A Technical, Economic, Energy and Environmental Assessment of Thermochemical Systems for Conversion of Sewage Sludge and Other Waste Biomass Materials

Prepared For:

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June 2005

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EXECUTIVE SUMMARY

TSS Consultants (TSS) carried out a technical assessment on the potential application of various thermochemical processes for the conversion of waste biomass at the East Bay Municipal Utility District (EBMUD) wastewater treatment plant in Oakland, California. The principle authors of this study have spent several years compiling a database of more than 400 organizations that have developed technologies for thermally converting biomass into energy, fuels and/or chemicals. The technologies developed by these 400 organizations are divided into nine categories. Seven of these nine categories utilize thermochemical processes and two employ thermo-biological processes. The thermo-biological processes were not considered for this study.

A promising candidate technology was chosen from each of the seven categories. Each of these candidate technologies was evaluated for the potential conversion of low, medium and high projections of biomass conversion at EBMUD. The comparative evaluation included assessments of each system's Economic viability (E1), Energy efficiency (E2), Environmental compatibility (E3), progress in each of the Research, Development, Demonstration and Deployment (RDD&D) Evaluation stages (E4), and its potential socio-political Effectiveness (E5).

Table 1 summarizes the results of this analysis. The numbers in *Italics* gives the ratings for E1-E5 and E6 is the total ranking. As based upon this analysis, Thermal Pyrolysis/Steam Reforming (no oxygen) (rating: 50) was chosen as a potentially viable technology for this application. The next two technologies, Integrated Thermal Gasification/Oxidation (rating: 49) and Thermochemical Gasification (no oxygen) (rating: 42) may also be suitable for this application. The Integrated Thermal Gasification/Oxidation system may be preferred if it is decided that heat is a more important energy product than electricity.

On the basis of the E5 analysis, the Thermal Pyrolysis/Gasification/Steam Reforming technology was chosen as the most promising technology and BCT/ACT (Denver, CO) is a capable, candidate supplier of this technology. Therefore, the BCT/ACT technology was selected as the candidate technology for the preliminary design/engineering of a full-scale production plant, the cost analysis and an evaluation of the probability of success.

Table 1 – Economic, Energy, Environmental, Evaluation and Effectiveness Comparison (E5) of Various Types of Biomass to Energy Technologies – Low Biomass Projection

Biomass to Energy Technologies [1]	(E1) Economic Analyses (Electricity Cost ($/KWH) & Amortized Cost) [2]	(E2) Energy Analyses (Electricity (KWH/yr & Heat (MT/yr))	(E3) Environmental Assessment	(E4) Evaluation (RDD&D [3] Validation)	(E5) Effectiveness	(E6) Total Rating
Thermal Pyrolysis/Steam Reforming (No Oxygen)	$0.048/KWH $4.07 M/yr *(17)*	$6.64 \times 10^{+7}$ KWH/yr & 1.0 MT/yr) *(9)*	*(8)*	*(8)*	*(8)*	*(50)*
Integrated Thermal Gasification/ Oxidation	$0.054/KWH $3.38 M/yr *(15)*	$3.76 \times 10^{+7}$ KWH/yr & 2.0 MT/yr *(7)*	*(7)*	*(13)*	*(7)*	*(49)*
Thermochemical Gasification (No Oxygen	$0.067/KWH $5.05 M/yr *(12)*	$6.20 \times 10^{+7}$ KWH/yr & 1.0 MT/yr *(8)*	*(8)*	*(6)*	*(8)*	*(42)*
Thermochemical Gasification (With Oxygen)	$0.079/KWH $5.17 M/yr *(8)*	$5.53 \times 10^{+7}$ KWH/yr & 0.90 MT/yr *(7)*	*(6)*	*(14)*	*(6)*	*(41)*
Thermal Pyrolysis (No Oxygen)	*Not Applicable*	*Not Applicable*	*(5)*	*(6)*	*(5)*	*Not Applicable*
Thermal Oxidation (Combustion)	$0.174/KWH $5.82 M/yr *(3)*	$2.57 \times 10^{+7}$ KWH/yr & 1.5 MT/yr *(5)*	*(2)*	*(18)*	*(2)*	*(30)*

[1] Numbers in *Italics* represent ratings for E1-E5 – See Section 3.2 for details on rating system criteria
[2] Total Costs = Straight-line deprecation of capital costs (20 years depreciation of capital expenditures) plus annual operating and maintenance costs. The electricity cost calculation assumes that the EBMUD facility will be able to utilize up to 2.0 million Therms of heat energy each year
[3] RDD&D: Research, Development, Demonstration and Deployment Assessment Stages.

Table 2 summarizes the capital and operating and maintenance (O&M) costs for the generation of electricity and heat for the BCT/ACT thermochemical conversion technology. The capital and O&M costs and electricity production costs were calculated on the bases of conversion system capacities of 225, 350 and 525 tons/day for the low, medium and high projections, respectively, of processed sludge and selected municipal waste. These systems were designed to be 25% larger in capacity than required to handle the expected low, medium and high projections as a contingency to accommodate occasional larger quantities of processed biomass than projected (see Section 6.5 for further discussion).

Table 2 – Capital and O&M Costs for the Generation of Electricity and Heat – BCT/ACT System

Biomass[1] (Tons/Day)	Electricity Output (MW)[2]	Heat Output (MT)[2]	Capital Cost ($M)[3]	O&M Cost ($M/Yr)[3]	Electricity w/o Heat Use ($/KWH)[4]	Production w/ Heat Use ($/KWH)
Low (184)	8.41	1.00	16.1-17.7	3.02-3.33	0.062	0.048
Medium (290)	13.3	1.50	23.3-25.6	3.91-4.30	0.051	0.039
High (418)	19.1	2.00	33.8-37.2	5.11-5.62	0.048	0.036

[1] Electricity and heat output based on 184, 290 and 418 tons/day of processed sludge and selected municipal waste
[2] MW = Megawatt
[2] MT = Millions of Therms
[3] Capital and O&M costs based on conversion system capacities: Low: 225 tons/day; Medium: 350 tons/day; High: 525 tons/day.
[4] KWH = Kilowatt hours

It is possible that fuels, such as ethanol, can be produced from those thermochemical systems that generate syngas. Although, the production of fuels, such as ethanol, can potentially yield a higher rate of financial return, it is not recommend that fuel production be considered at this time since the technologies for the conversion of syngas to alcohol and diesel fuels, at this plant size scale, has not been sufficiently developed and demonstrated. However, it is possible, that a fuel production system could be added to the thermochemical gasification system at a later date.

EBMUD currently has an air emissions permit for operation of their reciprocating engine/electrical generator systems. It is recommended that those systems be retrofitted with Selective Chemical Reduction (SCR) systems for reducing NOx and retrofit catalysts for reducing CO, particulates and hydrocarbons. It is expected that an emissions reduction of 40-60% for CO, particulates and hydrocarbons and 60-85% for NOx can be achieved for these criteria pollutants. This reduction can be used to help offset the air emissions from the proposed BCT/ACT system.

It has been found that the formation of hazardous air pollutants (HAP's) (e.g. dioxins) will be reduced by more than 100 times over traditional thermal oxidation/combustion systems using thermochemical gasification (with limited oxygen or air). As based upon fundamental chemical and thermodynamic principles, it is not expected that dioxins will be produced by thermochemical gasification (without oxygen or air) or by thermal pyrolysis/steam reforming (without oxygen or air). However, measurement of dioxins and other selected HAP's from these systems will be needed to confirm this prediction.

The thermal pyrolysis/steam reforming conversion of the biomass to syngas produces minimal levels of air emissions. The primary source of emissions will be from the engine/electrical generation systems, which is estimated to be 1-2 orders of magnitude lower than the current EBMUD internal combustion (IC) reciprocating engine/electricity generation systems. Therefore, no new permits may be needed if the existing engines are equipped with the retrofit control devices.

Although the BCT/ACT technology and some of the other candidate thermochemical systems show a high potential for the conversion of EBMUD sewage sludge and other waste biomass materials, further efforts will be required to better quantify the economic, energy, environmental and effectiveness of these systems for the EBMUD application. Some recommended future efforts include testing of the EBMUD biomass waste, the measurement of emissions from the conversion system and IC engine/generator, a detailed mass and energy balance analysis of the BCT/ACT technology using the EBMUD feedstock, and a more detailed engineering analysis of heat recovery and use at the EBMUD facility.

In conclusion, some of the thermochemical conversion technologies outlined in this paper shows great future promise for the clean and energy efficient conversion of waste biomass and fossil biomass (e.g. coal) to energy, fuels and chemicals.

1. INTRODUCTION

1.1 Project Objectives

The objective of this study was to carry out a technical assessment on the potential application of various thermochemical processes for the conversion of waste biomass at the East Bay Municipal Utility District (EBMUD) wastewater treatment plant in Oakland, California. This assessment included the following tasks:

Task 1 – Review technical data provided by EBMUD and relevant background materials.

Task 2 – Review various options for the possible thermochemical conversion of EBMUD biomass materials to syngas (primarily a mixture of methane, hydrogen and carbon monoxide), electricity and fuels. Choose a candidate system and assess its applicability in terms of economics, energy efficiency and potential emissions. Identify potential technological, operational and maintenance risks.

Task 3 – Carry out a preliminary assessment of processing and manufacturing systems, equipment and materials balances for a full-scale commercial plant.

Task 4 – Calculate the energy balances and energy efficiencies for a proposed commercial plant.

Task 5 – Conduct a preliminary environmental assessment to identify any potential environmental impact issues.

1.2 Project Management

TSS was retained by EBMUD to assess the technical and economic viability of emerging thermochemical technologies for the conversion of waste biomass to electricity and/or fuels. TSS is a renewable energy and environmental consulting firm located in Sacramento, California. TSS provides consulting services to renewable energy project developers, owners, operators, investment banks and public agencies. TSS provides essential development team expertise for conducting feasibility studies, economic and environmental risk assessments, raw material procurement, market contract negotiations, permitting and construction of proposed new renewable energy facilities, evaluating emerging renewable energy technologies for investors, and assessment of existing renewable energy facilities for purchase or refinance. Additional information about TSS as well as the staff resumes are provided on the website: www.tssconsultants.com. Dennis Schuetzle, Alan Jacobson, Fred Tornatore, Loyd Forrest and Greg Tamblyn of TSS Consultants are the primary authors of this study. These individuals have over 100 years of Research, Development, Demonstration and Deployment (RDD&D) experience in energy and environmental technologies.

2. EBMUD WASTE TREATMENT FACILITY

2.1 Wastewater Treatment Plant

EBMUD's wastewater treatment plant is located in Oakland near the east end of the San Francisco-Oakland Bay Bridge. EBMUD provides primary wastewater treatment to peak flows of up to 320 million gallons per day (MGD). This primary treatment is used to remove floating materials, oils, greases, sand, silt and organic solids heavy enough to settle in water.

2.2 Secondary Treatment of Wastewater

Secondary treatment is available for peak flows up to 168 MGD. A high-purity oxygen activated sludge process is used for secondary treatment. Secondary biological treatment is used to remove most of the suspended and dissolved organic and chemical impurities from the water.

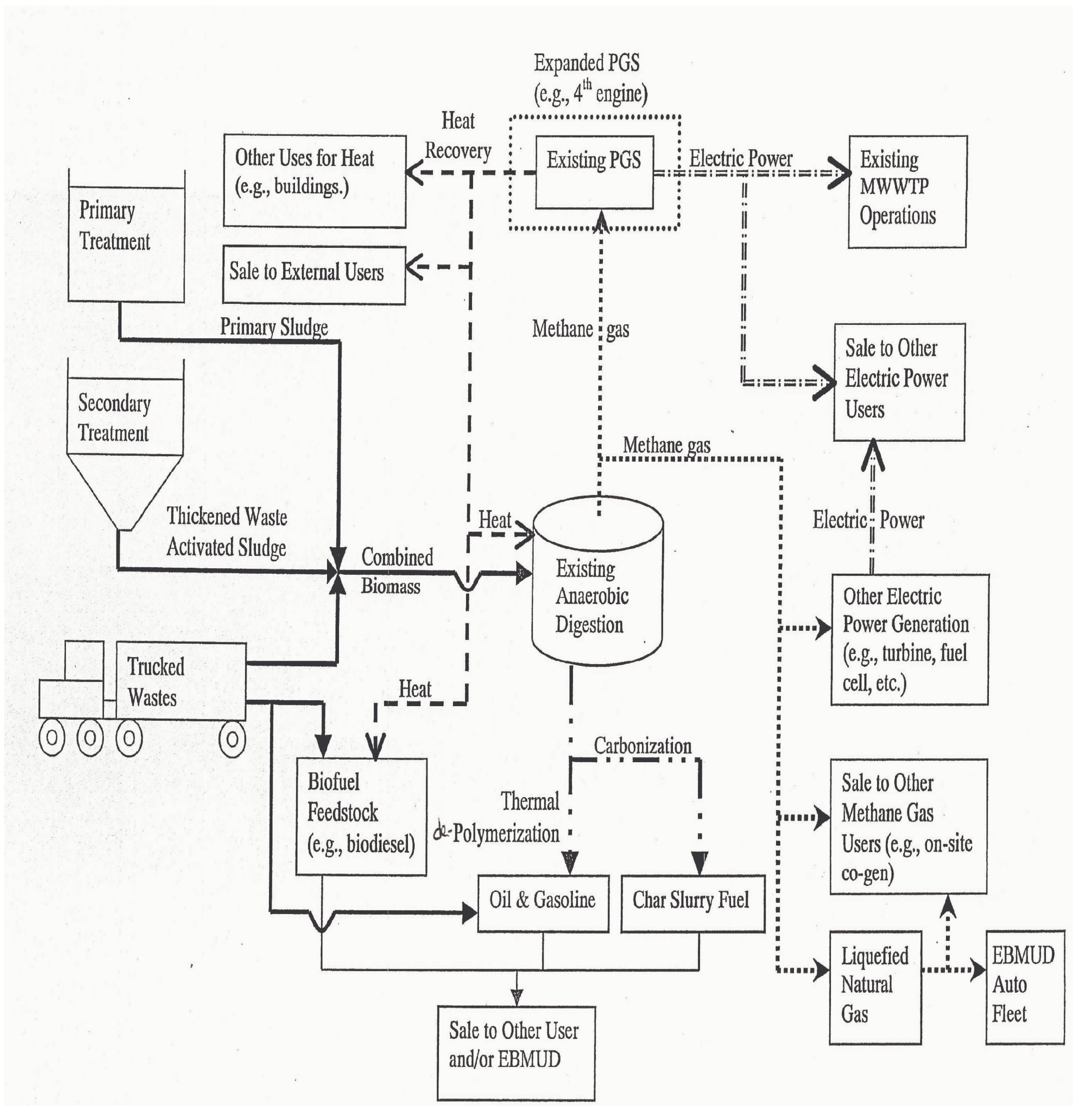
Eleven digesters are used for the anaerobic digestion of wastewater to produce biogas. The sludge generated from this process is de-watered and available as a 23% solids biomass source for conversion to electricity, heat and/or fuels production.

3. BIOMASS RESOURCE MANAGEMENT

3.1 An Overview of Biomass Resource Management Options

The following schematic (Figure 1) outlines the various biomass resource options available to EBMUD.

Figure 1 – Schematic for Various Biomass Resource Options at EBMUD



3.2 Current and Projected Biomass Feedstock's

The MWWTP produces 180 tons/day (TPD) (*current)* of sludge at 23% solids content. It is estimated that in the future the plant will produce from 330 tons/day (*medium projection)* to 560 tons/day (*high projection)* of sludge at the 23% solids content.

EBMUD believes that Norcal can deliver dry wastes, such as paper, cardboard, plastic and rubber to mix in with the sludge. It was estimated that the following dry materials could be collected to mix in with the sludge:

Table 3 – EBMUD Biomass Feedstock Projections

Projection	Bio-Solids (wet TPD)	Mixed Dry Materials (TPD)
Low	180	80
Medium	333	120
High	560	160

The average energy content of paper and cardboard is about 5,300 BTU/lb for glossy magazine paper to about 8,000 BTU/lb for newsprint (HHV). Cardboard varies from about 7,000 to 7,500 BTU/lb. A mixture of paper products in refuse averages about 7,000 BTU/lb (as received). A mixture of different plastics has an average energy content of 17,200 BTU/lb (HHV).

The heat content of the dry Biosolids is 6,620 BTU/lb. Elemental analysis of the Biosolids gave an ash composition of 37.9%. The ash is primarily comprised of 47.1% SiO_2, 17.9% Al_2O_3 and 8.65% CaO.

Table 4 gives the average composition and energy content of U.S. tires. These values are used for energy calculations and assessments presented in Sections *4.2.1* and *4.3.2.*

Table 4 – Composition and Energy Content of U.S. Tires (Dodds and Domenico – 1983)

Tire Belt Type	Energy Content (BTU/lb)[1]	Components (Wgt%)							
		Moisture	Ash	S	C	H	N	O	Volatiles
Fiberglass	14,000	0.00	11.7	1.29	75.8	6.62	0.20	4.39	0.0
Steel-belted	11,500	0.00	25.2	0.91	64.2	5.00	0.10	4.40	0.0
Nylon	14,900	0.00	7.20	1.51	78.9	6.97	<0.10	5.42	0.0
Polyester	14,700	0.00	6.50	1.20	83.5	7.08	<0.10	1.72	0.0
Kevlar-belted	16,900	0.00	2.50	1.49	86.5	7.35	<0.10	2.11	0.0
Average (assumes equal mix of each tire type)	14,400	0.00	10.6	1.28	77.8	6.60	0.10	3.61	0.0

[1] Higher Heating Value (HHV)

The heat content, water content and inorganic content of the bio-solids, paper, cardboard, plastics, rubber, food, and green yard waste is summarized in Appendices 8.1, 8.2 and 8.3

4. EVALUATION CRITERIA FOR THERMOCHEMICAL BIOMASS CONVERSION TECHNOLOGIES

The principle authors of this study have spent several years compiling a database, including technical and business details, for about 400 organizations that have developed thermal technologies for the conversion of biomass into energy, fuels and/or chemicals. These 400 technologies were divided into nine major categories as follows:

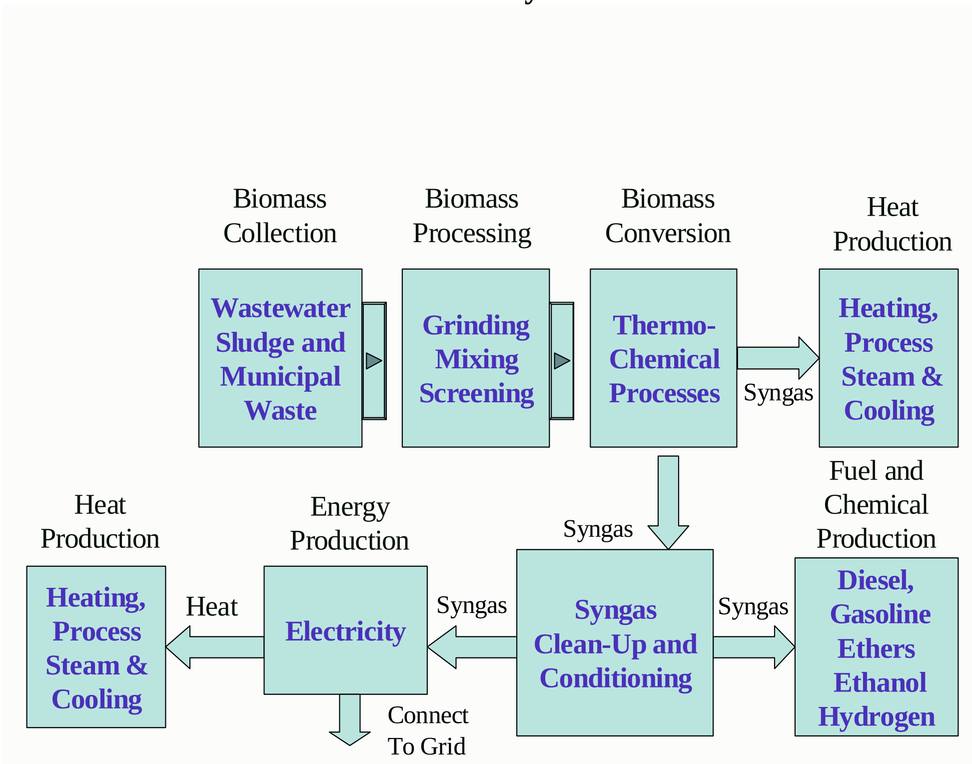
1. Thermal Oxidation (*Combustion at/or near Stochiometry)* (Energy Production)
2. Thermochemical Gasification (*with partial oxygen or air*) (Syngas Production)
3. Thermal Pyrolysis/Steam Reforming *(no oxygen)* (Syngas Production)
4. Integrated Thermal Gasification/Oxidation (Energy Production)
5. Thermochemical Gasification (*no oxygen)* (Syngas Production)
6. Thermal Pyrolysis (*no oxygen)* (Oil Mixtures of Varying Composition)
7. Super High Temperature (3,500-4,000 ^{o}F) Thermochemical Conversion (*with partial oxygen or air)*
8. Thermophilic Anaerobic Digestion (Biogas Production)
9. Thermochemical Gasification/Aerobic Digestion (Ethanol Production)

Thermophilic Anaerobic Digestion (Biogas Production) and Thermochemical Gasification/Aerobic Digestion (Ethanol Production) were not considered in this study for the EBMUD application.

The other seven technology categories were evaluated for possible application to low, medium and high projections of biomass in terms of economic viability (E1), energy efficiency (E2), environmental (E3), an evaluation of the RDD&D stage for which the technology has been validated (E4), and the potential socio-political effectiveness (E5) of the technology.

These seven technologies have key processes that are common to each. These common processes are illustrated in Figure 2.

Figure 2 – Key Processes Evaluated for the Conversion of EBMUD Solid Waste Streams to Electricity and/or Fuels



Each of these technologies was evaluated in terms of their ability to:

- Accept a dewatered and dried sludge (~40 weight % water content)
- Accept sludge mixed with other materials such as shredded paper, plastic, wood, cardboard and rubber

In addition, each candidate system was evaluated using TSS Consultants' "**5E** Assessment Model." This **5E** model was used to rank each technology's ability to effectively convert the EBMUD biomass waste stream. The details of the **5E** assessment criteria are summarized in Sections 4.1-4.6.

4.1 Economic Analysis (E1)

The economics of fuel production ($/MMBTU), energy production ($/KWH) and amortized costs ($/Yr) for each technology was compared. The ranking for E1 varied from 0 to 20, where a rating of 17-20 is a system that produces energy and/or fuels at a cost that is more than 20% below that of current wholesale values (including incentives) at the plant site. We used a wholesale electricity value of $0.060/KWH for the analyses in this paper.

The criteria for the economic ratings are summarized as follows:

17-20: >20% below the wholesale energy value: < $0.048

14-16: 0% to 20% below the wholesale energy value: $0.048-$0.060

11-13: 20% to 0% above the wholesale energy value: $0.060-$0.072

7-10: 20% to 40% above the wholesale energy value: $0.072-$0.084

0-6: >40% above the wholesale energy value: >$0.084

4.2 Energy Analysis (E2)

This assessment compared the energy efficiencies for the production of syngas, electricity, heat, steam, and combined heat and power, depending on the desired energy and/or fuel product that will be produced at the plant site. The most energy efficient system is given a ranking of 10. The criteria for the production of electricity are as follows:

9-10: 30%- 35% thermal energy efficiency

8-9: 25%- 30% thermal energy efficiency

6-7: 20%- 25% thermal energy efficiency

4-5: 15%- 20% thermal energy efficiency

0-3: <15% thermal energy efficiency

4.3 Environmental Assessment (E3)

The environmental assessment was based upon the potential impact of each system with respect to air, water and solid waste emissions. A technology that results in environmental benefits on a total life-cycle assessment (LCA) or systems analysis is provided with a ranking of 9-10. A summary of the environmental assessment ratings is as follows:

9-10: Positive environmental benefits for the organization/region.

7-8: Minimal or no environmental impact is anticipated.

5-6: There will be a modest increase in emissions, which will be within the limits of the current EPA environmental permits.

4-5: There will be a moderate increase in emissions. However this increase will be acceptable to EPA after approval of the incremental environmental permits.

0-3: There will be a significant increase in emissions at levels that are not acceptable to the EPA and local community.

4.4 Evaluation (E4) – RDD&D Assessment

This assessment evaluated progress for the Research, Development, Demonstration and Deployment (RDD&D) stages of each candidate technology. Since each of these steps is very important to the long-term success of the deployed production facility, E4 is given a total value of 20. A summary of the ranking criteria for each of the RDD&D validation stages is as follows:

0-5: **Research** – Laboratory studies have been successfully carried out using bench-scale experiments to validate key chemical and physical principles. Computer models have been used to analyze and validate the technology. These studies have been documented in patents and/or publications in peer-reviewed journals.

0-5: **Development** – All unit and chemical/physical processes have been validated on a 0.5-10 ton/day pilot plant. Processes for the preparation and introduction of the biomass have been perfected. Accurate mass and energy balance measurements for each unit process have been made. The unit processes have been run for a sufficient time period to insure that mass and energy conversion efficiencies have not degraded with time.

0-5: **Demonstration** – The objective of the demonstration plant is to fully establish and develop specifications as necessary for the construction of a full-scale demonstration plant. This demonstration plant should be able to process more that >20-25 tons/day of biomass per year. Its design includes the incorporation of on-line chemical and physical sensors and control systems to run the plant continuously as a totally integrated system for several days. The hardware for recycle loops is included so that recycling process can be fully evaluated.

0-5: **Deployment** – This final stage includes the engineering and design of a commercial scale plant within the expected capital costs. The operating and maintenance costs are within due diligence estimates, as determined after the plant has been running for 329 days/year @24 hrs/day for 1-2 years. The energy and/or fuel production yields are within anticipated specifications.

4.5 Effectiveness (E5)

Effectiveness evaluates selected socio-political factors such as government regulations, organizational objectives, environmental stewardship and stakeholder needs. A summary of the socio-political ratings is:

0-5: The project is favorable to all interested parties such as government regulatory groups, NGO's, and environmental groups, and other relevant organizations.

0-5: The plant will be located at a site that is acceptable to the local community.

4.6 Total Rating (E6)

The total possible score for E6 of 70 is derived from the following: E1 (20 points) + E2 (10 points) + E3 (10 points) + E4 (20 points) + E5 (10 points)

5. EVALUATION OF THE SEVEN CATEGORIES OF THERMO-CHEMICAL BIOMASS CONVERSION TECHNOLOGIES

This section provides technical and business background for each of the seven categories of thermochemical biomass conversion technologies. A competent, candidate supplier was chosen for each of the seven categories. The capability of the conversion technology supplied by each candidate suppliers was evaluated in terms of Economic viability (E1), Energy efficiency (E2), Environmental compatibility (E3), progress in each of the RDD&D Evaluation stages (E4), and its potential socio-political Effectiveness (E5).

5.1 Thermal Oxidation (Combustion at/or Near Stochiometry)

Thermal oxidation is another term for combustion or incineration. Examples of such systems include coal and natural gas fired power plants, waste to energy (WTE) plants, as well as wood-fired stoves and fireplaces.

5.1.1 RDD&D Evaluation (E4)

Currently, there are about 120 WTE plants operating in the U.S (Miller, 2002). Most of these plants combust waste biomass to generate electricity and/or steam. These plants process 30-35 million tons of waste biomass per year resulting in the generation of approximately 2,800 MWH of electricity. The average capital investment for a WTE plant in the U.S. is $3,700/KWH.

Covanta Energy was chosen as the candidate supplier for the thermal oxidation technology (Covanta, 2005). Covanta is the world's leading operator of large-scale WTE facilities with 26 facilities in 16 states and one facility in Italy. Since this is a well-established technology it was given a high rating of 18.

5.1.2 Energy Analysis (E2)

The Covanta Energy systems generate steam with an average energy efficiency of 80% (HHV). If a high-pressure steam turbine is used with an energy efficiency of 21% then the thermal energy conversion efficiency (TECE) for electricity production is 17%. If a CHP system is used then it is possible to achieve a TECE of 34%. However, this option is not typically economically viable. Therefore, the energy analysis was given an economic rating of 3.

5.1.3 Environmental Assessment (E3)

Although a multitude of such systems operate worldwide, they can often produce unacceptable levels of emissions, including dioxins. Therefore, thermal oxidation was given a low environmental rating of 2.

5.1.4 Economic Assessment (E1)

The amortized cost for the candidate system with a maximum biomass input capacity of 225 tons/day was estimated at $5.82 M/Yr.

This system will produce 2.57 x 10^{+7} KWH/Yr of electricity and 1.5 million Therms of usable heat energy from the low biomass projection at a cost of $0.19/KWH if the 1.50 million Therms of energy are used at the EBMUD site. Since this is an unfavorable electrical energy cost, this technology was given an economic rating (E1) of 10.

5.1.5 Effectiveness (E5)

Effectiveness evaluates selected socio-political factors such as government regulations and environmental stewardship. The government regulatory groups, NGO's, environmental groups and other relevant organizations may view such a plant in the Bay Area as highly unfavorable. Therefore, this technology approach was given a low effectiveness rating of 2.

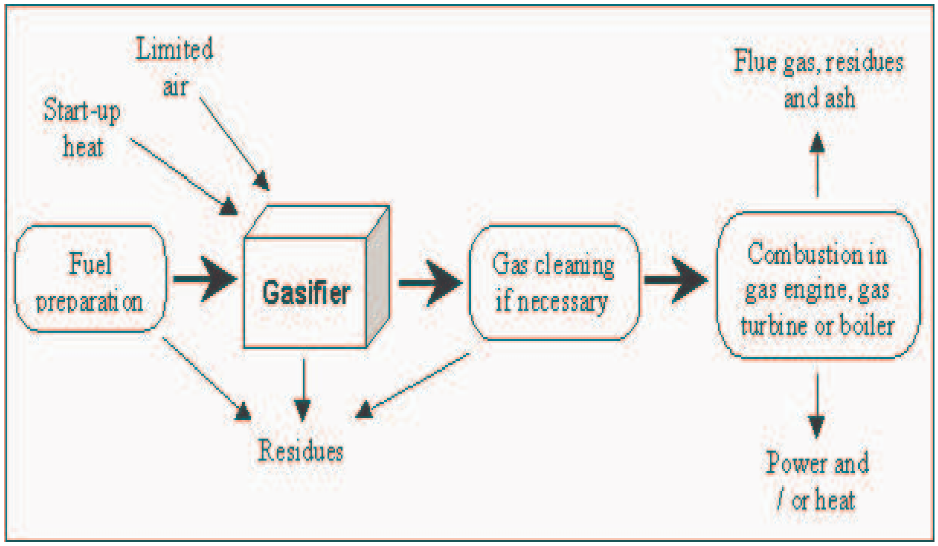
5.1.6 Total Rating (E6)

The total rating for E1-E5 is 30.

5.2 Thermochemical Gasification (With Partial Oxygen or Air)

Thermochemical gasification is a non-combustion process that typically refers to high temperature (typically 1500-2000 ^{o}F) conversion of fossil or renewable biomass (carbon containing) materials under partial oxidation conditions using sub-stoichiometric air or oxygen to produce fuel gases (synthesis gas or syngas). The composition of syngas is primarily CO, H_2, methane, and lighter hydrocarbons in association with CO_2 and N_2, depending on the process used. Syngas may be utilized as a substitute for natural gas in internal combustion engines, gas turbines or boilers to produce power and/or heat. Syngas can also be used to produce fuels (e.g. alcohols, gasoline or diesel) via Fischer-Tropsch (F-T) or other catalytic processes. Hydrogen can be separated from the other syngas components through membrane separation. The process flow diagram for a typical thermal gasification process, using air as a partial oxidant, is included as Figure 3.

Figure 3 – Process Flow Diagram for a Typical Gasification System (With Partial Oxygen or Air)



During the 1700's in Europe, thermochemical gasification processes were widely used to produce a gaseous fuel (town gas) for street lanterns. These "coal gas works" were used all over the World until natural gas became widely available and inexpensive during the 1940's. These plants produced gas whose combustion was so clean that it was used in non-vented household appliances such as cookers and heaters, without adverse effects (Woodgas, 2005)

Small gasifiers were developed to operate vehicles, boats, trains and electric generators during World War I. During World War II, many vehicles were modified to include small biomass gasifiers. Typical modifications included A) a gas generator, B) a gas reservoir and C) carburetor modifications and additional plumbing to transport, filter and meter the syngas into the engine. These gasifiers powered nearly 90% of Swedish vehicles during this period of time. These small gasifiers became un-economical when oil and natural gas became plentiful and inexpensive.

5.2.1 RDD&D Evaluation (E4)

Chevron Texaco, Phillips Conoco (Global Energy) and Shell (Lurgi) have developed this type of biomass to syngas production systems for the production of electricity in the 100-500 MW output range.

The largest facility of this type in the U.S. is the Great Plains Synfuels plant in Beulah, North Dakota (Basin Electric Power Cooperative, 2003). This plant has been operating successfully since 1984 using 170,000 tons/day of coal (fossil biomass). The primary products are natural gas, ammonia, ammonium sulfate, phenol, cresylic acid, naptha and electricity.

The Wabash River Coal Gasification Project was the first full-size commercial gasification-combined cycle plant built in the United States. Located outside West Terre Haute, Indiana, the plant started full operations in November 1995. The plant can generate 292 MW of electricity – 262 MW of which are supplied to the electric grid. This is one of the world's largest single train gasification combined cycle plants operating commercially.

During the past several years many organizations have focused their efforts on the development of small (1-25 MW), economical systems for the conversion of waste materials to energy. Only a few of these organizations have successfully demonstrated their technologies by building and systematically testing full-scale operating systems.

Carbona was chosen as the candidate supplier for the thermochemical gasification (with partial oxygen or air). Carbona has demonstration projects in Denmark, India and Finland (Bain, 2005). Since Carbona has made progress in building plants in several countries and they have carried out a significant level of R&D, especially in cooperation with the Gas Technology Institute, this technology received an E4 rating of 14.

5.2.2 Energy Analysis (E2)

The Carbona system typically generates syngas with energy contents in the range of 180-250 BTU/ft^3 at an average thermal energy conversion efficiency of 66%.

Another 12% of the biomass energy input into the system could be extracted as heat energy from the thermochemical reactor. However, it is usually not economically practical to extract and utilize this heat.

The Thermal Energy Conversion Efficiency (TECE) (%) for electricity generation is 26% and for a combined heat and power system it could be possible to achieve an efficiency of 39%. Therefore this system was given an energy rating of 7.

5.2.3 Environmental Assessment (E3)

Although gasification is a high-temperature process, it is quite different than thermal oxidation or combustion. Thermal oxidation or combustion of biomass may form toxic dioxins and furans when the gas is cooled in the presence of oxygen. Since gasification is a carefully controlled, closed system, there are no emissions of criteria and toxic air pollutants until the syngas is combusted.

The treated syngas is a very clean fuel and as a result it produces very low levels of emissions when combusted in a reciprocating engine/generator or gas turbine. Table 5 gives the emissions of hydrocarbons, nitrogen oxides; particulate matter and carbon monoxide from a thermochemical gasification system with a combined cycle gas turbine.

Table 5a – Emissions of Criteria Air Pollutants from a Thermochemical Gasification System (with partial oxygen) using a Combined Cycle Gas Turbine[1]

Air Pollutants	Emission Level
Nitrogen Oxides	479 g/MWH
Sulfur Oxides	2 g/MWH
Particulate Matter	3.7 g/MWH
Carbon Monoxide	5.1 g/MWH

[1] GE Model MS-6101FA combined cycle gas turbine at 37.2% efficiency (HHV) with syngas.

Except for nitrogen oxides, the emissions from this thermochemical gasification system are well below the 2005 EPA New Source Performance Standards (NSPS) for Power Plants as summarized in Table 5b.

Table 5b – 2005 EPA New Source Performance Standards (NSPS) for Power Plants[1]

Air Pollutants	Emission Level
Nitrogen Oxides	453 g/MWH
Sulfur Oxides	263 g/MWH
Particulate Matter	95 g/MWH
Carbon Monoxide	27 g/MWH

[1] U.S. EPA (2005)

Since this is an air-injected system, the carbon dioxide emissions are higher than that of the thermochemical gasification systems with no oxygen. In addition, the oxygen can cause some partial oxidation of hydrocarbons, which is expected to increase the production of side products, some of which could increase the environmental risk. Therefore, this environmental rating (E3) is 6.

5.2.4 Economic Assessment (E1)

The estimated amortized cost for the Carbona system that has a maximum biomass input capacity of 225 tons/day is estimated at $5.17 M.

This system is expected to produce 5.53 x 10^{+7} KWH/Yr of electricity and 1.00 million Therms of usable heat energy from the low biomass projection at a cost of $0.079/KWH if the 0.90 million Therms of heat energy are used at the EBMUD site. Therefore, the economic rating (E1) for this technology is 8.

5.2.5 Effectiveness (E5)

Although gasification is more popular in Europe, it is expected to become more prominent in the U.S. as waste disposal becomes more costly due to restricted landfill capacities, the associated increase in transportation costs to dispose of waste at alternate sites and higher energy costs. In the year 2000, over 55% of all trash, mainly cardboard boxes, food waste, and newspaper, was still being disposed in landfills in the United States (Miller, 2002). Since this technology is becoming better understood and accepted, it received an E5 rating of 6. This system was not rated as high as the thermochemical processes without oxygen or air, since there are concerns that the presence of oxygen could result in the formation of undesirable environmental pollutants.

5.2.6 Total Rating (E6)

The total rating for this technology is 41.

5.3 Thermal Pyrolysis/Gasification/Steam Reforming (No Air or Oxygen)

In principle, all thermochemical gasification processes include pyrolysis, steam reforming and oxidation. However, the design of the conversion system, biomass particle size, residence time, presence or absence of oxygen, water concentration and temperature all play a critical role in the composition of the products (e.g. syngas) and the thermal energy efficiency for the production of these products.

This Section refers to those systems that operate in the absence of air or oxygen and in which the thermochemical conversion chamber has been designed to convert the biomass to syngas in two steps – pyrolysis followed by steam reforming.

5.3.1 RDD&D Evaluation

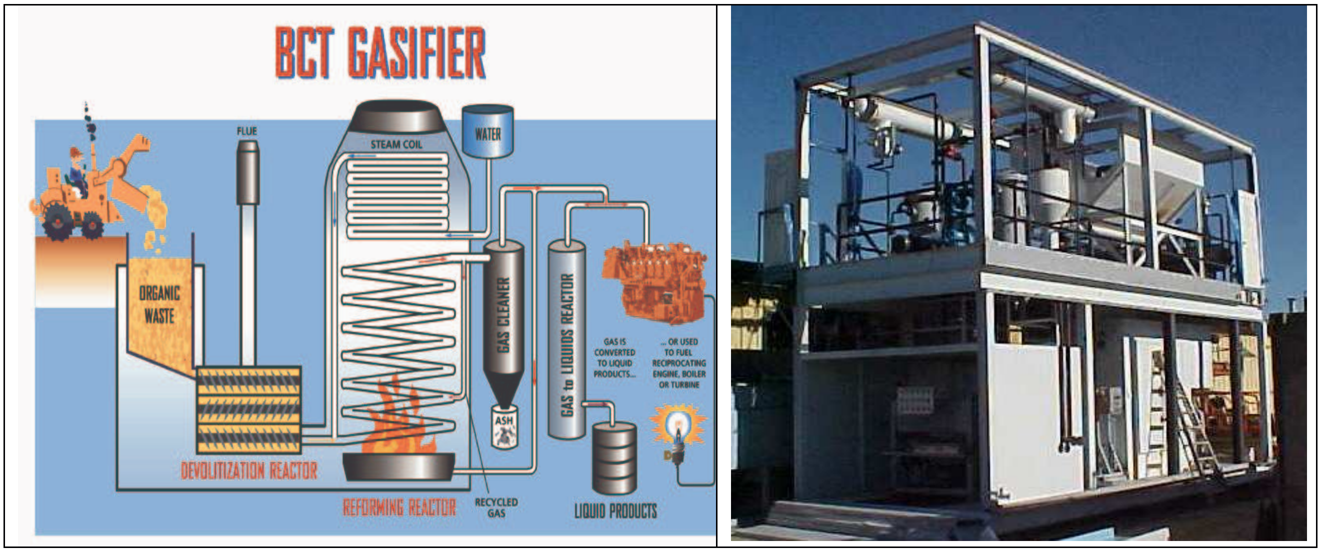
BCT/ACT was chosen as the candidate supplier for the thermal pyrolysis/steam reforming technology. This patented technology has the ability to handle a wide range of biomass solids with moisture content of up to 40%.

Figure 4 is a photograph of the 25 ton/day demonstration system and Figure 5 illustrates the primary unit processes.

The biomass feedstock is ground to 1-2" diameter to increase conversion efficiency. The feedstock is fed into a compressor to remove excess air for optimal conversion of biomass to syngas. During compression of the feedstock, heat is applied to remove any entrained oxygen prior to pyrolysis.

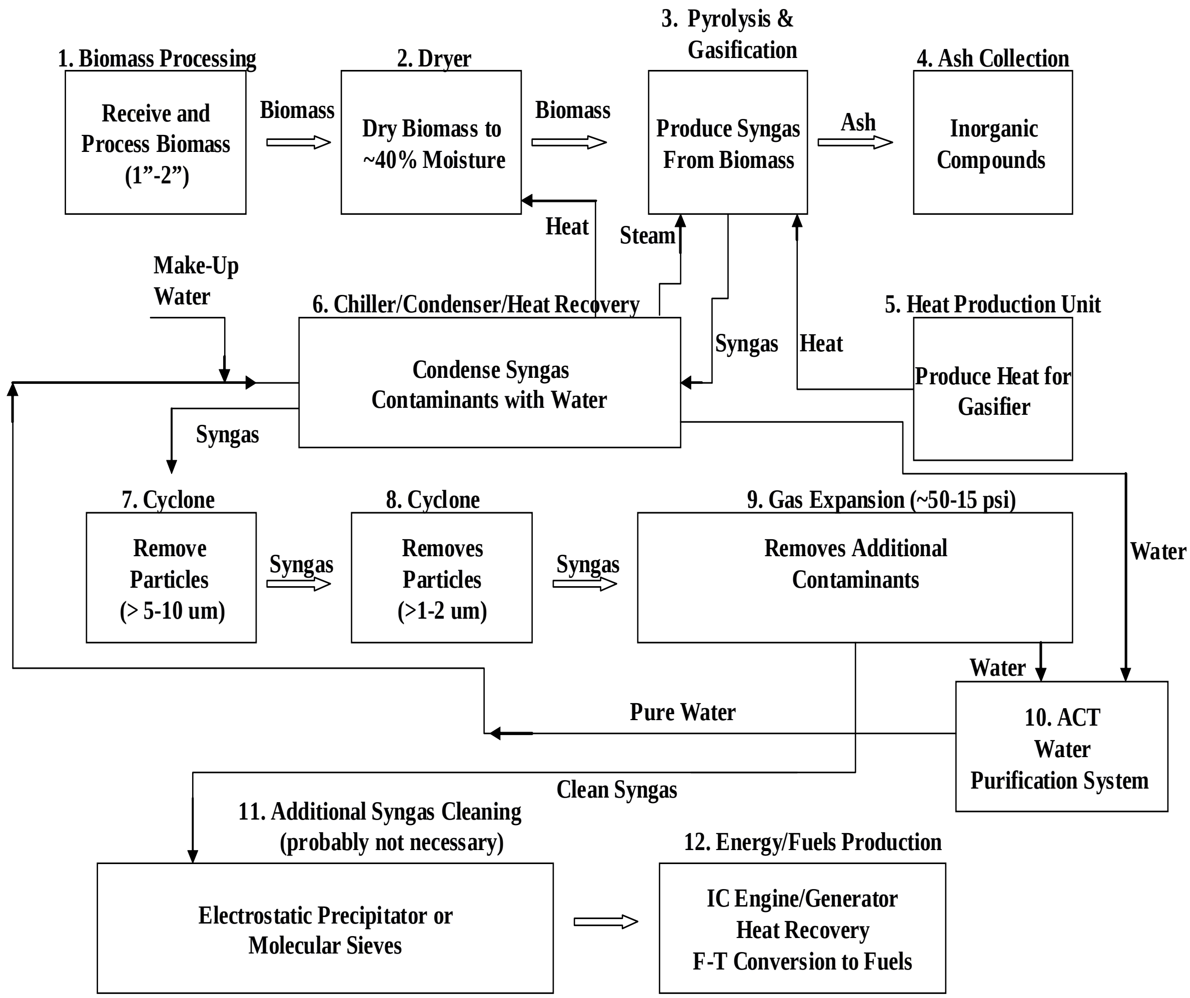
The pyrolysis process is carried out under reducing conditions at about 450^{o} F. A gasification/steam-reforming step (1500-1800° F) is utilized to convert the pyrolysis products (large chain molecule, tar and char) into smaller gas molecules. The high temperature gas is then fast quenched and cleaned to remove contaminants. The high BTU syngas (~500 BTU/SCF) can be used directly in an internal combustion engine, gas turbine, or converted to clean burning diesel fuel, ethanol, or hydrogen. The ash is removed from the system after the pyrolysis step and can be used in a number of inert applications.

Figure 4 – BCT/ACT Processes for Pyrolysis and Gasification/Steam Reforming and Photograph of the 25 Ton/Day Demonstration System



A unique feature of this system is the integrated cyclones and water condenser within the biomass gasification chamber. This design conserves space and reduces the loss of heat energy.

Figure 5 – Process Schematic for the BCT/ACT system



The BCT/ACT group has spent the past ten years carrying out bench-scale experiments to validate key chemical and physical principles. The Advanced System for Process Engineering (ASPEN) model was used to help delineate the thermodynamics of the system. The results from this model compares well with the experimental results. The BCT/ACT group has been granted one patent for their technology.

An 8 ton/day pilot plant has been built and used to generate mass and energy balance measurements for each unit process. The group needs to run the pilot system for a sufficient period of time to insure that mass and energy conversion efficiencies do not degrade with time.

A 25 ton/day demonstration/production plant has been built for Saskatchewan Energy. This system will be shipped to Canada for continuous operation. As a result, the RDD&D Evaluation is given a rating of 8.

5.3.2 Energy Analysis (E2)

The BCT/ACT system typically generates syngas with energy content in the range of 400-600 BTU/ft^3 at an average thermal energy conversion efficiency of 75%. This system has the highest energy efficiency of any system and the highest syngas energy content of any thermochemical biomass conversion system that has been developed for biomass inputs of less than 1,000 tons/day. Therefore, this system is given an energy analyses rating of 9.

Another 10% of the biomass energy input into the system could be extracted as heat energy from the thermochemical reactor. However, it is usually not economically practical to extract and utilize this heat for an external operation.

5.3.3 Environmental Assessment (E3)

The emission of nitrogen oxides, sulfur oxides and particulate matter from the BCT/ACT system syngas is summarized in Table 6. These emissions are below that of the 2005 EPA New Source Performance Standards (NSPS) for Power Plants (EPA, 2005) summarized in Table 5b.

Although BCT/ACT has not measured the emissions from a reciprocating engine/generator using their syngas as a fuel, it is expected that the emissions of these three pollutants should not be greater than those values listed in Table 6.

Table 6 – The Emission Level of Nitrogen Oxides Sulfur Oxides and Particulate Matter in the BCT/ACT Syngas

Air Pollutants	Emission Level
Nitrogen Oxides	150 g/MWH
Sulfur Oxides	5.6 g/MWH
Particulate Matter	3.0 g/MWH

A unique feature of this system is the integrated ACT patented water purification system, which results in a closed-loop, zero emissions system.

In conclusion, the thermal pyrolysis/steam reforming system is expected to be a very environmentally friendly technology and therefore it was given an environmental assessment rating of 8.

5.3.4 Economic Assessment (E1)

The estimated amortized cost for the BCT/ACT system that has a maximum biomass input capacity of 225 tons/day was estimated at $4.07M.

This system is expected to produce 6.64 x 10^{+7} KWH/Yr of electricity and 1.00 million Therms of usable heat energy from the low biomass projection at a cost of $0.048/KWH if the 1.00 million Therms of energy are used at the EBMUD site. Since this is a very favorable electrical energy cost, this technology was given an economic rating (E1) of 17.

5.3.5 Effectiveness (E5)

Government regulatory groups, NGO's, environmental groups and other relevant organizations may view such a plant in the Bay Area as favorable. Therefore, this technology approach received a relatively high effectiveness rating of 8.

5.3.6 Total Rating (E6)

The total rating for this technology is 50.

5.4 Integrated Thermal Gasification/Oxidation

The Integrated Thermal Gasification/Oxidation system is a process that relies on both thermal gasification and oxidation principles for the efficient conversion of biomass to usable energy.

5.4.1 RDD&D Evaluation (E4)

Biomass Energy Concepts (BEC) (Kunkel et al, 2005) was chosen as the candidate supplier for the thermal gasification/oxidation technology.

This patented technology has the ability to handle a wide range of biomass solids with moisture content of up to 40%. The BEC Integrated Thermal Gasification/Oxidation system is based on high temperature gasification of biomass material and subsequent oxidation of the produced gas. The conversion chamber is ceramic lined with an arched roof allowing for all radiated heat to be reflected back onto the biomass pile. The arched roof and air controls promote multi-level biomass conversion.

The first step in biomass conversion is the gasification of biomass to syngas. This is accomplished in the lower reducing, or oxygen deprived, section of the conversion chamber. In this section the temperature ranges from 600-800°F. As the feedstock is reduced and syngas is produced the gas migrates to the upper section of the conversion chamber where oxidizing conditions exist. In the upper section of the chamber, fans introduce oxygen, which allows for the oxidation of the syngas, thus producing thermal energy. As thermal energy develops within the conversion chamber, the ceramic lined wall radiates energy back onto the biomass pile feeding the conversion process. In the upper portion of the chamber the temperature ranges from 2000-2400°F. By combusting the syngas within the conversion chamber, this system takes advantage of higher biomass conversion efficiency and lower equipment costs. Thermal energy is used to produce high value steam, which can be used for electricity generation in a steam turbine as well as lower grade heat for other processes.

BEC has had a demonstration system operating continuously for more than a couple of years in Pennsylvania, a 40 ton/day system is operating at a wood products plant in the Sacramento, CA area, and a waste wood production plant is planned for New Mexico. Therefore, this system was given an E4 rating of 13.

5.4.2 Energy Analysis (E2)

The BEC system has a product thermal energy conversion efficiency of 80% (HHV), which is similar to that of the thermal oxidation systems. The %TECE for production of electricity is also similar (17%). However, this system is ideal for applications in which a large amount of high-grade heat is needed – the combined heat and power TECE for this system is 52%. Therefore, this system was given an E2 rating of 7.

5.4.3 Environmental Assessment (E3)

Traditional thermal oxidation systems rely on the oxidation of biomass to produce relatively small amounts of energy due to low conversion efficiencies. The Integrated Thermal Gasification/Oxidation system has achieved higher conversion efficiencies and lower environmental impacts through optimal biomass conversion engineering and design.

This system doesn't have the problems that often beset a thermal oxidation (combustion) system. The emissions from this system are slightly lower than that of the thermochemical gasification system (with oxygen) but higher than that of the thermochemical gasification system (without oxygen). Therefore, the E3 rating is 7.

5.4.4 Economic Assessment (E1)

The estimated amortized cost for the BEC system that has a maximum biomass input capacity of 225 tons/day was estimated at $3.38 M.

This system is expected to produce 3.76 x 10^{+7} KWH/Yr of electricity and 2.00 million Therms of usable heat energy from the low biomass projection at a cost of $0.054/KWH if the 2.00 million Therms of energy are used at the EBMUD site. Since this is a very favorable electrical energy cost, this technology was given an economic rating (E1) of 15.

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5.4.5 Effectiveness (E5)

Government regulatory groups, NGO's, environmental groups and other relevant organizations may view such a plant in the Bay Area as favorable since a full-scale production plant has been built in the Sacramento area and in Japan. Therefore the E5 rating is 7.

5.4.6 Total Rating (E6)

The total rating for this technology is 49.

5.5 Thermochemical Gasification (No Oxygen)

Several organizations have developed thermochemical gasification systems that operate in the absence of air or oxygen. The oxygen, necessary for the thermochemical reactions, is derived from steam. This process is referred to as steam reforming. The steam is either generated from the water in the biomass or injected into the system if the biomass has less than 15% water content.

The Battelle/FERCO (Mann and Spath, 1997) and Pearson Technologies (Schuetzle et. al, Feb. 2005) are two of the most promising systems of this type. The Pearson Technology was chosen as the candidate system and the details of the 5E assessment criteria are summarized in Sections 5.5.1 to 5.5.6.

5.5.1 RDD&D Evaluation (E4)

Battelle/FERCO and Pearson have carried out research and development on their technologies during the past ten years since the 1980's. DOE, NREL and private sources of funding have supported these R&D efforts.

Schuetzle et al (2005) recently carried out a comprehensive technical and business analysis of the Pearson Technology, which was used to help assess their technology with respect to the 5E assessment criteria.

The biomass, as received, is dried to a moisture content of about 15%, and ground fine enough (~ 3/16") to be fed, along with superheated steam, into a gas-fired primary reformer. The reformer is externally heated so that the product gas is not diluted by nitrogen from the combustion air. Air is also removed from the injected biomass to minimize dilution of the syngas product with nitrogen. The organic material in the feedstock is efficiently gasified (>98% conversion efficiency), leaving only the inorganic materials (ash). The raw syngas then passes through a series of several cleaning steps to remove any ash or tars (e.g. heavy hydrocarbons) that could be detrimental to the reciprocating engine/generator systems and/or which will result in increased emissions.

The overall process uses standard chemical engineering design practices from the chemical industry to maximize recovery of excess heat and generate the required steam, minimizing natural gas consumption. A proprietary design for the gasifier resolves earlier problems with indirect feed heating, and provides the heat of reaction to convert wood (cellulose and lignin) to syngas without having to burn the wood or straw, which dilutes the syngas with nitrogen. These advances, plus pressurized operation, result in smaller gas volumes and much smaller equipment. Even though this results in higher unit costs of high-pressure vessels and piping, the overall effect is lower total equipment costs. Another critical design feature is the use of multiple, redundant gas cleaning operations to protect the downstream systems (e.g. catalysts) in the event of gasifier malfunctions.

Laboratory studies have been successfully carried out using bench-scale experiments to validate key chemical and physical principles. This technology has been granted one international patent.

All unit and chemical/physical processes have been validated on an 8 tons/day pilot plant. Processes for the preparation and introduction of the biomass have been perfected. Accurate mass and energy balance measurements have been made for each unit process. Some of the unit processes have been run for a sufficient time to insure that mass an energy conversion efficiencies have not degraded with time (Schuetzle et. al, Feb.

2005). A demonstration plant has not been built and a production system has not been deployed. Therefore, this system was given an E4 rating of 6.

5.5.2 Energy Analysis (E2)

The Pearson system typically generates syngas with energy content in the range of 300-400 BTU/ft^3 at an average thermal energy conversion efficiency of 70%. Another 10% of the biomass energy input into the system could be extracted as heat energy from the thermochemical reactor. However, it is usually not economically practical to extract and utilize this heat. This is relatively high thermal energy conversion efficiency; therefore the E2 rating is 8.

5.5.3 Environmental Assessment (E3)

This technology is expected to be a very environmentally friendly technology and therefore it was given an environmental assessment rating of 8.

5.5.4 Economic Assessment (E1)

The estimated amortized cost for the Pearson system, that has a maximum biomass input capacity of 225 tons/day, was estimated at $4.44 M/yr.

This system is expected to produce 6.20 x 10^{+7} KWH/Yr of electricity and 1.00 million Therms of usable heat energy from the low biomass projection at a cost of $0.072/KWH if the 1.00 million Therms of energy are used at the EBMUD site. This is a reasonable electrical energy cost, this technology was given an economic rating (E1) of 12.

5.5.5 Effectiveness (E5)

Government regulatory groups, NGO's, environmental groups and other relevant organizations may view such a plant in the Bay Area as favorable. Therefore the potential effectiveness of this technology was rated 8.

5.5.6 Total Rating (E6)

The total rating for this technology is 42.

5.6 Thermal Pyrolysis (No Air or Oxygen)

Thermal pyrolysis involves the decomposition of biomass into char, tars, oil and gaseous hydrocarbons in the absence of ambient air or oxygen at 500-1000 ^{o}F. Several thermal pyrolysis systems have been developed that optimize the production of liquid fuels. Pyrolysis liquids (or pyrolysis oils) can be used in a boiler or undergo further processing to be used as engine fuels, chemicals and other products.

Most pyrolysis systems are very selective in the type of material they can process. Thermal pyrolysis systems work best for the processing of polymeric materials, such as plastic and rubber.

This technology was not rated since electricity and heat is not generated directly from this process.

5.7 Super High Temperature (3,500-4,000 ^{o}F) Thermochemical Conversion (With Air or Oxygen)

Several organizations have developed super high temperature processes for the thermochemical conversion of biomass to energy. TSS has evaluated several variations of this technology and has concluded that the Advanced Multi-Purpose (AMP Process) Converter and Power System Technology represent the best system of this type. The AMP Process is based upon a modified conventional steel blast furnace to efficiently convert mixed waste materials, containing inorganic and organic constituents to syngas (Schuetzle, Oct 2004).

The thermal energy efficiency for syngas production is 82%, which is about 7% higher than the most promising biomass conversion technologies that have been assessed to date.

The AMP Technology can economically and efficiently convert virtually any type of biomass (waste or fossil) at a variety of commercial scales (1,000 tons/day to 20,000 tons/day). Since the waste stream does not have to be dried and scrap metals need not be removed from the waste stream, the amount of pre-processing and sorting of the biomass is greatly reduced. This offers the AMP Technology a significant advantage over competing technologies.

The blended syngas composition is significantly higher in energy value (430 - 480 BTU/cu. ft.) than typically generated by the "best in class" thermochemical biomass conversion technologies (with air or oxygen) evaluated to date (300-400 BTU/cu. ft).

The AMP Converter converts biomass materials at high temperatures (3,500-3,800 ^{o}F) within the enclosed furnace. Some emissions may escape into the atmosphere during the introduction of biomass into the system. However, it is expected that such emissions can be eliminated by engineering improvements in the biomass introduction system.

In addition to syngas, a revenue stream is generated from the secondary products such as processed slag for building materials, and the production of pig iron and non-ferrous metals.

Although this system can be economically viable for the conversion of mixed waste streams at high mass inputs (thousands of tons per day), it was not designed for waste streams at the hundreds of tons per day level and therefore it was not rated.

5.8 Summary of Results

Table 7 summarizes the thermal energy and fuel conversion efficiencies for the seven categories of thermochemical technologies under consideration for EBMUD. The primary products from these thermochemical processes are 1) syngas with a small quantity of heat or 2) heat. Electricity can be produced from the syngas using an IC engine (~40% average efficiency) or a Gas Turbine (~35% average efficiency) or from heat (steam) using a low or high-pressure steam turbine. The high-pressure steam turbine has an average efficiency of ~ 21%.

Table 7 – Thermal Energy and Fuel Conversion Efficiencies for the Seven Categories of Thermochemical Technologies under Consideration for EBMUD

Biomass Conversion Technologies	Product Thermal Energy Conversion Efficiency (TECE) (%)		TECE (%) with IC Engine (40%); Gas Turbine (GT) (35%); Steam Turbine (ST) (21%)		Fuel Conversion (Gallons/Ton Biomass)	
	Products	Heat Output	Electricity	Combined Heat & Power[1]	Ethanol[2]	Diesel[2]
Thermal Oxidation (Incineration)	Heat	80%	17% (ST)	34%	NA	NA
Thermal Gasification (With Oxygen)	66% Syngas	12%	26% (GT)	39%	ND	ND
Thermal Pyrolysis/Steam Reforming (No Oxygen)	75% Syngas	10%	30% (IC)	45%	75	34
Integrated Thermal Gasification/Oxidation	Heat	80%	17% (ST)	52%	NA	NA
Thermal Gasification (No Oxygen)	70% Syngas	12%	28% (IC)	42%	63	31
Thermal Pyrolysis	Oil Mixture	0%	NA	NA	ND	ND
Super-High Temperature Gasification	82% Syngas	5%	29% (ST)	43%	NA	NA

[1] These combined heat and power numbers represent a practical assessment of the heat that can be realistically utilized by a co-located facility.
[2] NA: Not Applicable; ND: Not Determined

Table 8 summarizes the results for the comparative evaluation of each system's Economic viability (E1), Energy efficiency (E2), Environmental friendliness (E3), progress in each of the RDD&D Evaluation stages (E4), and its potential socio-political Effectiveness (E5). The numbers in *Italics* gives the ratings for E1-E5 and E6 is the total ranking. As based upon this analysis, Thermal Pyrolysis/Steam Reforming (no oxygen) (rating: 51) was chosen as a potentially viable technology for this application. The next two technologies, Integrated Thermal Gasification/Oxidation (rating: 48 and Thermochemical Gasification (with oxygen) (rating: 45) may also be suitable for this application. The Integrated Thermal Gasification/Oxidation system may be preferred if heat is a more important energy product than electricity. On the basis of the "E5" analysis, the Thermal Pyrolysis/Steam Reforming technology was chosen as the most promising technology and BCT/ACT (Denver, CO) is a capable, candidate supplier of this technology and therefore it was chosen for the detailed E5 analysis.

Table 8 – Economic, Energy, Environmental, Evaluation and Effectiveness Comparison (E5) of Various Types of Biomass to Energy Technologies – Low Biomass Projection

Biomass to Energy Technologies [1]	(E1) Economic Analyses (Electricity Cost ($/KWH) & Amortized Cost) [2]	(E2) Energy Analyses (Electricity (KWH/yr & Heat (MT/yr))	(E3) Environmental Assessment	(E4) Evaluation (RDD&D [3] Validation)	(E5) Effectiveness	(E6) Total Rating
Thermal Pyrolysis/Steam Reforming (No Oxygen)	$0.048/KWH $4.07 M/yr *(17)*	$6.64 \times 10^{+7}$ KWH/yr & 1.0 MT/yr) *(9)*	*(8)*	*(8)*	*(8)*	*(50)*
Integrated Thermal Gasification/ Oxidation	$0.054/KWH $3.38 M/yr *(15)*	$3.76 \times 10^{+7}$ KWH/yr & 2.0 MT/yr *(7)*	*(7)*	*(13)*	*(7)*	*(49)*
Thermochemical Gasification (No Oxygen	$0.067/KWH $5.05 M/yr *(12)*	$6.20 \times 10^{+7}$ KWH/yr & 1.0 MT/yr *(8)*	*(8)*	*(6)*	*(8)*	*(42)*
Thermochemical Gasification (With Oxygen)	$0.079/KWH $5.17 M/yr *(8)*	$5.53 \times 10^{+7}$ KWH/yr & 0.90 MT/yr *(7)*	*(6)*	*(14)*	*(6)*	*(41)*
Thermal Pyrolysis (No Oxygen)	*Not Applicable*	*Not Applicable*	*(5)*	*(6)*	*(5)*	*Not Applicable*
Thermal Oxidation (Combustion)	$0.174/KWH $5.82 M/yr *(3)*	$2.57 \times 10^{+7}$ KWH/yr & 1.5 MT/yr *(5)*	*(2)*	*(18)*	*(2)*	*(30)*

[1] Numbers in *Italics* represent ratings for E1-E5 – See Section 3.2 for details on rating system criteria
[2] Total Costs = Straight-line deprecation of capital costs (20 years depreciation of capital expenditures) plus annual operating and maintenance costs. The electricity cost calculation assumes that the EBMUD facility will be able to utilize up to 2.0 million Therms of heat energy each year
[3] RDD&D: Research, Development, Demonstration and Deployment Assessment Stages.

6. DESIGN OF A PRODUCTION PLANT

As described in Section 5.8, the BCT/ACT system was chosen as the candidate system for the design of a full-scale production plant. This candidate system was assessed in terms of:

- Biomass Materials Processing
- Biomass Introduction
- Production Plant Design
- Production of Syngas, Electricity and Heat
- Economics
- Emissions
- Probability of Success

6.1 Biomass Materials Processing

The BCT/ACT system requires that the materials input to the system be at least 60% solids content. Some drying of the sludge (to 50-60% water) will be required in addition to mixing in the quantity of dry materials listed in Table 3. There would be more than enough heat from the proposed reciprocating engine/ generator systems (not the current units) to dry the current, medium and high projection levels of sludge.

6.1.1 Drying of Sludge

TSS recommends that an inclined-disc dryer be used for drying the sludge. The inclined-disc dryer effectively dries raw material using indirect heating under a sealed condition. Drying can pass through the adhesion phase to produce a good granulate without requiring any additional equipment. The heat can be transferred from the engines by steam or oil.

Although the use of oil as a heat transfer medium may be more suitable for sewage treatment plants because the low-pressure operation does not require a certified boiler operator, EBMUD operates a high-pressure boiler on site that is used to provide digester heat as a back up to the currently operating IC engines.

The digested bio-solids, dewatered to between 20 and 25% total solids, can be stored in a sludge cake hopper and could be fed into the dryer by a screw conveyor or slurry dosing pump. Obviously, a short distance between silo and dryer is advantageous.

It will require 60-80 KWH of energy per 1,000 kg of water that is removed from the sludge (Table 9)

Table 9 - Sludge Drying System Parameters

Heating media	Heat-transfer oil from 160 to 220°C Steam from 4 to 12 bar
Degree of drying:	Drying to approx. 40-50% solid matter
Thermal input:	Approximately 3,000 kJ/kg evaporated water
Heat recovery:	>90% of the absorbed heat
Dryer power consumption, incl. heat generation and vapor treatment depending upon the process:	60 to 80 KWH/1,000 kg evaporated water

6.1.2 Shredding and Mixing of Selected Municipal Waste Materials

The paper, cardboard' plastic, and rubber should be sized to 1.0"-2.0" to ensure adequate feedstock homogenization using any one of several commercially available grinders. An open trough pub mill can be used to homogenize the feedstock.

6.2 Biomass Introduction

Once the feedstock is well mixed a feed screw conveyor, equipped with variable frequency drive can be utilized to transfer the feedstock to the conversion system.

6.3 Production Plant Design

A full-scale production plant for the low, medium and high projections of EBMUD biomass was designed as based upon the 25 ton/day BCT/ACT demonstration system. This design was used to estimate the capital and O&M costs for the three production plants that could process the low, medium and high biomass projections to produce electricity and heat.

6.4 Production of Syngas, Electricity and Heat

Appendices 8.1 to 8.3 summarize the production of syngas, electricity and heat for the low, medium and high projections of biomass listed in Table 3. The electricity outputs for the low, medium and high biomass projection are

8.41 MW, 13.3 MW and 19.1 MW, respectively. In addition, approximately 1.0, 1.5 and 2.0 MT of heat energy will be generated.

6.5 Economics

Appendix 8.4 summarizes the details for determining the capital and O&M costs for the BCT/ACT Thermal Pyrolysis/ Steam Reforming System at the Low Biomass Production Scenario. The capital and operating and maintenance costs listed in this Table were based upon discussions and e-mail communications from BCT/ACT and other relevant equipment suppliers and construction companies. An additional 10% was added to each quote, resulting in a low and high range for each item. In addition, a contingency of 20% was added to help insure that the total capital and O&M costs represent an upper limit. Once the Engineering and Design phase of this project has been approved by EBMUD, TSS Consultants will obtain firm quotes from each supplier.

These systems were designed to be 25% larger in capacity than required to handle the expected low, medium and high projections as a contingency to accommodate occasional larger quantities of processed biomass than expected.

The low biomass projection system utilizes two 100-130 ton/day conversion systems at a total capital cost of $3.77-$4.15 M; the medium biomass projection system utilizes two 150-200 ton/day conversion systems at a total capital cost of $5.10-$5.61 M; and the high biomass projection system utilizes three 150-200 ton/day conversion systems at a total capital cost of $7.65-$8.42 M.

An additional $775,000 to $852,000 was added as a contingency for the addition of electrostatic precipitators, in case the levels of particulate matter in the Syngas are found to pose a durability problem for the reciprocating engines/generators.

Per the recommendation of Alicia Cohn and John Hake (April 7, 2005 e-mail), TSS used $0.073/KWH for electricity and $0.90/Therm for natural gas. Labor costs were set at $133,000 per full time employee (FTE) and $50,000-$95,000 for temporary employees and skilled tradesman.

Cohn and Hake of EBMUD suggested TSS calculate engineering, construction management and administration at 20% of the equipment and civil capital costs. TSS used 14% for the management, engineering and design, 2% for the system startup and validation, 1% for the training and documentation and 7% for the installation, which is in line with their recommendations.

A preliminary design was developed for the plant and the construction costs were based on the construction of a single story factory to house biomass to energy equipment, sorting and processing equipment, biomass storage, and an office building for staff, as well as necessary roads and parking estimates. The cost of the building and facilities were based on Means Square Foot Costs 2003 (Means 2003). A location factor was used to help estimate the construction costs per square foot for a facility sited in Northern California. TSS estimated that about five acres of land would be required for this facility.

Tables 10, 11 and 12 summarize the electricity and heat (steam) and ethanol outputs (329 days/year @24 hrs/day).

Table 10 - Projected Economic Value of Electricity and Heat – Low Biomass Input Projection (see Table 3)

ECONOMIC CALCULATIONS (E1) - ELECTRICITY PRODUCTION		
Electricity Value	0.073	$/KWH
	4,848,000	$/Year
Heat Value	0.90	$/Therm
(1,000,000 Therms)	900,000	$/Year
ECONOMIC CALCULATIONS (E1) - ETHANOL PRODUCTION		
Ethanol Yield	75	Gallons/Ton Feedstock
	4,528,000	Gallons/Year
Ethanol Value	1.25	$/Gallon
	5,660,000	$/Year

Table 11 - Projected Economic Value of Electricity and Heat – Medium Biomass Input Projection (see Table 3)

ECONOMIC CALCULATIONS (E1) - ELECTRICITY PRODUCTION		
Electricity Value	0.073	$KWH
	7,675,000	$/Year
Heat Value	0.90	$/Therm
(1,500,000 Therms)	1,350,000	$/Year
ECONOMIC CALCULATIONS (E1) - ETHANOL PRODUCTION		
Ethanol Yield	75	Gallons/Ton Feedstock
	7,156,000	Gallons/Year
Ethanol Value	1.25	$/Gallon
	8,944,688	$/Year

Table 12 - Projected Economic Value of Electricity and Heat – High Biomass Input Projection (see Table 3)

ECONOMIC CALCULATIONS (E1) - ELECTRICITY PRODUCTION		
Electricity Value	0.073	$KWH
	10,982,000	$/Year
Heat Value	0.90	$/Therm
(2,000,000 Therms)	1,800,000	$/Year
ECONOMIC CALCULATIONS (E1) - ETHANOL PRODUCTION		
Ethanol Yield	75	Gallons/Ton Feedstock
	10,304,000	Gallons/Year
Ethanol Value	1.25	$/Gallon
	12,880,000	$/Year

Appendices 8.4, 8.5 and 8.6 provide details of the capital and O&M costs for the BCT/ACT Thermal Pyrolysis/ Steam Reforming system at the medium and high biomass production scenarios. These capital and O&M costs and electricity production costs were calculated on the bases of conversion system capacities of 225, 350 and 525 tons/day for the low, medium and high projections, respectively, of processed sludge and selected municipal waste.

Table 13 summarizes the estimated capital cost in millions of dollars ($M), the operating and maintenance (O&M) cost/year ($M/Yr) and the electricity production costs ($/KWH) for the three biomass scenarios.

The cost of producing electricity, without heat use, is 0.062, 0.051 and 0.048 $/KWH for the low, medium and high biomass input projections, respectively and 0.048, 0.039 and 0.036 $/KWH for electricity production and use of 1.00, 1.50 and 2.00 million Therms of heat at the low, medium and high biomass input projections, respectively.

Table 13 - Capital and O&M Costs for the Generation of Electricity and Heat – BCT/ACT System

Biomass[1] (Tons/Day)	Electricity Output (MW)	Heat Output (MT)[2]	Capital Cost ($M)[3]	O&M Cost ($M/Yr)[3]	Electricity w/o Heat Use ($/KWH)	Production w/ Heat Use ($/KWH)
Low (184)	8.41	1.00	16.1-17.7	3.02-3.33	0.062	0.048
Medium (290)	13.3	1.50	23.3-25.6	3.91-4.30	0.051	0.039
High (418)	19.1	2.00	33.8-37.2	5.11-5.62	0.048	0.036

[1] Electricity and heat output based on 184, 290 and 418 tons/day of processed sludge and selected municipal waste
[2] MT = Millions of Therms
[3] Capital and O&M costs based on conversion system capacities: Low: 225 tons/day; Medium: 350 tons/day; High: 525 tons/day

6.6 Environmental Assessment

The principal environmental concerns at the EBMUD facility, in regards to the recommendations in this report, center about the potential increase in air emissions that may significantly affect the facility air permit and permitting requirements. This section of the report focuses on the air emissions current conditions and future conditions under a selected scenario.

EBMUD currently operates under a Title V Major Facility air permit (A0591) issued by the Bay Area Air Quality Management District (BAAQMD). This permit contains all applicable federally or non-federally enforceable air quality requirements related to the facility. It is considered a major facility because it has the “potential to emit” (per BAAQMD Regulation 2-6-212) more than 100 tons per year of a regulated air pollutant. The air pollutants are various species of nitrogen oxides (NOx) and carbon monoxide.

The NOx and CO is emitted exclusively from the three internal combustion engines and one hot water boiler, which currently use digester gas (primarily) to produce process heat for the facility and electricity for the facility and sometimes the electrical grid. Source testing is required on the three internal combustion engines for NOx and CO (plus particulates, organic reactive gases, and SO2). In 2004, source testing revealed for NOx and CO the following:

The individual engines met their permitted emission limits for NOx (140 ppm @ 15% O2) and CO (2000 ppm @ 15% O2) by a considerable degree. This is accomplished in large part by the 1995 modification of the engines. Cooper Industries Clean-Burn Heads were added to the engines to meet (or exceed) the permit conditions.

Nonetheless, the facility emissions of NOx have been projected to exceed 50 tons per year (TPY) in the BAAQMD’s Permit Evaluation and Statement of Basis for the ongoing Title V permit renewal. Above the 50 TPY emission offsets were required at a ratio of 1.15 to 1. Such offsets can be costly ($25,000-plus per ton of pollutant). However, under BAAMQD’s Small Facility Banking Account, the facility was able to get the necessary emission offset credit for free. This is reported to have saved in excess of $1M.

The candidate gasification system proposed in Section 5.3 will utilize biomass as described to produce a syngas which in turn will be combusted most likely in large internal combustion engines, both those currently on site and by the addition of new (and state of the art) internal combustion engines. Under this environmental analysis, it can be assumed that the gasification system will not generate any air emissions that would not be passed through the internal combustion engines, so any contribution by the gasification system itself is nil.

Under the low megawatt/heat cogeneration scenario in Table 10, the facility could install four 2.5 Megawatt state of art internal combustion engines. GE-Jenbacher, Deutz Corporation, and others that manufacture large internal combustion engines and accompanying electric generators and heat recovery systems produce such engines. These new engines, without any add-on emission controls can easily meet the facility’s Title V permit. However, with the need for Best Available Control Technology (BACT), the use of Selective Catalytic Reduction (SCR) systems on the individual engines can significantly reduce the NOx emissions for the engines. Reductions up to 90% (and higher) have been routinely achieved with SCR emission control systems on a large internal combustion engine. An SCR system would cost in range of $180 to $200K (or the equivalent of the cost of buying 7 to 8 tons of NOx emission offsets).

Using a GE-Jenbacher 2.5 MW engine as an example, coupled with an SCR emissions control unit, the NOx emissions for one year (assuming 8000 operating hours) could be reduced to less than 2 TPY. Thus the total NOx for the four units would be under 8 TPY. Further, assuming that the three existing engines are retrofitted with SCR the total NOx for seven engines could be well under 50 TPY. Thus, the facility has the potential to become a provider of emission credits, which could be sold to recoup the costs of the SCR retrofits on the existing three engines.

The addition of four internal combustion engines using syngas from an onsite gasification system, coupled with SCR emission control systems appear to be able to be permitted at the site. If SCR systems are not retrofitted on the existing three engines then emission offsets may have to be purchased. To avoid this expense it is recommended that the three existing engines be retrofitted with SCR systems to significantly reduce the NOx emissions from these engines. It is recommended that a cost analysis for various scenarios be carried out, with and without SCR, and with and without retrofit catalyst in Phase II of this project.

Appendices 8.1, 8.2 and 8.3 give the ash production at 44 tons/day, 72.5 tons/day and 108.6 tons/day for the low, medium and high biomass input projections. This ash will be comprised of 99+ % inorganic material and its composition will be similar to that of the inorganic materials in the input biomass.

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