Combined Heat & Power Cycle Fueled By Digester Gas

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New Thinking

University of Wyoming

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Project Background

- Waste Water Treatment
- Anaerobic Digestion
- ~200 cfm digester gas production
- Majority is flared

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Project Background: Sludge

- Heating required
- Digester gas and purchased natural gas
- 460 kW in winter months
- $7,000 NG bill December 2012

Project Overview

Project Objective: Utilize digester gas to provide the most value to the WWTP.

Approach: Because of the high value of electricity, it is desirable to produce as much electricity as possible while simultaneously using waste heat where applicable.

Project Overview

- Power Cycles Considered
  - Sterling Engine
  - Piston Cylinder Engine
  - Rankine Cycle
  - Gas Turbine Engine

- Environment Aspect
  - Utilizing a currently flared source of energy
  - Localized power generation leads to CO_2 offset

Thermodynamic Modeling

Digester Gas Potential

$$200\ cfm \rightarrow\ 223\,\frac{lb_m}{hr}$$

$$\dot{Q}_{av} = \dot{m}_{CH_4} * LHV$$

$$\dot{Q}_{av} = 223\,\frac{lbm}{hr} * 21520\,\frac{Btu}{lbm} = \mathbf{4.8 * 10^6\,\frac{Btu}{hr}}\ \ (\mathbf{1400\ kW})$$

Gas Turbine Engine

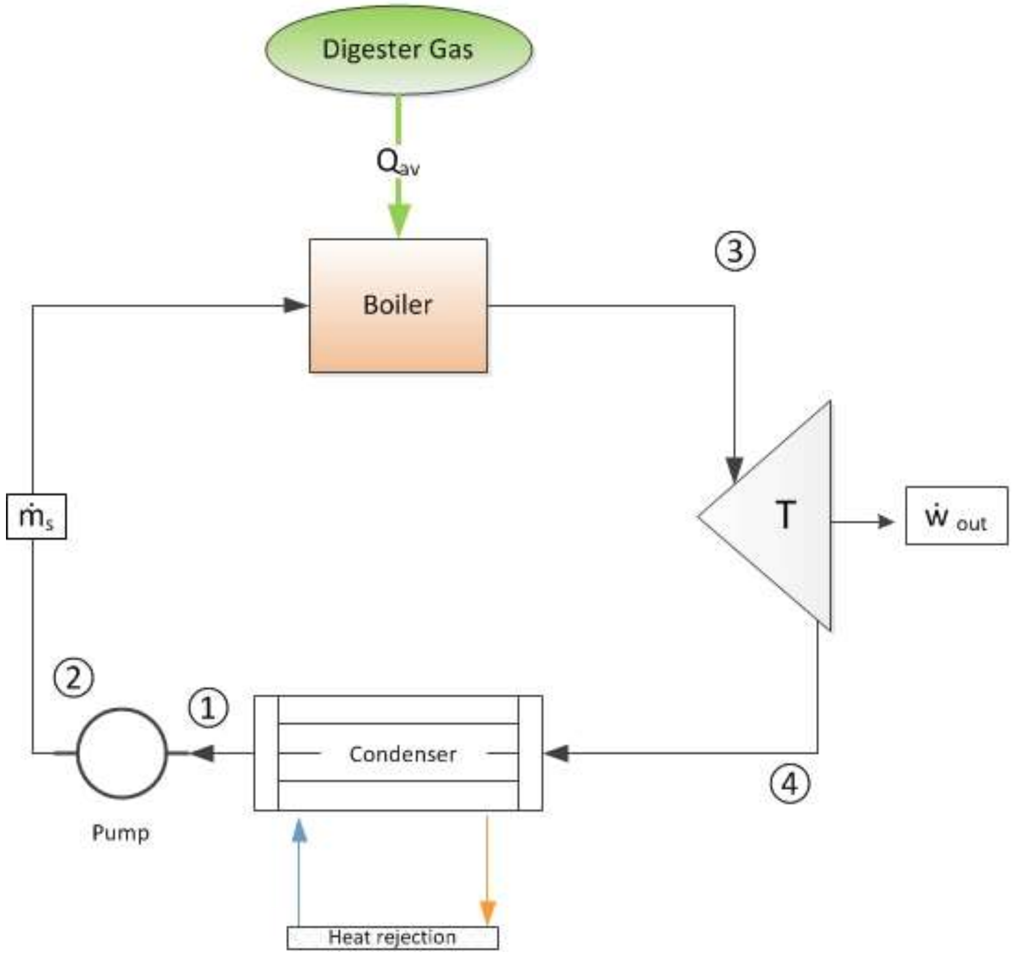
- 400 kW_e, 29% Efficiency
- Waste Heat Recovery is feasible
- Provides all necessary sludge heating

Rankine Cycle

- 210 kW_e, 15 % Efficiency
- Waste Heat Recovery is not feasible
- Requires supplemental purchased natural gas

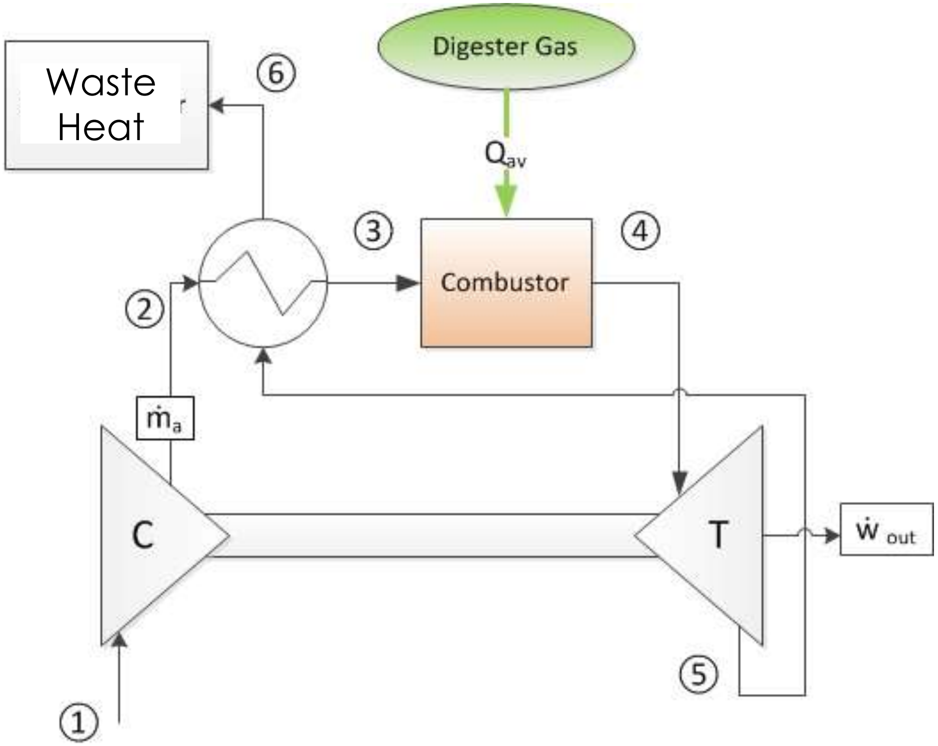
Thermodynamic Modeling: Rankine Cycle

- **Input Parameters**
  - Q_{av} = 4.8x10^6 Btu/hr
  - P_2= 900 psia
  - T_3 = 1000 °F
  - P_4 = 2 psia
- **Assumptions**
  - 10% pressure drop across boiler
  - 75% Pump efficiency
  - 80% Turbine efficiency
  - 93% Generator efficiency
- **Results**
  - Net Power = 210 kW_e
  - Cycle efficiency = 15%



Thermodynamic Modeling: Gas Turbine Engine

- **Input Parameters**
  - $Q_{av} = 4.8 \times 10^6$ Btu/hr
  - T_1 P_1 = atmosphere
  - T_4 = 2000 °F
  - Pressure Ratio = 5.8 (Optimized)
- **Assumptions**
  - 4% pressure drop
  - 80% Compressor efficiency
  - 85% Turbine efficiency
  - 80% Regenerator effectiveness
  - 93% Generator efficiency
- **Results**
  - Net Power = 400 kW_e
  - Cycle efficiency = 29%



Economic Modeling: Assumptions

- No cost for digester gas entering power cycle
- Sludge Heating Requirement: 460 kW
- Capital cost for sludge heater of $120,000 (GTE only)
- Value of electricity is 8.3 ¢/kWhr (eia.gov)
- Value of methane is 1.3 ¢/kWhr (eia.gov)

Economic Modeling: Assumptions

- 1% annual increase in the value of electricity (eia.gov)
- No annual increase in the value of methane (eia.gov)
- 3.25% annually compounding interest rate on capital costs (Wall Street Journal)
- Cycle Lifetime: 240 months
- Gas turbine requires overhaul at 120 months

Economic Modeling: Parameters

Rankine

- Installed Cost: $1{,}200 \frac{\$}{kW} * 210\ kW_e = \$\ 252{,}000$
- O&M cost: $0.004 \frac{\$}{kWhr} * 210\ kW_e\ * \frac{24*365}{12} \frac{hr}{month} = 615\ \frac{\$}{month}$
- Sludge Heating cost: $0.013 \frac{\$}{kWhr} * 460\ kW\ * \frac{24*365}{12} \frac{hr}{month} = 4{,}400 \frac{\$}{month}$
- Electricity Value: $0.083 \frac{\$}{kWhr} * 210\ kW_e * \frac{24*365}{12} \frac{hr}{month} = 12{,}700 \frac{\$}{month}$

Gas Turbine Engine

- Installed Cost: $2{,}000 \frac{\$}{kW} * 400\ kW_e + \$120{,}000 = \$\ 920{,}000$
- O&M cost: $0.010 \frac{\$}{kWhr} * 400\ kW_e\ * \frac{24*365}{12} \frac{hr}{month} = 2{,}900\ \frac{\$}{month}$
- Electricity Value: $0.083 \frac{\$}{kWhr} * 400\ kW_e * \frac{24*365}{12} \frac{hr}{month} = 24{,}000 \frac{\$}{month}$

References: (EPA.gov; Giampaolo, Tony, 2009; Pipattanasomporn, M.; DOE)

Economic Modeling: Analysis

- F given A $F = A * \frac{(1+i)^n - 1}{i}$
- P given A $P = A * \frac{(1+i)^n - 1}{i(1+i)^n}$
- F given P $F = P * (1 + i)^{-n}$
- P given F $P = F * (1 + i)^n$
- F given P & g $F = P * \frac{(1+i)^n - (1+g)^n}{i - g}$

Economic Modeling : Results

Rankine Cycle				
Number of Periods, n	240	months		
Interest Rate, i	0.0027	per month		
	Annuity A ($/month)	Growth Rate g (per month)	Present Worth P ($)	Future Worth F ($)
Capital Cost			$252,000	$482,000
O & M cost	$615		$108,000	$208,000
Sludge heating	$4,400		$776,000	$1,485,000
Electricity Value	$12,700	0.00083	$2,451,000	$4,691,000
Salvage Value			$6,300	$12,000
Total			$1,308,700	$2,504,000

Gas Turbine				
Number of Periods, n	240	months		
Interest Rate, i	0.0027	per month		
	Annuity A ($/month)	Growth Rate g (per month)	Present Worth P ($)	Future Worth F ($)
Capital Cost			$920,000	$1,761,000
Overhaul at 120 months			$460,000	$636,000
O & M cost	$2,900		$511,000	$979,000
Sludge heating	$0		$0	$0
Electricity Value	$24,400	0.00083	$4,709,000	$9,012,000
Salvage Value			$23,000	$44,000
Total			$2,795,000	$5,592,000

Plans & Specifications: Gas Turbine Engine Selection

- Flex Energy MT250
- 2 Units (rated 250 kW each, 200 kW at 6000ft)
- Integrated Heat Recovery Unit (HRU) for Hot Water Production
- Low Pressure/Low Caloric Digester Gas Compatible
- Integrated Fuel Compressor
- Capable of dual mode electrical integration

Plans & Specifications: Sludge Heater

- Counter-flow tube in tube arrangement
  - Allows for easy cleaning of surfaces
  - Larger heat transfer than parallel flow

- HRS Heat Exchanger
  - Corrugated inner tube
  - Removable inner tube

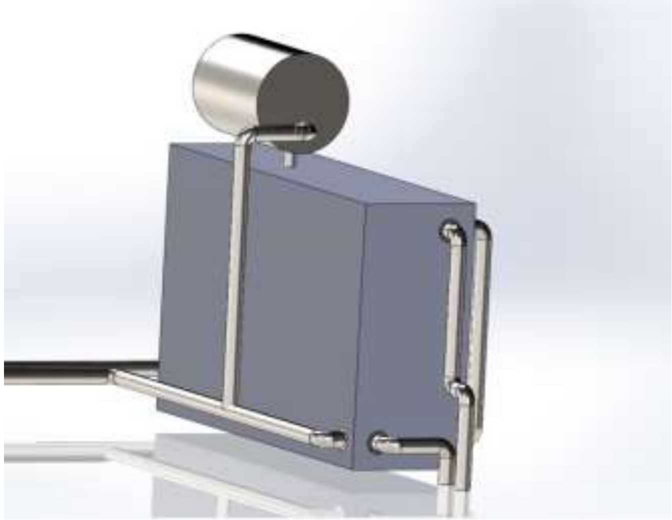
Plans & Specifications: Sludge Heater Design

- Required surface area (A_{req}) found from log mean temperature difference method

$$A_{req} = \frac{\dot{Q}}{U * \Delta T_{lm}}$$

- Model and number of passes required (N_{req}) found using available surface area (A_{av}) from manufacturer

$$N_{req} = \frac{A_{req}}{A_{av}}$$



- Approximate dimensions could be determined from number of passes and manufacturer data

- Includes water makeup/expansion tank

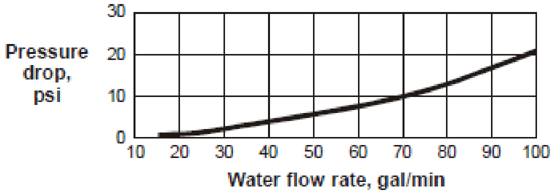
Plans & Specifications: Water Pump

- Volumetric flowrate selected from GTE manufacturer data to meet sludge heating requirements

- From sludge heater design and piping layout, head losses were determined

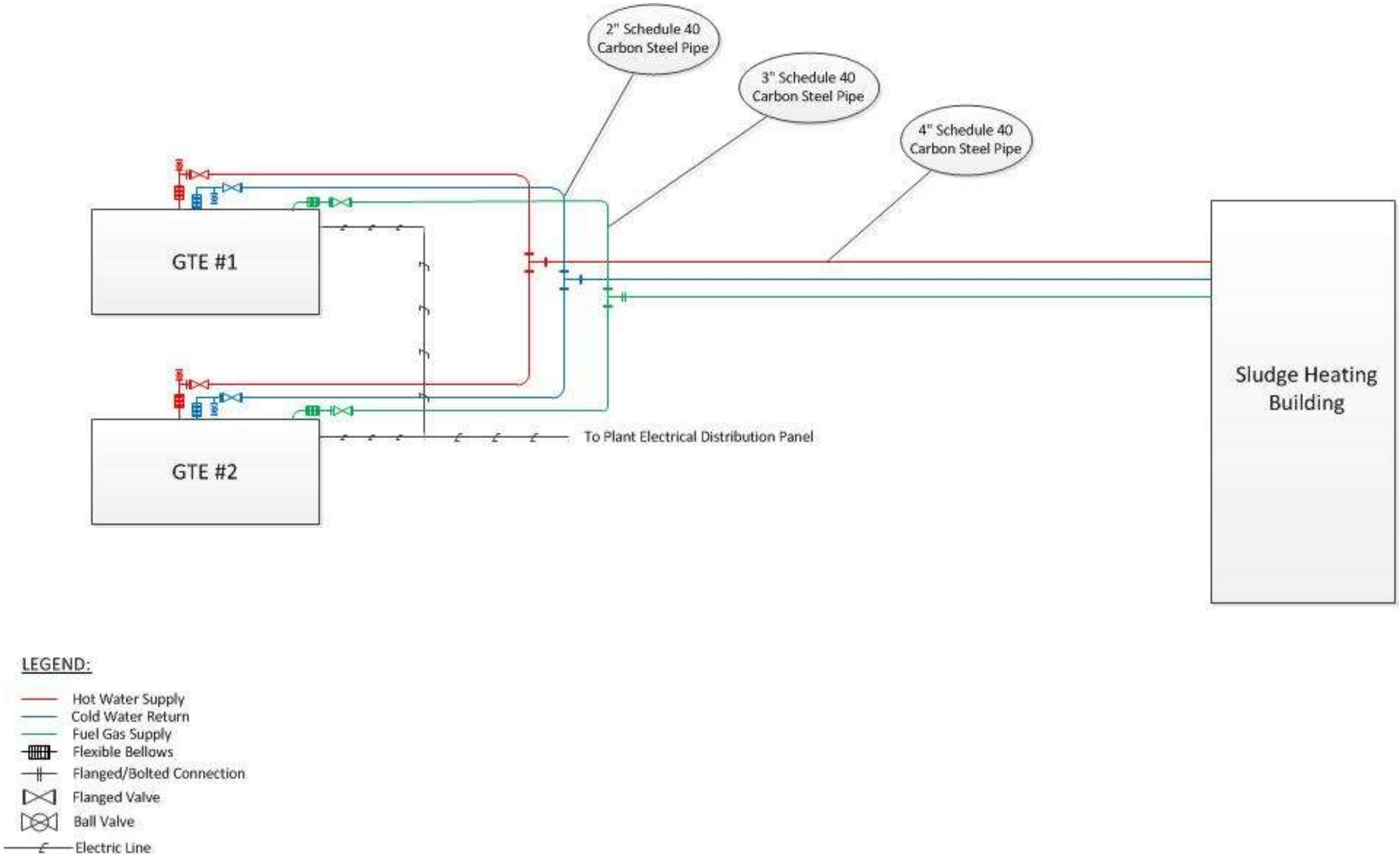
$$h_{L,major} = f\left(\frac{l}{D}\right)\left(\frac{V^2}{2g}\right) \qquad h_{L,minor} = K_L\left(\frac{V^2}{2g}\right)$$

- From manufacturer data, head loss in HRU was determined

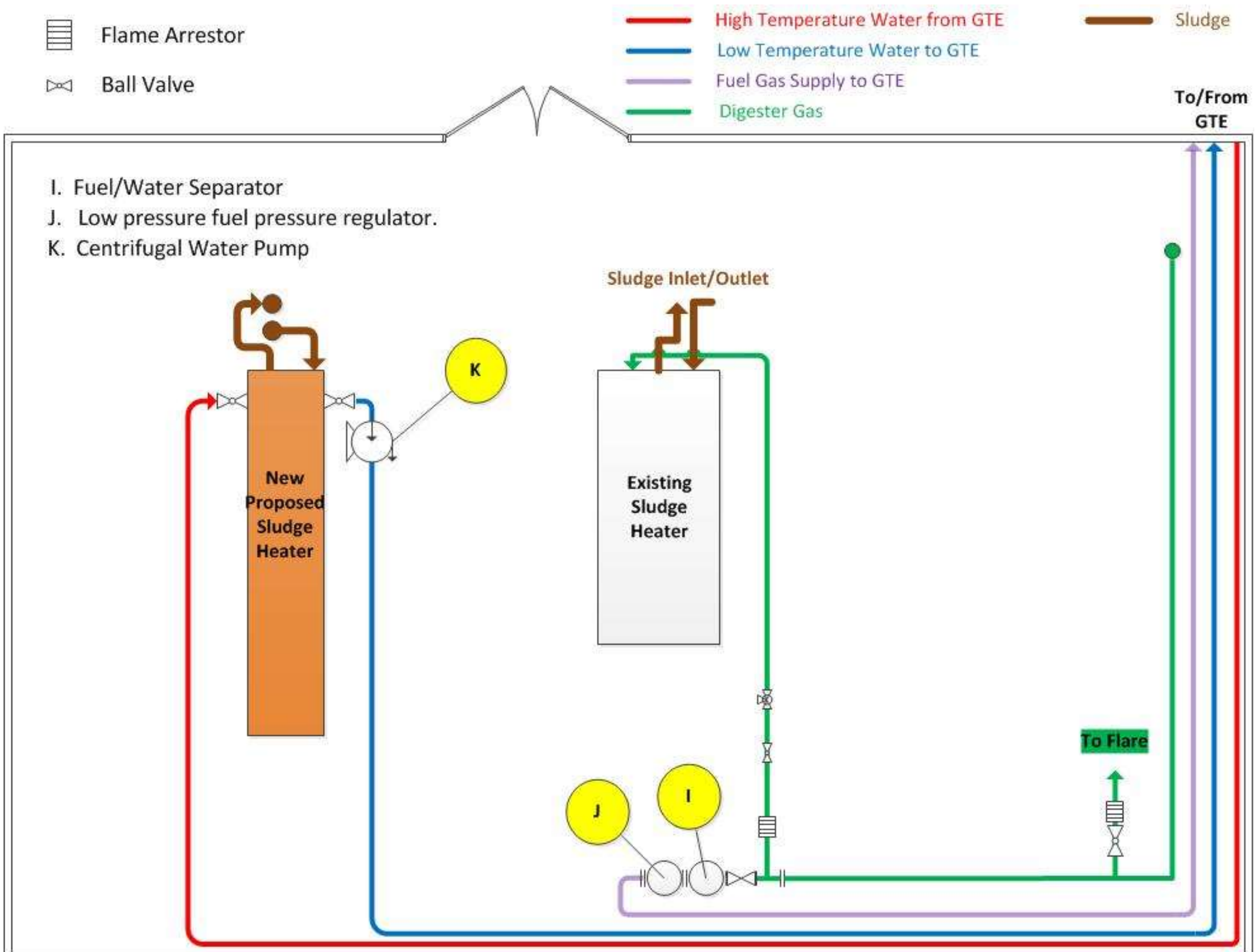


- Pump was selected to match total head loss (25 psi) and flowrate (100 gal/min)

Plans and Specifications: Pipe Layout



Plans and Specifications: Pipe Layout



Conclusion

- Combined heat and power overall efficiency:

$$\frac{400\ kW_{electricty} + 460\ kW_{SludgeHeating}}{1400\ kW_{Digestergas}} = 61\%$$

- Offset to electricity and natural gas costs to WWTP
- 140 million Lbs. CO_2 Offset

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Questions?