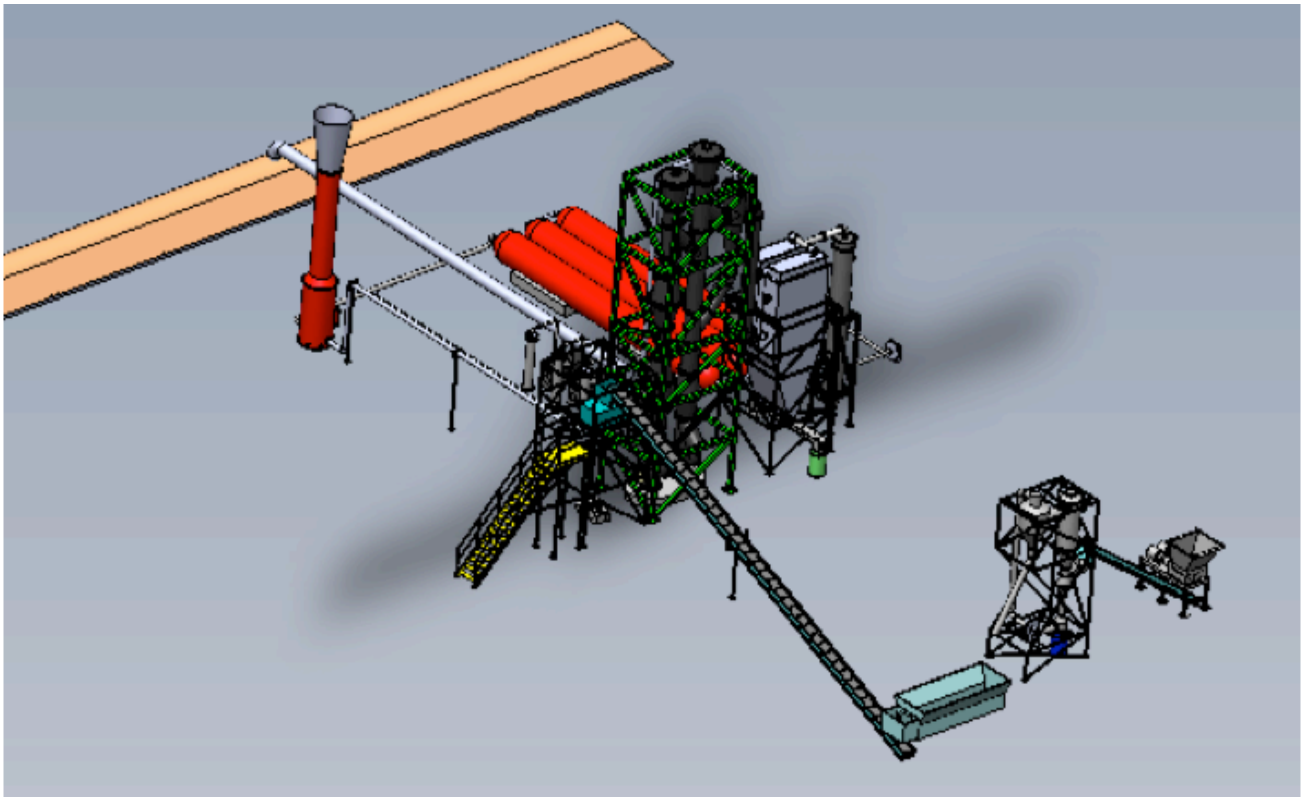
Source: Envirotec

Fly ash is composed of light particulate-matter that is entrained in the fuel-gas product stream and is first removed using special filter equipment. Ash is recovered in loose particulate form and used as a soil amendment when mixed 50/50 with compost (shredded wood that has been composted), or the fly ash can be disposed in the landfill. Fly ash and carbon-char are used in the manufacture of concrete products, or in road-base formulations, depending upon the composition.

The final scrubber is a water-based scrubbing system that removes an acid gasses present, and particularly provides the water-environment where ammonia (NH3, produced during gasification) reacts with hydrogen chloride (HCl, also liberated during gasification of PVC) to form ammonium chloride, a salt that, when precipitated from the scrubber-brine, can be used as a fertilizer component.

The fuel-gas leaving the aqueous scrubbing system will flow through a demister to remove moisture carried in the form of a fine aerosol mist. At this point, the gas purification process is complete. The gas will be heated to 25-degrees above the dew-point to prevent condensation of moisture during delivery of the fuel-gas product to gas compression and then to the electric power generation equipment.

Figure 2.6 Preliminary design: Feeding, Gasifier, Reformer, Gas-scrubbing, Enclosed flare.



Source: Taylor Energy

The gas cleaning system is equipped with an emergency flare that would burn fuel-gas during start-ups and during any emergency off-specification conditions. The flame is shielded from view.

2.4 Electric Power Generation

Electric power will be generated using the fuel-gas to fire a well-proven gas turbine engine. The proposed Energy Facility will employ one GE10-1 Industrial Gas Turbine. The engine has output capacity of 11,250 kWh, with approximately 31% simple cycle efficiency. The GE10-1 gas turbine is selected for use with low-BTU fuel-gas derived from RDF gasification. A heat recovery steam generation (HRSG) is added to the system; the steam produced is injected into the gas turbine to increase mass flow and reduce emissions, while increasing the power cycle efficiency to 42%. The power cycle is called a "Steam Injected Gas Turbine;" and know in the industry as a STIG Cycle or Cheng Cycle Gas Turbine.

Figure 2.7   GE10-1 Gas Turbine Engine for operation with Low-BTU fuel-gas

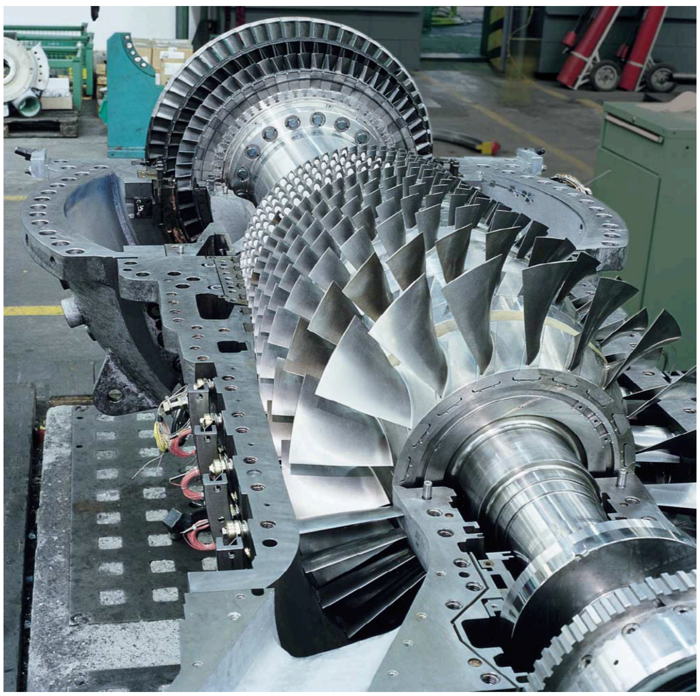


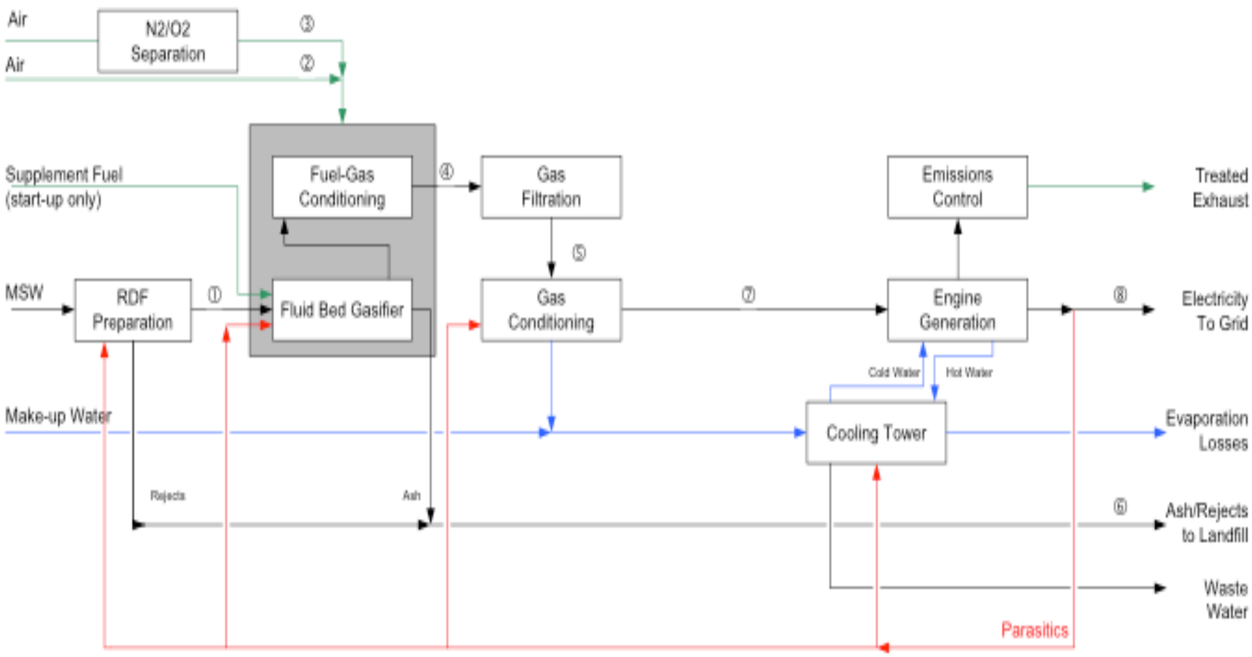
Photo Credit: General Electric

2.5 Power Island – Steam Injected Gas Turbine (STIG)

The gas turbine is to be provided by General Electric (GE) and packaged by a company with experience designing and fabricating skid mounted power generation equipment for industrial applications. The power island supplier provides complete services for the power production modules, including the skid design, fabrication of the power plant skids, and includes the installation and start-up of the turbine engines. They also provide a long-term maintenance sub-contract that includes periodically rebuilding the turbines and other moving parts. The over-all thermal efficiency for the process is improved by employing the advanced STIG Cycle shown above, where Heat Recovery Steam Generation (HRSG) is used to produce steam that is injected into the gas turbine, reducing air emission and increasing the power output. The gas turbine provides gross power output of 11.25 MWe at 42% efficiency by employing the STIG Cycle.

2.6 Mass and Energy Balance

Figure 2.10 Preliminary Mass and Energy Balance



Process Info	Feed Input	Air Input	O2 Input	Gasifier Output	Clean Output	Ash Output	Syngas Input	Power Output
Process stream	1	2	3	4	5	6	7	8
Mass flow, lb/hr	32500	19250	2400	54150	48325	5825	48325	
Temp. F	50	70	70	1742	400	120	120	750
MMBTU/hr (LHV)	162			-38.6	118	-5.4	118	
ACFM								
SCFM		4123	500	10350	10350		10350	
Pressure psia	14.7	24.7	21.7	14	12.7		154.7	
BTU/scf					190			
Moisture	17.50%				9%		4%	
Char lb/hr						450		
Dolomite lb/hr	500					500		
Power Output MMBTU/hr (gross max.)								50.5
Power Output kWe/hr (gross max.)								14,812
Internal power requirement								2,500
Net Maximum Output								12,312

Net Power Output	13,300	kWh	
Gross Power Output	15,000	kWh	
Engine/Generator Eff.	43.3	%	
Engine Heat Rate	7880	BTU/kWh	
Engine syngas input	118	MM BTU/hr	
Engine power output	55.1	MM BTU/hr	
Net cycle eff.	31.5	%	
Fuel-gas density	190	Btu/scf	
32,500 lbs/hr	RDF (As Stored)		
Fuel Composition	LHV	LHV	
Energy	7,363	4970	Btu/lb
Moisture	0.00%	17.50%	
Ash	0.00%	15.00%	
C	47.68%	32.91%	
H2	6.94%	4.68%	
N2	1.54%	1.04%	
O2	41.85%	28.25%	
S	0.46%	0.31%	
Cl	1.54%	1.04%	
	100.00%	100.00%	

Source: UCRiverside

3.0 Environmental Benefits

Accomplishing the conversion of Waste-to-Energy using gasification technology is presently the cleanest method available for using Municipal Solid Waste (MSW) as an energy resource. The historic method of burning MSW with excess air is technically feasible; modern methods used to control air emissions have proven to be reliable and work well enough so that traditional "incineration" technology can be permitted for operation within most jurisdictions. However, gasification is always cleaner than incineration. Why? Because incineration methods mix air with the waste-fuel to enable combustion—and then exhaust gases are cleaned post-combustion; whereas, gasification methods heat the waste to make fuel-gas that is cleaned first; then the clean-gas is mixed with air to enable combustion. Consequently, the fuel-gas volume (resulting from gasification) that is subject to cleaning is $1/5^{th}$ the volume of the combustion exhaust resulting from incineration.

The ability to clean a gas is a function of the volume. Smaller gas volume results in cleaner gas and lower air emissions. Therefore, gasification has emerged as the cleanest method for using solid fuels for power generation. For example, coal-gasification is always cleaner when compared to coal-combustion. Biomass-gasification is always cleaner when compared to biomass-combustion. RDF gasification is only recently emerging as the best alternative for optimum environmental performance when used to convert MSW into a clean fuel-gas product that is comparable to pipeline natural gas in purity.

3.1 Air Emissions

Fuel-gas is cleaned and scrubbed to achieve a purity level comparable to pipeline natural gas. The clean-gas is then used as fuel in a traditional gas turbine that includes heat recovery steam generation. The proposed facility will use one GE10-1 gas turbine engine with 11,250 kWh gross output. This STIG Cycle power plant is designed for ultra-low emissions, so that criteria emissions are minimized.

Combustion of clean fuel-gas in the gas turbine engine will be the primary source of emissions from the waste conversion equipment. The power generating equipment will utilize the STIG Cycle (steam injection) to reduce air emissions to levels that are below the California regulatory limits.

Additional NOx reduction can be achieve using SCR technology, which relies on a catalyst to convert NOx into inert nitrogen (N2), which is returned to the atmosphere. However, when the STIG Cycle is employed, SCR is generally not needed for compliance. Carbon monoxide (CO) and minor component, such as volatile organic compounds (VOC) are projected to be well below the regulatory limits.

3.2 Fuel-gas Output (volume-%)

The waste-to-energy system includes gasifier, tar-reformer, filters, scrubbers, and a gas turbine engine. These systems can meet or exceed all European and U.S. emissions standards.

	Gasifier	Tar-cracker	Gas Clean-up (typical)
CO	8.82	10.0	10-22
H2	7.36	8.61	8-14
CH4	5.46	6.51	4-6
CxHy	3.24	4.88	1-2
NH3	0.26	0.25	0.05-0.1

CO2	14.09	15.65	15-18
H2O	13.66	9.48	0.82 (saturated at 40 F)
N2+Ar	46.83	46.48	40-45
C10H8	0.25	0.023	0.01-0.02
H2S, PPMv	78	48	20-4
HCl, PPMv	139	90	25-35
HCN, PPMv	30	20	20-30
HHV, BTU/scf	184	250	302
Tars, g/Nm3	13.8	1.2	0.5
M.W.	26.7	26.5	26
Density, lb/ft3	0.074	0.071	0.070
Char, wt-%	15.7	5.0	0.01
Ash, wt-%	13.8	12	0.08

3.3 Exhaust Emissions (adjusted to 11% O2)

Exhaust Emissions (adjusted to 11% O2)

	Design Limit	Nominal
CO, mg/Nm3	2.5-5	1.8-3.6
Particulates. mg/Nm3	3-7	2-5
HCl, mg/Nm3	0.5-2	0.4-1.4
HF + HBr, mg/Nm3	<0.1	<0.1
SO2, mg/Nm3	5-15	<3.6
Heavy Metals, mg/Nm3	2.2	<1.6
NOx, mg/Nm3	200-300	140-214
PCB, ng/Nm3	163.0	<0.1
PCDD/PCDF, ng/Nm3	13.1	<9.3
Specific Heavy Metals		
Lead (Pb), mg/Nm3	<0.005	Nil
Cadmium (Cd), mg/Nm3	<0.0004	Nil
Mercury (Hg) , mg/Nm3	0.008-0.05	Nil

3.4 Residues from the Waste-to-Energy Facility

All RDF processing at the Renewable Energy Facility will be performed inside the materials handling building, which is under negative pressure to control fugitive dust and odors.

Waste products generated by the facility include:

Liquid waste:

- Domestic wastewater from staff bathrooms,
- Wash water from cleaning the tipping floor,
- Condensed cooling water.

Gaseous waste:

Steam and carbon dioxide, carbon monoxide and minor air emission components

Solid waste:

- Fly ash that is captured by the emissions control equipment,
- Salts removed from the water treatment system.

	Ash and Char (wt-%)
Carbon-char	5.4
SiO2	33.93
Al2O3	16.21
TiO2	2.3
Fe2O3	3.32
CaO	23.2
MgO	2.09
Na2O	4.43
K2O	1.54
P2O5	1.59
SO3	2.85
Cl	2.9
As	0.000923
Cd	0.0002
Pb	0.034
Hg	Nil

Fly ash combined with carbon-char are potentially used in the manufacture of concrete products, or a soil amendment when mixed 50/50 with compost (shredded wood that has been composted); initially, the fly-ash would be disposed in the nearby landfill.

4.0 Project Input and Outputs

The Materials Receiving and Storage Facility is designed to process 300-wet-ton/day RDB. The system is composed of two parallel trains, each processing 150-wet-ton/day RDB. Two RDF storage and feeding lines, two parallel gasification reactors, one power generation train. Each gasification reactor is designed to process a maximum of 150 ton/day of RDB, which equates to an input capacity of 300-wet-ton/day RDB. Detailed projections and plant capacity are discussed below and in Sections 4.1, 4.2, and 4.3. At 85% on-line capacity, each process train is designed for an average (365 day/year) daily capacity of 255-ton/day input, resulting in average output of 8,075 kWh net power (8760 hr/yr). To achieve this result, the power train will generate 9.5-MW per hour, operating at a minimum of 7,446 hours per year. Sections 4.1, 4.2, and 4.3 below provide the nominal design basis (11-MWe gross, 9.5-MWe Net) and show how the capacity and on-line availability are calculated.

4.1 Plant Design Basis

The proposed waste-to-energy facility uses the composition and energy content below as the basis for the plant design:

Municipal Garbage Energy Content (prepared by Bechtel Technology, 2001)

RDF Feed	RDF-fluff	Dry	Dry, Ash-Free
	Wt%	Wt%	Wt%
C	32.19	39.01	47.68
H	4.68	5.67	6.94
O	28.25	34.24	41.85
N	1.04	1.26	1.54
S	0.31	0.37	0.46
Cl	1.04	1.26	1.54
Ash	15.00	18.18	0
Moisture	17.50	0	0
Total	100	100	100
Dulong HHV, Btu/lb	5406	6553	8009
USBom HHV, Btu/lb	5879	7127	8711
Dulong LHV, Btu/lb	4970	6024	7363

4.2 Design Capacity

The nominal design basis (at the MRF or landfill) calls for receiving and processing 432-wet-ton/day MSW, assuming 25% debris, glass, grit, and recyclables, including metals. Therefore, removing 25% non-energy materials will result in 324-wet-ton/day feedstock is available for energy use. The design basis assumes 25% moisture; preliminary processing removes 2% moisture. Therefore, the nominal RDB design basis is 317-wet-ton/day MSW with 23-wt% moisture and assumes that RDF is dried during production to result in 300-ton/day of RDB-fluff with 17.5-wt% moisture, containing 5,000 Btu/lb, LHV.

Feed rate: 300 wet-ton/day RDB, containing 5,000 Btu/lb-wet @ 17.5-wt% moisture

300 ton/day x 2,000 pound/ton = 600,000 pounds per day

600,000 pounds/day / 24 hours per day = 25,000 pound per hour

5,000 Btu/pound-dry LHV x 72% (net gasification eff.) = 3,600 Btu/pound as fuel-gas

3,600 Btu/pound as fuel-gas x 25,000 lb/hr = 90,00,000 Btu/hr (90 mm Btu/hr)

90 mm Btu/hr x 42% (net STIG-cycle eff.) = 37.8 mm Btu/hr (as electricity)

37.8 mm Btu/hr (as electricity) x (1 kWe / 3,412 Btu) = 11,075 kWh (gross power output)

Parasitic Power Uses	(1,575 kWh)
Net	9,500 kWh

4.3 The system design for 85% Online Availability

The design calls for processing 300-ton/day capacity, with minimum operating 85% availability.

Name Plate Capacity	300 ton/day RDB-fluff
25,000 pounds per hour x 0.443 kWe per pound =	11,075 kWh (gross output)
Operating Hours at 85% online	7,446 hours/year
25,000 lb/hr x 7,446 hr/yr / 2000 #/ton	93,075 ton/ year RDF-fluff
93,075 ton/ year RDF / 0.70 RDF/MSW	132,964 ton/year MSW
132,964 ton/year MSW / 365 day/year capacity)	364 wet-ton/day MSW (@85%
Net output, 85% (7,466 hr/yr)	9.5 MWe
Pro-forma (average output for 8,760 hr/yr)	8,075 kWh

5.0 Projections—Budgetary

Available Energy as Heat:

25,000 pounds per hour x 5,000 Btu/pound = 125 mm Btu/hr

Each of the two (2) lines, feeding 150 ton/day of RDB, with a total capacity of 300-ton/day. Each of the two (2) gasification reactors, processing 150-ton/day RDB, which equates to an input capacity of 300-ton/day RDF, produced (at the MRF or landfill) from a total of 432-ton/day MSW.

Input: 300-ton/day RDB, producing 90 mm Btu/hr fuel-gas output

Gasification system

11,075 kWh (gross) x $1,430/kWh=	$ 15,837,250.00

Power Generation Island

11,075 kWh (gross) x $1,270/kWh=	$ 14,065,250.00
Engineering Design:	$ 1,175,000.00

Commissioning, start-up management	$ 1,500,000.00
Total	$ 32,577,500.00
Cost per kW Installed ($ 32,577,500 / 9,500 kW)=	$ 3,429 / kW (installed capacity)

This budgetary price does not include the facility for converting MSW into RDB at the MRF or landfill, or the buildings proposed to house the Maui Renewable Power Facility. This price does not include the cost of interconnecting to the power grid, i.e., the cost for step-down transformers, or the payment of taxes, and does not include the payment of fees, events, or operations that are unique to the project site.

6.0 Analysis and Evaluations

The material/energy balances of the overall process proposed for Demonstration have been analyzed using Aspen Plus process simulation software.

6.1 Background

There is significant literature available on gasification of carbonaceous matter that can be used to design the process model approach. It is well established that the high temperature decomposition of carbonaceous feed occurs in two stages. At lower temperatures (400-600 ºC), devolatilization takes place, resulting primarily in chars and liquid products and at higher temperatures (600-1000 ºC), gaseous products occur because of several series-parallel reactions. Presence of a gasifying agent significantly influences these stages, and the overall process can be summarized as follows, with the pyrolysis step much faster than the gasification.

Devolatilization (pyrolysis, thermal decomposition):

Feed + Heat (400-1200 ºC) → Coke (char) + Liquids (tar) + gases

Gasification:

Feed + Gasifying agent + Heat (700-1400 ºC) → Gases (H_2, CO…)

+ Minerals (ash)

The equilibrium trends for the C-H-O system are shown below[1].

Table 6.1. Equilibrium trends for the C-H-O system

	Temperature ↑	Pressure ↑	H/O ratio ↑
X_{H2O}	↓	↑	↷
X_{H2}	↑	↓	↑

X_{CO}	↑	↓	↓
X_{CO2}	↷	1	↓
X_{CH4}	↷	2 ↑	↑

Source: UCRiverside

1 – Maximum constant, but shifts to higher temperature

2 – Maximum shifts to higher temperatures

The system is also influenced by the reactivity of carbon with various species, as shown below (1073 K and 0.1 atm)[8].

$$r_{O_2} \gg r_{H_2O} > r_{CO_2} > r_{H_2}$$

$$10^5 \quad 3 \quad 1 \quad 3.1^{-3}$$

However, the actual product gas composition depends on the rate at which equilibrium is attained, i.e., reaction velocity and this information can only be obtained through experimental work. The reaction velocity depends on various parameters such as the flow rate (residence time), reactor volume and type, T, P and the feedstock composition. For all the gasification reactions, the rate is slow at lower temperatures and increases exponentially with temperature[9]. However, even at very high temperatures, the rate of gasification is considerably slower than that of the oxidation reactions and traditionally, a catalyst is employed in the absence of oxygen.

Industrial processes have been designed to carry out individual gasification reactions in different temperature ranges by using multiple stages and to an extent, to optimize the reactions separately. The optimal feed composition and process parameters such as the feed rate and temperature in these two stages need to be evaluated in order to obtain maximum efficiency and desired product composition. The main purpose of the process simulation is to perform such optimization work effectively in order to help support the experimental work and to perform analysis and evaluation for technology development.

6.2 Aspen-Plus Simulation Development

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[8] P.L. Walker jr, F. Ruskino jr and L.G. Austin, Adv. Catalysis XI, 133, 1959

[9] H.D. Schilling, B. Bonn and U. Krauss, Coal Gasification-Existing processes and new developments, Graham & Trotman Ltd, 1981

A detailed Aspen Plus process model has been developed and can be used to predict process behavior, and material and energy balances. 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. A brief description of the process model used to perform the simulations is given below.

Process Description

Figure 1 shows the Process Flow Diagram (PFD) of the Aspen model under development. A detailed description of the technology including unique advantages is discussed in the original proposal. The feedstock is supplied to the entrained-flow gasifier (employing a primary spouted bed receiver) through an extruder feeder and the gasification process is enhanced through a Pulse Deflagration Burner. The product stream from the gasifier is then sent to the reformer that includes a Pulse Detonation Burner. The product gas stream from the reformer goes through conventional gas cleanup/upgrading steps including ash/char separation, filtration, and gas cooling.

The proposed feedstock is Refuse Derived Biomass (RDB). The key properties include:

Fixed carbon: 8.0% (0.0970 lb/lb-dry-feed

Volatile matter: 57.0% (0.6909 lb/lb-dry-feed)

Moisture content: 17.5% wet basis

Mineral ash: 17.5%

Calorific Value: 6,000 – 6,900 Btu/lb-dry-feed

The basic parameters of the proposed Jet Spouted Bed followed by an entrained-flow section, integrated with Pulse-Detonation-Reformer include[10]:

Temperature: 800 ˚C (1472 ˚F)

Air input: 29.8 scf/lb-wet-feed

Power for compression of primary air: 15.8 kWh/ton-dry-feed

Power for oxygen production (enrichment to 33%): 41.6 kWh/ton-dry-feed

Fuel-gas heating value: 227 Btu/scf

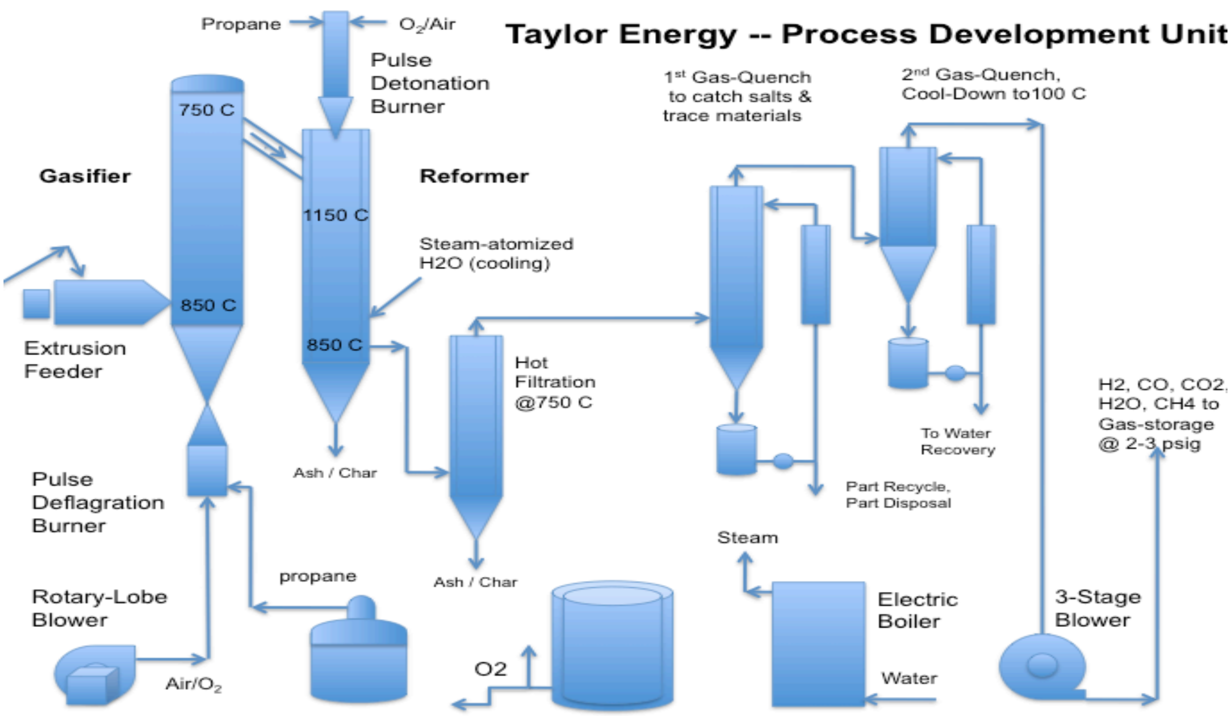
Fuel-gas density: 20.3 scf/lb

Fuel-gas production: 26.9 scf/lb-wet-feed

Efficiency (gasification and reforming): 72.9%

[10] Taylor Energy technical reports DK-99-2 & DK-98-3

Figure 6.1 Process Flow Diagram of the Taylor Energy Gasification System



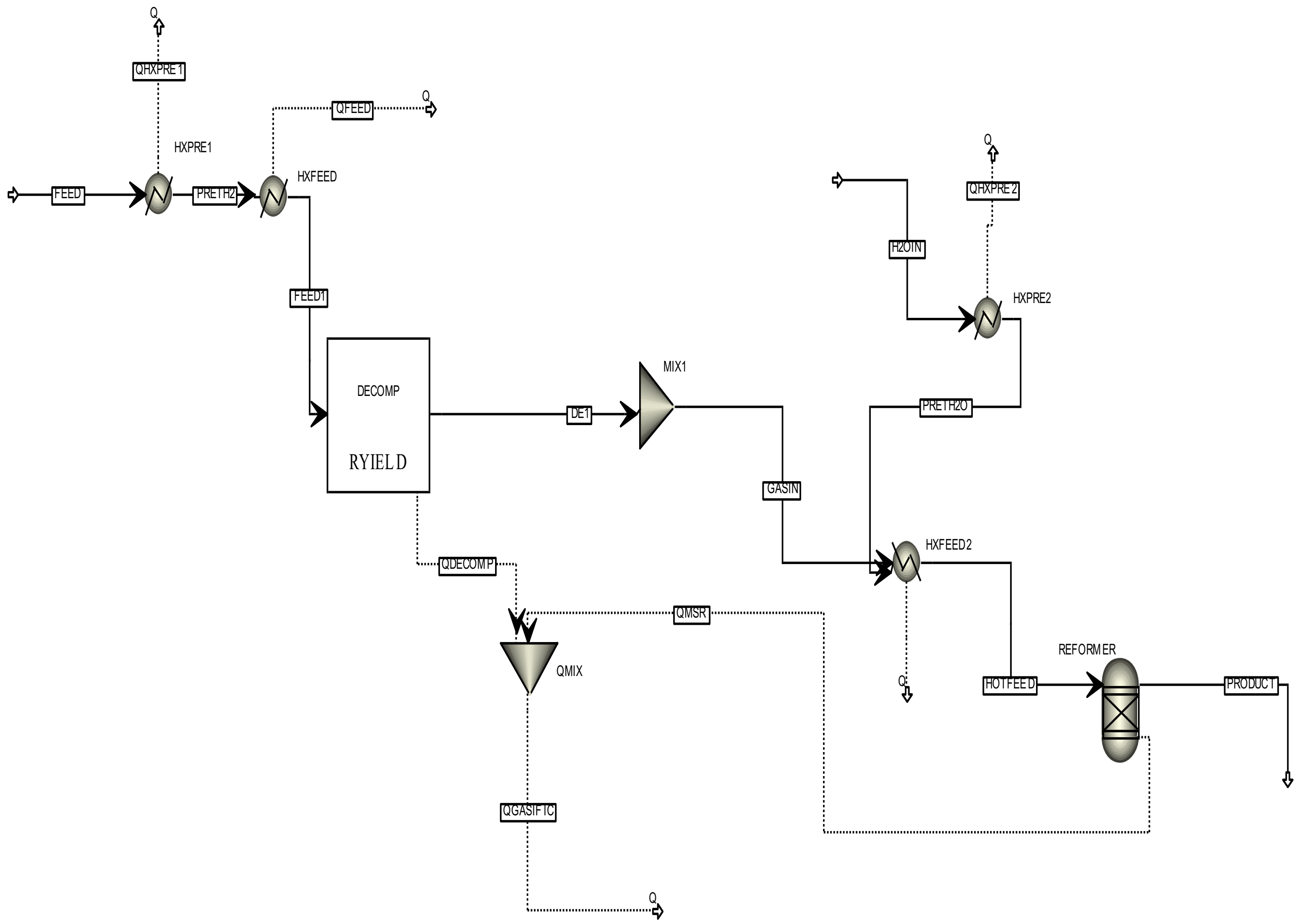
Source: Taylor Energy

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

The solid feedstock is fed into the gasifier on a steady basis at predetermined feed/air ratios. The model simulates the gasifier 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 biomass or coal into its basic elements based on yield information using the RYIELD block. The components are then sent to the gasification block (RGIBBS), which calculates the equilibrium product gas composition using the Gibbs free energy minimization approach.

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 ash and unreacted char are removed from the reactor as a solids-stream and the product gas is subjected to gas cleanup in order to remove trace contaminants that can include ammonia, hydrogen chloride, and hydrogen sulfide. The clean gas stream is then cooled down in two quench steps and is sent to gas storage. Figure 6.2 below shows the gasifier model in the Aspen Plus user interface.

Figure 6.2 Gasifier Model in the Aspen Plus User Interface



Source: UCRiverside

<u>Downstream Processes</u>

Downstream processes such as methane reforming for fuel production or combustion-based power generation are simulated using specific versions of the model. The fuel production module is discussed below. The clean product gas then enters the Steam Methane Reformer (SMR). The SMR is simulated using a built-in REQUIL equilibrium block. The reactions considered in the SMR are given below.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2, \quad \Delta H = 206 \text{ kJ/mol}$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2, \quad \Delta H = 165 \text{ kJ/mol}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2, \quad \Delta H = 247 \text{ kJ/mol}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2, \quad \Delta H = -40 \text{ kJ/mol}$$

The product gas from the SMR is then sent through a separator where the excess H_2 is removed for recycle to the SHR. The gas is cooled sufficiently in order to be used in the Fischer-Tropsch reactor. The Fischer-Tropsch reactor block used an external model, which is called by the Aspen Plus through a FORTRAN module. This external model was empirically developed by Hamelinck et al.[11] to predict the selectivity of the Fischer-Tropsch process and can be expressed as below.

$$S_{C_{5+}} = a_1 + a_2.T + a_3.\frac{[H_2]}{[CO]} + a_4.([H_2]+[CO]) + a_5.P_{Total}$$

Where,

Sc_{5+} – Mass fraction of hydrocarbons in the product with 5 or more carbon atoms

a_i – Empirical parameters

$[H_2]$ and [CO] - Concentrations of H_2 and CO expressed as fraction of the feed

T – Temperature (K)

P – Pressure (bar)

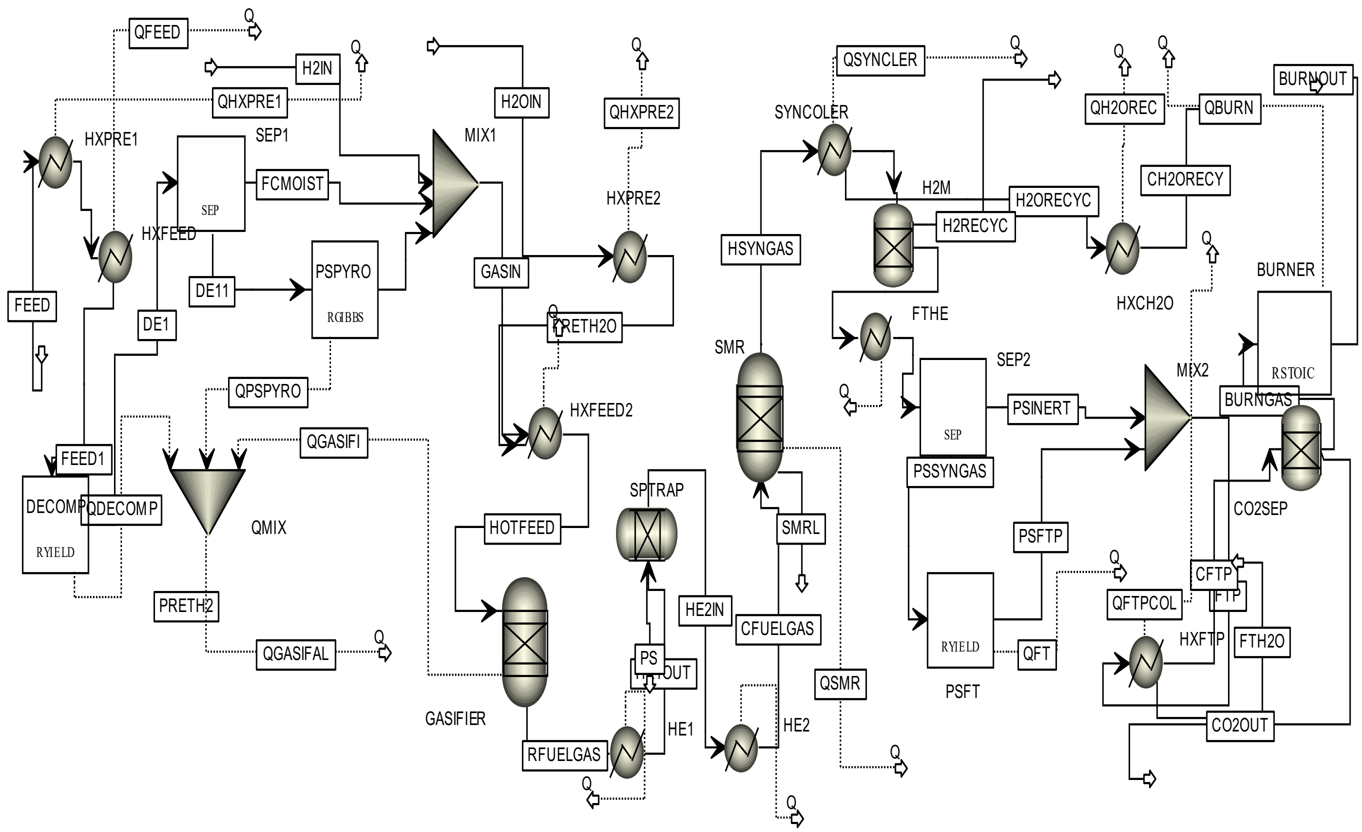
According to Hamelinck et al., a least sum of squares fit of the above model with proprietary data resulted in the following equation, which was also found to be in accord with experimental results using a cobalt catalyst reported by Dry[12]. This equation is used to simulate the FT reactor.

$$S_{C_{5+}} = 1.7 + 0.0024T + 0.088\frac{[H_2]}{[CO]} + 0.18([H_2]+[CO]) + 0.0078p_{Total}$$

11 C.N. Hamelinck, A.P.C. Faaij, H. Uil and H. Boerrigter, Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential, Energy, 29, 2004

12 M.E. Dry, The Fischer–Tropsch synthesis, Catalysis: science and technology, edited by J.R. Anderson and M. Boudart, Berlin, Germany, Springer; 1981, 160–253

Figure 6.3 Integrated Aspen-Plus simulation Process Flow Diagram



Source: UCRiverside

The Aspen Plus simulations of SHR and SMR are based on equilibrium assumptions whereas the FTR is simulated by means of an empirical expression. While the simulation results can be used to perform heat and mass balances, to design experiments and to understand process behavior, it must be noted that experiments conducted in laboratory or pilot scale reactors may not be under equilibrium. Figure 6.3 shows the process flow diagram for fuel production from the Aspen simulation user interface.

The different efficiency values calculated using the simulation results are listed below.

CCE = Chemical Conversion Efficiency based on the number of moles of carbon converted into product gases. CCE is defined for each reactor separately

OCE = Overall Conversion Efficiency of the process based on the number of moles of carbon converted into product gases excluding CO_2

OCE HHV = Overall Conversion Efficiency of the process based on the HHV (Higher Heating Value) of the feed and the final product

Power Generation Module

The power generation module involves gas cleanup followed by a combustion block that simulates the stoichiometric combustion of the gas in an engine. The combustion efficiencies and electric output are based on the engine performance specifications.

Preliminary Results

Based on the equilibrium predictions, the net thermal efficiency of the process varies significantly, from 38% to 70% for fuel production and 35% to 70% for power generation. The values are highly sensitive to the process parameters including operating temperature, feed composition, and pressure. Experimental data on carbon conversion, product gas composition, yield, and energy use will be used to update the model in order to evaluate process performance for the specific feedstock/product combinations and further optimization.

6.3 Life Cycle Assessment

Two of the most important criteria used for the technological evaluation of industrial systems are the total energy consumption and the net emissions of the desired pathway. Conventional methods of evaluation often focus on a limited number of steps in a production pathway and are inadequate in their ability to quantify the "cradle-to-grave" energy use and emissions. LCA models iteratively calculate the energy use and emissions associated with specific pathways using large databases consisting of information on various stages of the pathways and some user-specified input values. An LCA of the gasification process for fuel production was conducted and the results are given below.

Greenhouse gases. The key GHGs considered by the LCA and their Global Warming Potential (GWP) compared to CO_2 are given in the Table below. The GWPs are the 100-year warming potential values published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and are often referred to as the IPCC 2007 GWPs[13]. The GHG emissions for each pathway are calculated for each GHG and are reported on a carbon dioxide equivalent (CO_2e) basis using the GWPs.

Table 6.2 Global Warming Potentials of the key GHGs

GHG Name	100 Year GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Chlorofluorocarbons (CFC-12)	10,900
Hydrofluorocarbons (HFC-134a)	1,430

Source: UCRiverside

Energy use. The categories of energy use are listed below.

- Total and fossil energy used per unit of energy produced for each stage of the fuel production steps

[13] IPCC 2007, Climate Change 2007: Working Group I: The Physical Science Basis, from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html.

- Total energy used per kilometer driven for the fuel used in vehicles
- Fossil energy used per kilometer driven for the fuel used in vehicles
- The proportions of types of energy used for each stage of the fuel production cycle

A number of software packages are available that include extensive databases and ‘pathways’ that can be used to evaluate most of the existing technology/pathway options. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is one such model that is widely used in academic studies, especially in the United States. This study is conducted using the CA-GREET 2.0 Tier 2 model (CA-GREET 2017). The CA-GREET model is a modified version of the GREET model consisting of California specific assumptions.

The basic assumptions used in model are listed below:

- Analysis year: 2015
- Feedstock: Baseline pathway-petroleum oil; Biomass gasification pathway- forest residue
- CAMX grid (California-Mexico grid) mix is considered as regional electricity mix for utility supply for all the cases except solar or wind.
- CA Crude is selected for regional crude oil use
- Natural gas (NG) feedstock is considered as North American (NA) NG
- Final product FT Diesel use: passenger car with 24.81 MPGGE
- Baseline case uses Conventional low sulfur diesel refining process for fuel production
- Process efficiency: Baseline case- 89.3% (Conventional low sulfur diesel refining); Biomass gasification to FT Diesel- 49%
- Co-product credits: none
- Steam/electricity export credits: none

The Well to Tank (WTT) results of the FT-Diesel production life cycle analysis are presented in Table 6.3 below. The total and fossil energy use are listed including specific petroleum, coal and natural gas use information. The fuel production process relies on natural gas and petroleum whereas the Biomass gasification to FTD process uses some natural gas and petroleum along with the renewable resource. The table also presents the GHG emissions in CO_2 equivalent values. The GHG emission for the baseline case is 29.8 kg CO_2e/mmBtu fuel, while the GHG emission for the biomass gasification process is -69.9 kg CO_2e/mmBtu fuel.

Table 6.3 WTT analysis of FT-Diesel production from biomass

Item	Energy usage or emission (Btu/mmBtu or g/mmBtu)	
	Baseline conventional Diesel	Biomass gasification to FTD
Total Energy	313,163	1,124,378
Fossil Fuels	309,598	82,299
Coal	3,791	816
Natural Gas	245,588	13,580
Petroleum	60,219	67,903
CO_2 (w/ C in VOC & CO)	25,823	-69,883
CH_4	139.80	9.10
N_2O	0.49	0.24
GHGs	29,464	-69,585
VOC: Total	9.85	3.55
CO: Total	20.69	12.96
NOx: Total	43.15	32.87
PM10: Total	4.03	2.60
PM2.5: Total	3.49	1.88
SOx: Total	26.16	7.84

Source: UCRiverside

The Well to Wheel (WTW) results is presented in Table 6.4 below. The results include the total energy use per mile driven using the specified fuel and the GHG emissions. The WTW analysis shows that the biomass gasification pathways use significantly higher amounts of energy per mile of the vehicles driven. The GHG emission from vehicle using the baseline fuel production process is 392 gCO_2e/mile driven, while it is 24 gCO_2e/mile driven for the biomass gasification pathway

Table 6.4 WTW analysis of FT-Diesel production from biomass

Item	Energy usage or emissions (Btu/mile or g/mile)							
	Baseline conventional Diesel				Biomass gasification to FTD			
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	478	702	3,769	4,949	130	4,107	3,769	8,006
Fossil Fuels	470	697	3,769	4,935	130	180	0	310
Coal	8.25	6.04	0.00	14.29	0.41	2.67	0.00	3.08
Natural Gas	427	498	0	926	14	37	0	51
Petroleum	34	193	3,769	3,996	115	141	0	256
CO_2 (w/ C in VOC & CO)	39	59	294	392	-277	14	287	24
CH_4	0.41	0.11	0.09	0.62	0.01	0.02	0.09	0.13
N_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHGs	49	62	297	408	-277	15	290	28
VOC: Total	0	0	0	0	0.00	0.01	0.08	0.09
CO: Total	0.03	0.05	2.73	2.81	0.02	0.03	2.73	2.78
NOx: Total	0.09	0.07	0.23	0.40	0.04	0.09	0.23	0.36
PM10: Total	0.01	0.01	0.02	0.04	0.00	0.01	0.02	0.03
PM2.5: Total	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.02
SOx: Total	0.03	0.07	0.00	0.10	0.00	0.03	0.00	0.03
VOC: Urban	0.01	0.01	0.05	0.07	0.00	0.00	0.05	0.06
CO: Urban	0.00	0.02	1.91	1.94	0.00	0.00	1.91	1.91
NOx: Urban	0.01	0.03	0.16	0.21	0.00	0.00	0.16	0.17
PM10: Urban	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.02
PM2.5: Urban	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
SOx: Urban	0.00	0.05	0.00	0.05	0.00	0.00	0.00	0.00

Source: UCRiverside

7.0 Engineering Design Calculations for Gasification Process

This section uses an empirical based design/calculation approach that can be compared with the ASPEN modeling approach presented in Section 6.0. A key issue is the net energy conversion efficiency for the thermal gasification process. The following calculations show the engineering design basis that is likewise used to project the net RDB gasification efficiency for thermal conversion of RDB into fuel-gas, which projected at 72.9% when deployed at Commercial Scale. The efficiency for the much smaller Demonstration Scale system is projected to be somewhat less than 68%, due to higher heat losses. The process will employ low-pressure air enriched to 33% O_2 input in order to increase the BTU content of the fuel-gas product to 270 BTU/scf, which enables the fuel-gas to be used for combustion in existing engine generating equipment, and in gas turbines.

7.1 RDB to be gasified and product pattern in a gasification reactor

[Necessary data are adopted from Technical Report DK-84-4]

- RDB to be gasified (note d.f. = dry feed)
  - Gross heating value 3839 kcal/kgd.f. = 6909 Btu/lb d.f.
  - Water content 18.0% wet basis
  - Mineral/metal 17.5%
  - On the basis of 1 kg of d.f.
    - Volatile matter 0.691 kg
    - Fixed carbon 0.134 kg
    - Mineral/metal 0.175 kg
    - Water 0.215 kg
- Product pattern in the circulating (gasification at 720C = 1328F)
  - Volume of dry gas 0.4913 Nm^3/kgd.f. = 7.87 scf/lb d.f.
  - Gross heating value of 5204 kcal/Nm^3 = 585 Btu/scf
  - dry product gas
  - Mass of tar 0.0504 kg/kgd.f. = 0.0504 lb/lb d.f.
  - Mass of char 0.1176 kg/kgd.f. = 0.1176 lb/lb d.f.
  - Water formed 0.174 kg/kgd.f. = 0.174 lb/lb d.f.

7.2 Necessary heat for gasification

Necessary heat = $Fs(0.24)(Ts_2 - 750) = 613.38 + 275.0\ Wp + L_1$ [kcal/kgd.f.]

Wp is the ratio of water vapor used for fluidization

In the Modified Fluid Bed Pyrox, steam is not used, then Wp = 0

The approximate value of heat loss L_1 is estimated in technical report DK-98-4 for 300 tons per day plant.

Surface Area

$\pi(3m)(6m) + \pi(5m)(10m) + \pi(7.2m)(13m) + \pi(5m)(3m) + [\pi(2.4m)(4.5m) + \pi(1.6m)(8m)](4) = 851.4m^2$

Thermal insulation is made to keep surface temperature of the reactor at 80C = 176F.

Heat transfer coefficient at the outer surface is estimated as:

Natural convection $h_c = 5.9$ kcal/m^{2}hr°C

Radiant heat $h_r = 5.8$ kcal/m^{2}hr°C

$h_c + h_r = 11.7$ kcal/m^{2}hr°C = 2.396 Btu/ft^{2}hr°F

Assume 20% more heat loss through the support structure of the reactor.

[(851.4 m^2)(11.7 kcal/m^{2}hr°C)(80°C – 20°C)(1 + 0.2)] / [(1,000,000 kg feed/24hr)(1 – 0.175)kg d.f./kg feed] = 20.9 kcal/kg d.f.

Thus, necessary heat for gasification in the Modified Single-Fluid-Bed is calculated to be:

613.38 + 20.9 = 634.2 kcal/kgd.f. = 1142 Btu/lb d.f.

7.3 Amount of the air to burn carbon completely

(0.1172 kg/kg d.f.)(22.4 Nm^3/12 kg)(1/0.21) = 1.042 Nm^3 air/kg d.f.

7.4 Heat balance for combustion of carbon in the bed

Letting 0.1172 kg carbon/kg d.f. to be burnt in the bed to give necessary heat for gasification, heat balance in the bed should be checked.

[Heat Input]

Combustion heat of carbon

(7838 kcal/kg c)(0.1172 kg c/kg d.f.) = 918.6 kcal/kg d.f.

[Heat Output]

Necessary heat for gasification = 634.2 kcal/kg d.f.

Apparent heat of combustion gas

(0.1172 kg c/kg d.f.)([22.4 Nm^3/(12 kg c)(0.21)])(0.34 kcal/Nm^3°C)(720°C-20°C) = 247.9 kcal/kg d.f.

Heat output = 634.2 + 247.9 = 882.1 < 918.6 kcal/kg d.f.

7.5 Estimation of heating value

From Table 3, page 32, in technical report DK-98-1, density of gas produced from MSW, c.a. 4600~5000 kcal/Nm^3 (517~562 Btu/scf) is found to be 1.0 kg/Nm^3. Thus, volume of cracked gas from recycled tar stream is estimated as:

(0.0302 kg/kgd.f.)(1/1.0 kg/Nm^3) = 0.0302 Nm^3/kgd.f.

Volume of combustion gas is given by:

(0.1172 kg c/kgd.f.)(22.4 Nm^3/[(12kg C)(0.21)] = 1.042 Nm^3/kgd.f.

Thus, low heating value of product gas from the Modified Fluid Bed PYROX is estimated to be:

1790 kcal/Nm^3

7.6 Gasification efficiency

η = [(5402)(0.4913) + (0.0302)(0.6)(8000) kcal/kgd.f.] / 3839 kcal/kgd.f.

= 0.729

= 72.9%

7.7 Heating Value of fuel-gas product

Gasification efficiency is high in the Autothermal Fluid-Bed; however, heating value of product gas is rather low, 1790 kcal/Nm^3 = 201.2 Btu/scf. It goes without saying that the higher the heating value, the safer it is to burn, and therefore we prefer to increase its heating value, for example, up to 2500 kcal/Nm^3 = 281 Btu/scf. In order to increase the heating value of the product gas, we have the following three options:

- Feeding of dry RDB
- Pre-heat of the partial oxidation air
- Enrichment of O_2 in the air, using O_2 unit

7.8 Heating Value of product gas increased by drying the feedstock

[(5402 kcal/ Nm^3)(0.4913 Nm^3/kgd.f.) + (0.0302 kg tar/kg d.f.)(0.6)(8000 kcal/kg tar)] / (0.4913 Nm^3/kg d.f. + 0.0302 Nm^3/kgd.f. + 0.730 Nm^3/kg d.f.)

= 2236 kcal/Nm^3

Dry feed is extremely effective to increase the heating value of product gas.

Water content	0.175 kg/kg d.f. $\rightarrow$ 0
Heating value	1790 kcal/Nm^3 $\rightarrow$ 2236 kcal/Nm^3
	(25% increase using dry-RDF)

Oxygen Enrichment to 33% O2 has the impact of increasing the BTU content to 270 BTU/scf, which is the approach employed and is preferable to additional drying of the shredded feedstock.

APPENDIX C:
SYSTEMS MODELING AND ANALYSIS, 600 WET-TON/DAY,
DR. ARUN RAJU, UC RIVERSIDE

Introduction

Techno-economic and life cycle analysis of MSW conversion using the shockwave gasification technology was conducted as part of the project. The objective of this analysis was to evaluate the following parameters for the shockwave gasification technology:

- Material and energy balances
- Process conversion and thermal efficiencies
- Life cycle greenhouse gas (GHG) emissions, and
- Life cycle criteria pollutant emissions

Technology evaluation using advanced modeling techniques is a critical in evaluating anticipated performance at different scales and process parameters, and in designing experiments and optimizing process parameters based on desired performance metrics. Aspen Plus is a well-known process simulation software that allows complex chemical processes to be simulated using built-in databases under steady and non-steady state conditions. A detailed Aspen model was developed for the proposed pathway using a semi-empirical approach where experimental conversion data were used to modify the built-in reactor modules. The semi-empirical approach allows the simulation to more accurately predict process performance by using experimental data. The simulation results, along with the experimental data were used to conduct the economic and life cycle analysis for the technology. The economic analysis uses a discounted cash flow approach to predict economic performance including the Internal Rate of Return (IRR) on investment for the proposed pathway. The Aspen simulation results and the economic analysis results are presented in the following sections of this chapter.

Two important criteria for the selection of a suitable fuel/vehicle pathway are the total energy consumption and the net emissions of the desired pathway. It is not enough to simply consider the vehicle performance and emissions characteristics, but the entire life cycle of the fuel must be considered. Well to wheels (WTW) analysis of energy consumption and emissions, referred to as Life Cycle Analysis (LCA) is considered the most effective way to perform such analysis. The WTW analysis results for the shockwave gasification technology performed using the Aspen Plus modeling results along with the CA-GREET model for life cycle analysis are presented in this chapter.

Economic Analysis of 46-MWe Power Generation / Waste Gasification Plant

Cold gas efficiency	85.7%
Syngas energy content (MMBtu/SCF)	151.1
Power generated	49.1
Auxiliary load	2.5
Net power export	46.6
Plant electric efficiency	45%

Source: UCRiverside

Total Plant Cost (TPC) and Total Required Capital (TRC) for a nominal 600-wet-TPD plant MSW-to-Power plant (500 TPD dry basis) were estimated with project life of 20-years excluding construction period. TPC was evaluated by determining equipment and installation cost adding indirect cost and project contingency. TRC was estimated by adding financial cost and working capital on the TPC. Operation and maintenance cost were also determined to calculate Internal Rate of Return (IRR) with 10% discount rate in the cash flow analysis.

Equipment employed in the study were sized and cost estimated using literature values and the Aspen Icarus software. The gasification system cost was estimated using data from literature to be 450 $/kw_e$ and the cost of the power generation system is assumed to be 1500 $/kw_e$. A scaling factor α (range between 0.6-0.8) is used to scale the cost of equipment to a different size by adjusting the initial cost, $Cost_o$.

$$Cost_{new} = Cost_o \times (Size_{new}/Size_o)^{\alpha}$$

Capital structure and cost estimation methodology used in the economic analysis is given in Table 1.

Table 1: Methodology for capital cost estimation

Parameter	Method
Total purchased equipment cost (TPEC)	Literature and Aspen software
Total installed cost (TIC)	TPEC * installation factor
Indirect cost (IC)	
Engineering and supervision	25% of TPEC
Construction expense	27% of TPEC
Legal and contractor's fees	17% of TPEC
Engineering procurement and construction cost (EPC)	TIC + IC
Contingency	10% of EPC cost
Total plant cost (TPC)	EPC + Contingency
Working capital (WC)	
Start-up cost	0.5% of EPC
Insurance and taxes	1% of EPC
Payroll overhead	26% of labor cost
Plant overhead	70% of labor cost
Financial cost (FC)	
Financial fee	3% of loan
Interest during construction	8% interest rate
Total Required Capital (TRC)	TPC + WC + FC

Source: UCRiverside

Indirect costs (IC) as a percentage of TPEC included engineering and supervision (25%), construction expenses (27%), and legal and contractor's fees (17%) [McGraw, Plant design and economics for chemical engineers]. Project contingency was added as 10% of Total Direct and Indirect Cost (TDIC). TDIC was set as the sum of TIC and IC. EPC was determined by adding project contingency to TDIC. Working Capital (WC) included start-up cost and insurance and tax as percentage of EPC (0.5% and 1%) along with payroll and plant overhead as percentage of annual labor cost (26% and 70%). A 3% financial fee and interest rate of 8% during construction period is added as Financial Cost (FC). Lastly, Total Required Capital (TRC) was determined by adding working capital and financial cost thereby represents the overall investment required for the project.

Detailed capital cost for each operation area along with TPC and TRC is given in Table 2. A balance of plant (BOP) cost of 11% of EPC was used in waste water treatment and cooling tower facility along with miscellaneous cost.

Table 2: Investment cost breakdown for MSW power plant

Capital Costs	MM$
Area 100: Pretreatment	5.9
Area 200: Gasification	11.2
Area 300: Gas Processing	2.5
Area 400: Power Island	39.5
Instrument and control	3.9
Balance of plant	4.6
Total install equipment cost	67.5
Indirect cost	28.9
EPC	96.4
Project contingency	9.6
Total Plant Cost	106.1
Financial cost	8.6
Working capital	2.3
Total Required Capital	116.9

Source: UCRiverside

Labor requirements were also estimated based on plant design and economics for chemical engineer's handbook, changing the number of employees to reflect the specific requirements for this project. It was assumed that there would be one plant engineer required for this operation and one plant manager. The plant engineer would oversee the fuel handling, gasification operations and power generation. Based on a four-shift system, there was assumed to be half a shift supervisor per shift, half a maintenance technician per shift, and three operators per shift. One operator would handle the fuel processing portion of the system, one would handle the gasification island and the gas cleanup system, and one would handle the power island. Finally, two clerks are assumed to handle the incoming MSW trucks, telephone calls, and administrative work. Labor rates were inflated at 2% per year for the salaries listed in the Table 3.

Table 3: Break down of labor cost in plant

	Number	Salary ($/yr)	Total Cost ($/yr)
Plant Manager	1	87,200	87,200

Plant Engineer	1	87,200	87,200
Shift Supervisor	2	64,100	128,200
Maintenance Technician	2	57,600	115,200
Shift Operators	12	47,700	572,400
Clerks and Secretaries	2	31,000	62,000
Total Salaries			**1,052,200**

Source: UCRiverside

IRR is calculated as an economic indicator within the plant life using discounted cash flow analysis. Levelized Cost of Electricity (LCOE) is determined based on the expression below.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + V_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where,
LCOE =Average lifetime levelized cost of electricity
I_t = Investment expenditures in the year t
V_t = Variable O&M cost in the year t
F_t = Fixed O&M cost in the year t
E_t = Electricity generation in the year t
r = Discount rate
n= Lifetime of the plant

Major inputs in the financial model are listed in Table 4.

Table 4: Major financial model inputs

Project economic life (yr)	20
Debt (%)	55
Equity (%)	45
Payment term (yr)	10
Interest (%)	8
MSW gate fee ($/ wet ton)	30
Discount rate (%)	10
Tax rate (%)	38
Electricity sale price ($/Mw)	90

Source: UCRiverside

A debt/equity financial structure of 55/45 is set with 8% loan interest rate and 38% income tax in the cash flow analysis. The lifetime of the plant was assumed to be 20 years in addition with two-year construction period and first six-month 70% production capacity ramp-up period. Straight line depreciation method is used in the whole plant through project lifetime with plant salvage value of zero. Working capital was applied before plant operation and recovered at the end of the project life. A 10-year repayment term was used in the loan period with one-year grace period on principal repayment.

MSW feedstock cost is assumed to be zero since it is considered as waste. A 30 $ per wet ton MSW was given as payback from MSW tipping fee and disposal cost. A first-year construction price of 90 $/Mwh for electricity is used. Escalation factors of 3% is employed in power sale price to reflect inflation factor within plant lifetime. Variable operation costs including all consumable chemicals and waste disposal were assumed to be 2% of EPC cost with a 2% yearly escalation factor. The economic analysis results are shown in Table 5.

Table 5: Financial model outputs

IRR (%)	18.64
NPV (MM$)	45.80
Payback time (yr)	10.1
LCOE ($/Mwh)	118

Source: UCRiverside

The financial model shows an 18.64% IRR with LCOE of 118 $/kw. The payback period of the plant is 10.1 years excluding the two-year construction period.

MM$.Sensitivity Analysis

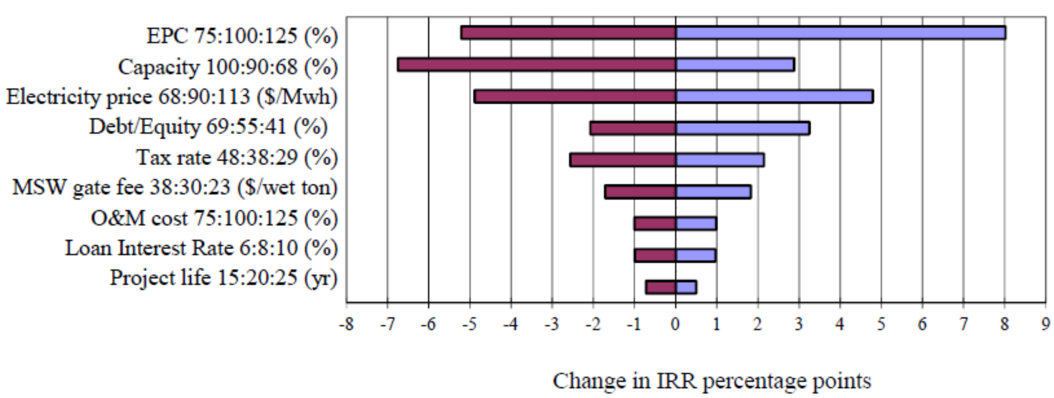
With the exception of plant feed and output rates, all financial model inputs were varied to determine the project financial sensitivities. The range of model input variables used in the sensitivity analysis is listed in Table 6. Input changes for the model were based on previous IRR calculation inputs. IRR sensitivity was evaluated using a ±25% change in the unit input. The variables and their impact on the financial outputs were then ranked to determine the model inputs of highest sensitivity, as shown in Figure 1.

Table 6: Range of values used in the sensitivity analysis

Model input	Baseline	(+25%) High Range	(-25%) Low Range
EPC cost ($MM)	96.4	120.5	72.3
Capacity (%)	90	100	68
Electricity sale price ($/Mwh)	90	113	68
Payback of MSW gate fee ($/ wet ton)	30	38	23
O&M Cost ($MM)	4	5	3
Project life (Yrs)	20	25	15
Debt (%)	55	69	41
Tax rate (%)	38	48	29
Loan Interest Rate (%)	8	10	6

Source: UCRiverside

Fig 1: Relative sensitivities of major plant inputs, +/-25%



Source: UCRiverside

Based on IRR sensitivity analysis results, the most influential factor is EPC since it dominates the project contingency, capital depreciation and total amount of loan capital. Because other model inputs are based on a percentage of the plant EPC cost, changes in this variable has a multiplier impact on the overall economic results. Plant capacity is the second most important factor that determines the amount of power generation. The IRR decreases by 6.8% if the plant capacity drops from 90% to 68%. Electricity sale price is the third important factor that affects the plant revenue directly and IRR varies ±4.9% while electricity sale price changed by ±25%. Debt/Equity, tax rate and payback of MSW gate fee also have important effect on IRR range from ±1.7% to ±3.2%. O&M cost, loan interest and project life have less impact on IRR within ± 1.0%.

Analysis and Evaluations

Aspen Plus modeling of Waste Gasification through Power Generation

Feedstock -- The average chemical composition of the MSW feedstock and its energy content is given in Table 1. The energy content of the dry-MSW sample is 7,690 Btu/lb (17.9 MJ/kg) in HHV.

Table 1: Feedstock composition

Proximate	Volatile Matter	71.1
	Fixed Carbon	14.6
	Ash	14.4
Ultimate	C	43.4
	H	5.6
	O	35.5
	N	0.77
	S	0.26

Source: UCRiverside

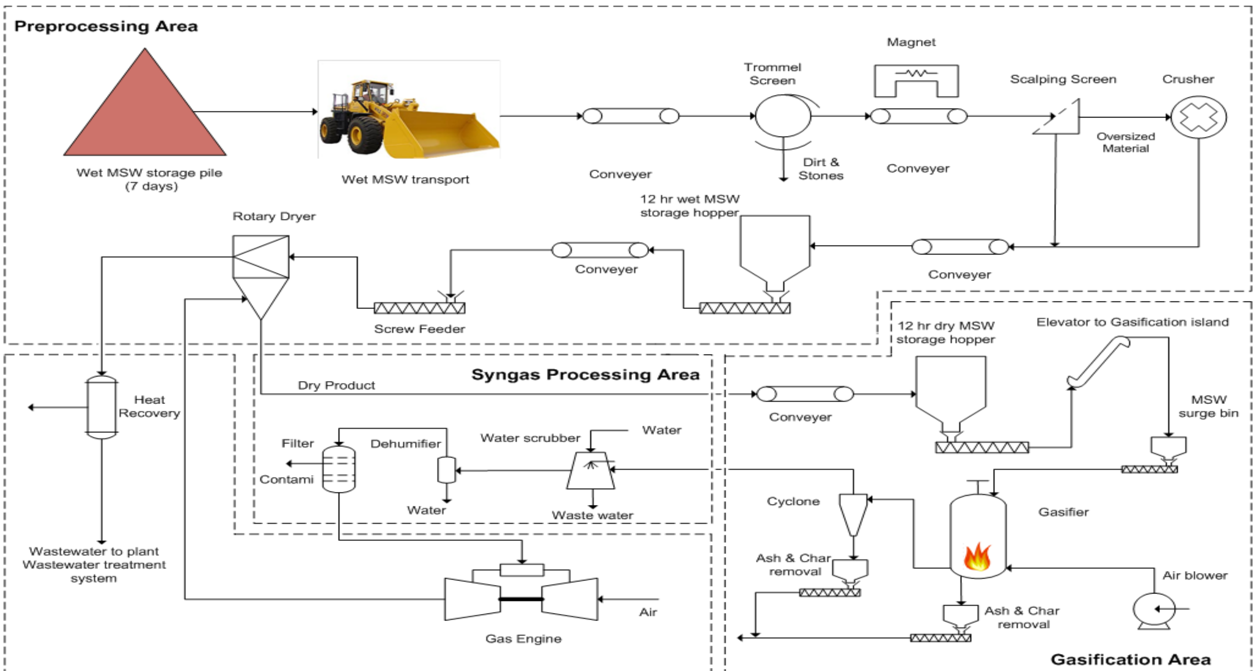
Process Design --The plant is assumed to be located near a landfill or a waste processing facility and the waste material is composed of both organic and inorganic residues. Cost of MSW gathering, loading and unloading and transportation is included in the analysis.

The power generation plant process diagram is shown in Figure-1. The plant includes a feedstock preprocessing area where wet-MSW is dried and shear-shredded according to the gasifier requirements. The MSW is then gasified in the gasification area to produce a medium/high energy content syngas. The raw syngas is cooled and cleaned to remove contaminants and undesired components in the syngas processing area. The power island converts the syngas into electricity using a combined cycle gas turbine or an internal combustion engine depending on the configuration. The plant size is 500 dry metric tons per day of MSW throughput. Except for the gasifier, all technology components such as the feed pretreatment system, syngas cleanup system, and gas turbine/engine are considered mature, and commercially available. The overall gasification process can be summarized as follows, with the pyrolysis step much faster than the gasification.

Pyrolysis: Feed + Heat (400-1200 ºC) → Coke (char) + Liquids (tar) + gases

Gasification: Feed + Gasifying agent + Heat (700-1400 ºC) → Gases (H_2, CO…) + Minerals (ash)

Figure-1. Flow diagram of the waste to power conversion facility



Source: UCRiverside

The key reactions involved are listed below[114].

$$C + 2H_2 \leftrightarrow CH_4 \qquad \Delta H_{1000K} = -89.9\ kJ/mol \qquad (1)$$

$$C + CO_2 \leftrightarrow 2CO \qquad \Delta H_{1000K} = 170.7\ kJ/mol \qquad (2)$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H_{1000K} = 136.0\ kJ/mol \qquad (3)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H_{1000K} = -34.7\ kJ/mol \qquad (4)$$

$$C + O_2 \leftrightarrow CO_2 \qquad \Delta H_{1000K} = -394.5\ kJ/mol \qquad (5)$$

$$2C + O_2 \leftrightarrow 2CO \qquad \Delta H_{1000K} = -222.0\ kJ/mol \qquad (6)$$

Reaction 1 is the hydrogasification reaction which accounts for most of the methane production. Reactions 5 and 6 are combustion reactions, traditionally employed for generating

[14] Carbon and Coal Gasification, NATO ASI Series, eds., J.L. Figueiredo and J.A. Moulijn, Martin Nijhoff Publishers, 1986

the required process heat by supplying oxygen or air into the gasifier. Reactions 2, 3 and 4 are the steam gasification reactions.

The following subsections provide information on the specific areas of the conversion facility.

Feedstock Pretreatment (Area 100)

This area contains feedstock size reduction and screening steps as well as drying. The feedstock is first transported from storage pile to a trammel screen where stones and dirt are removed after initial category. The feedstock then enters scalping screening after going through an electromagnet to removal the iron metal in the feedstock. Oversized material is filtered out and crushed into small pieces in a crusher and particle size less than 20-mm is conveyed to storage bin with 12 hr storage capacity. The MSW with an initial moisture content of 40% is dried using the tail gas drying system. The material is continuously fed from the intermediate storage facility to a plug screw feeder. The wet feed then enters the dryer via a disc shredder and is dispersed into an atmosphere of hot exhaust. The exhaust acts as a transport gas for the material through a drying duct where the moisture evaporates via direct heat exchange with hot tail gas from the gas engine. The dried product is separated from the exhaust in a high efficiency cyclone and discharged to the gasifier at approximately15-20% moisture by weight.

Gasification (Area 200)

The gasification area hosts the gasifier and accessary equipment that convert the feedstock into syngas. Dried feedstock is transported to a gasifier elevator from a dry MSW storage bin with a 12-hr storage capacity. The feedstock is then delivered into the gasifier from the surge bin. The gasifier is described in the main section of the report. The feedstock undergoes devolatilization as it flows through the gasifier, producing char, higher hydrocarbons and gaseous products. The air supply ensures the combustion reactions that provide the energy for the devolatilization, drying and gasification reactions. A medium BTU content syngas is produced; the ash is collected and removed in cyclones. The temperature of the gasification reactor is controlled by the amount of air fed to the gasifier, feed rate, and other parameters. Cyclones are used to capture escaping fine particles in the syngas and all the solid residues from storage bin are removed for storage and disposal. The carbon conversion at high temperature (about 1350°C) is almost complete; tars and oils are almost completely converted to CO, CO_2, H_2 and H_2O in the gasifier. The raw syngas is finally cooled down in the heat exchanger before it enters gas cleanup unit.

Syngas Processing (Area 300)

This area includes syngas conditioning and cleanup systems. The raw syngas contains particulate matter and other contaminants including ammonia, chlorine and sulfur species that are cleaned up before delivery to the power island. A water-scrubber is used for gas cooling, which also removes fine fly-ash and trace-tars to limit downstream plugging. The syngas is cooled to 40°C to condense the water followed by contaminant removal. The scrubbing water is recycled at a 90% rate and a dehumifier is used to condense additional water-vapor in the gas phase. At last, filter beds filled with sorbent are used if necessary, to meet the fuel specifications for the power generation system.

Power Island (Area 400)

Clean syngas is combusted in an advanced gas turbine based combined-cycle employed for power generation. An alternate option for power generation using a reciprocating gas engine was also evaluated. The exhaust from the gas engine is initially blown to a rotary drier for feedstock drying. The steam in the exhaust is condensed for heat recovery and the tail gas goes to the stack, while the condensed water is pumped into the waste-water treatment system. Power generated is used for plant requirements and for export to the grid for sale.

Process modeling

The process model was developed using the Aspen Plus software. Aspen Plus is a steady-state process simulator that includes extensive thermodynamic data-bases, built-in routines for common unit operations, and the ability to properly handle complex solids including biomass, MSW, and other waste matter. The Aspen simulation is controlled using FORTRAN routines (calculator blocks). For example, when necessary, the various design specifications were modified or fixed to reduce the number of independent variables used in the calculations. The process would automatically adjust those associated variables, i.e., the dependent variables, when the independent input variables were modified by the calculator block or a design specification. This was necessary to reduce unnecessary computing time without loss of overall model accuracy. The major simulation blocks used in the model are listed in Table 2.

Table 2: Major simulation blocks used in the model

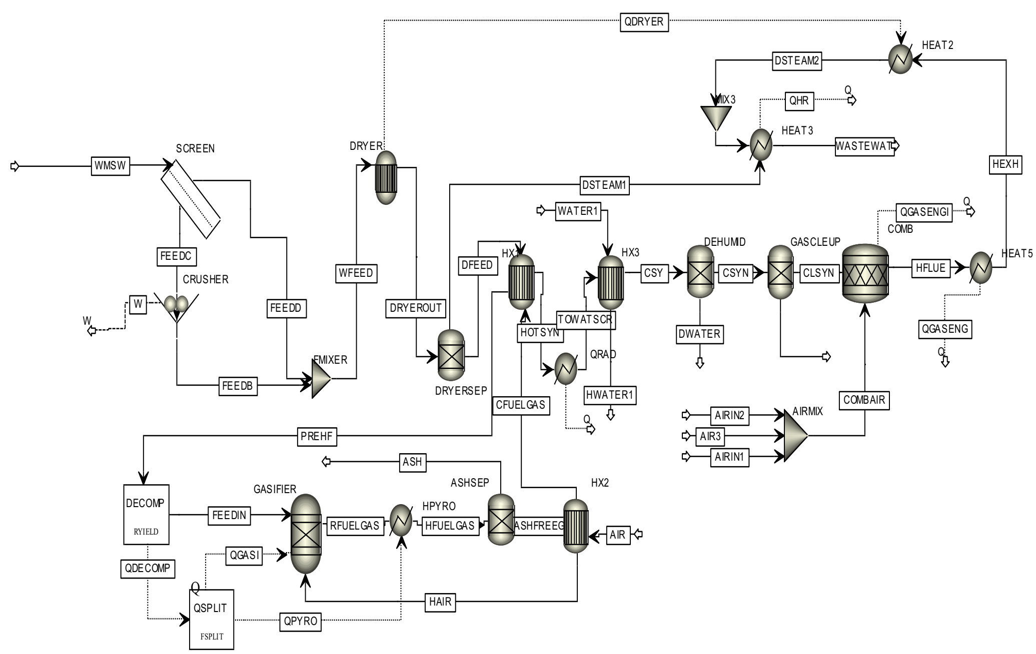
Operation area	Unit operation	Aspen plus model	Specifications
A100	Feedstock screening	Screen	Rigorous simulation of the trommel and scalping screen
	Feedstock shredding	Crusher	Rigorous simulation of particle size reduction
	Rotary dryer	RYield	Rigorous simulation of MSW drying
A200	Gasifier	RGibbs	Rigorous equilibrium simulation of the product mass distribution based on Gibbs free energy minimization
	Cyclone	Cyclone	Simplified simulation of ash and char capture
	Air blower	Pump	Simplified simulation of gasifier air supply
A300	Water scrubber	HeatX	Simplified simulation of heat exchange between raw syngas and water
	Dehumifier	Separation	Simplified simulation of water removal
	Filter	Separation	Simplified simulation of dust and contaminants removal

A400	Gas turbine	Rstoic	Rigorous simulation of syngas combustion
	Heat recovery	HeatX	Simplified simulation of heat exchanger

Source: UCRiverside

The gasifier is simulated in the model in two blocks: the 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 first step is the decomposition of the feedstock, resulting in the production of char from carbon, and gases from the volatile portion. This devolatilization step is followed by the actual gasification, which can be described as the reaction between the carbon in char form and air. The decomposition block converts the non-conventional feedstock such biomass or coal into its basic elements based on yield information using the RYIELD block. The components are then sent to the gasification block (RGIBBS), which calculates the equilibrium product gas composition using the Gibbs free energy minimization approach. 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 ash and unreacted char are removed from the reactor in a solids stream and the product gas is subjected to gas cleanup in order to remove contaminants such as sulfur. The power generation system is simulated using a combustion model and heat exchanger units. The model uses of 20-40% excess air with specific operational parameters from commercial systems. A simplified version of the Aspen flow diagram is given in Figure 2.

Fig 2: Aspen Plus flow diagram



Source: UCRiverside

Results

The Aspen model was run under a range of process conditions to perform initial sensitivity analysis. The most viable conditions were selected for further optimization with respect to thermal and electric efficiencies. The net energy efficiency was maximized through waste heat recovery and thermal integration of the facility.

The key parameters affecting net plant energy efficiency include the feedstock moisture content, power generation technology option, and thermal integration. The plant energy conversion efficiency ranges from 28% to 47% based on these parameters. The lower range of energy efficiency values correspond to a reciprocating engine configuration with minimal waste heat recovery and little thermal integration. The upper range efficiency corresponds to a combined cycle system with a 20% feed moisture content and optimized waste heat recovery.

The optimal power plant performance data from the optimized model for the 500 TPD MSW (dry basis) throughput facility is given in Table 3. Based on the process simulation results, syngas (CO and H_2) volume fraction is 38.5% among the gases in the gasifier outlet with cold gas efficiency of 85.7%. The fraction rises up to 41.6 after steam condensation and the fuel gas goes to the power generation section with energy content of 151.1 Btu/SCF. The overall power generation in the gas engine is 49.1 MW with 46.6 MW export to the grid after the auxiliary loads in the plant. The total plant electricity efficiency (electricity/thermal input) is 45% using a combined cycle power generation system.

Table 3: Power plant performance

Plant performance	
MSW (20% moisture, ton/day)	625
Air to gasifier (ton/day)	799
Gasifier operating pressure (psi)	40
Gasifier exit temperature (°C)	1200
Gasifier exit gas composition (Vol%)	
H_2	15.94
CO	22.68
CO_2	5.69
CH_4	0.84
H_2O	7.18
N_2	46.75
Ar	0.54
Others (C_{2+}, H_2S, NO, etc.)	0.38
Syngas composition to gas engine (Vol%)	
H_2	17.17
CO	24.43
CO_2	6.13
CH_4	0.91
N_2	50.38
C2+	0.41

Ar	0.58
Cold gas efficiency	85.7%
Syngas energy content (MMBtu/SCF)	151.1
Power generated	49.1
Auxiliary load	2.5
Net power export	46.6
Plant electric efficiency	45%

Source: UCRiverside

Life Cycle Assessment

Two of the most important criteria used for the technological evaluation of industrial systems are the total energy consumption and the net emissions of the desired pathway. Conventional methods of evaluation often focus on a limited number of steps in a production pathway and are inadequate in their ability to quantify the "cradle-to-grave" energy use and emissions. LCA models iteratively calculate the energy use and emissions associated with specific pathways using large databases consisting information on various stages of the pathways and some user-specified input values. An LCA of the gasification process for power generation was conducted and the results are given below.

Greenhouse gases. The key GHGs considered by the LCA and their Global Warming Potential (GWP) compared to CO_2 are given in the Table below. The GWPs are the 100-year warming potential values published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and are often referred to as the IPCC 2007 GWPs[15]. The GHG emissions for each pathway are calculated for each GHG and are reported on a carbon dioxide equivalent (CO_2e) basis using the GWPs.

Table 4. Global Warming Potentials of the key GHGs

GHG Name	100 Year GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Chlorofluorocarbons(CFC-12)	10,900
Hydrofluorocarbons (HFC-134a)	1,430

Source: UCRiverside

Energy use. The categories of energy use are listed below.

- Total and fossil energy used per unit of energy produced for each stage of the power generation process
- Total energy used per MJ of energy produced
- Fossil energy used per MJ of energy produced

[15] IPCC 2007, Climate Change 2007: Working Group I: The Physical Science Basis, from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html.

- The proportions of types of energy used for each stage of power generation cycle

A number of software packages are available that include extensive databases and 'pathways' that can be used to evaluate most of existing technology/pathway options. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model is one such model that is widely used in academic studies, especially in the United States. This study is conducted using the CA-GREET 2.0 Tier 2 model (CA-GREET 2017). The CA-GREET model is a modified version of the GREET model consisting of California specific assumptions.

The basic assumptions used in model are listed below:

- Analysis year: 2015
- Feedstock: Baseline-California power mix; Biomass gasification pathway- forest residue
- CAMX grid (California-Mexico grid) mix is regional electricity mix for utility supply
- CA Crude is selected for regional crude oil use
- Natural gas (NG) feedstock is considered as North American (NANG)
- Final product FT Diesel use: passenger car with 24.81 MPGGE
- Process efficiency: Biomass gasification to power: 45%
- Steam/electricity export credits: none

The Well to Pump (WTP) results of the biomass to power life cycle analysis are presented in Table 5. The total and fossil energy use are listed including specific petroleum, coal and natural gas use information. The table shows the emissions of all the major greenhouse gases in CO_2 equivalent values. The GHG emission for the baseline case is 105.2 g CO_2e/MJ while the GHG emission for the biomass gasification process is 21 g CO_2e/MJ. The criteria pollutant emission information is also shown in the table. The results show significant GHG emission reductions compared to the grid mix.

Table 5. Well-to-Pump Energy Consumption and Emissions: MJ or g per MJ of Electricity

	Baseline electricity (CAMX Mix)	Electricity from biomass gasification
Total Energy	1.08	1.47
WTP Efficiency	48.0%	40.5%
Fossil Fuels	0.81	0.12
Coal	0.12	0.00
Natural Gas	0.66	0.08
Petroleum	0.03	0.04
CO2 (w/ C in VOC & CO)	97.81	12.96
CH4	0.263	0.039

N2O	0.003	0.024
GHGs	105.2	21.0
VOC: Total	0.017	0.007
CO: Total	0.107	0.040
NOx: Total	0.148	0.051
PM10: Total	0.015	0.014
PM2.5: Total	0.011	0.008
SOx: Total	0.111	0.003
VOC: Urban	0.003	0.001
CO: Urban	0.026	0.007
NOx: Urban	0.029	0.007
PM10: Urban	0.001	0.003
PM2.5: Urban	0.001	0.001
SOx: Urban	0.002	0.001

Source: UCRiverside

Conclusions

The 500-dry-ton/day embodiment modeled and analyzed by UC Riverside represents an advanced version of the gasification process that operates at 400-psi, which serves to boost the over-all plant efficiency to 45%, compared to 31.5% efficiency for a near-atmospheric pressure gasification cycle integrated with a steam-injected gas turbine used for power generation.

The financial model shows an 18.64% IRR with LCOE of 41.01 $/kw. The payback period of the plant is 10.1 years excluding the two-year construction period with an NPV of 41.01 MM$. The Well to Pump (WTP) results of the biomass to power life cycle analysis show that the GHG for the shockwave gasification pathway is21 g CO_2e/MJ. The results show significant GHG emission reductions compared to the grid mix.

A demonstration-scale project is based on a 40-ton/day embodiment that will receive two tractor-trailers loads per day, each containing about 20-ton of refuse derived biomass. Power output would be 1.7 MW based on using IC engines designed for operation on low-BTU gases. Permitting a 1.7 MW demonstration scale MSW-to-Power project would not be problematic because the environmental impacts are minimal and would allow for a negative declaration.

APPENDIX D: Technical Advisory Committee

A Technical Advisory Committee meeting was held on January 23, 2017. The participants are listed below:

- Mr. Bob Bradley, Biomass Power Plant Developer
- Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy
- Dr. Sam Young, Retired Naval Captain
- Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering
- Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology

Meeting comments and the subsequent discussion are listed below:

<u>Mr. Bob Bradley, Business Man, Biomass Power Plant Development</u>

Data should be in a form that is comprehensible to the non-scientist; simple graphic output images. He would we like to know the permitting constraints; the permit values for emissions for the Imperial Valley? My response: yes.

The 160-acre site owned by his company, ML Energy, located in the Imperial County, is permitted for thermal processing of biomass and refuse derived biomass. A natural gas pipeline is at the foot of the property; transformers and power connections exist to export 30-MWe of power to the grid.

<u>Mr. Mike Fatigati, Renewable Energy Consultant, Specializing in Biomass-to-Energy</u>

Concern about any waste water treatment issues; organics in the waste water.

My response: Nitrogen compound sin the feed form ammonia NH3 during gasification, which reacts with HCl (also formed during gasification), forming ammonium chloride that precipitates as a salt in the final water scrubbing system. However, for successful operation, heavy organic fractions must be removed from the fuel-gas up-stream from the aqueous scrubbing system to preclude a water treatment issue. The Reformer and High-Temperature-Granular-Filter are intended to remove heavy organics from the products gases by thermal cracking. A favorable market response can be expected (“I would be excited…”) if pulse-jet burner is “as good as” a plasma burner – without the high initial cost and the high operating cost.

Dr. Sam Young, Retired Naval Captain

Requested information about the schedule; and about the environmental performance. My response: The testing will be completed by the end of June and the draft -reports will be submitted by the end of the year. Environmental issues will certainly need to be addressed thoroughly during demonstration scale operation, running extended test campaign. After this program, next step is to achieve 500 hours of operation, in preparation for demonstration scale.

Dr. Arun Raju, Gasification Expert, Ph.D. in Chemical Engineering

Discussed the ASPEN modeling and analytical work that will be performed as project deliverables.

Ms. Nicole Davis, Deputy Administrator, Center for Energy Research and Technology

Requested information about scale-up program; we responded with information about the CEC's demonstration programs.