Gasification of Sludge and Biosolids – A Review of Technology Fundamentals and the Current Commercial Status

October 24 | 2012
Agenda

- Background
- Process Fundamentals
- Types of Gasifiers
- Commercial Status
- Energy Balances
- Gasification Relative to Today’s Issues
- Summary
Background – History of Gasification

• Charcoal formation (pyrolysis)
  • Several thousand years old

• Gasification
  • Large scale use on coal in the 1800’s; wood in 1900’s
  • New focus → alternative feedstocks

Process Fundamentals

General Steps
1. Drying
2. Pyrolysis (volatilization)
3. Combustion (oxidation)
4. Gasification (reduction)

Main Types of Gasifiers
• Fixed bed
• Fluidized bed

Heat → Carbon Feedstock → Pyrolysis Reactions

Tars
$H_2$
$CH_4$

Char
Reaction Pathways

**Combustion (Oxidation) Reactions**

\[
C + \frac{1}{2}O_2 \rightarrow CO \\
\Delta H = -111 \text{ MJ/kmol}
\]

\[
CO + \frac{1}{2}O_2 \rightarrow CO_2 \\
\Delta H = -283 \text{ MJ/kmol}
\]

\[
H_2 + \frac{1}{2}O_2 \rightarrow H_2O \\
\Delta H = -242 \text{ MJ/kmol}
\]

**Gasification (Reduction) Reactions**

\[
C + CO_2 \leftrightarrow 2CO \\
\Delta H = +172 \text{ MJ/kmol}
\]

\[
C + H_2O \leftrightarrow CO + H_2 \\
\Delta H = +131 \text{ MJ/kmol}
\]

\[
C + 2H_2 \leftrightarrow CH_4 \\
\Delta H = -75 \text{ MJ/kmol}
\]

\[
CO + H_2O \leftrightarrow CO_2 + H_2 \\
\Delta H = -41 \text{ MJ/kmol}
\]

\[
CH_4 + H_2O \leftrightarrow CO + 3H_2 \\
\Delta H = +206 \text{ MJ/kmol}
\]
Heating Methods

Feedstock Combustion:

Char + Limited O$_2$ $\rightarrow$ CO$_2$ + CO + H$_2$O + Heat

External Heat Sources:

Induction Heater (Pyromex)  
Plasma Torch (Westinghouse)
Technologies – Fixed Bed Gasifiers

**Updraft Gasifier**
- Feed: 45-50% DS possible

**Downdraft Gasifier**
- Feed: >80% DS

http://www.uaex.edu/Other_Areas/publications/publications_list.asp
Technologies – Fluidized Bed Gasifiers

**Bubbling Fluidized Bed**
- Feed: >85% DS

**Circulating Fluidized Bed**
- Feed: >85% DS

http://www.uaex.edu/Other_Areas/publications/publications_list.asp

Feedstock Properties

- Prefer undigested sludge
- Higher volatile content and less ash preferred

Proximate Analysis of Various Biosolids Feedstocks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>“Typical” Undigested Sludge ¹</th>
<th>“Typical” Digested Sludge ¹</th>
<th>“Fresh Solids” ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash, %</td>
<td>25-30</td>
<td>40-50</td>
<td>5.5-8.5</td>
</tr>
<tr>
<td>Volatile, %</td>
<td>65-70</td>
<td>40-50</td>
<td>86.3</td>
</tr>
<tr>
<td>Fixed C, %</td>
<td>5-10</td>
<td>5-10</td>
<td>7.9</td>
</tr>
<tr>
<td>HHV, Btu/lb</td>
<td>6,500-8,500</td>
<td>3,000-5,500</td>
<td>7,500-8,000</td>
</tr>
</tbody>
</table>

Sources: 1. Stamford Waste to Energy Draft Report; 2. Gikas et al., 2011
Syngas Properties

- Low energy content
  - 100-130 Btu/ft$^3$ typical (air-blown)
  - Biogas $\sim$550 Btu/ft$^3$
  - Natural gas $\sim$950 Btu/ft$^3$
- Primarily CO and $H_2$
- Usually highly diluted with $N_2$
- Syngas conditioning required for use in a gas engine
- Thermal oxidation of syngas avoids gas cleaning

**Example Syngas Composition (v/v)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>9%</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>14%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>20%</td>
</tr>
<tr>
<td>Methane</td>
<td>7%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>50%</td>
</tr>
</tbody>
</table>
## Gasification vs. Incineration

<table>
<thead>
<tr>
<th>Gasification</th>
<th>Incineration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying required as pretreatment step</td>
<td>Drying not required as pretreatment step</td>
</tr>
<tr>
<td>Designed to maximize feedstock conversion to CO and H$_2$</td>
<td>Designed to maximize feedstock conversion to CO$_2$ and H$_2$O</td>
</tr>
<tr>
<td>Reducing environment</td>
<td>Highly oxidizing environment</td>
</tr>
<tr>
<td>Limited oxygen</td>
<td>Excess air</td>
</tr>
</tbody>
</table>
Biosolids Gasification Configurations

Two Stage Gasification
- Syngas cleaning
- Internal combustion engine
- Produce electricity and recoverable heat

Close-Coupled Gasification
- No syngas cleaning
- Syngas thermally oxidized
- Heat recovery and/or power generation from flue gas

Dewatering → Wet Sludge

Main Energy Sink

Energy for Drying

Excess Energy

Drying → Gasification → Syngas Utilization
**Close-Coupled Gasification**

1. Dried Sludge
2. Limited O\(_2\) or External Heat
3. Gasification
4. Syngas
5. Excess O\(_2\)
6. Process Heat
7. Thermal Oxidation
8. Flue Gas Treatment
9. Stack

**Two Stage Gasification**

1. Dried Sludge
2. Internal Combustion Engine
3. Syngas Cleaning
4. Syngas
5. Internal Combustion Engine
6. Process Heat
7. Electricity
8. Stack
### Commercial Status

- Biosolids gasification still in embryonic stages

#### Pilot-scale and demonstration facilities:
- M2R/Pyromex – Emmerich, Germany (trials in 2010)
- Nexterra – Kamloops, BC (trials in 2009)
- Primenergy – Tulsa, Oklahoma (trials in 2008)
- Stamford Biogas – Stamford, CT (2008)

#### Full-scale installations:
- Kopf – Balingen, Germany (2002-present)
- Kopf – Mannheim, Germany (in commissioning phase)
- MaxWest – Sanford, FL (September 2009-present)
- Tokyo Bureau of Sewerage – Kiyose, Japan (July 2010-present)
Kopf Full-Scale Installations

- Capacity:
  - Balingen: 5.4 tpd
  - Mannheim: 13.7 tpd

Photos courtesy of Kopf
Process Diagram for Kopf Gasification Plant
MaxWest Full-Scale Installation

- Capacity: 80 tpd (wet)
- Owned and operated by MaxWest
- Dryer requires some supplemental natural gas

Photos Courtesy of MaxWest
Photos and Schematics of MaxWest System

Fluidized Bed Gasifier (Gen #2 Unit)

Cyclone

Thermal Oxidizer

Courtesy of MaxWest
Sanford Facility Process Flow Diagram

Courtesy of MaxWest
Staffing Requirements

- Sanford facility staffing requirements
  - 6 full-time operators
  - Plant manager and administrator
  - Owned and operated by MaxWest

- Now offering gasification equipment as capital sale

- Typical installed cost in the range of $7-10M
M2R/Pyromex Demonstration Unit

- 1 tpd demonstration unit
- Solids from raw wastewater screening (after headworks screens)
  - “Fresh solids” from 200-350 µm fabric screen filter
- “Ultra-high temperature gasification”
  - ~1150°C
  - No oxygen

Gikas et al., 2011
Syngas from “Fresh Solids”

- Trials with solids from Adelanto, CA WWTP
- January and June of 2010
- Syngas properties
  - CO = 31.5%
  - H₂ = 49.2%
  - CH₄ = 7.73%
  - CO₂ = 3.20%
  - 8.83% “unidentified gases”

Gikas et al., 2011
Stamford, CT Waste to Energy Project

- High electricity costs
  - $0.18/kwh
  - City identified need for up to 15 MW additional power

- Proposed gasification system to generate electricity
  - 25 tpd (dry) facility
  - Produce 1-3 MW of electricity from syngas

- 2007 - Thermal drying facility constructed

- Pilot gasification facility
  - Trailer mounted fixed-bed updraft gasifier (0.53 tpd)

- 2008 to 2009 - Full-scale trials with three vendors
  - Primenergy, Nexterra, Kopf
Stamford Pilot Gasifier

- Gasification pilot donated to UCONN for research in March 2012...
The public balked at the project's $40 million price tag, and the WPCA board voted to kill the venture in early 2010 after losing faith in its technical and economic feasibility.

Read more:
Energy Balance Considerations

- Net Energy = Energy Outputs – Energy Inputs

- Main energy outputs
  - Electric power
  - Heat

- Main energy inputs (parasitic loads)
  - Dryer
  - Blowers
  - Gasifier startup
  - Gasifier external energy needs
    - Induction heater, plasma torch, etc.
  - Syngas cleanup
Power Generation Options

- Fuel cells – not currently used with syngas
- Gas turbines – require minimum heating value of 450 Btu/ft$^3$ and pressurization of syngas
- Internal combustion engines – possible
  - Requires minimum heating value of ~140 Btu/ft$^3$
  - Still may need to blend with natural gas
Energy Required for Drying

- **Thermodynamics**
  - Typically 1,400-1,700 Btu/lb of water evaporated

- **Heat sources:**
  - Natural gas, methane, propane, electric power
  - Recovered heat, waste heat
  - Solar

For a 25 dtpd drying facility:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Energy Required (MMBtu/hr)</th>
<th>Natural Gas Cost ($/yr)</th>
<th>Power Cost ($/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15% Solids Feed</td>
<td>17.4</td>
<td>$1,181,000</td>
<td>$2,006,000</td>
</tr>
<tr>
<td>20% Solids Feed</td>
<td>12.2</td>
<td>$827,000</td>
<td>$1,404,000</td>
</tr>
<tr>
<td>25% Solids Feed</td>
<td>9.0</td>
<td>$614,000</td>
<td>$1,043,000</td>
</tr>
</tbody>
</table>

25 dtpd gasification + thermal oxidation system could yield approx. 8-10 MMBtu/hr

Assumes 1,500 Btu/lb water evaporated, 90% dry solids product, natural gas = 1,030 Btu/cf, natural gas =$8/1000-cf, power = $0.045/kWh
Energy Balances Presented in Literature

- 5 tpd two-stage gasification system (~4-6 mgd WWTP)
- Energy balances NOT from actual full-scale operation

<table>
<thead>
<tr>
<th>Air-Blown Gasifier ¹</th>
<th>M2R/Pyromex Gasifier ²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net output</strong> = 165 kW</td>
<td><strong>Net output</strong> = 295 kW</td>
</tr>
<tr>
<td><strong>Assumptions:</strong></td>
<td><strong>Assumptions:</strong></td>
</tr>
<tr>
<td>• Syngas HHV = 190 Btu/ft³</td>
<td>• Syngas HHV = 338 Btu/ft³</td>
</tr>
<tr>
<td>• System parasitic load = 75 kW</td>
<td>• System parasitic load = 116 kW</td>
</tr>
<tr>
<td>• Biosolids dried to 90% solids</td>
<td>• Biosolids dried to 78% solids</td>
</tr>
</tbody>
</table>

- M2R also presented energy balances in recent paper for a hypothetical 20 mgd WWTP (Noll, 2012)
- Claimed net electrical energy output of nearly 2:1 vs. anaerobic digestion

Energy Balances Presented in Literature

• From Stamford Waste to Energy project report:
  • Biosolids feed rate = 3,695 lb/hr
  • Syngas production rate = 2,595 scfm
  • Syngas LHV = 117 Btu/scf
  • Quantity of syngas = 84,287 scf/ton-biosolids
  • Cold gas efficiency = 69.4%
  • Gross electric power production = 1,869 kW
  • Net electric power production = 1,623 kW

• Proposed facility footprint of 140’x100’

• Project killed due to cost and technical feasibility
Energy Balances from Operating Facilities

- Kopf – Balingen plant
  - Digested sludge
  - Equivalent to approx. 7.2 mgd
  - Original plant used solar drying
    - Produced ~70 kW of electric power
      - 15 kW needed for parasitic loads
      - ~55 kW net
    - Produced ~140 kW of thermal energy
      - Used to heat digesters at the WWTP
    - Rebuilt in 2006 – added belt dryer
      - Most of the gas now used for heating the belt dryer

Courtesy of Kopf
Energy Balances from Operating Facilities

• MaxWest facility in Sanford, FL

• Main goal is an energy-neutral system
  • Current input to dryer is 16% solids
  • Needs to be dried to 90% solids
  • Current system requires natural gas supplement for dryer

• According to MaxWest, achieving energy-neutral requires:
  • 23-25% solids feed depending on ratio of primary/secondary sludge
Economics of Two-Stage Sludge Gasification

- Economics largely dependent on electricity cost
- Renewable energy tariff

<table>
<thead>
<tr>
<th>Case</th>
<th>National Average Wholesale Electricity Rate</th>
<th>New England Average Industrial Electricity Rate + RE Tariff ($0.0435/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Cost, $/kWh</td>
<td>$0.042</td>
<td>$0.093</td>
</tr>
<tr>
<td>Tipping Fee, $/DT</td>
<td>$70</td>
<td>$70</td>
</tr>
<tr>
<td>Annual Operating Revenue, $</td>
<td>$41,624</td>
<td>$61,742</td>
</tr>
<tr>
<td>Annual Operating Cost, $</td>
<td>($36,995)</td>
<td>($41,551)</td>
</tr>
<tr>
<td>Capital Costs, $</td>
<td>($269,815)</td>
<td>($269,815)</td>
</tr>
<tr>
<td>CAPEX per kW, $/kW</td>
<td>$4,652</td>
<td>$4,652</td>
</tr>
<tr>
<td>Payback Years</td>
<td>21</td>
<td>7</td>
</tr>
</tbody>
</table>

Costs presented in USD per dry ton per day operating capacity; source: US EPA, 2012
Air Emissions Regulatory Requirements

• Currently no specific EPA regulations
  • Case by case basis
  • May be classified as incinerators

• Criteria air pollutants
  • Sulfur oxides (SOx)
  • Carbon monoxide (CO)
  • Nitrogen oxides (NOx)
  • Particulate Matter (PM)

• Hazardous air pollutants
  • Hydrogen chloride (HCl)
  • Dioxins and furans (chlorinated organics)
## Air Emissions Data

### Emission Limits in 40 CFR Part 60 – Final Rule for SSIs

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Units</th>
<th>Existing FB SSIs</th>
<th>New FB SSIs</th>
<th>MaxWest Gen #1</th>
<th>MaxWest Gen #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium (Cd)</td>
<td>mg/dscm</td>
<td>0.0016</td>
<td>0.0011</td>
<td>0.0000723</td>
<td>-</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>ppmvd</td>
<td>64</td>
<td>27</td>
<td>7.87</td>
<td>16.1</td>
</tr>
<tr>
<td>Hydrogen Chloride (HCl)</td>
<td>ppmvd</td>
<td>0.51</td>
<td>0.24</td>
<td>1.8</td>
<td>0.321</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>mg/dscm</td>
<td>0.037</td>
<td>0.0010</td>
<td>0.00798</td>
<td>-</td>
</tr>
<tr>
<td>Oxides of Nitrogen (NO\textsubscript{x})</td>
<td>ppmvd</td>
<td>150</td>
<td>30</td>
<td>432.17</td>
<td>15.4</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>mg/dscm</td>
<td>0.0074</td>
<td>0.00062</td>
<td>0.000819</td>
<td>-</td>
</tr>
<tr>
<td>Dioxins/Furans</td>
<td>ng/dscm</td>
<td>0.10</td>
<td>0.0044</td>
<td>0.0285</td>
<td>-</td>
</tr>
<tr>
<td>Particulate Matter (PM)</td>
<td>mg/dscm</td>
<td>18</td>
<td>9.6</td>
<td>9.6</td>
<td>8.23</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO\textsubscript{2})</td>
<td>ppmvd</td>
<td>15</td>
<td>5.3</td>
<td>4.17</td>
<td>0.0</td>
</tr>
</tbody>
</table>

2. Source: data provided by MaxWest
Gasification Relative to Today’s Issues

**Energy**
- Potential for energy generation (depends on syngas quality)
- Drying required as a pretreatment step
- Heat recovery mostly used for drying

**Emissions**
- Reduced relative to incineration
- Lower air requirements
- Reducing environment

**Regrowth/Reactivation**
- Pathogens destroyed
- No biosolids to dispose of

**Resource Recovery**
- POTENTIAL P recovery from ash
- No N recovery

**Process Reliability**
- Four full-scale installations worldwide
- One full-scale installation in North America
Be Aware of the Process Cycle History…

Development / No. Installed

Time

First Pilot

First Demo

First Applications

First Applications

Third Generation, Mature Technology

Second Generation

Anaerobic Digestion

Incineration

Biosolids Drying

Thermal Hydrolysis

Biosolids Gasification

SCWO

Biological Solids Gasification

Biosolids Drying
Questions?

Thank You!


