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ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Advanced Recycling of Municipal Solid Waste

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) 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 solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & 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 CEC is committed to ensuring public participation in its research and development programs that 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 Municipal Solid Waste is the final report for Contract Number EPC-14-045 conducted by Taylor Energy. The information from this project contributes to Energy Research and Development Division's EPIC Program.

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

ABSTRACT

During the past decade, pulse-detonation engines have emerged as a high-priority technology for the 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 three-ton per day capacity. The researchers tested the system performance using post-sorted municipal solid waste as the renewable energy feed. Advancing this novel gasification technology intended for waste processing and biopower generation can help California generate municipal waste-based biopower, including conversion of 30 million tons per year of municipal waste into usable biopower. Using the Aspen Plus Chemical Process Simulator (AP) 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 per day; whereas, the initial design was only for half that capacity. As a result of preliminary testing, the levelized cost of power is expected to be reduced to $118 per megawatt – a 30 percent reduction when compared to commercial-scale municipal solid waste 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 levelized cost of power. This project development effort fulfills an important California market requirement for municipal solid waste use at the community scale.

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

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Introduction

According to CalRecycle, 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). Waste-to-energy projects could recover 75 percent of all MSW as refuse-derived biomass (RDB). This is a substantial source of energy since the per capita disposal rate of refuse-derived biomass in the United States is 4.4 pounds per person per day, or about one ton per person per year.

Currently, California and the United States can benefit from the economic use of MSW as a gasification feed, particularly in the 2-megawatt electrical (MWe) to 40-MWe net power output range. Industry has overlooked this size range because the business opportunity is too small for large companies such as General Electric and Shell, while the research and development effort is too complex and too costly for smaller business entities. There is a market demand to address MSW as an "opportunity feedstock" and to address the equipment size range required 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 based-businesses. Taylor Energy is developing a novel shockwave-powered gasification technology intended for community-scale power generation. The system cost projection is $3,750 per kilowatt-hour (kWh) of installed capacity, at a 300-ton per day scale (10 MWe).

Project Purpose

Advancing this novel gasification technology helps California by potentially converting a portion of the 30-million tons per year of MSW into useful biopower and other energy products. The technology is projected to reduce the levelized cost of power by 30 percent compared to commercial-scale MSW combustion systems.

The California Energy Commission funded Taylor Energy to test the gasification of RDB recovered from MSW. Applying pulse-detonation technology to waste biomass gasification substantially improves 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 size reduction and enhanced mixing. This technology 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. This project has substantially advanced shockwave technology applied to gasification and reforming methods. In addition to clean power, industry can use this technology to convert MSW residues into renewable methane and ethylene-propylene fractions used to make renewable plastics.

Shockwave-powered gasification shows substantial potential to reduce overall costs and lower the levelized cost of power. This project fulfills the market requirement for MSW use 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 a pilot-scale test facility at the University of California, Riverside. The gasification process includes key stages to accomplish thermo-chemical conversion of MSW feed into fuel gases. At an initial stage, a jet-spouted bed converts the solids into volatile substances. At a second-stage, the tar vapors are cracked into low molecular weight gases. These two stages convert the feed into gases and into materials that are size-reduced, entrained, and elutriated with the fuel-gases. Carbon char and trace aerosol tars are removed in the next stage. The resulting fuel-gas is cleaned with wet-scrubbers.

Modular construction was used for the gasification reactor and the reformer. The reactor spool-sections were bolted together using custom-made graphite gaskets to form for the seals. This modular construction method served to reduce the overall installation cost.

One of the goals was to reduce costs when compared to existing MSW combustion systems. For example, the parasitic utility costs were minimized by reducing the air input pressure to three pounds per square inch gauge (psig), using pressure-gain combustion (pulse-detonation). Currently, no other fluid-bed or entrained-flow gasification system can operate employing such a low pressure-drop budget. This process maximizes the system-capacity relative to the reactor volume.

The gasification rate is controlled by three process parameters: time, temperature, and turbulence, along with the particle size, which controls the rate of heat and mass transfer between gases and solids. The gasifier and the reformer operate just below the ash-fusion temperature, at 2102°F (1150 °C), well above the 1742°F (950 °C) limit for typical fluidized bed gasifiers. Shockwaves increase gas-solids mixing and reduce particle size.

Project Results

Taylor Energy has performed proof-of-concept testing by operating the gasification system at equilibrium conditions during approximately four-hour to eight-hour test periods. It takes about one hour to heat and reach thermal equilibrium conditions. Typically, the gasification system was heated using wood shavings, then it was switched to feeding the RDB.

Initially, pulse-deflagration burners were installed and tested on the bottom of the jet-spouted bed. Next, start-up tests were performed using a pulse-detonation burner designed by Taylor Energy. The pulse-detonation burner is installed on the bottom of the jet spouted bed gasification reactor and generates repetitive shockwaves. Proof-of-concept testing and early-stage developments was measured with this configuration.

Ceramic beads were the fluidized-bed material of choice. They provided the most robust environment for gasification due to the greater number of collisions providing rapid ablation of the feed materials. The steel beads are indestructible; but their higher density resulted in fewer collisions and a lower ablation rate of the feed.

Taylor Energy used an infrared analyzer to measure four key gases to control the process: carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and oxygen (O_2). Tedlar bags were used to sample and analyze the gas to evaluate trace components and to verify that the gas compositions are suitable for power generation. The fuel-gas composition data is summarized in Chapter 3, Project Results.

Technology/Knowledge Transfer/Market Adoption

The technology developed at pilot-scale is designed for scale-up to a single train capacity of 1,200 tons per day RDB gasification, producing 40 megawatts electric (MWe) of net power to the grid. This technology is intended to be used at community-scale and replicated at multiple locations. The knowledge gained from this project can be used by the thermochemical conversion community and MSW industry to increase understanding of new conversion pathways, and new methods of using shockwave power to intensify MSW gasification.

Taylor Energy intends to establish a demonstration-scale project that generates 1.7 MWe, processing about 40 tons per day of 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 required to verify any advanced gasification concept.

The commercial module Taylor Energy plans to market is a 427-ton per day plant exporting 10 MWe. For permitting purposes in California, 500 tons per day is the optimum size for early projects. 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. It is 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.

Benefits to California

This project will result in ratepayer benefits of rural and urban economic development, reduced environmental impacts, and increased national security. Economic benefits come from smaller electric bills, achieved by lowering the cost of renewable power, which makes up an increasing portion of the energy mix. Economic benefits would also be derived from the additional labor required to process the RDB. Environmental benefits include decreased impacts from global climate change by using renewable feedstocks instead of fossil fuels. It would reduce the number and size of landfills. Security benefits include reduced reliance on natural gas delivered via interstate pipelines used to import fossil fuels compared to using an instate resource.

One measure of the project value is the estimated 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 per megawatt-hour (MWh) in 2018, increasing to about $158 per MWh in 2024. Assuming a mean power price of $158 per MWh for existing waste-to-energy derived power, the measurable cost savings is estimated to be $40 per MWe for every megawatt of power generated using the proposed new shockwave gasification-reforming technology.

Future work includes a follow-on Taylor Energy and University of California, Riverside project funded by the California Energy Commission to compare several different power generation cycles using forest residues and to accumulate 500 hours of operating data in preparation for a 1.7 MWe demonstration project.

CHAPTER 1: Project Justification

Background

In California, waste-haulers dump 30 million tons per year of organic materials into existing landfills — the equivalent energy 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).[2] Future waste-to-energy projects could use 55 percent of all MSW generated yearly. This is a major potential source of energy since the per capita disposal rate of refuse-derive biomass in the United States is 4.4 pounds per person per day, or about one ton per person per year.

Currently, California and the United States can benefit from the economic use of MSW as a gasification feed, particularly in the one megawatt electrical (MWe) to 20 MWe net power output range. Industry has overlooked this size range because the business opportunity is too small for major companies such as General Electric and Shell, while the research and development effort is too complex and too costly for smaller business entities. There is a real market demand to address MSW as an "opportunity feedstock" and to address the equipment size range required 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-based 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 per kilowatt-hour (kWh) of installed capacity, at a 300-tons per day scale (10 MWe). The Energy Commission funded Taylor Energy to design, construct, and test a pilot-scale gasification system intended to process refuse-derived biomass recovered from MSW.

The Taylor Energy gasification technology, currently at technology readiness level 3 to 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 thermochemical processing, working to optimize gasification/reforming methods for use at a 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, as described in the agreement objectives.

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

[2] Ibid.

- 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 ratepayer benefits of higher electrical reliability and lower cost, by developing distributed generation capacity that uses a renewable resource otherwise disposed of in landfills. One ton of MSW reclaimed from landfills contains the energy equivalent of two barrels of oil. Assuming 30 percent net conversion to electric power; about one ton of MSW is consumed to make one MWh of electricity. The levelized cost of power is estimated to be $118 per MWh (for 10-MW scale), which results in ratepayer savings of $32 per MWh compared to grid supplied power that will likely average $150 per 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 estimates, based on equipment costs, and projected mass and energy balances, anticipate system cost of less than $3,750 per kWh of installed capacity. Design, construction, and start-up testing will provide necessary research and verification of this breakthrough in waste processing.

Objectives

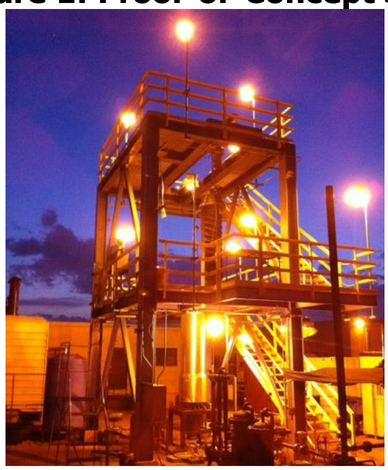
The objectives of this project were to:

- Operate the gasification/reforming process continuously for eight hours, with RDB input of three pounds per minute (1.08-million British thermal units [MMBTUs] per hour, based on energy content of 6,000 BTUs per pound for RDB). Average fuel-gas output should be 0.80 MMBTU per hour, having energy content of 230 BTU per standard cubic foot (scf), demonstrating 74 percent net conversion efficiency of feed into fuel-gas.
- Operate the thermal-chemical gasification process with an over-all stoichiometric ratio of 0.28; using oxygen enriched air at 33 percent oxygen, to achieve carbon conversion greater than 90 percent 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 greater than 7 Hz using transient plasma ignition, firing the pulse burners with excess air.
- During the proof-of-concept testing, establish the durability of stainless-steel pulse-combustor(s) with no observable failures resulting from the high-temperature and pulse-detonation operation.
- Establish process heat and mass balance by a semi-empirical method and semi-empirical 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 per day modular system.
- Confirm from the project findings that the levelized cost of power of $118 per MWh, including a 10 percent return on equity, is supported based on a 300-ton per day modular system.
- Estimate carbon footprint for the process and the products by Life Cycle Analysis through greenhouse gases, regulated emissions, and energy in transportation.

Project Objective

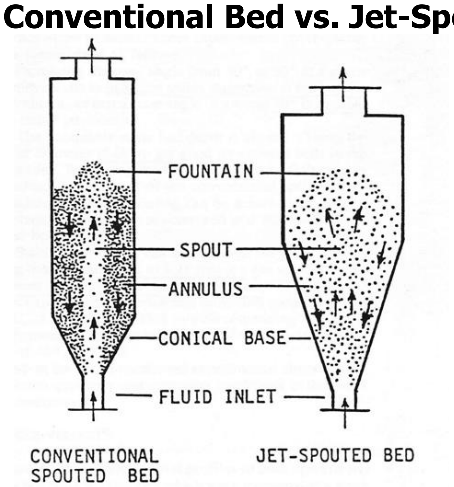
The objective of this project was to research and develop thermal-catalytic recycling technology that promises to overcome the technical and economic barriers preventing the use of MSW as an energy resource in California. The project goal was to verify key subsystems for advanced recycling of MSW, producing clean fuel-gas for electric power generation. This was to be done 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 that could, by 2020, be cost-competitive with fossil fuel products. The pilot-scale facility expanded on proof-of-concept testing that had previously been performed at large bench-scale, using the jet-spouted bed gasification reactor (Figure 1.) The fluid-bed dynamics of our jet-spouted bed gasification reactor are illustrated and compared to conventional spouted-bed (Figure 2).

Figure 1: Proof-of-Concept Site



Source: Taylor Energy

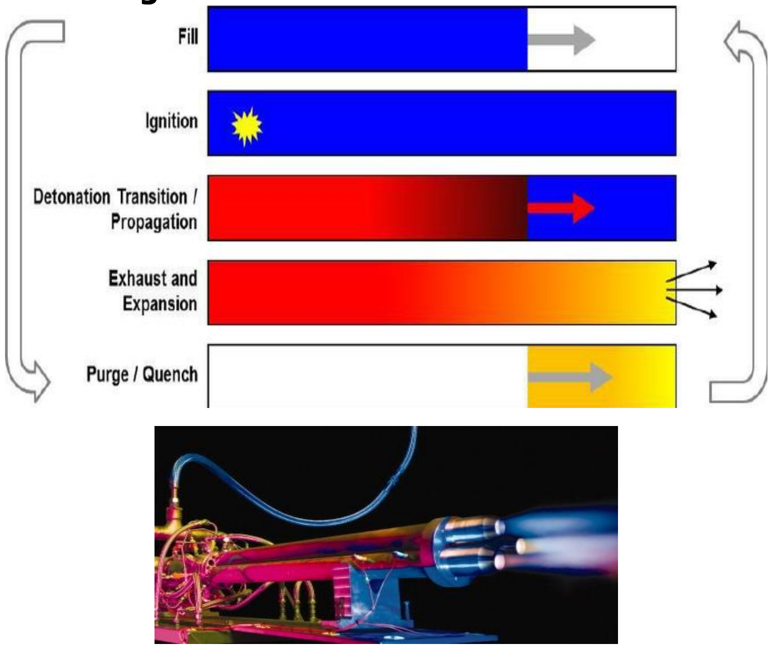
Figure 2: Conventional Bed vs. Jet-Spouted Bed



Source: D. Kunni

Funded by an Energy Innovations Small Grant, a pulse-detonation-burner was compared with a pulse-deflagration-burner. Pulse-detonation burners operate by igniting an air-fuel mixture in a tube (Figure 3).

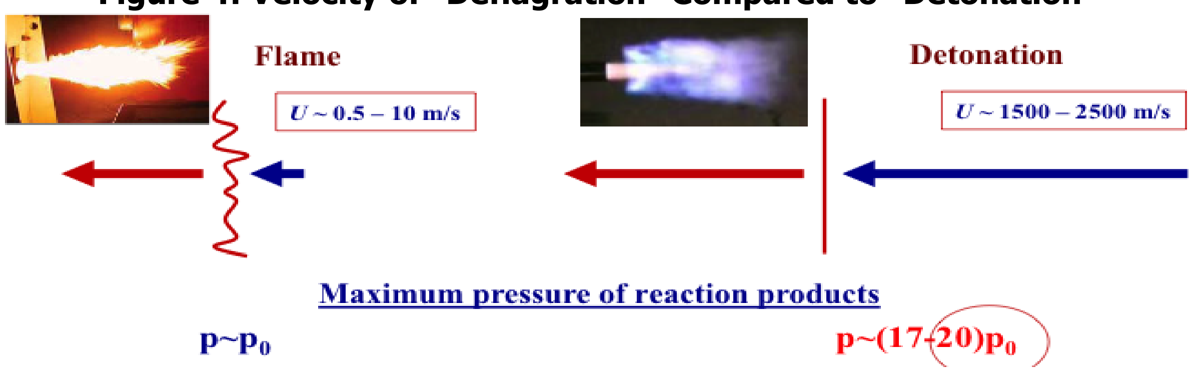
Figure 3: Pulse-Detonation Burner



Source: ResearchGate, University of Cincinnati; photo FlugRevue.de

The flame front velocity of "detonation" compared to "deflagration" (Figure 4). The discharge velocity from a pulse-detonation burner is reported to reach 2,000 meters per second, and the pressure-gain can be 20 times that of the input pressure.

Figure 4: Velocity of "Deflagration" Compared to "Detonation"



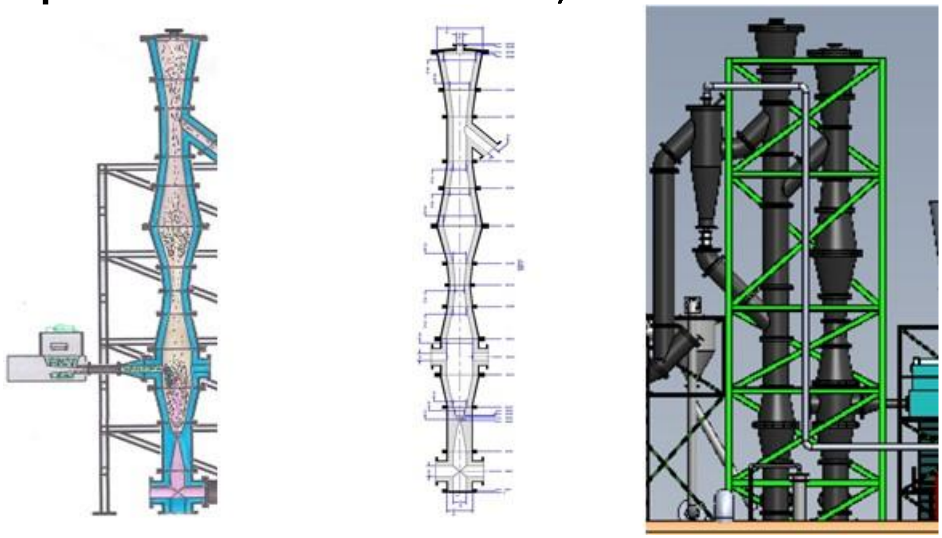
m/s = meters per second

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 jet-spouted bed 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. The jet-spouted-bed gasification system (Figure 5) 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 5: Jet-Spouted Bed Gasification Reactor, Two- and Three-Dimension 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 meters per second 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.

Taylor Energy 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 BTUs per standard cubic foot, intended for economic production of renewable electric power.

Existing Waste Gasification Technology

Waste-to-energy plants are generating 0.84 quadrillion BTUs per year, or 2.2 percent of United States electric power.[4] As of 2018, 85 plants employ thermal technology to process MSW in 23 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

[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

- Recycling has peaked at 34.7 percent
- Only 10.4 percent of MSW in the United States is used for waste-to-energy

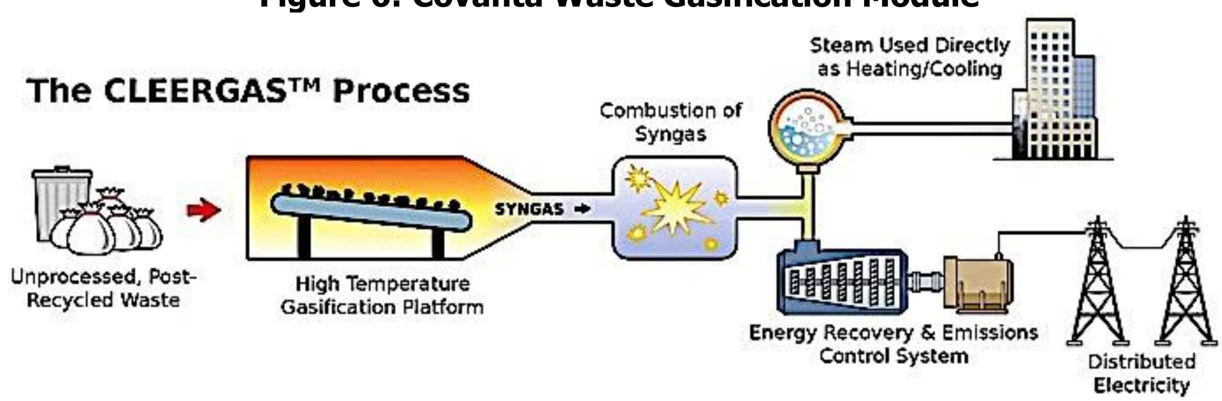
In California, about 0.9 million tons of MSW were burned (transformed) at three permitted MSW mass burn facilities. Provisions in the Public Resources Code, sections 40201 and 41783 allow limited diversion credit for transformation. MSW-powered generating plants typically operate 90 percent of the time,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

There are many successful waste-to-energy 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 an 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 Environmental Solutions (Covanta) has developed a 300-ton per day modular (two-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 6 is not a true gasification process, as defined by the Gasification Technology Council, because the process employs a two-stage combustion method, followed by a heat recovery steam generator used to power a steam turbine.

Figure 6: Covanta Waste Gasification Module



Source: Covanta Environmental Solutions

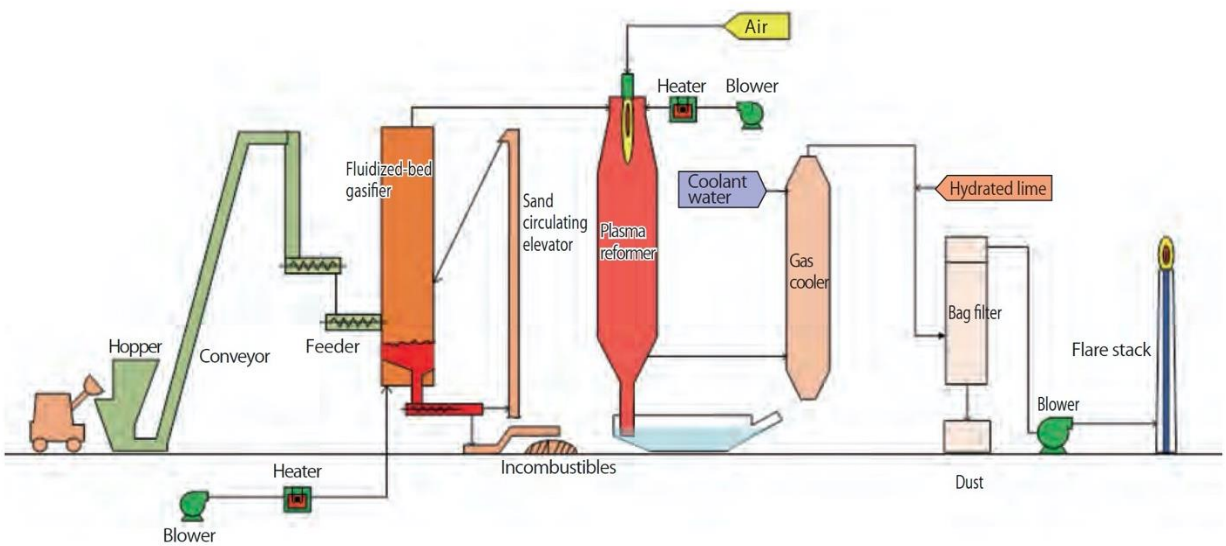
New waste-to-energy projects are in the pipeline in several states and provinces, including Florida, Maryland, Puerto Rico, and Ontario, Canada; but it is not easy to locate, permit, and finance, large mass-burn facilities. The permitting process is especially arduous for large waste-to-energy facilities. Public opposition is often a substantial 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 shorter timeline 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 from 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 7 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 United States.

Figure 7: 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 waste-to-energy 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 to 100,000 tons per day feed input. Community-scale required for distributed power generation is 300 to 1,200 tons per day, using refuse-derived biomass recovered from MSW.[4]

There are many village-scale gasifiers with less than 100 kWh capacity. The up-draft or down-draft gasifiers, exemplified by Ankor Scientific, Community Power Corporation, and others,

American Gas Association, Full-Fuel-Cycle Energy and Emission Factors for Building Energy Consumption- 2018 Update. Jan. 2019. https://w have demonstrated small-scale systems that operate continuously and provide some benefits. This type of technology is said to scale-up to about one MWe; however, only when using uniform (ideal) biomass feed materials. The up-draft and down-draft systems require a uniform feed. For example, during World War II, when "a million" vehicles operated on producer gas, a huge cottage industry was also required to make uniform feed required 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 systems. Nevertheless, these systems cannot handle garbage unless it is pelletized; and the cost of producing refuse-derived fuel -pellets is considered prohibitive.

Fluid-bed gasification systems (both bubbling fluidized bed and circulating fluidized bed types) are applicable to RDB feeds. However, when applied to MSW-derived fuels, the traditional bubbling fluidized bed and circulating fluidized bed systems have been costly to build and costly to operate; especially at a 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 fluidized bed being tested by West Biofuels, LLC (based on Gussing Renewable Energy's dual fluidized bed 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 Gussing dual fluidized bed 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 dual fluidized bed designed by the Battelle Columbus Laboratory, has also been proven too costly to construct and to operate when applied to medium-scale power generation. According to Taylor Energy, "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 8 shows a Pyrox-type dual fluidized 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 is too costly to deploy for electric power generation.

Figure 8: Pilot-Scale Pyrox Dual Fluidized Bed Gasification System (Five Tons Per Day)

Source: Taylor Energy

Sierra Energy is developing an oxygen-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 downstream from the high-temperature primary stage.

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 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 one-MWe to 20-MWe power output range appropriate for community-scale projects. This size range is overlooked by industry because the business opportunity is small for large companies like General Electric and Shell, while the research and development effort is complex and costly for smaller business entities. There is a real market demand to address refuse-derived biomass as an "opportunity" feedstock recovered from MSW; and to optimize the economic returns for the plant sizes required for distributed power generation in California communities.

Economic Benefits

In California, 30 million tons of organic materials are being added to 80 landfills each year; equivalent to disposing of 60 million barrels of oil per year. The project goal for the system cost is $3,750 per kWh of capacity at 300 tons per day (10 MWe). According to the Black & Veatch screening model developed for biomass gasification, the levelized cost of power would be $118 per 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 Pacific Gas and Electric Company territory is projected to increase to about $158 per MWh in 2024. The measurable cost savings is estimated to be $40 per MWh for every megawatt of power generated using refuse-derived fuels.

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

Table 1: MSW Feedstock Available and Potential Distributer Power

Characteristic	Description
Mass	30 million tons/yr. MSW / 8,760 hrs./yr. = 3,424 tons/hr. MSW 3,424 tons/hr. x 75% recovery as RDB = 2,568 tons/hr. RDB 2,568 tons/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

MWth = megawatt thermal

Source: Taylor Energy

Table 2: Measurable Value — Potential Energy Cost Savings

Value	Potential Cost Savings
3,330 MWh x $40/MWh x 8760 hrs./y x 0.90 availability	= $ 1.05 billion per year

Source: Taylor Energy

The project findings expect to confirm that the production cost of renewable power using RDB as the feed will provide cost savings benefits of $40/MWh.

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. The jet-spouted bed can be seen during operation in Figure 9, looking into a side port, located opposite the feeder.

Figure 9: Jet-Spouted Bed During Start-up Testing

Source: Taylor Energy

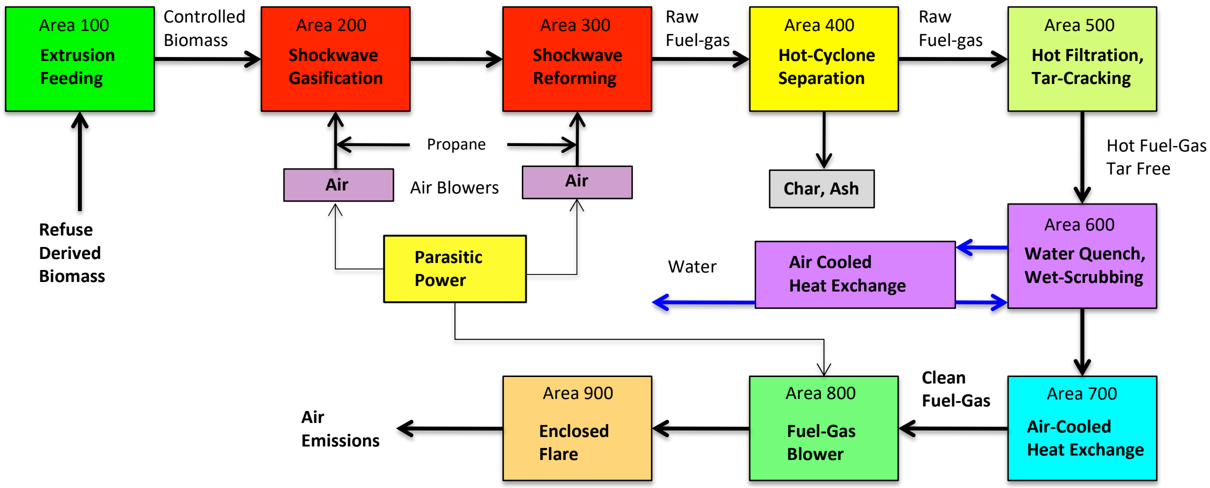
Pilot-Scale System Design and Installation Plan

The syngas process being developed by Taylor Energy is designed to handle difficult waste materials, including MSW that has been recovered as RDB-fluff. RDB-fluff is the combustible fractions within MSW that are recovered by shredding and size-reducing the MSW, then using air classification and screening to separate the light fractions that include 90 percent of the 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 jet-spouted bed, and to increase the thermal chemical reaction rates at the molecular level by 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). Figure 10 shows a flow diagram of the project approach. A detailed description of the process is included in subsequent sections; the completed pilot-scale gasification/reforming system is shown in Figure 11.

Figure 10: Block Flow Diagram Showing Project Approach



Source: Taylor Energy

Figure 11: Waste/Biomass Gasification Test Facility, at the University of California, Riverside

Source: Taylor Energy

Taylor Energy designed and constructed a pilot-scale test facility at the University of California, Riverside. The gasification process shown in Figure 1 includes the key stages to accomplish thermal-chemical conversion. At an initial stage, a jet-spouted bed devolatilizes the feed (Area 200) and at a second-stage, the 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 (Area 400) – recycling of the char is performed as required. At another stage, a moving-bed tar-cracker removes trace aerosols (Area 500). For testing purposes, fuel-gas cleaning was accomplished using wet-scrubbers (Area 600 and Area 700).

System Operation Overview

The system is operated using 3-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 standard cubic feet per minute (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 per pound for RDB), with average fuel-gas output of 0.80 MMBTU per hour, 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.

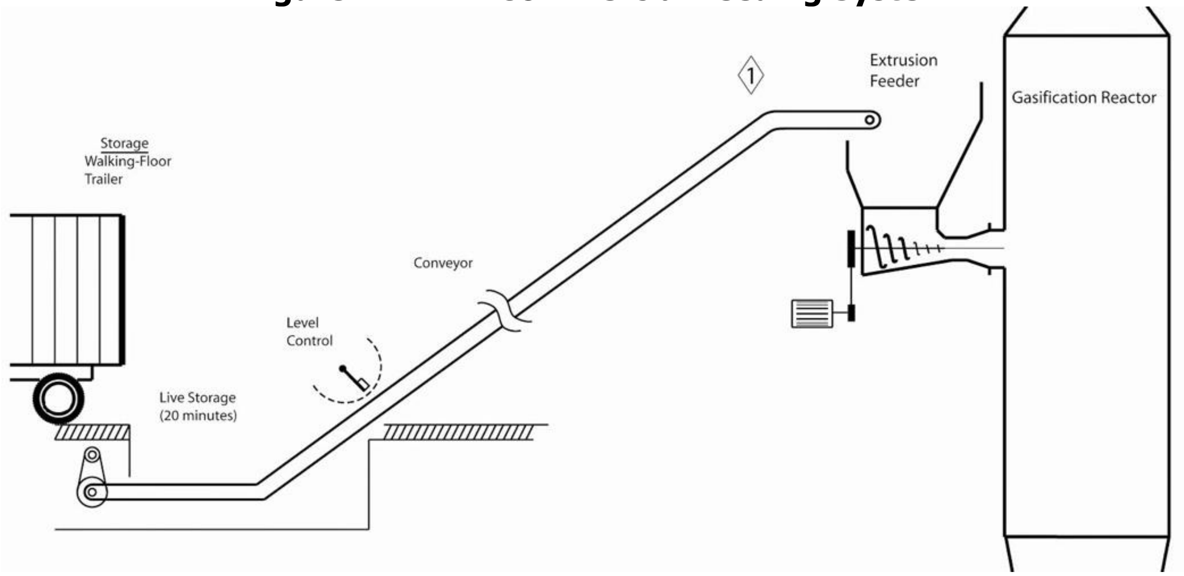
The program objective was to quantify the system inputs and outputs; to develop a reliable mass and energy balance; and to identify any operating difficulties that would prevent commercialization of the technology at large-scale. For example, the program sought to identify erosion, corrosion, or deposition 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, 8-hour continuous runs that established equilibrium conditions for the process.

System Design — How the System Works

Feeding Refuse-Derived Biomass Into the Gasification Reactor

A commercial-scale feeding system is shown in Figure 12**.** RDB-fluff is conveyed by belt-conveyor (at 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.

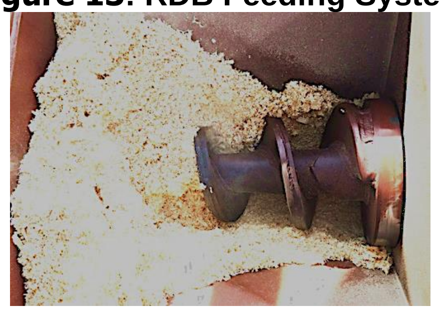
Figure 12: RDB Commercial Feeding System



Source: Taylor Energy

The Komar extrusion-feeder is a high-torque auger-feeder that forces RDB-fluff into the gasification reactor, forming a feed-plug that seals the gasification reactor from ambient-air infiltration. Typically, the gasification system was heated using wood shavings (Figure 13), then it was switched to feeding-in the RDB (Figure 14).

Figure 13: RDB Feeding System



Source: Taylor Energy

Figure 14: Komar Feeder — Extruding RDB

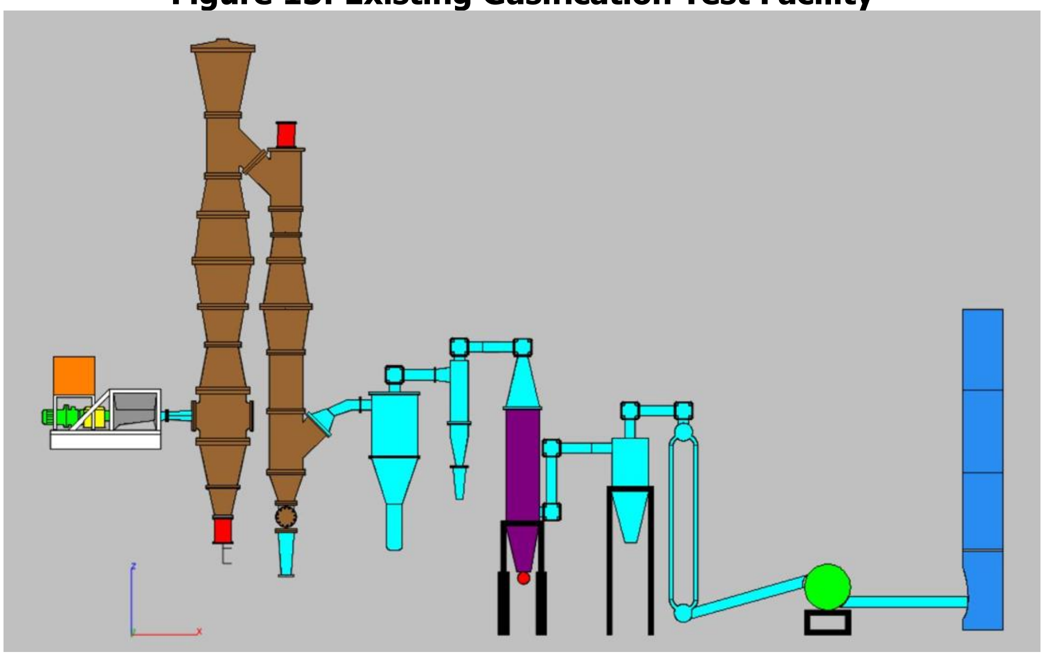
Source: Taylor Energy

The Komar extrusion-feeder is effective for feeding RDB-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 RDB 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 carbon dioxide into the feeder is also provided. Feeding RDB-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.

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 to 28 percent of the energy in the feed was combusted within the process to generate heat and combustion products. Thus, the heat 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 five percent by weight of the products. The new technology shown in Figure 15 focuses on the internal operation of the gasification reactor and improves conversion of tar fractions into low-molecular weight fuel-gases.

Figure 15: Existing Gasification Test Facility



Source: Taylor Energy

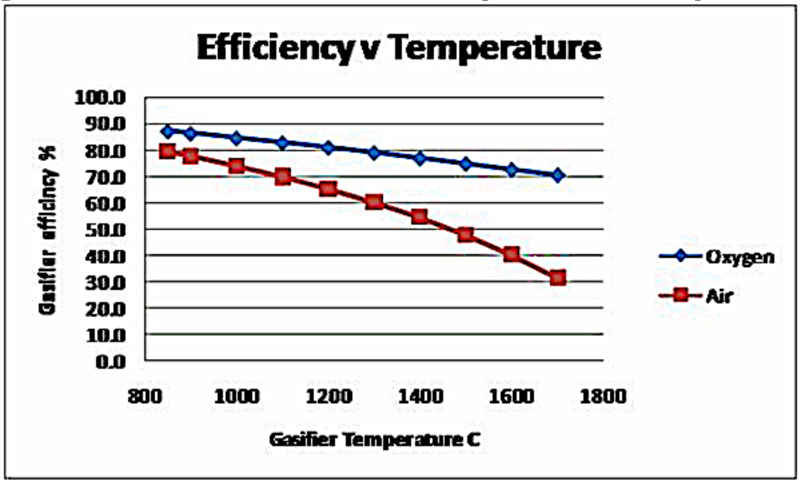
Looking at the over-all stoichiometry, the thermal-chemical process operates with a stoichiometric ratio of 0.28, using oxygen-enriched air to 33 percent oxygen to achieve carbon conversion less than 90 percent as measured by feedstock/products/char analysis.

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 substantial 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 to 15 percent of the energy input can appear as carbon-char when gasification is accomplished at 1382 ^{o} F (750ºC).

Therefore, operating at a 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. Figure 16 plots the gasification efficiency versus the operating temperature.

Figure 16: Gasification Efficiency Versus Temperature



Source: Taylor Energy

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.

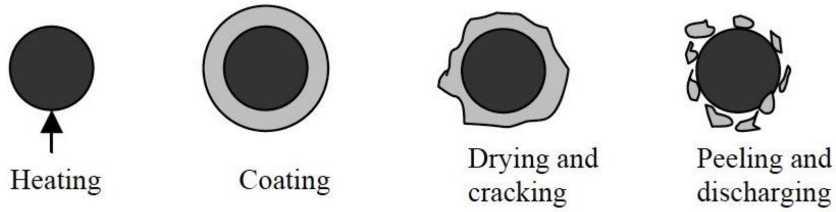
For fluid-bed systems, the greatest constraint on maximum high-temperature operation is that above a certain point, ash-fusion becomes the limitation. During fluid-bed operation, the formation of sticky ashes (eutectics) can result in bed agglomeration that "freezes" the bed and shuts down the system. 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 works its way into the center as shown in Figure 17. 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 17: 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. RDB-fluff includes ash components that contribute catalytic properties to the process. Carbon does not begin to react with water vapor until about 1562 ^{o} F (850°C) without a catalyst present. The moisture content in RDB-fluff is sufficient to provide the water required 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: oxygen, carbon dioxide, and water.

Oxygen (present in the air input) is the most highly oxidizing of these three gases; however, in a well-designed gasification reactor, carbon dioxide and water 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 carbon dioxide and water are reacted with carbon. However, the objective when trying to improve the centuries old gasification process is to move in the direction of 100 percent carbon use through greater reactivity with both carbon dioxide and water.

Gasification Reactor—Configuration Accomplishes Method

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

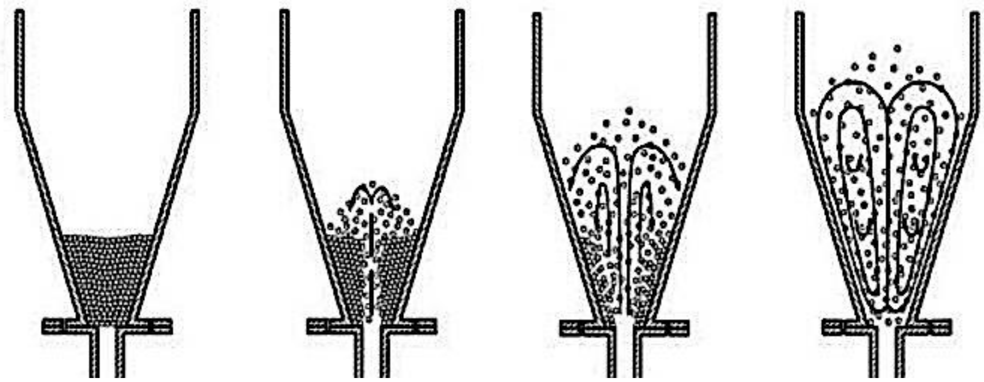
Jet-Spouted Bed

A typical circulating fluid bed, used successfully for RDB gasification, provides high rates of heat and mass transfer. The jet-spouted bed 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. **T**he jet-spouted bed shown in Figure 18 has been tested extensively for thermal processing applications and particularly used for gasification of coal and other carbonaceous feedstocks. However, the jet-spouted bed has not received much attention for commercial applications and is under-utilized, considering the benefits when compared to traditional circulating fluidized bed and bubbling fluidized bed gasification technology.

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

- 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 18: Jet-Spouted Bed Circulation Patterns

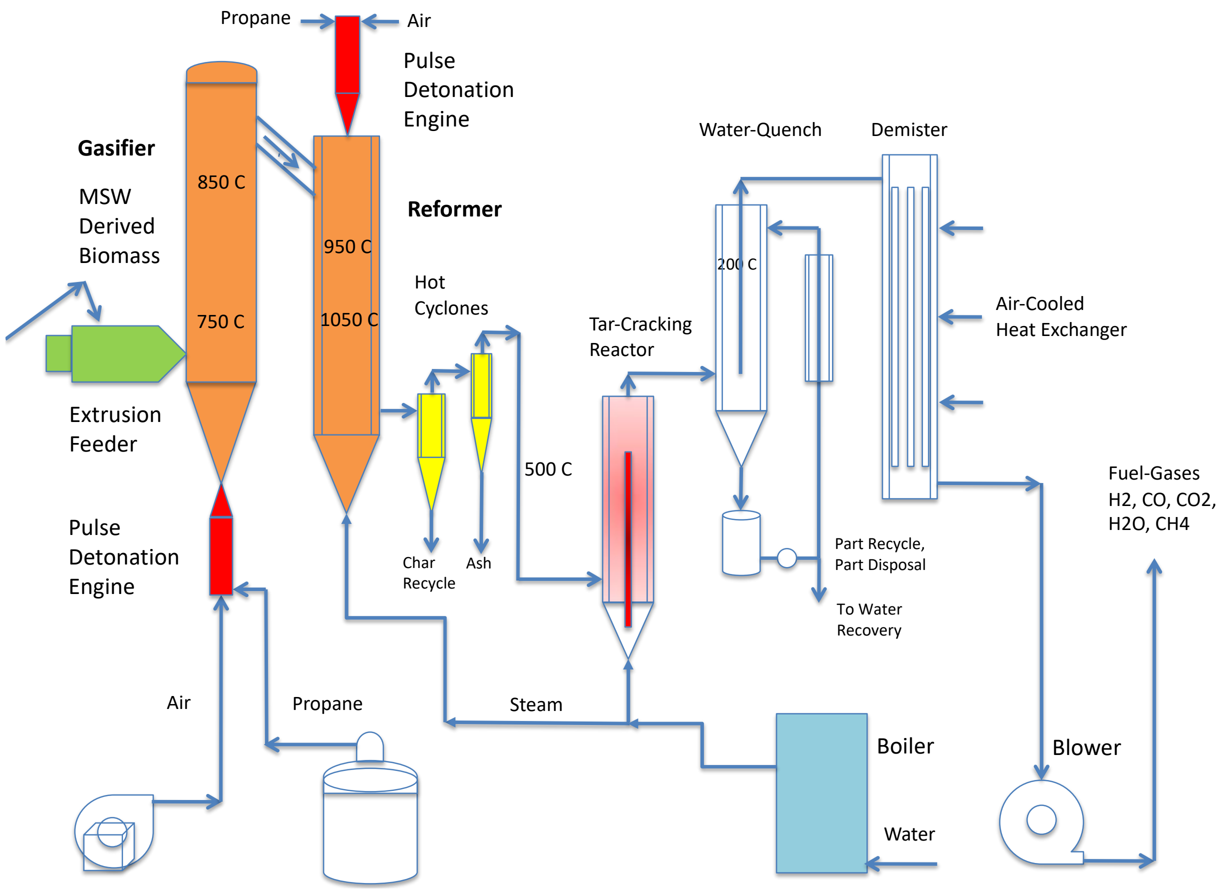


Source: D. Kunni

The jet-spouted bed is a type of fluidization regime with operating properties that are most favorable for RDB-fluff gasification. It contains difficult materials that are not gasified quickly in a typical bubbling fluidized bed or circulating fluidized bed — because the size of the waste material prevents heat and mass transfer. Employing the jet-spouted bed 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 jet-spouted bed, the pressure-drop that is typically used to enable uniform distribution of input gases (through a circulating fluidized-bed 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 circulating fluidized bed. 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 in Figure 19. Note that an air/propane mixture is provided to power the pulse-detonation burners.

Figure 19: 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 to 20 milliamps) 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). 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 ensure 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 circulating fluidized bed 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 jet-spouted bed gasification reactor are circulated internally using the high-velocity jet-spouted-bed; not circulated externally, as is done when employing a typical circulating fluidized bed 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 inches of 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 percent by weight of the syngas product. The Taylor syngas process anticipates cracking the final 5 percent 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 1742^{O} F (950ºC,) and if necessary, the down-leg reformer can operate up to 2012 ^{O} F (1,100ºC.) 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. F

Syngas Cooling

After the tar has been converted by thermal-catalytic-cracking at1742 ^{O} F (950ºC) to 2012 ^{O} F (1100ºC) the syngas can be cooled using steam and/or atomized water injection without experiencing excessive fouling due to deposition of sticky tar-char particles.

Gas Suction, Gas Compression, and 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

Air from the pulse-detonation blower 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, that is, 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 1742 ^{O}F (950ºC.) 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 1Hz to 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 a stoichiometric ratio of 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 1562 ^{o}F (850ºC), 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 carbon dioxide emissions from propane combustion will impact the over-all carbon dioxide emissions for the combined College of Engineering - Center for Environmental Research and Technology/Bourns facility. The emergency flare employs a pilot flame, which consumes about 10,000 BTUs per hour, 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 carbon dioxide neutral. The maximum feedstock input for the gasification reactor is 3 pounds per minute, equal to 180 pounds per hour; about 1-MMBTUs per hour.

Standard Shutdown Procedure

Turning off 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 it will dissipate harmlessly.

Hazardous Materials

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

Fabrication and Construction of Pilot-Scale System

The syngas process being developed by Taylor Energy is designed to handle difficult waste materials, including MSW that has been recovered as 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 RDB into low-molecular weight gases using partial oxidation methodology, also known as autothermal gasification. The gasification reactor and tar-reformer are shown in Figure 20.

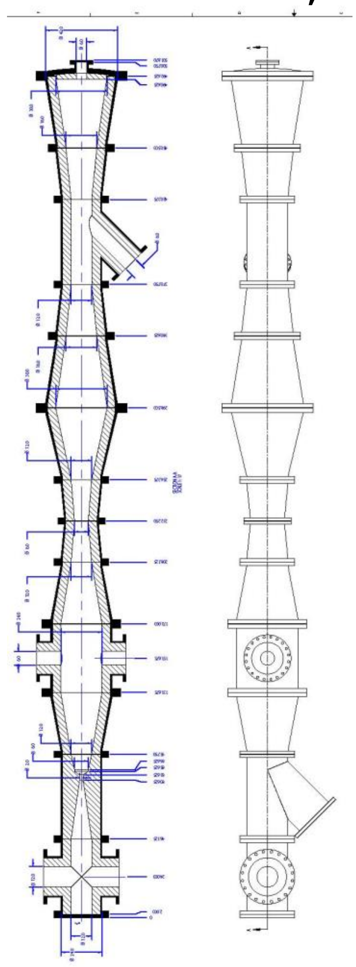
Figure 20: Gasifier (right), Tar-Reformer (left)

Source: 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 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 jet-spouted bed, 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 and Construction Report* summarizes pertinent elements of the engineering, design, construction, and fabrication relative to the gasification and reforming systems. The gasification reactor is shown in Figure 21. 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 requirements.

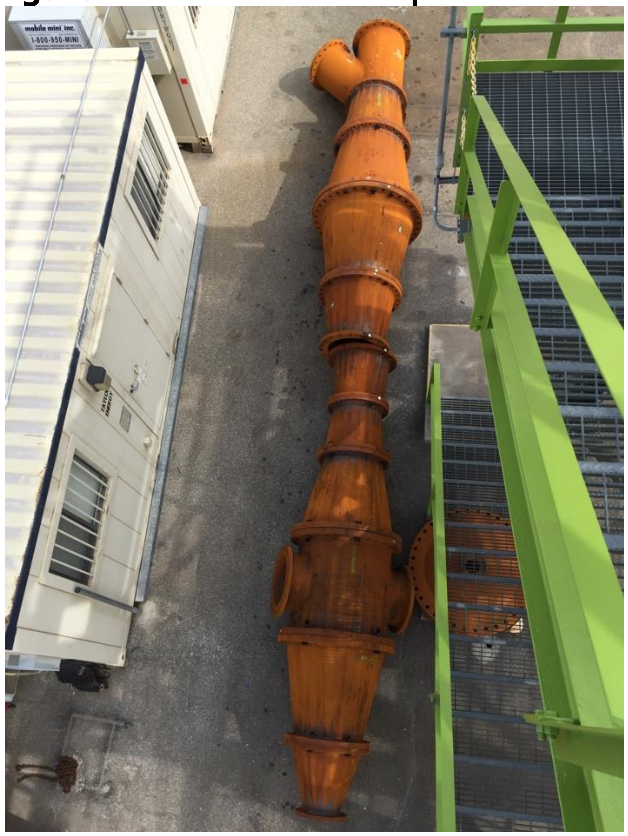
Figure 21: Jet-Spouted Gasification Reactor, 2-D Solids-Works Drawing



Source: Taylor Energy

Flanged pipe sections provided by US Pipe shown in Figure 22 are fastened together to form both the thermo-catalytic gasification reactor and the POx reformer (not shown).

Figure 22: Carbon-Steel "Spool Sections"



Source: Taylor Energy

Refractory

The reactor sections are lined with refractory; cast using five-inch to six-inch-thick layers of refractory on all the reactor internals, employing two layers: an inner insulating refractor lining, and 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.

The 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 required 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, California.

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 pounds per cubic foot) for the internal hard-face, and low-density cement (70 pounds per cubic foot) 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 Company.

Figure 23 shows a conical reactor section with the mold in place, ready for filling with refractory.

Figure 23: Casting Reactor Sections With Internal Mold

Source: Taylor Energy

After casting, the team removed the steel molds using an oxy-acetylene torch as shown below in Figure 24. When the team used cardboard tubes to cast straight sections, they burned them out using a light-oil starting fluid as shown in Figure 25.

Figure 24: Removing Steel Molds

Source: Taylor Energy

Figure 25: Burning out Cardboard Molds

Source: Taylor Energy

Fabrication and construction required casting 20 individual sections, two layers each. Forty separate casting operations were performed; the spool sections are shown in Figure 26.

Figure 26: Spool Section With Two Layers of Cast Refractory

Source: Taylor Energy

High Temperature Gasket Material

A high-temperature gasket material shown in Figure 27, 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 28 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 antioxidant in preparation for high-temperature oxidative service.

Figure 27: High-Temperature Gasket Material

Source: Taylor Energy

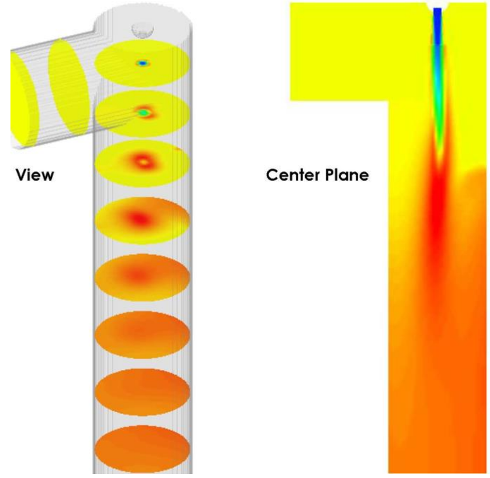
Figure 28: Grade-5 Carbon Steel Bolts

Source: 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 29. Carbon-char is not removed up-stream of the reformer; direct-coupling with the reformer is desirable because carbon-char produced in the jet-spouted bed gasification reactor is intended to react with oxygen, carbon dioxide, and water in the tar-reforming stage.

Figure 29: Tar-Reformer, Principle of Operation



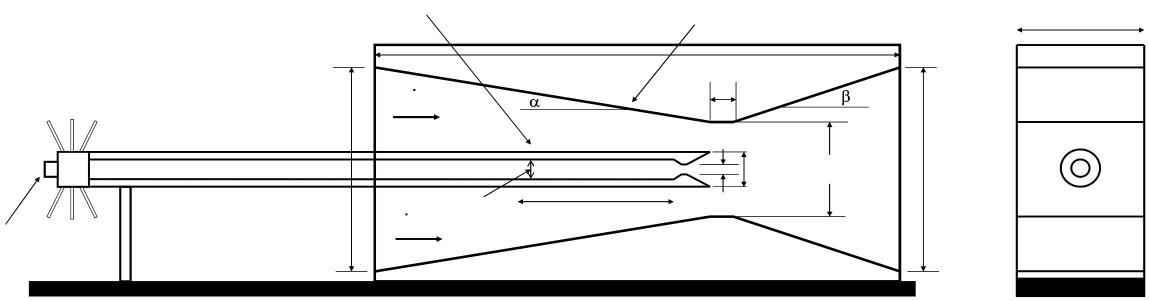
Source: Air Products

Tar-Reformer

Tar content in gasification products is routinely 5 to 15 percent by weight 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.

A converging – diverging nozzle section (used to enhance mixing) was added to the reformer, positioned in the center of the down-leg, (Figure 30) as an alternative to the draft-tube configuration that was originally planned.

Figure 30: Pulse Detonation-Powered Venturi-reformer, Fired in the Down Leg



Source: American Institute of Aeronautics and Astronautics, Inc., 2010-6882

Start-Up Planning and Preliminary Start-Up Testing

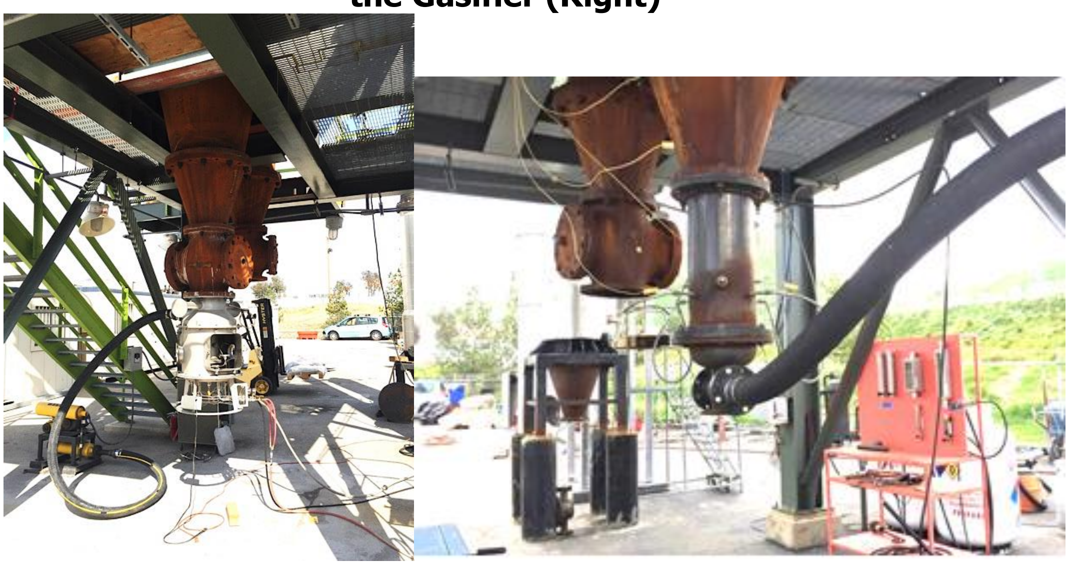
Safety Review and Safety Training

A safety review and training meeting was conducted for the gasifier/reformer system. As shown in Figure 31, a pulse- detonation burner was installed on top of the reformer section. Figure 32 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 shutdown procedures.

Figure 31: Installing the Detonation Burner on Top of the Reformer

Source: Taylor Energy

Figure 32: Pulse- Deflagration Burner (Testing on Left) Located at the Bottom of the Gasifier (Right)



Source: Taylor Energy

Taylor Energy used a Komar extrusion feeder with a variable frequency driver to control the feed rate as shown in Figure 33. The extrusion feeder forms a plug-seal with atmosphere.

Figure 33: Komar Extrusion Feeder and Variable- Frequency Drive That Controls the Feed Rate

Source: Taylor Energy

Preliminary Start-Up

Taylor Energy performed a preliminary start-up using the pilot-scale test system shown in Figure 34. The fuel-gas product was flared using the enclosed flare shown in Figure 35.

Figure 34: Pilot-Scale Facility

Source: Taylor Energy

Figure 35: Flare Used to Burn Fuel-Gas Products

Source: 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 the University of California, Riverside shown in Figure 36, the team tested a mild-gasification process using RDB as the energy feed. Pilot-scale pulse-detonation-burners were integrated with both the gasifier and the reformer to accomplish process intensification.

Figure 36: Taylor Energy's Gasification Test Facility Located at the University of California, Riverside

Source: Taylor Energy

The energy feedstock tested was an RDB-fluff that was 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 lighter weight fractions.

The resulting RDB-fluff, shown in Figure 37, contains most of the chemical energy available in MSW, including the plastic fractions. RDB is dried to 18 percent (by weight) 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 37: RDB Fluff

Source: 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 substantial 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 the 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 overall 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 (the expansion chamber), producing fuel-gases intended for renewable power production. The pulse-combustor was operated with excess oxygen in the exhaust gases.

The pulse-combustor prototypes were optimized 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. A pulse-detonation combustor integrated with a jet-spouted bed offers special benefits based on simple proof-of-concept testing. Compression waves that pass through the process are used 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 in Figure 38.

Figure 38: Pulse-Detonation Burner Installed on the Bottom of the Jet-Spouted Bed

Source: Taylor Energy

Planning, design, engineering, and construction phases were performed to build the gasification system shown in Figure 39. The program test plan included a short series of preliminary tests, integrated with the jet-spouted bed processing RDB, to verify the performance of the system when operating in the autothermal gasification mode.

Figure 39: Gasification System at Taylor Energy's Test Facility

Source: Taylor Energy

For initial testing of the pilot-scale burners, the approach used by the research team for preliminary testing was to mount the pulse-combustor prototype(s) on a horizontal test stand, as shown in Figure 40. The design uses one pre-combustion stage 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 40: Taylor Energy's Pulse-Detonation Test Stand

Source: Taylor Energy

The initial results for a carbon-steel and cast-refractory type pulse-detonation-burner prototype were promising. Taylor Energy 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 41.

Figure 41: Horizontal Operation; Firing at Night Using the Pulse-Detonation Test Stand

Source: Taylor Energy

It was decided to use a gaseous fuel injection manifold, that is easy to control with a simple on/off power control signal, for operating industrial solenoid valves that can operate at 10-Hz for six million cycles. Gas injection nozzles were designed and fabricated, each employing a nozzle orifice of less than five millimeters, inside diameter. Using gaseous fuel, continuous pulse-ignition was achieved, and the system was deemed a preliminary success and moved to the jet-spouted bed for further testing.

Next, the pulse-detonation prototype was tested 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 ranged from 1-Hz to 2.5-Hz. Twenty-five test sequences were performed in this mode of operation. Concurrently, the gasification reactor was operated and produced fuel-gas, which was combusted in an enclosed flare; the fuel-gas flame is shown in Figure 42.

Figure 42: MSW-Derived Fuel Gases Being Combusted Within an Enclosed Flare

Source: 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. Back-flow was largely prevented by the air-input flowing through a sonic nozzle.

The pulse-detonation burner showed great potential in this mode of operation by producing some substantial detonations. However, precise control of the fuel-injection and the spark timing have proved to be more difficult than anticipated. Thus far, the ignition events have been limited to 2.5 ignitions per second. Nevertheless, using this approach, a uniform pulse-combustion was established.

The necessary modifications were performed and 12-tests completed, achieving a pulse-detonation rate of 2.5 cycles per second. Figure 43 shows the prototype pulse-detonation-burner integrated with the jet-spouted bed; firing into the bottom of the jet-spouted bed. The pulse-detonation design was considered a high-reward embodiment.

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.

Figure 43: Pulse-Detonation Burner Integrated with Jet-Spouted Bed

Source: Taylor Energy

In parallel with the design and testing of the pulse-detonation burner 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, employed a fuel/air mixer and a spark ignition system. Initially, the team tested a stainless-steel prototype, shown in Figure 44, 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 44: Early Stainless Steel Pulse-Jet Burner Prototype

Source: Taylor Energy

Taylor Energy concluded that the use of a cast-refractory type combustor would offer substantial 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. Stainless-steel insertions were used to provide openings for fuel inputs and for instrumentation (temperature and pressure measurements), and to connect the spark-ignition system. Figure 45 shows the pulse-jet burner housing and the refractory casting within that housing. Figure 46 shows the pulse-jet-deflagration burner attached to the bottom of the jet-spouted-bed. Taylor Energy's goal was to compare operation of a pulse-deflagration burner with a pulse-detonation burner.

Figure 45: Burner Casting

Source: Taylor Energy

Figure 46: Integration with Jet-Spouted Bed

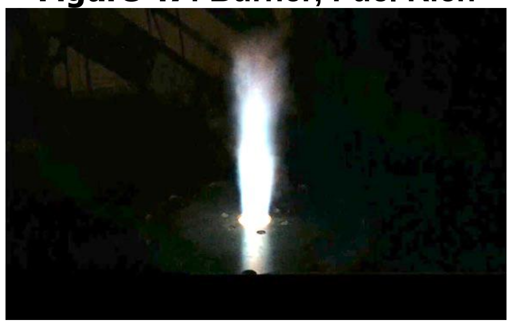
Source: Taylor Energy

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. The burner was successfully tested and operated 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 3590.6 ^{o} F (1,977°C). The lowest temperature achieved during fuel-lean operation was 1436 ^{o} F (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 3590.6^{o} F (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 47 – avoiding the range where the highest temperatures would damage the prototype burner's refractory. For example, compare the flame of a fuel-rich burner (Figure 47) to fuel-lean burner (Figure 48).

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 1652° F (900°C), employing fuel-lean operating chemistry. The burner temperature set the air-fuel mixture, which was repeatable with accuracy.

Figure 47: Burner, Fuel Rich



Source: Taylor Energy

Figure 48: Burner, Fuel Lean

Source: Taylor Energy

The research team tested two types of ceramic bed materials: 0.5 mm, 1 mm, and 3 mm beads that were commercially available; 2 mm and 5 mm ceramic balls, also commercially available. They were tested to evaluate the stability and durability of bed materials, and to evaluate the materials of construction used to fabricate the burner and the jet-spouted bed. The smaller beads were selected 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 half due to thermal stress from rapid heating.

Test Results

Taylor Energy tested the jet-spouted bed gasification reactor using RDB shredded to less than one inch diameter. The proximate and ultimate analyses are shown 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 BTUs per 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

Testing was started once the gasification reached 1562 °F (850°C.) 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 downstream 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 California Analytical Instruments analyzer. The sample gas is drawn through the system by a gas pump that is integrated into the analyzer's 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 that were 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 RDB as the energy feed. Fuel-gases were burned in an enclosed flare shown in Figure 49, which was constructed for this project. RDB fuel-gas can be seen burning within the flare during continuous operation in Figure 50.

Figure 49: Enclosed-Flare

Source: Taylor Energy

Figure 50: Flare Burning MSW-derived Fuel Gases

Source: Taylor Energy

The syngas composition shows the best three data points taken at 20-minute intervals during a 1-hour operating period with stable operating conditions with the pulse-burner operating at 1,652ºF (900ºC) to optimize power output to the gasification reactor. The average methane content was 7.46 percent by volume based on the data reported in Table 4.

Table 4: Analysis of Fuel-Gas Products

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

Source: Taylor Energy

The data in Table 5 shows that the average carbon-char content is 9.47 percent by weight 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 comes out. The data shows that the carbon-char fraction, when measured on a dry-basis, is 10.77 percent by weight of the dry feed.

Table 5: Analysis of Product Fractions: Carbon-Char Content

Products (weight%)	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 a 3-ton per day scale. Project results are used to develop a conceptual and preliminary engineering design for a demonstration-scale project that will convert 40 tons per day of RDB 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:

- A 300 dry-tons per 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.
- A 500 dry-tons per 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.

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).
Operate the thermal-chemical gasification process with over-all stoichiometric ratio of 0.28, using oxygen enriched air to 33 percent oxygen to achieve carbon conversion >90 percent as measured by feedstock / products / char analysis.	The system has not been operated with oxygen enrichment to 33 percent. The carbon conversion was less than 90 percent.	The system has not been operated with oxygen enriched air achieved to 33 percent oxygen content, due to the cost oxygen relative to other budget constraints; therefore, the carbon conversion was lower than projected.

Agreement Goals and Objectives	Achievements	Comments
Operate gasification reforming process continuously for 8 hours, with RDB input of 3 pounds per minute (1.08-MMBTUs per hour, based on energy content of 6,000 BTUs per pound for RDB), with average fuel-gas output of 0.80-MMBTUs per hour, having energy content of 230 BTUs per scf, demonstrating 74 percent net conversion efficiency of feed into fuel-gas.	Continuous operation >8 hours. RDB input of >3 pounds per minute. Firing input >1 MMBTUs per hour. Output >0.8 MMBTUs per hour. Average BTU content was less than 230 BTUs/scf. The net efficiency was less than 74 percent conversion to gas because of higher carbon content in the ash, which may require increasing the retention time for the solids	Average BTU content was greater than 127 BTU/scf to 190 BTU/scf because N_2 and CO_2 dilution were higher than projected. The net efficiency was calculated to be 68 percent; the carbon conversion requires improvement to increase net efficiency.
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 ignition was not used successfully.	The transient plasma systems ignition system did not perform well.
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 and mass balance by semi-empirical method and semi-empirical AP model development.	Achieved	A semi-empirical process heat and mass balance was prepared; and AP 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 per 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 per day modular system.

Agreement Goals and Objectives	Achievements	Comments
Confirm from the project findings that the levelized cost of power 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 levelized cost of power according to projections.
Estimate carbon footprint for the process and the products by life-cycle analysis through greenhouse gases, regulated emissions, and energy in transportation.	Achieved	Carbon life-cycle analysis modeling using greenhouse gases, regulated emissions, and energy in transportation 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 is entitled, *Syngas Process Development for Renewable-Methane Production.*

Proof-of-concept testing was accomplished using a 3-inch (interior diameter) pulse-detonation-burner, employing oxygen-enrichment and pre-combustion stages to accomplish the deflagration-to-detonation transition. Whereas, the present project embodiment uses a 4 inch (interior diameter) burner, 48 inches in length, constructed of water-cooled concentric metal tubes. The deflagration-to-detonation transition 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 substantial 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 development of detonation technology.

The key advancements in technical knowledge are summarized as:

- The detonation cell-size is of critical importance; according to deflagration-to-detonation transition -modeling performed by Afthon, the air/propane mixture requires a cell-size larger than 3 inches. Therefore, the use of a 4-inch internal diameter 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 larger than 3.5 inches internal 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 Hz to 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. A 4-inch (interior diameter) by a 48-inch-long deflagration-to-detonation transition-type burner provides about 3 times more power than was able to be fully used in the present gasification reactor and reformer configuration. For the tests performed, the burner output was turned down substantially by filling the detonation tube to 37 percent 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. Taylor Energy is only beginning to understand how to employ this new technology to enhance gasification and reforming methods. All of the thermochemical reactions that convert organic polymers into low-molecular weight gases are potentially enhanced.

Waste-to-Energy Evaluation, 40-tons Per Day, 1.7 MWe (Appendix B Summary)

Report Summary

An objective was to evaluate, in an environmentally responsible manner and at demonstration scale, a 40-ton per day gasification facility employing advanced MSW recycling technology integrated with electric power generation, using RDB as the feedstock.

Based on the project feasibility study, a 40-ton per day scale (36 tonne/day), using an average of two tractor-trailer loads per day, each carrying 20-tons of MSW, has been determined to be the optimum capacity. This is based partially on the transportation logistics. Figure 51 shows the walking-floor tractor-trailer used to transport the RDB.

Figure 51: Walking-Floor Type Tractor-Trailer to Transport RDB

Source: 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 7:00 a.m. and 4:00 p.m., 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 in the following steps:

- Receive an average of 40-tons per 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
- Generate Electricity using medium-speed internal-combustion engine-generators

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 52. 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).

Figure 52: Refuse-Derived Biomass Recovered From Shredded MSW

Source: Taylor Energy

The feed basis used to define RDB for this evaluation is listed in Table 7 as "Rev 1," compared to other feeds.

Table 7: RDB Ultimate Analysis in Rev 1 Compared to MSW and Other Feeds

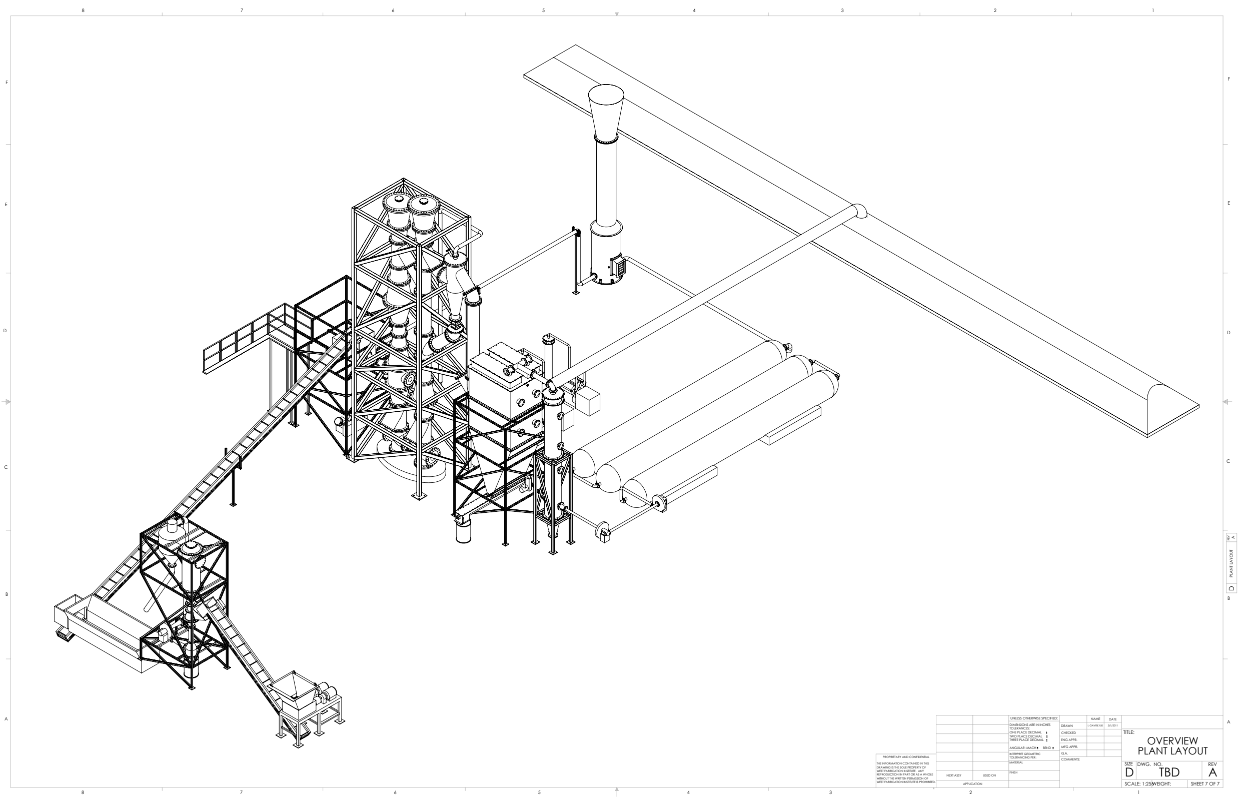
Element	HHV, Btu/scf	Pilot 700˚C MunWast Mol%	Pilot MunWast Mol%	Pilot Plastic	Demo 40t/d MW Mol%	Pulp	Pap+Plas Mixed Waste	Raw MSW	Battelle RDF	Rev 1 Proposed Design
C		37.74	37.74	75.4	33.4	37.5	55.1	48.43	47.31	47.6-31
H		5.01	4.93	12.2	4.42	4.88	8.6	7.06	6.61	6-4.5
N		1.79	1.61		1.26	1.28	0.2	0.99	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 three-dimensional drawings were performed using SolidWorks; one image is shown in Figure 53. The design includes a front-end shear-shredder, and a pneumatic classification system used to recover RDB from material recycling facility residues. Note also that a portion of the fuel-gas product is stored at low-pressure (3 to 5 psig) in three storage tanks. 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 per second.

Figure 53: 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 RDB; 36 metric tonnes per day (40 short tons/day) RDB containing up to 21 percent 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 percent 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, 300 Dry-tons Per Day (425 Wet-tons), 9.5 MWe (Appendix C Summary)

Report Summary

The objective is to evaluate a 300 dry-tons per day commercial waste-to-energy facility, using RDB as the energy feedstock in an environmentally responsible manner. Then to use this renewable energy source to produce electricity on or near a landfill in California, providing 9.5 MWe of base-load electrical output for delivery to the electrical grid, fulfilling the economic requirements of the project developers.

The facility will use 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 remain unchanged. This pricing will not increase the operating expenses for the commercial haulers and will ensure adequate feedstock for RDB 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 7:00 a.m. and 4:00 p.m., 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 following these steps:

- Convert 425 wet-tons per day MSW into 300 tons per day RDB (at or near the landfill site)
- Transport 300 tons per day RDB 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
- Generate electricity using steam injected gas turbine technology (STIG cycle)

RDB is received and stored in a 60,000 square foot, clear-span metal building. The building should be approximately 49 feet high at its roof eave and rise to 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 RDB until it is conveyed to the gasifiers. Adjacent to the RDB receiving and storage building, shown in Figure 54, is an uncovered, exterior screened area of approximately 60,000 square feet that contains most of the gasification and power generation equipment. It includes two parallel gasification trains, each sized to process 150 tons per day of RDB; providing a total RDB gasification capacity of 300 tons per day.

Relative to a plot plan, the perimeter screening fence should be 30 feet high along the west side and 20 feet high along the north side with an enhanced screening element in the northwest corner, which rises to approximately 48 feet, serving to shield conversion equipment somewhat from view. The area also contains a 10,000 square-foot sound-insulated building to house the power generation equipment, composed of 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 percent availability, the pro-forma output is projected to be 8,075 kW per hour, based on 8,760 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 16,000 square feet.

Figure 54: Conceptual Design for a Nominal 432-wet-ton Per Day Waste-Biomass Gasification Facility

Source: City of Kona HI

Refuse Derived Biomass 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
- RDB 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 55. A landfill facility will typically be open about 312 days per year.

Figure 55: MSW On the Tipping Floor

Source: Taylor Energy

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

It is anticipated that the facility will receive no more than five waste collection vehicles per hour between the hours of 7:00 a.m. and 4:00 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.

Refuse Derived Biomass Production

The proposed RDB facility will employ one, 500-ton per day processing line, intended to operate 7 hours per day (one work shift per day). Using a bucket type front-loader, MSW is pushed into the primary shredder (Figure 56), operated by one person seated inside an air-conditioned/heated cab.

Figure 56: Primary Shear-Shredder Used for Stage-1 MSW Size Reduction

Source: SSI

After primary shredding, the coarse-shredded feedstock is sent to the secondary shredder (Figure 57) for final size reduction, reducing the size to less than two inches diameter. A belt-conveyor delivers this product to the air classification systems, to separate the heavy fractions, resulting in the production of a homogeneous RDB-fluff, which is directed to storage piles located adjacent to load-out holes.

Figure 57: Rotary-Shear Shredder Used Two-Stage Size Reduction and for RDB Production

Source: SSI

Refuse Derived Biomass-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 RDB-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 feet wide by 10 feet deep by 60 inches long, providing at least two 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 58. The fuel-gas analysis is listed in Table 8.

Figure 58: Walking- Floor Storage Controls RDB Feed Rate to Gasifier

Source: Taylor Energy

Table 8: Analysis of Fuel-Gas Products

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

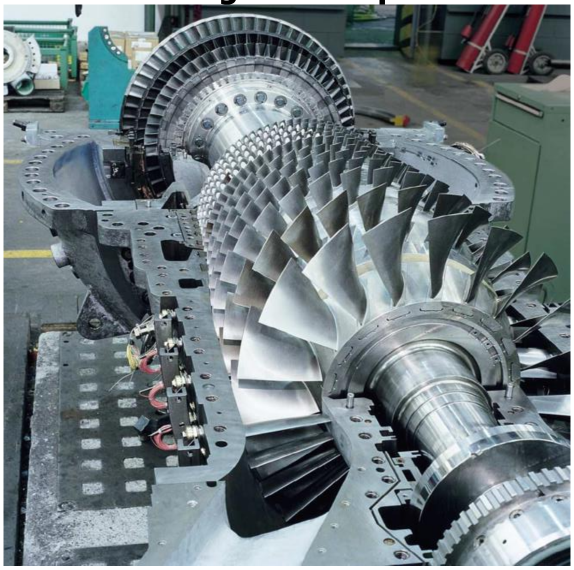
PPMv = parts per million volume

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 59). The engine has output capacity of 11,250 kWh, with 31 percent simple-cycle efficiency. The GE10-1 gas turbine is selected for use with low-BTU fuel-gas derived from RDB gasification. A heat recovery steam generator 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 percent. The power cycle is called a "Steam Injected Gas Turbine" and known in the industry as a STIG-cycle or Cheng-cycle gas turbine, which increases the power output.

Figure 59: 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 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 in Figure 60, where heat recovery steam generation (HRSG) is used to produce steam that is injected into the gas turbine, reducing air emissions and increasing the power output. The gas turbine provides gross power output of 11.25 MWe at 42 percent efficiency by employing the STIG cycle.

Figure 60: Steam- Injected Gas Turbine Used to Increase Efficiency

Source: General Electric

Design Capacity

The nominal design basis (at the material recovery facility, or landfill) calls for receiving and processing 432 wet-tons per day MSW, assuming 25 percent debris, glass, grit, and recyclables, including metals. Therefore, removing 25 percent non-energy materials will result in 324-wet-ton/day feedstock is available for energy use. The design basis assumes 25 percent moisture; preliminary processing removes 2 percent moisture. Therefore, the nominal RDB design basis is 317 wet-tons per day MSW with 23 percent (by weight) moisture and assumes that RDB is dried during production to result in 300 tons per day of RDB-fluff with 17.5 percent (by weight) moisture, containing approximately 5,000 BTUs per pound, lower heat value.

- Feed rate: 300 wet-tons per day RDB, containing 5,000 BTUs per pound-wet, at 17.5 percent moisture by weight
- 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 Output: 9,500 kWh

Projections—Budgetary

- Available Energy as Heat:
  - 25,000 pounds per hour x 5,000 BTUs per pound = 125 MMBTUs per hour
  - Each of the two lines, feeding 150 tons/day of RDB, with a total capacity of 300 tons/day.
  - Each of the two gasification reactors, processing 150 tons/day RDB, which equates to an input capacity of 300 tons/day RDB, produced (at the material recovery facility, or landfill) from a total of 432 tons/day MSW. Input: 300 tons/day RDB, producing 90 MMBTUs/hour fuel-gas output.
- Gasification System: 11,075 kWh (gross) x $1,430/kWh=$ 15,837,250
- Power Generation Island: 11,075 kWh (gross) x $1,270/kWh=$ 14,065,250
- Engineering Design: $1,175,000 : Commissioning, start-up management: $ 1,500,000
- Total: $ 32,577,500
- 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 material recovery facility, 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, such as 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.

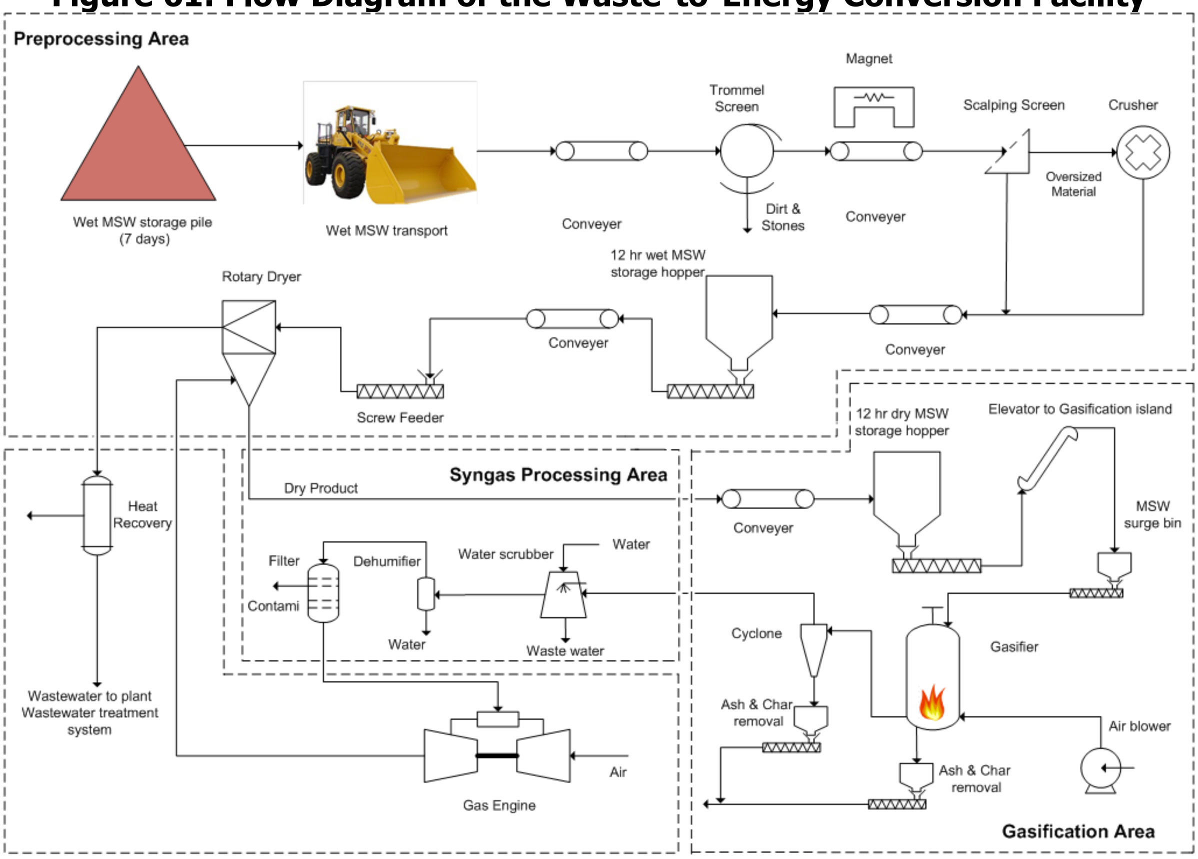
Systems Modeling and Analysis, 600 Wet-Ton/Day MSW Feed (Appendix D Summary)

Report Summary

The plant is assumed to be located near a landfill or a waste processing facility and the waste material is composed of 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 61. 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 61: Flow Diagram of the Waste-to-Energy Conversion Facility



Source: University of California, Riverside

Projected system performance is summarized in Table 9.

Table 9: Projected System Performance

Performance Metric	Value
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: University of California, Riverside

Total plant cost and total required capital for a nominal 600 wet tons per day MSW-to-energy plant (500 tons per day, dry basis) were estimated with project life of 20 years excluding construction period. Total plant cost was evaluated by determining equipment and installation cost adding indirect cost and project contingency. Total required capital was estimated by adding financial cost and working capital on the total plant cost. Operation and maintenance costs were also determined to calculate the internal rate of return with 10 percent discount rate in the cash flow analysis. Major inputs in the financial model are listed in Table 10.

Table 10: Major Financial Model Inputs

Input	Value
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: University of California, Riverside

A debt/equity financial structure of 55/45 is set with 8 percent loan interest rate and 38 percent income tax in the cash flow analysis. The lifetime of the plant was assumed to be 20 years in addition, with a two-year construction period and the first six months at 70 percent 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 per MWh for electricity is used. An escalation factor of 3 percent is employed in the electricity sale price to reflect inflation factor within plant lifetime. Variable operation costs including all consumable chemicals and waste disposal were assumed to be 2 percent of engineering, procurement, and construction cost with a 2 percent yearly escalation factor. The economic analysis results are shown in Table 11.

Table 11: Financial Model Outputs

Input	Value
Internal rate of return (%)	18.64
Net present value (MM$)	45.80
Payback time (yr)	10.1
Levelized cost of energy ($/MWh)	41.01

Source: University of California, Riverside

The financial model shows an 18.64 percent internal rate of return with levelized cost of energy of $41.01/kW. The payback period of the plant is 10.1 years excluding the 2-year construction period, with a net present value of $45.8 million.

Sensitivity Analysis

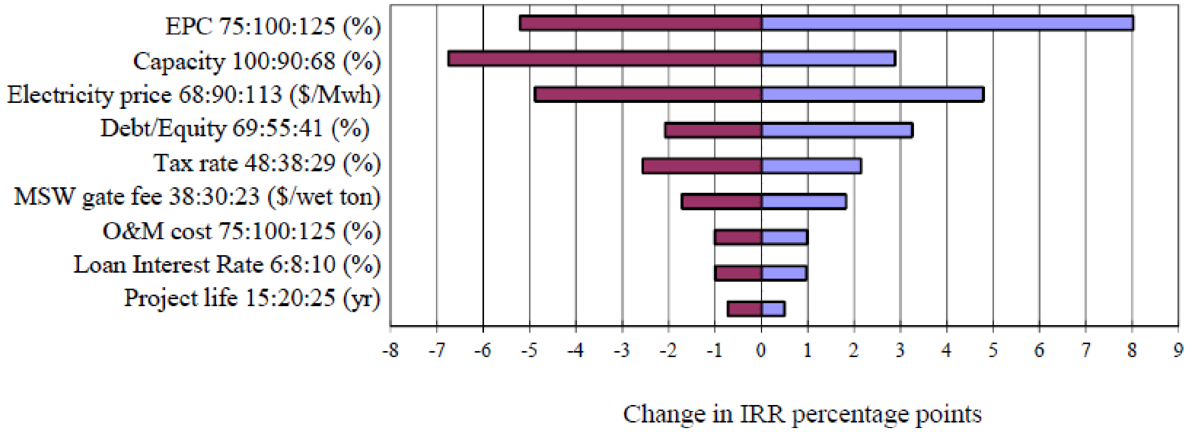
Except for plant feed and output rates, all financial model inputs were varied to determine the project financial sensitivities. The range of model input variables used in the sensitivity analysis is listed in Table 12 Input changes for the model were based on previous internal rate of return calculation inputs. Internal rate of return sensitivity was evaluated using a ±25 percent 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 62.

Table 12: Range of Values Used in the Sensitivity Analysis

Model input	Baseline	(+25%) High Range	(-25%) Low Range
Engineering, procurement, and construction (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 (years)	20	25	15
Debt (%)	55	69	41
Tax rate (%)	38	48	29
Loan Interest Rate (%)	8	10	6

Source: University of California, Riverside

Figure 62: Relative Sensitivities of Major Plant Inputs, +/-25%



Source: University of California, Riverside

Based on the internal rate of return sensitivity analysis results, the most influential factor is engineering, procurement, and construction cost because 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's engineering, procurement, and construction 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 internal rate of return decreases by 6.8 percent if the plant capacity drops from 90 percent to 68 percent. The electricity sale price is the third-most important factor that affects the plant revenue directly and internal rate of return varies ±4.9 percent while electricity sale price changed by ±25 percent. Debt/Equity, tax rate, and payback of MSW gate fee, also have an important effect on the internal rate of return range from ±1.7 percent to ±3.2 percent. Operation and maintenance cost, loan interest, and project life have less impact on internal rate of return within ± 1.0 percent.

Conclusions

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

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 across a wide range of energy sector stakeholders. To facilitate this knowledge transfer, Taylor Energy and the University of California, Riverside will share the results of this project in industry workshops and through public reports published on the Taylor Energy website.

University of California, 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 which could also benefit by being informed about emerging waste-to-energy systems.

Taylor Energy has already shared project results at a symposium sponsored by University of California, 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 in Table 13.

Table 13: 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 1,200 tons per day RDB thermal-processing capacity producing 40 MW of net power to the electric 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 tons per day of 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 required to verify an advanced gasification concept. A 1.7 MW plant is an economic scale for various venues around the world. Catalina, for example, has the demand for a 40 ton per day waste-to-energy project. The team considers the small-size plants to be semi-commercial endeavors because the economics require some unique constraints 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 per day plant exporting 10 MWe. For permitting purposes in California, 500 tons per 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 RDB in the United States 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 use 75 percent of all MSW landfilled to generate more than 3,300 MWe. At least 50,000 tons per 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 California Public Utilities Commission's data access requirements for EPIC data and results.

Technical Advisory Committee

A technical advisory committee (TAC) was formed and consisted of diverse professionals. Based on the technical expertise and knowledge of market applications of TAC members, guidance was provided for project improvements. TAC membership included the following:

- 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

CHAPTER 5: Conclusions/Recommendations

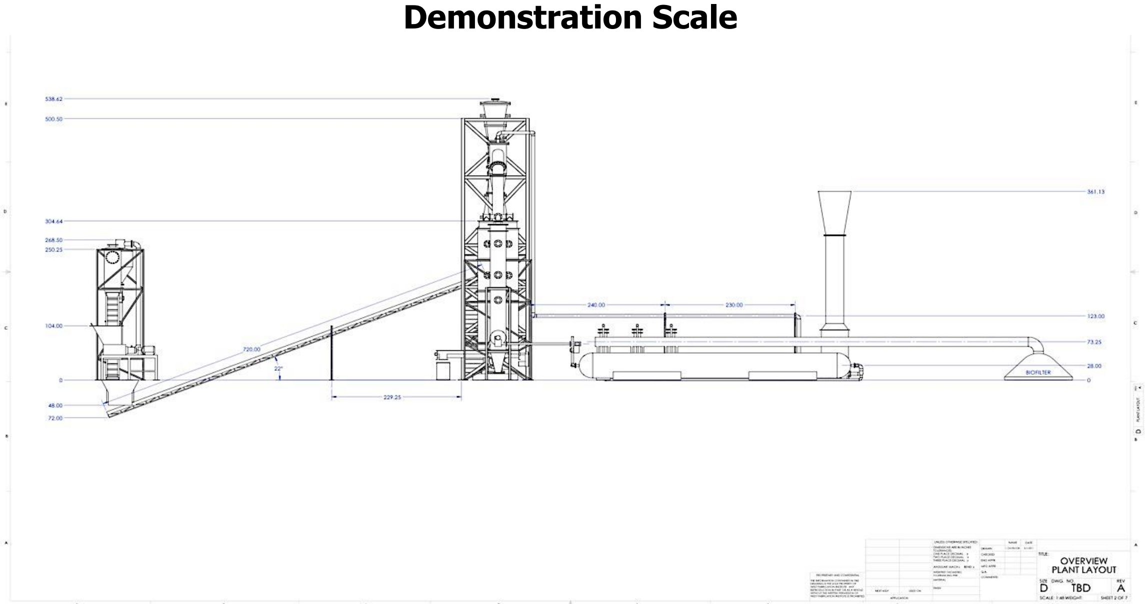
Introduction

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. 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 required 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 use 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 funds 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 63 shows the preliminary design for construction of a modular type 40-ton per day waste gasification system used to generate 1.7 MWe.

Figure 63: RDB Gasification/Reforming System Designed for 40-TPD Demonstration Scale



Source: Taylor Energy

Recommended Improvements

Improve Pulse-Detonation Burner

The pulse-detonation burner (Figure 67) fires at 2.5 Hz. The optimum firing rate may be around five to seven Hz.

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 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 that takes pressure off the feeding system; however, the team has not been able to operate the equipment at a sufficiently high temperature to demonstrate effective carbon-char reforming—the equipment must reach 1,832ºF (1,000˚C) to 2,192ºF (1,200 ºC). 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 Remova

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 carbon dioxide and water vapor to make more syngas.

Future work includes a subsequent Taylor Energy-University of California, Riverside 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.

CHAPTER 6: Benefits to Ratepayers

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 a 300-ton per day scale, the levelized cost of power would be $118 per MWh, based on our process cost projections and operating cost estimates. Figure 58 shows our concept for a 300-dry-ton per day waste-to-energy facility using gasification integrated electric power generation.

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 per MWh in 2018, increasing to about $158 per MWh in 2024. Assuming a mean power price of $158 per MWh for existing waste-to-energy-derived power, the measurable cost savings is estimated to be $40 per MWe for every megawatt of power generated using the proposed new shockwave gasification-reforming technology.

LIST OF ACRONYMS

Term	Definition
°C	Degrees Centigrade
°F	Degrees Fahrenheit
AD	Anaerobic digestion
AP	Aspen Plus Chemical Process Simulator Software
$CaMg(CO_3)_2$	Calcium magnesium carbonate
CEC	California Energy Commission
CE-CERT	College of Engineering - Center for Environmental Research and Technology
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CxHy	Hydrocarbons
EPIC	Electric Program Investment Charge
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
H_2O	Water
HRSG	Heat recovery steam generation
Hz	Hertz
kWh	Kilowatt-hour
Mm	Millimeter
MMBTU	Million British thermal units
MSW	Municipal solid waste
MW	Megawatt
MWe	Megawatt electrical
MWth	Megawatt thermal
N_2	Nitrogen
NH_3	Ammonia
O&M	Operation and maintenance
O_2	Oxygen
PbS	Sulfide

Term	Definition
PDE	Pulse-detonation engine
POx	Partial oxidation
psia	Pounds per square inch absolute
Psig	Pounds per square inch gauge
RDB	Refuse derived biomass
RM	Renewable methane
RNG	Renewable Natural Gas
RPM	Revolutions per minute
scf	Standard cubic feet
scfm	Standard cubic feet per minute
STIG	Steam injected gas turbine
TAC	Technical Advisory Committee
TPD	Tons per day
WRI	Western Research Institute
WTW	Well to Wheel

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