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Prepared by:

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Waste-to-Energy Evaluation
Renewable Energy Generation

300 ton/day
9.5 MWe

Prepared for:

California Energy Commission
EPC-14-045, Advanced MSW Recycling
Task 6 Analysis and Evaluations
(1st-Draft)

1.0 Technology Description--Introduction

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

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



Figure 1.1 RDF Production Facility, Receiving and Processing 432 wet-ton/day MSW

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

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

1.1 Appearance of the proposed Waste-to-Energy Facility

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



Figure 1.2 Power Island, RDB Receiving (300 wet-ton/day), and Administration Buildings

Adjacent to the RDF receiving and storage building, shown in **Figure 1.2**, is an uncovered, exterior screened area of approximately sixty thousand (60,000) square feet, which contains most of the gasification and power generation equipment, which includes two parallel gasification trains, each sized to process 150-ton/day RDB, providing a total RDB gasification capacity of 300-ton/day. The perimeter screening fence is thirty (30) feet high along the West side and twenty (20) feet high along the North side with an enhanced screening element in the Northwest corner, which rises to approximately forty-eight (48) feet, serving to shield conversion equipment somewhat from view.

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

1.2 RDF Facility, Operational Summary

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

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

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

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



Figure 1.3 MSW on the Tipping Floor

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

1.3 MSW--Bulk Properties of RDB

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

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

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

Table 1.1 Ultimate Analysis of MSW and RDB



Figure 1.4 Shredded MSW

1.4 RDB Production

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



Figure 1.5 Primary size reduction

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



Figure 1.6 Rotary-Shear shredder used for RDB production

1.8 RDB-Fluff Storage

The RDB is transported in walking floor tractor-trailers to the Renewable Energy Facility, and delivered to the storage area, constructed of steel reinforced concrete floor with two push-walls constructed of steel reinforced concrete, where the RDB-fluff is piled and moved about with a front-loader. The storage capacity of the facility is large enough to contain two days of RDF-fluff.

Periodically, RDB is pushed into live-bottom storage bunkers, where it is stored on a walking-floor conveyor, which controls the feed-rate to the gasifier.

The storage bunkers are 10' wide x 10' deep x 60" long, providing at least 2-hours of storage capacity, so that the RDB-feedstock is continuously withdrawn by the means of a Rate Control System that feeds the gasification process.



Figure 1.7 Walking Floor Storage Controls RDB Feed Rate to Gasifier

2.0 Introduction to Gasification Technology

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



Figure 2.1 Cars and Buses all used Solid Fuels During WWII

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



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

2.2 RDB Gasification Integrated with Power Generation

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

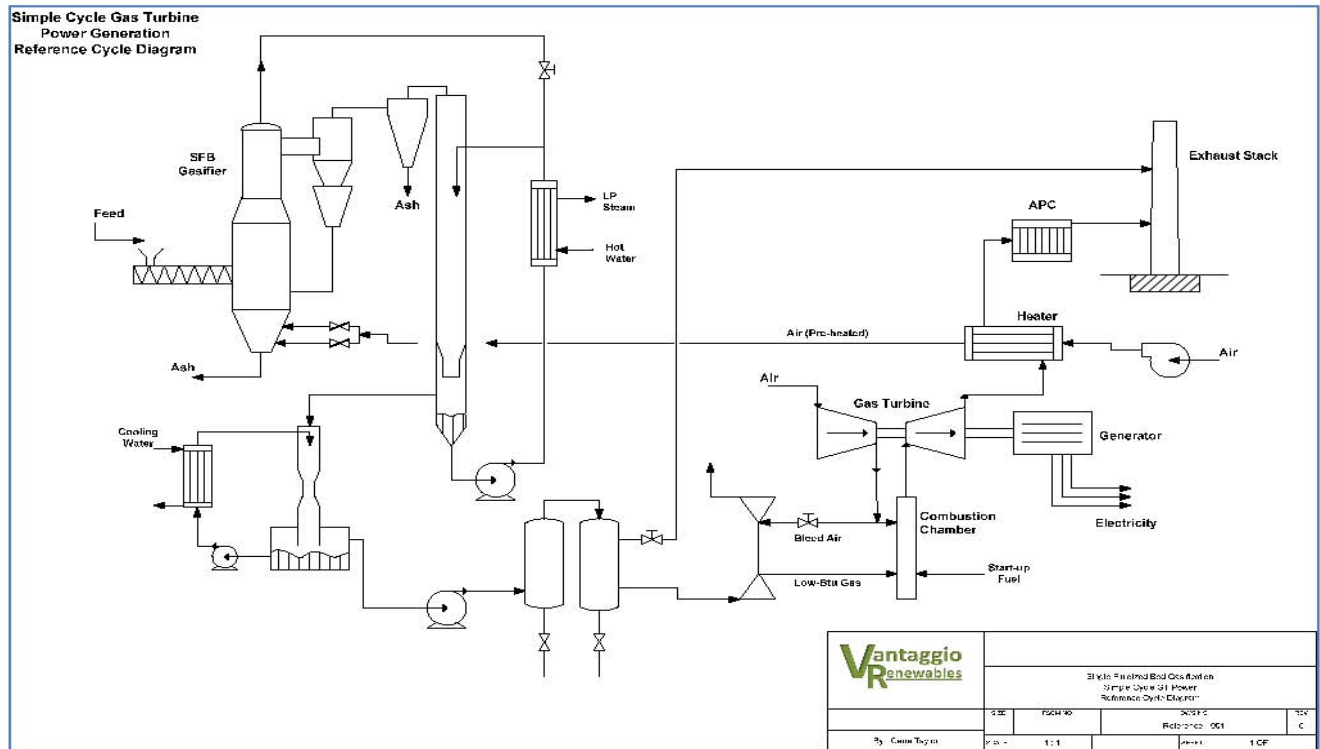


Figure 2.3 Gasification Process integrated with STIG Gas Turbine Power Generation

The RDF is metered into an entrained-flow gasifier, operated near atmospheric, using an extrusion-screw type auger-feeder that forms a seal, isolating the gasification system from the ambient air.

Oxygen-enriched air is provided to oxidize 25% of fuel input, which generates the heat necessary to heat RDB, converting the biomass and plastic residues into low-BTU fuel-gas and carbon-char.

The Taylor Energy gasification reactor with integrated reformer designed to process RDB is shown below:



Figure 2.4 Taylor Energy Gasification Reactor and Reformer Used for RDB Processing

2.3 Gas Cleaning System

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

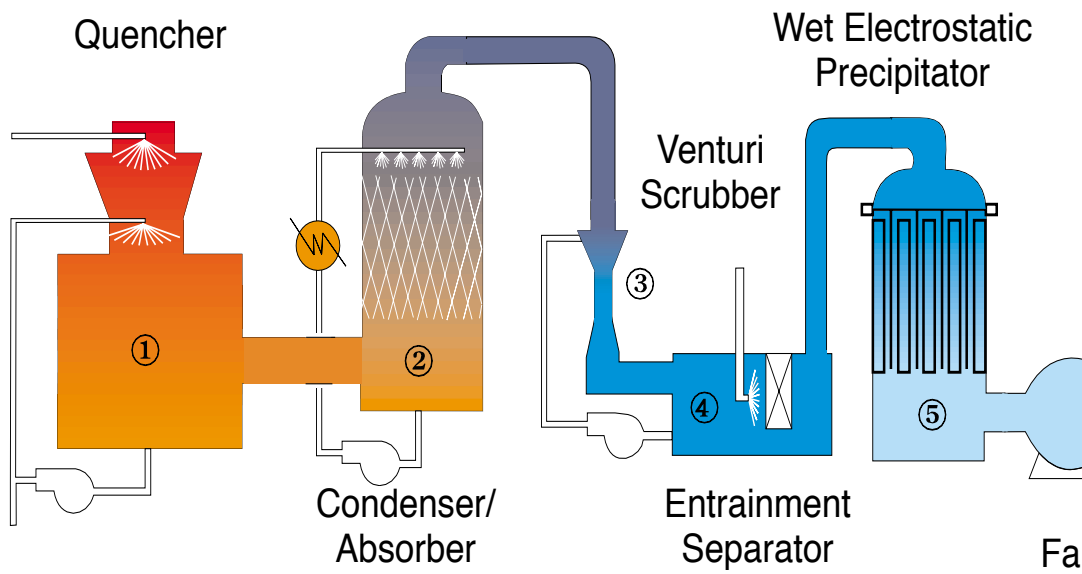


Figure 2.5 Fuel-gas cleaning system

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

The final scrubber is a water-based scrubbing system that removes an acid gasses present, and particularly provides the water-environment where ammonia (NH_3 , produced during gasification) reacts with hydrogen chloride (HCl , also liberated during gasification of PVC) to form ammonium chloride, a salt that, when precipitated from the scrubber-brine, can be used as a fertilizer component.

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

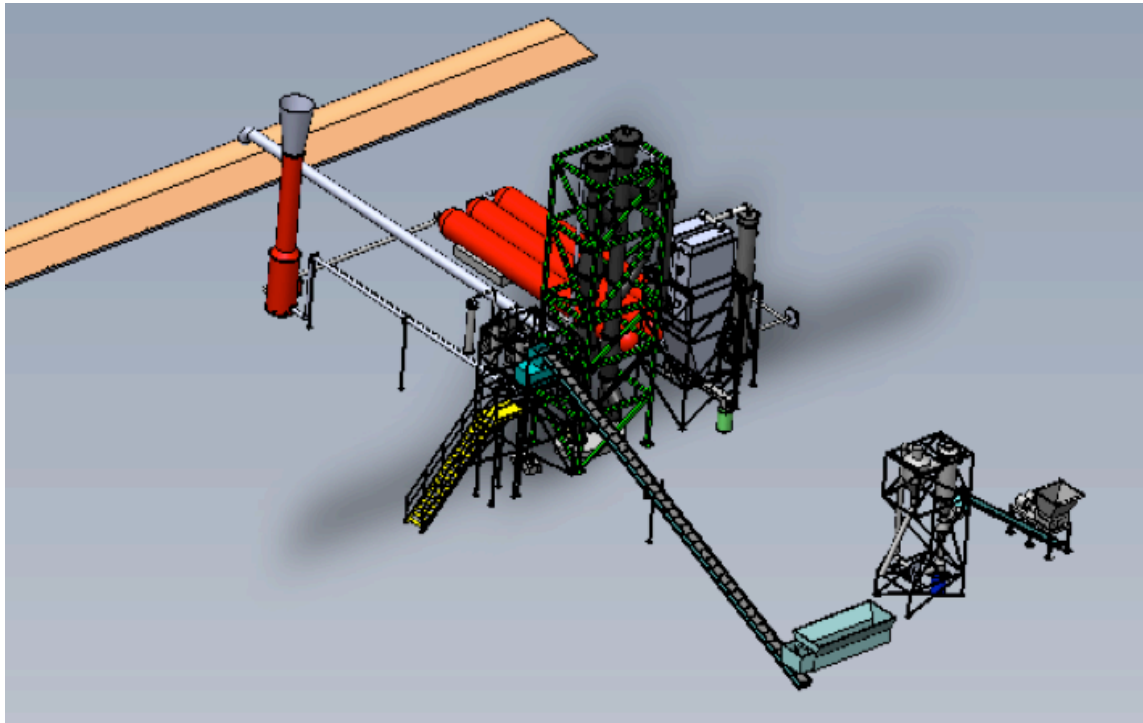


Figure 2.6 Preliminary design: Feeding, Gasifier, Reformer, Gas-scrubbing, Enclosed flare

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



Figure 2.7 The facility will employ an enclosed flare

2.4 Electric Power Generation

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

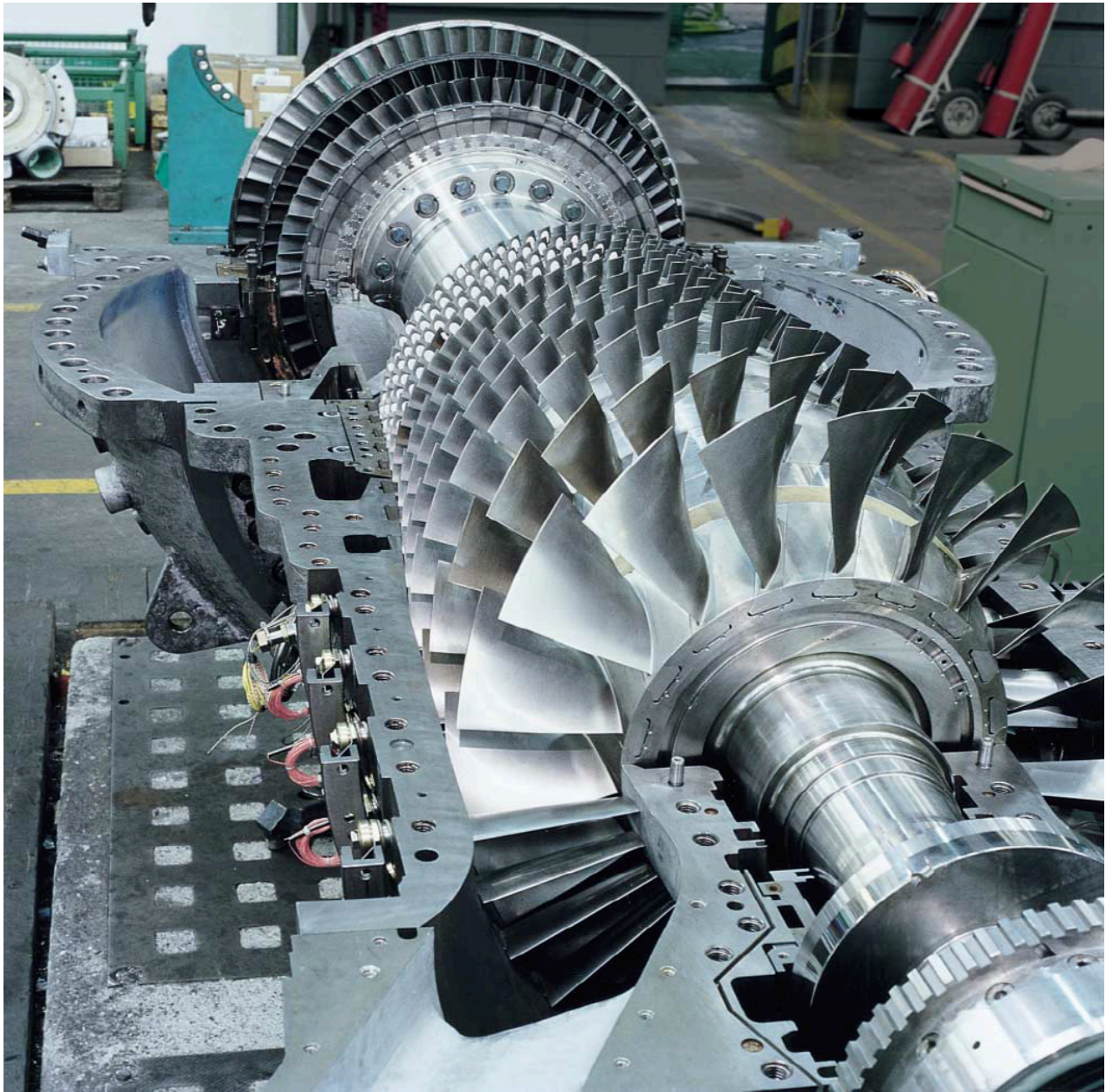


Figure 2.8 GE10-1 Gas Turbine Engine for operation with Low-BTU fuel-gas

2.5 Power Island – Steam Injected Gas Turbine (STIG)

The gas turbine is to be provided by General Electric (GE) and packaged by a company with experience designing and fabricating skid mounted power generation equipment for industrial applications.

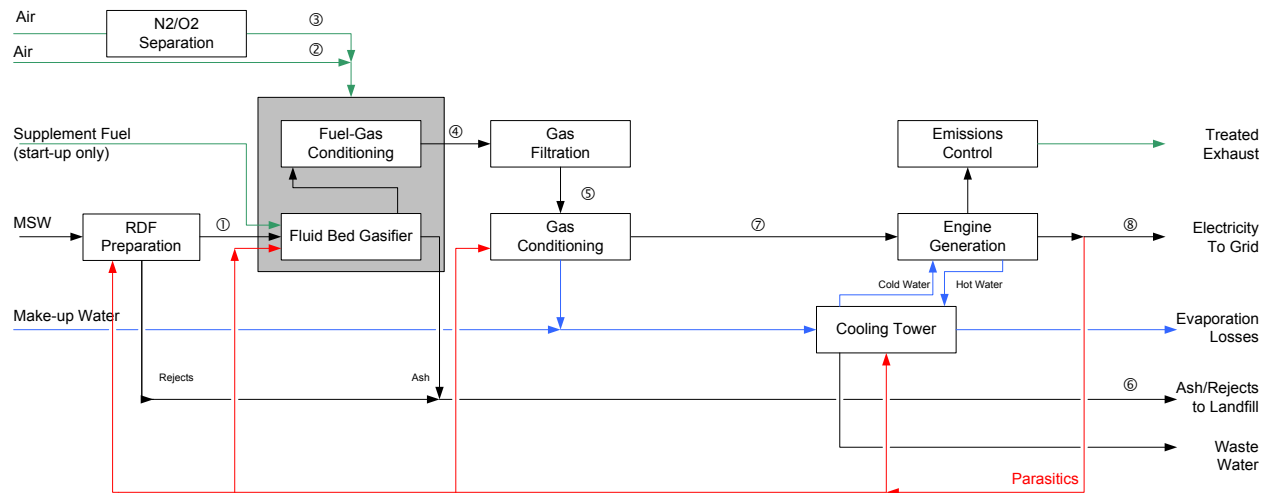
The power island supplier provides complete services for the power production modules, including the skid design, fabrication of the power plant skids, and includes the installation and start-up of the turbine engines. They also provide a long-term maintenance sub-contract that includes periodically rebuilding the turbines and other moving parts.



Figure 2.9 Steam Injected Gas Turbine (STIG) used to Increase Efficiency

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

2.6 Mass and Energy Balance



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

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

Figure 2.10 Preliminary Mass and Energy Balance

3.0 Environmental Benefits

Accomplishing the conversion of Waste-to-Energy using gasification technology is presently the cleanest method available for using Municipal Solid Waste (MSW) as an energy resource.

The historic method of burning MSW with excess air is technically feasible; modern methods used to control air emissions have proven to be reliable and work well enough so that traditional “incineration” technology can be permitted for operation within most jurisdictions.

However, gasification is always cleaner than incineration. Why? Because incineration methods mix air with the waste-fuel to enable combustion—and then exhaust gases are cleaned post-combustion; whereas, gasification methods heat the waste to make fuel-gas that is cleaned first; then the clean-gas is mixed with air to enable combustion. Consequently, the fuel-gas volume (resulting from gasification) that is subject to cleaning is 1/5th the volume of the combustion exhaust resulting from incineration. The ability to clean a gas is a function of the volume. Smaller gas volume results in cleaner gas and lower air emissions. Therefore, gasification has emerged as the cleanest method for using solid fuels for power generation. For example, coal-gasification is always cleaner when compared to coal-combustion. Biomass-gasification is always cleaner when compared to biomass-combustion.

RDF gasification is only recently emerging as the best alternative for optimum environmental performance when used to convert MSW into a clean fuel-gas product that is comparable to pipeline natural gas in purity.

3.1 Air Emissions

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

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

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

3.2 Fuel-gas Output (volume-%)

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

Gasifier		Tar-cracker	Gas Clean-up (typical)
CO	8.82	10.0	10-22
H ₂	7.36	8.61	8-14
CH ₄	5.46	6.51	4-6
C _x H _y	3.24	4.88	1-2
NH ₃	0.26	0.25	0.05-0.1
CO ₂	14.09	15.65	15-18
H ₂ O	13.66	9.48	0.82 (saturated at 40 F)
N ₂ +Ar	46.83	46.48	40-45
C ₁₀ H ₈	0.25	0.023	0.01-0.02
H ₂ S	78 PPM _v	48 PPM _v	20-40 PPM _v
HCl	139 PPM _v	90 PPM _v	25-35 PPM _v
HCN	30 PPM _v	20	20-30
HHV	184 BTU/scf	250 BTU/scf	302 BTU/scf
Tars	13.8 g/Nm ³	1.2 g/Nm ³	0.5 g/Nm ³
M.W.	26.7	26.5	26
Density	0.074 lb/ft ³	0.071 lb/ft ³	0.070 lb/ft ³
Char	15.7 wt-%	5.0 wt-%	0.01 wt-%
Ash	13.8 wt-%	12 wt-%	0.08 wt-%

3.3 Exhaust Emissions (adjusted to 11% O₂)

	Design Limit	Nominal
CO, mg/Nm ³	2.5-5	1.8-3.6
Particulates, mg/Nm ³	3-7	2-5
HCl, mg/Nm ³	0.5-2	0.4-1.4
HF + HBr, mg/Nm ³	<0.1	<0.1
SO ₂ , mg/Nm ³	5-15	<3.6
Heavy Metals, mg/Nm ³	2.2	<1.6
NO _x , mg/Nm ³	200-300	140-214
PCB, ng/Nm ³	163.0	<0.1
PCDD/PCDF, ng/Nm ³	13.1	<9.3
Specific Heavy Metals		
Lead (Pb), mg/Nm ³	<0.005	Nil
Cadmium (Cd), mg/Nm ³	<0.0004	Nil
Mercury (Hg), mg/Nm ³	0.008-0.05	Nil

3.4 Residues from the Waste-to-Energy Facility

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

Waste products generated by the facility include:

Liquid waste:

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

Gaseous waste:

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

Solid waste:

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

Ash and Char (wt-%)

Carbon-char	5.4
SiO ₂	33.93
Al ₂ O ₃	16.21
TiO ₂	2.3
Fe ₂ O ₃	3.32
CaO	23.2
MgO	2.09
Na ₂ O	4.43
K ₂ O	1.54
P ₂ O ₅	1.59
SO ₃	2.85
Cl	2.9
As	0.000923
Cd	0.0002
Pb	0.034
Hg	Nil

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

4.0 Project Input and Outputs

The Materials Receiving and Storage Facility is designed to process 300-wet-ton/day RDB. The system is composed of two parallel trains, each processing 150-wet-ton/day RDB. Two RDF storage and feeding lines, two parallel gasification reactors, one power generation train.

Each gasification reactor is designed to process a maximum of 150 ton/day of RDB, which equates to an input capacity of 300-wet-ton/day RDB. Detailed projections and plant capacity are discussed below and in Sections 4.1, 4.2, and 4.3.

At 85% on-line capacity, each process train is designed for an average (365 day/year) daily capacity of 255-ton/day input, resulting in average output of 8,075 kWh net power (8760 hr/yr). To achieve this result, the power train will generate 9.5-MW per hour, operating at a minimum of 7,446 hours per year.

Sections 4.1, 4.2, and 4.3 below provide the nominal design basis (11-MWe gross, 9.5-MWe Net) and show how the capacity and on-line availability are calculated.

4.1 Plant Design Basis

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

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

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

4.2 Design Capacity

The nominal design basis (at the MRF or landfill) calls for receiving and processing 432-wet-ton/day MSW, assuming 25% debris, glass, grit, and recyclables, including metals. Therefore, removing 25% non-energy materials will result in 324-wet-ton/day feedstock is available for energy use. The design basis assumes 25% moisture; preliminary processing removes 2% moisture.

Therefore, the nominal RDB design basis is 317-wet-ton/day MSW with 23-wt% moisture, and assumes that RDF is dried during production to result in 300-ton/day of RDB-fluff with 17.5-wt% moisture, containing approximately 5,000 Btu/lb, LHV.

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

300 ton/day x 2,000 pound/ton = 600,000 pounds per day
 600,000 pounds/day / 24 hours per day = 25,000 pound per hour

5,000 Btu/pound-dry LHV x 72% (net gasification eff.) = 3,600 Btu/pound as fuel-gas
 3,600 Btu/pound as fuel-gas x 25,000 lb/hr = 90,00,000 Btu/hr (90 mm Btu/hr)

90 mm Btu/hr x 42% (net STIG-cycle eff.) = 37.8 mm Btu/hr (as electricity)
 37.8 mm Btu/hr (as electricity) x (1 kWe / 3,412 Btu) = **11,075 kWh** (gross power output)
 Parasitic Power Uses (1,575 kWh)
Net 9,500 kWh

4.3 The system design for 85% Online Availability

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

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

5.0 Projections—Budgetary

Available Energy as Heat:

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

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

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

Gasification system

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

Power Generation Island

11,075 kWh (gross) x \$1,270/kWh= \$ 14,065,250.00

Engineering Design: \$ 1,175,000.00

Commissioning, start-up management \$ 1,500,000.00

Total \$ 32,577,500.00

Cost per kW Installed (\$ 32,577,500 / 9,500 kW)= \$ 3,429 / kW (installed capacity)

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

6.0 Analysis and Evaluations

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

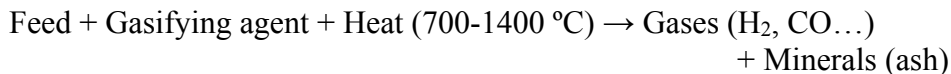
6.1 Background

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

Devolatilization (pyrolysis, thermal decomposition):



Gasification:



The key reactions involved are listed below¹¹.



Reaction 1 is the hydrogasification reaction, which essentially accounts for the methane production. Reactions 5 and 6 are combustion reactions, traditionally employed for generating the required process heat by supplying oxygen or air into the gasifier. Reactions 2, 3 and 4 are the steam gasification reactions.

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

The equilibrium trends for the C-H-O system are shown below¹.

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

	Temperature ↑	Pressure ↑	H/O ratio ↑
X_{H_2O}	↓	↑	↷
X_{H_2}	↑	↓	↑
X_{CO}	↑	↓	↓
X_{CO_2}	↷	1	↓
X_{CH_4}	↷	↑ 2	↑

1 – Maximum fairly constant, but shifts to higher temperature

2 – Maximum shifts to higher temperatures

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

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

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

However, the actual product gas composition depends on the rate at which equilibrium is attained, i.e., reaction velocity and this information can only be obtained through experimental work. The reaction velocity depends on various parameters such as the flow rate (residence time), reactor volume and type, T, P and the feedstock composition. For all the gasification reactions, the rate is very slow at lower temperatures and increases exponentially with temperature³. However, even at very high temperatures, the rate of gasification is considerably slower than that of the oxidation reactions and traditionally, a catalyst is employed in the absence of oxygen.

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

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

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

6.2 Aspen-Plus Simulation Development

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

Process Description

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

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

- Fixed carbon: 8.0% (0.0970 lb/lb-dry-feed)
- Volatile matter: 57.0% (0.6909 lb/lb-dry-feed)
- Moisture content: 17.5% wet basis
- Mineral ash: 17.5%
- Calorific Value: 6,000 – 6,900 Btu/lb-dry-feed

The basic parameters of the proposed Jet Spouted Bed followed by an entrained-flow section, integrated with Pulse-Detonation-Reformer include⁴:

- Temperature: 800 °C (1472 °F)
- Air input: 29.8 scf/lb-wet-feed
- Power for compression of primary air: 15.8 kWh/ton-dry-feed
- Power for oxygen production (enrichment to 33%): 41.6 kWh/ton-dry-feed
- Fuel-gas heating value: 227 Btu/scf
- Fuel-gas density: 20.3 scf/lb
- Fuel-gas production: 26.9 scf/lb-wet-feed
- Efficiency (gasification and reforming): 72.9%

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

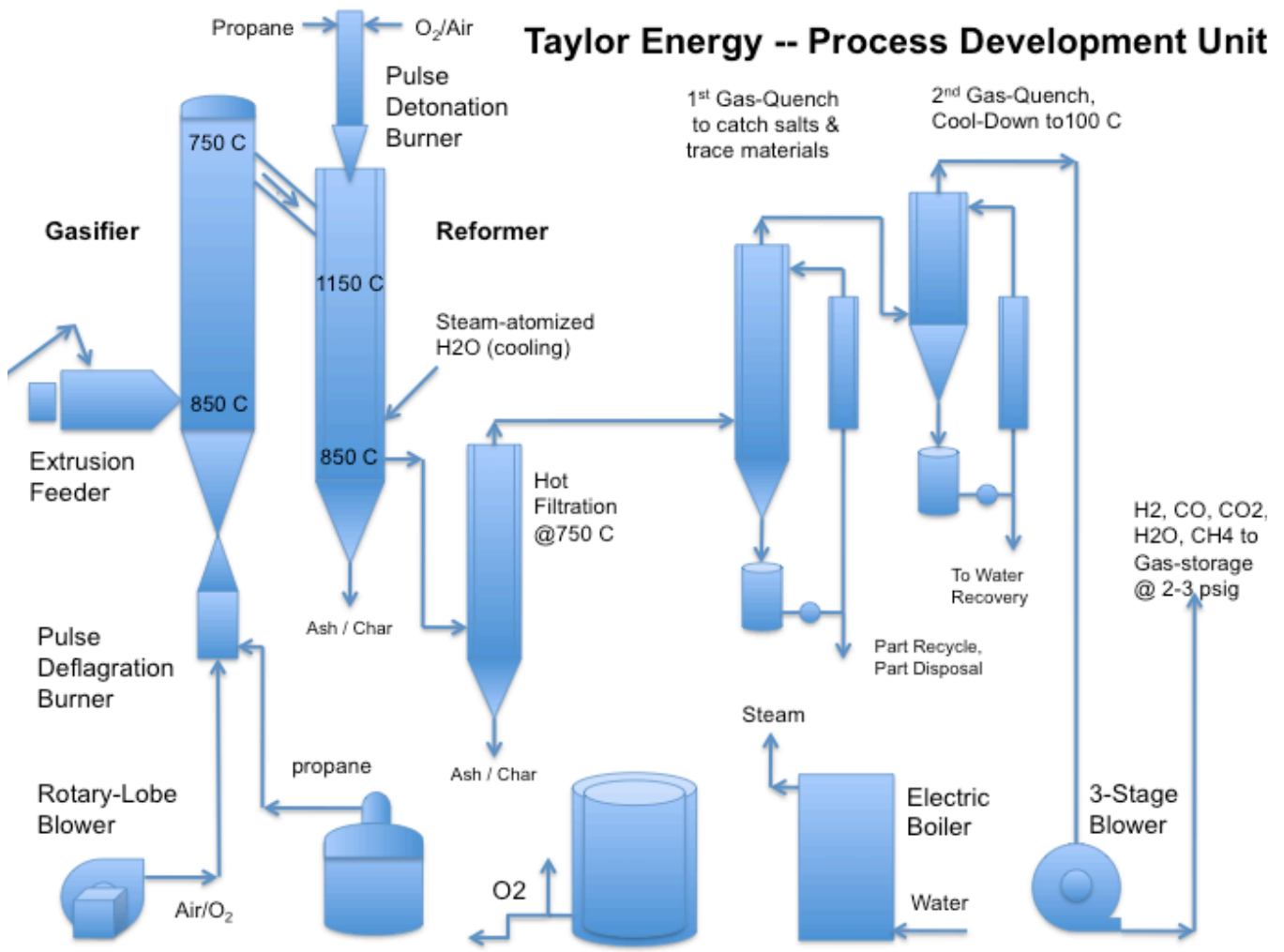


Figure 6.1 Process Flow Diagram of the Taylor Energy Gasification System

Description of Aspen Plus Simulation

The solid feedstock is fed into the gasifier on a steady basis at predetermined feed/air ratios. The model simulates the gasifier using decomposition and gasification units. These units are based on built-in Aspen reactor blocks and calculate the equilibrium composition in the reactor under the given conditions by means of Gibbs free energy minimization. The model uses the Peng-Robinson equation of state for thermodynamic calculations. The decomposition block converts the non-conventional feedstock such as biomass or coal into its basic elements on the basis of yield information using the RYIELD block. The components are then sent to the gasification block (RGIBBS), which calculates the equilibrium product gas composition using the Gibbs free energy minimization approach.

The carbon conversion information, feed flow rates and compositions, and the reactor operating conditions are supplied by the user based on existing experimental data. The ash and unreacted char are removed from the reactor as a solids-stream and the product gas is subjected to gas cleanup in order to remove trace contaminants that can include ammonia, hydrogen chloride, and hydrogen sulfide. The clean gas stream is then cooled down in two quench steps and is sent to gas storage.

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

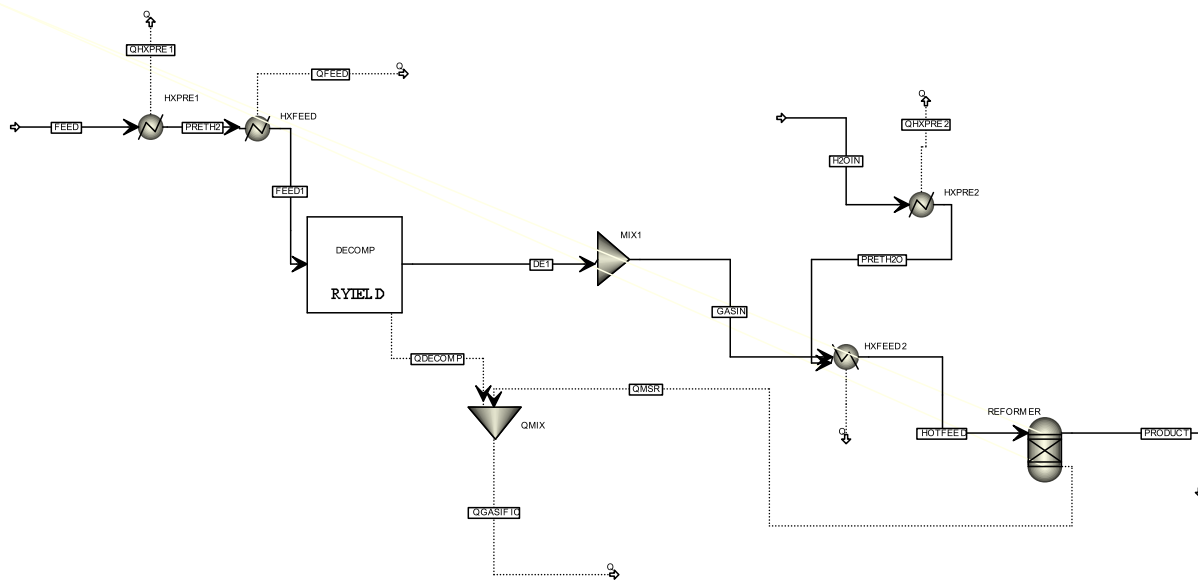
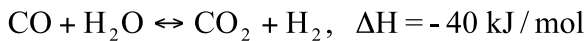
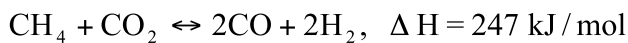
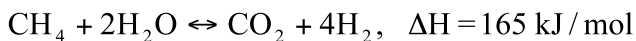
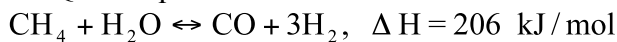


Figure 6.2 Gasifier Model in the Aspen Plus User Interface

Downstream Processes

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

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



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

$$S_{C_{3+}} = a_1 + a_2 \cdot T + a_3 \cdot \frac{[\text{H}_2]}{[\text{CO}]} + a_4 \cdot ([\text{H}_2] + [\text{CO}]) + a_5 \cdot P_{\text{Total}}$$

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

Where,

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

a_i – Empirical parameters

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

T – Temperature (K)

P – Pressure (bar)

According to Hamelinck et al., a least sum of squares fit of the above model with proprietary data resulted in the following equation, which was also found to be in accord with experimental results using a cobalt catalysts reported by Dry⁶. This equation is used to simulate the FT reactor.

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

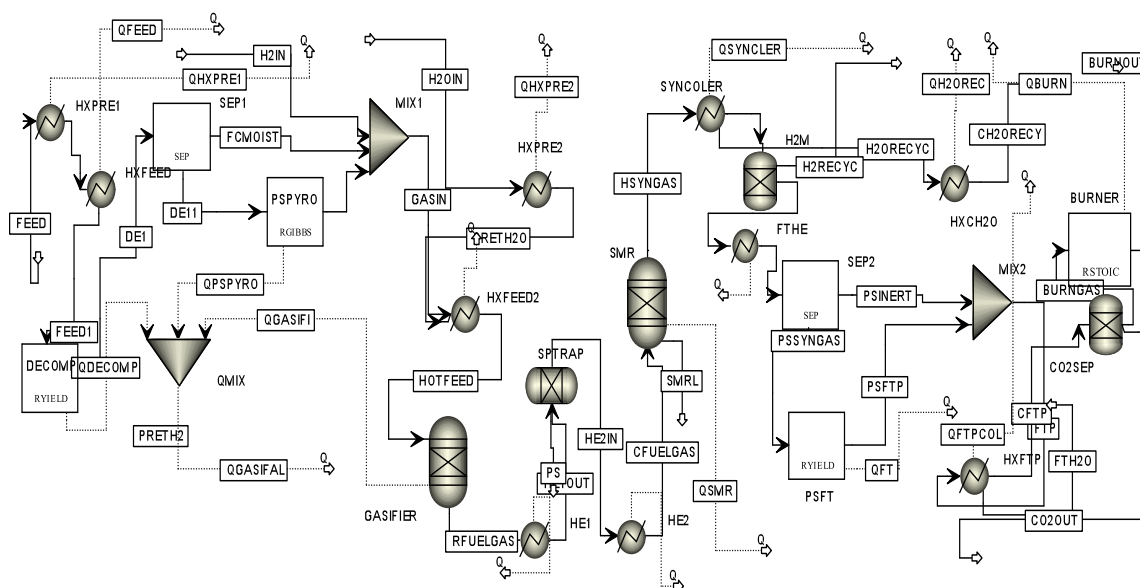


Figure 6.3 Integrated Aspen-Plus simulation Process Flow Diagram

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

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

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

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

OCE = Overall Conversion Efficiency of the process based on the number of moles of carbon converted into product gases excluding CO₂

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

Power Generation Module

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

Preliminary Results

Based on the equilibrium predictions, the net thermal efficiency of the process varies significantly, from 38% to 70% for fuel production and 35% to 70% for power generation. The values are highly sensitive to the process parameters including operating temperature, feed composition, and pressure.

Experimental data on carbon conversion, product gas composition, yield, and energy use will be used to update the model in order to evaluate process performance for the specific feedstock/product combinations and further optimization.

6.3 Life Cycle Assessment

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

Greenhouse gases. The key GHGs considered by the LCA and their Global Warming Potential (GWP) compared to CO₂ are given in the Table below. The GWPs are the 100-year warming potential values published by the Intergovernmental Panel on Climate Change (IPCC) in 2007 and are often referred to as the IPCC 2007 GWPs⁷. The GHG emissions for each pathway are calculated for each GHG and are reported on a carbon dioxide equivalent (CO₂e) basis using the GWPs.

GHG Name	100 Year GWP
Carbon dioxide (CO ₂)	1
Methane (CH ₄)	25
Nitrous Oxide (N ₂ O)	298
Chlorofluorocarbons(CFC-12)	10,900
Hydrofluorocarbons (HFC-134a)	1,430

Table 6.2 Global Warming Potentials of the key GHGs

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

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

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

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

The basic assumptions used in model are listed below:

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

The Well to Tank (WTT) results of the FT-Diesel production life cycle analysis are presented in Table 6.3 below. The total and fossil energy use is listed including specific petroleum, coal and natural gas use information. The fuel production process relies on natural gas and petroleum whereas the Biomass gasification to FTD process uses some natural gas and petroleum along with the renewable resource. The table also presents the GHG emissions in CO₂ equivalent values. The GHG emission for the baseline case is 29.8 kg CO₂e/mmBtu fuel, while the GHG emission for the biomass gasification process is -69.9 kg CO₂e/mmBtu fuel.

Table 6.3 WTT analysis of FT-Diesel production from biomass

Item	Energy usage or emission (Btu/mmBtu or g/mmBtu)	
	Baseline conventional Diesel	Biomass gasification to FTD
Total Energy	313,163	1,124,378
Fossil Fuels	309,598	82,299
Coal	3,791	816
Natural Gas	245,588	13,580
Petroleum	60,219	67,903
CO ₂ (w/ C in VOC & CO)	25,823	-69,883
CH ₄	139.80	9.10
N ₂ O	0.49	0.24
GHGs	29,464	-69,585
VOC: Total	9.85	3.55
CO: Total	20.69	12.96
NOx: Total	43.15	32.87
PM10: Total	4.03	2.60
PM2.5: Total	3.49	1.88
SOx: Total	26.16	7.84

The Well to Wheel (WTW) results are presented in Table 6.4 below. The results include the total energy use per mile driven using the specified fuel and the GHG emissions. The WTW analysis shows that the biomass gasification pathways use significantly higher amounts of energy per mile of the vehicles driven. The GHG emission from vehicle using the baseline fuel production process is 392 gCO₂e/mile driven, while it is 24 gCO₂e/mile driven for the biomass gasification pathway.

Table 6.4 WTW analysis of FT-Diesel production from biomass

Item	Energy usage or emissions (Btu/mile or g/mile)							
	Baseline conventional Diesel				Biomass gasification to FTD			
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	478	702	3,769	4,949	130	4,107	3,769	8,006
Fossil Fuels	470	697	3,769	4,935	130	180	0	310
Coal	8.25	6.04	0.00	14.29	0.41	2.67	0.00	3.08
Natural Gas	427	498	0	926	14	37	0	51
Petroleum	34	193	3,769	3,996	115	141	0	256
CO ₂ (w/ C in VOC & CO)	39	59	294	392	-277	14	287	24
CH ₄	0.41	0.11	0.09	0.62	0.01	0.02	0.09	0.13
N ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GHGs	49	62	297	408	-277	15	290	28
VOC: Total	0	0	0	0	0.00	0.01	0.08	0.09
CO: Total	0.03	0.05	2.73	2.81	0.02	0.03	2.73	2.78
NOx: Total	0.09	0.07	0.23	0.40	0.04	0.09	0.23	0.36
PM10: Total	0.01	0.01	0.02	0.04	0.00	0.01	0.02	0.03
PM2.5: Total	0.01	0.01	0.01	0.02	0.00	0.01	0.01	0.02
SOx: Total	0.03	0.07	0.00	0.10	0.00	0.03	0.00	0.03
VOC: Urban	0.01	0.01	0.05	0.07	0.00	0.00	0.05	0.06
CO: Urban	0.00	0.02	1.91	1.94	0.00	0.00	1.91	1.91
NOx: Urban	0.01	0.03	0.16	0.21	0.00	0.00	0.16	0.17
PM10: Urban	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.02
PM2.5: Urban	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
SOx: Urban	0.00	0.05	0.00	0.05	0.00	0.00	0.00	0.00

7.0 Engineering Design Calculations for Gasification Process

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

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

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

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

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

- RDB to be gasified (note d.f. = dry feed)
 - Gross heating value 3839 kcal/kgd.f. = 6909 Btu/lb d.f.
 - Water content 18.0% wet basis
 - Mineral/metal 17.5%
 - On the basis of 1 kg of d.f.
 - Volatile matter 0.691 kg
 - Fixed carbon 0.134 kg
 - Mineral/metal 0.175 kg
 - Water 0.215 kg
- Product pattern in the circulating (gasification at 720C = 1328F)
 - Volume of dry gas 0.4913 Nm³/kgd.f. = 7.87 scf/lb d.f.
 - Gross heating value of dry product gas 5204 kcal/Nm³ = 585 Btu/scf
 - Mass of tar 0.0504 kg/kgd.f. = 0.0504 lb/lb d.f.
 - Mass of char 0.1176 kg/kgd.f. = 0.1176 lb/lb d.f.
 - Water formed 0.174 kg/kgd.f. = 0.174 lb/lb d.f.

7.2 Necessary heat for gasification

Necessary heat = $F_s(0.24)(T_{s_2} - 750) = 613.38 + 275.0 W_p + L_1$ [kcal/kgd.f.]

W_p is the ratio of water vapor used for fluidization

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

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

Surface Area

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

Thermal insulation is made to keep surface temperature of the reactor at $80\text{C} = 176\text{F}$.

Heat transfer coefficient at the outer surface is estimated as:

Natural convection	$h_c = 5.9 \text{ kcal/m}^2\text{hr}^\circ\text{C}$
Radiant heat	$h_r = 5.8 \text{ kcal/m}^2\text{hr}^\circ\text{C}$
	$h_c + h_r = 11.7 \text{ kcal/m}^2\text{hr}^\circ\text{C} = 2.396 \text{ Btu/ft}^2\text{hr}^\circ\text{F}$

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

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

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

$$613.38 + 20.9 = 634.2 \text{ kcal/kgd.f.} = 1142 \text{ Btu/lb d.f.}$$

7.3 Amount of the air to burn carbon completely

$$(0.1172 \text{ kg/kg d.f.})(22.4 \text{ Nm}^3/12 \text{ kg})(1/0.21) = 1.042 \text{ Nm}^3 \text{ air/kg d.f.}$$

7.4 Heat balance for combustion of carbon in the bed

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

[Heat Input]

Combustion heat of carbon

$$(7838 \text{ kcal/kg c})(0.1172 \text{ kg c/kg d.f.}) = 918.6 \text{ kcal/kg d.f.}$$

[Heat Output]

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

Apparent heat of combustion gas

$$(0.1172 \text{ kg c/kg d.f.})([22.4 \text{ Nm}^3/(12 \text{ kg c})(0.21)])(0.34 \text{ kcal/Nm}^3\text{C})(720^\circ\text{C}-20^\circ\text{C}) = 247.9 \text{ kcal/kg d.f.}$$

$$\text{Heat output} = 634.2 + 247.9 = 882.1 < 918.6 \text{ kcal/kg d.f.}$$

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

7.5 Estimation of heating value

From Table 3, page 32, in technical report DK-98-1, density of gas produced from MSW, c.a. 4600~5000 kcal/Nm³ (517~562 Btu/scf) is found to be 1.0 kg/Nm³. Thus, volume of cracked gas from recycled tar stream is estimated as:

$$(0.0302 \text{ kg/kgd.f.})(1/1.0 \text{ kg/Nm}^3) = 0.0302 \text{ Nm}^3/\text{kgd.f.}$$

Volume of combustion gas is given by:

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

Thus, low heating value of product gas from the Modified Fluid Bed PYROX is estimated to be:
1790 kcal/Nm³

7.6 Gasification efficiency

$$\begin{aligned}\eta &= [(5402)(0.4913) + (0.0302)(0.6)(8000) \text{ kcal/kgd.f.}] / 3839 \text{ kcal/kgd.f.} \\ &= 0.729 \\ &= 72.9\%\end{aligned}$$

7.7 Heating Value of fuel-gas product

Gasification efficiency is high in the Autothermal Fluid-Bed, however, heating value of product gas is rather low, 1790 kcal/Nm³ = 201.2 Btu/scf. It goes without saying that the higher the heating value, the safer it is to burn, and therefore we prefer to increase its heating value, for example, up to 2500 kcal/Nm³ = 281 Btu/scf. In order to increase the heating value of the product gas, we have the following three options:

- Feeding of dry RDB
- Pre-heat of the partial oxidation air
- Enrichment of O₂ in the air, using O₂ unit

7.8 Heating Value of product gas increased by drying the feedstock

$$\begin{aligned}&[(5402 \text{ kcal/ Nm}^3)(0.4913 \text{ Nm}^3/\text{kgd.f.}) + (0.0302 \text{ kg tar/kg d.f.})(0.6)(8000 \text{ kcal/kg tar})] / (0.4913 \text{ Nm}^3/\text{kg} \\ &\text{d.f.} + 0.0302 \text{ Nm}^3/\text{kgd.f.} + 0.730 \text{ Nm}^3/\text{kg d.f.}) \\ &= 2236 \text{ kcal/Nm}^3\end{aligned}$$

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

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

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

8.0 Appendix

Summary of Mass and Energy Calculations

Feed rate is 390 wet-ton/day RDB containing 5,000 Btu/lb-wet @ 17.5 wt% moisture
 390 ton per day / 24 hr/day = 16.25 ton/hr; 16.25 ton/hr x 2000 lbs/ton= 32,500 lbs/hour
 32,500 lbs/hour x 5,000 Btu/lb = 162.5 MM Btu/hr
 RDB Gasifier Design Basis

Net Power Output	13,300	kWh
Gross Power Output	15,000	kWh
Engine/Generator Eff.	43.3	%
Engine Heat Rate	7880	BTU/kWh
Engine syngas input	118	MM BTU/hr
Engine power output	55.1	MM BTU/hr
Net cycle eff.	31.5	%
Fuel-gas density	190	Btu/scf

32,500 lbs/hr RDF (As Stored)

Fuel Composition	HHV	LHV
Energy	7,363	4,970 Btu/lb
Moisture	0.00%	17.50%
Ash	0.00%	15.00%
C	47.68%	32.91%
H2	6.94%	4.68%
N2	1.54%	1.04%
O2	41.85%	28.25%
S	0.46%	0.31%
Cl	<u>1.54%</u>	<u>1.04%</u>
	100%	100%

Process Info	Feed Input	Air Input	O2 Input	Gasifier Output	Clean Output	Ash Output	Syngas Input	Power Output
Process stream	1	2	3	4	5	6	7	8
Mass flow lb/hr	32500	19250	2400	54150	48325	5825	48325	
Temp. F	50	70	70	1742	400	120	120	750
MMBTU/hr	162			(38.6)	118	(5.4)	118	
ACFM								
SCFM		4123	500	10350	10350		10350	
Pressure psia	14.7	24.7	21.7	14.0	12.7		154.7	
BTU/scf					190			
Moisture	17.5%				9%		4%	
Char lb/hr						450		
Dolomite lb/hr	500					500		
Power Output MMBTU/hr (gross max.)								50.5
Power Output kWe/hr (gross max.)								14,812
Internal power requirement								2,500
Net Maximum Output								12,312

Feed Rate	390	Short Ton per Day RDB
Pounds/hour	32,500	lb/hr
RDF (LHV)	5,000	BTU/lb
Fuel Input (LHV)	162	MM BTU/hr
RDF Moisture	17.5	wt%
Gas energy out	118	MM BTU/hr
Syngas Eff.	72.8	%
Char energy content	5.4	MM BTU/hr
Char energy-loss	3.3	% of Fuel Input Energy
Oxygen required	0.25	Stoichiometric Ratio (S.R.)
Air mass flow	19,250	lb/hr
O2 mass flow	2,400	lb/hr
Air volume flow	4,123	scfm
O2 volume flow	500	scfm
Fuel-gas	10350	scfm
Molecular weight		26

Gasification Reactor

Gasifier, Diameter	6	ft, Inside Diameter
	8	ft, Outside Diameter
Expanded Bed level	10	ft (Jet-Spouted-Bed height)
Bed area	28.26	ft ²
Total gas flow	7,500	scfm
@1382 F	26,250	acfm (750 C)
@1382 F	437	acfs (750 C)
Velocity, superficial	15.5	ft/sec (fps)
Gas flow@1562 F	29,175	acfm (850 C)
@1562 F	486	acfs (850 C)
Velocity, superficial	17.2	ft/sec (fps)

Tar-cracker

Tar-cracker, Diameter	6	ft, Inside Diameter
	8	ft, Outside Diameter
Tar-cracker area	26.87	ft ² (down-flow)
@1562 F	486	acfs
Velocity, superficial	18.1	ft/sec (fps) (down-flow)
Ash	5,825	lb/hr
Char mass flow	450	lb/hr