Critical Thinking Questions – Thermal Conversion Solutions

I. Thermal Conversion Basics

1. Thermal conversion is the use of heat to rapidly transform wastes into fuels, byproducts and/or power

2. Waste reduction, energy production, diversion from landfills

3. 1885; Governors Island in New York, NY

4. Answers will vary. At time of writing these solutions, 86 facilities are in the US.

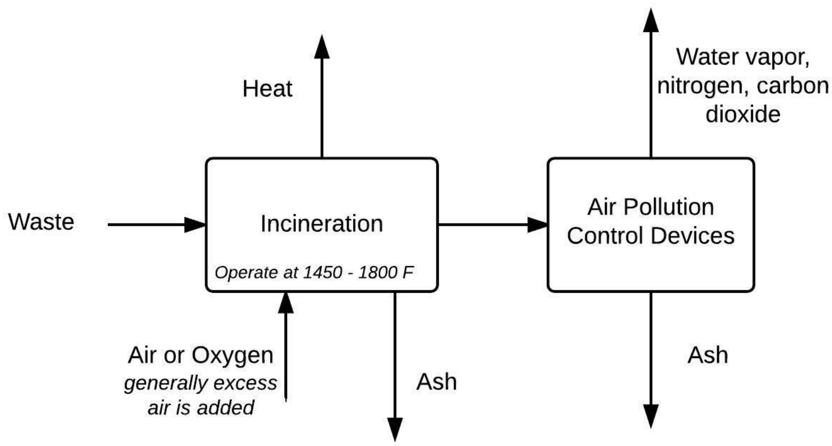
5. Answer varies based on state. View: Columbia University Waste Map (http://www.seas.columbia.edu/earth/recycle/) or the directory of facilities (http://energyrecoverycouncil.org/wp-content/uploads/2016/05/ERC-2016-directory.pdf).

6. Different technologies:
   Mass burn facilities: The most common type of combustion process. Mass burn units burn unprocessed MSW in a single combustion chamber under conditions of excess air.
   Modular systems: These are small portable systems that burn unprocessed, mixed MSW.
   Refuse derived systems: These systems require incoming waste be processed to a mixture that is suitable as a fuel (including shredding, and removing of non-combustible materials).

7. Yes. Germany (99 facilities)

II. Waste to Energy Processes

1.



2.

Components of waste combustion:

1. Waste is received and, if needed, stored.
2. Waste enters the furnace (temperature range is generally 1450 – 1800^{o}F).
3. Waste is burned. Air is added at levels greater than those stoichiometrically required.
4. Energy is created from the heat/steam.
5. Gases are cleaned using a variety of techniques.
6. Any ash is taken to a landfill.
7. Metals are recovered, if possible.

3. nitrogen gas, carbon dioxide, water vapor, ash, heat

4. answers will vary

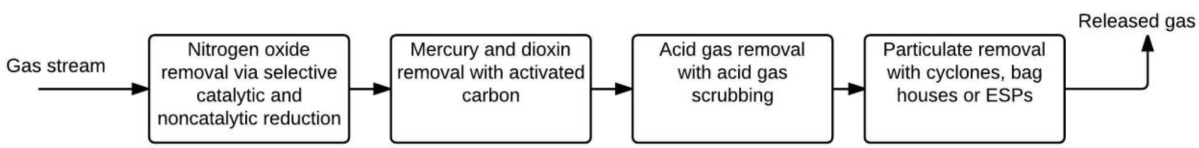
5. answers will vary

III. Emissions from Waste to Energy Facilities

1. Based on the EPA website, electricity generation from fossil fuel sources emit significantly more mercury, volatile organic compounds, carbon monoxide, hazardous air pollutants, and particulate matter.

2. Air pollution control devices:
   - Dust removal: cyclones, ESPs; bag houses
   - Acid gas neutralization: acid scrubbing; alkaline scrubbing
   - Low volatility organic compounds (PCDD/F, PCB, PAH): activated carbon; bag house with catalytic filter
   - Nitrogen Oxides: selective catalytic and noncatalytic reduction

3.



IV. Overview of Thermal Conversion Processes and Techniques

1. Answers will vary. The energy expended for evaporation and waste diversion from landfills are two topics that may be discussed.

2. Answers will vary

3. Answers will vary

4.

Term	Definition
Waste combustion	Thermal processing of solid waste by chemical oxidation with stoichiometric or excess amounts of air
Hydrothermal carbonization	A wet, relatively low temperature (180 – 350 ºC) thermal conversion process that occurs under autogeneous pressures. Materials are converted into solid, liquid, and gas products.
Pyrolysis	Thermal processing of waste in the absence of oxygen at temperatures below ~500ºC
Gasification	Thermal processing of wastes under less than stoichiometric oxygen levels in the presence of temperatures greater than ~500ºC. A syngas containing hydrogen, carbon dioxide, carbon monoxide, and methane results.
Ultimate analysis	Quantitative analysis of elements in a sample, usually C, H, O, N, S, and ash
Van Krevelen Diagram	A plot of atomic O/C vs atomic H/C that is commonly used to classify coals
HHV	Higher heating value: gross calorific value (assumes water is in the liquid phase following combustion)
LHV	Lower heating value: net calorific value (assumes water is in the vapor state following combustion)

5. Generally, as the amount of air added increases, flue gas temperature decreases.

6. Generally, as the amount of energy in the waste increases, flue gas temperature increases.

7. Generally, as the amount of moisture increases, flue gas temperature decreases.

8.

Waste Composition

Component	Wet Weight	%MC	J/g wet waste
Food Waste	6	70	4645
Paper	38	6	16721
Cardboard	8	5	16256
Plastics	6	2	32513
Textiles	3	10	17418
Rubber	1	2	23224
Leather	0.8	10	17418
Yard Waste	15	60	6503
Wood	4	20	18579
Glass	6.7	2	139
Tin Cans	8	3	697
Aluminum	2	2	0
Other Metal	1.5	3	697
Dirt. Ash. Etc.	0	8	6967

Component	C	H	O	N	S	Ash
Food Waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	0	0	10
Textiles	55	6.6	31.2	4.6	0.15	2.5
Rubber	78	10	0	2	0	10
Leather	60	8	11.6	10	0.4	10
Yard Waste	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Glass	0.5	0.1	0.4	0.1	0	98.9
Tin Cans	4.5	0.6	4.3	0.01	0	90.5
Aluminum	4.5	0.6	4.3	0.01	0	90.5
Other Metals	4.5	0.6	4.3	0.01	0	90.5
Dirt, Ash.	26.3	3	2	0.5	0.2	68

Determine the Mass of Each Element

Component	Wet Weight	%MC	Dry Weight	C	H	O	N	S	Ash	Energy (J)
Food Waste	6	70	1.8	0.86	0.12	0.68	0.047	0.01	0.09	27870
Paper	38	6	35.72	15.54	2.14	15.72	0.107	0.07	2.14	635398
Cardboard	8	5	7.6	3.34	0.45	3.39	0.023	0.02	0.38	130048
Plastics	6	2	5.88	3.53	0.42	1.34	0.000	0.00	0.59	195078
Textiles	3	10	2.7	1.49	0.18	0.84	0.124	0.00	0.07	52254
Rubber	1	2	0.98	0.76	0.10	0.00	0.020	0.00	0.10	23224
Leather	0.8	10	0.72	0.43	0.06	0.08	0.072	0.00	0.07	13934.4
Yard Waste	15	60	6	2.87	0.36	2.28	0.204	0.02	0.27	97545
Wood	4	20	3.2	1.58	0.19	1.37	0.006	0.00	0.05	74316
Glass	6.7	2	6.566	0.03	0.01	0.03	0.007	0.00	6.49	931.3
Tin Cans	8	3	7.76	0.35	0.05	0.33	0.001	0.00	7.02	5576
Aluminum	2	2	1.96	0.09	0.01	0.08	0.000	0.00	1.77	0
Other Metals	1.5	3	1.455	0.07	0.01	0.06	0.000	0.00	1.32	1045.5
Dirt, Ash	0	8	0	0.00	0.00	0.00	0.000	0.00	0.00	0
TOTALS	100		82.341	30.94	4.09	26.20	0.611	0.12	20.36	1257220.2

Calculate the amount of water in the waste

17.659 g (wet weight – dry weight)

Step 2 and 3: Determine moles of O_2 Required

Component	Weight (g)	Molecular Weight	Moles (g-mole)	Moles O2 required (g-mole)
Carbon	30.94	12	2.578	2.578
Hydrogen	4.09	1	4.089	1.022
Oxygen	26.20	16	1.637	-0.818
Nitrogen	0.61	14	0.0436	0
Sulfur	0.12	32.1	0.003	0.004
Water	17.659	18	0.981	0
Inerts	20.36			0
Total	99.99			

Associated Combustion Reactions

$C + O_2 \rightarrow CO_2$ *(assume all C goes to CO_2)

$4H + O_2 \rightarrow 2H_2O$

$2O \rightarrow O_2$

$2N \rightarrow N_2$

$S + O_2 \rightarrow SO_2$

Amount of O_2 required for 100g of waste = 2.79

Step 4: Combustion products – Flue Gas Composition

Component	Moles going in (g-moles)
Carbon	2.579
Hydrogen	4.089
Oxygen	1.637
Nitrogen	0.044
Sulfur	0.00379
Water	0.981
Ash	

Combustion Product	
Component	Moles (g-mole)
CO_2	2.579
H_2O	3.026
O_2	0.000
N_2	0.0218
SO_2	0.004

Step 5: Moles of air required/100 g of waste

Air Composition	
Component	Mole Fraction
CO_2	0.0003
N_2	0.7802
O_2	0.2069
H_2O	0.0126

Moles Air required for 100 g waste =13.465 g-moles

Step 6: Composition of Supplied Air

Component	g-Mol
CO_2	0.004
N_2	10.505
O_2	2.786
H_2O	0.169

Total = 13.465

Step 7: Flue Gas Composition

	Moles of Flue Gas			
Components	Comb. Products	Air Supply	Total	Percent
CO_2	2.58	0.0040	2.58	15.84
H_2O	3.03	0.1700	3.20	19.59
O_2	0.00	0.0000	0.00	0.00
N_2	0.02	10.5100	10.53	64.55
SO_2	0.00	0.0000	0.00	0.02
Sum:	5.63	10.6800	16.31	100.00

Step 8: Calculate flue gas enthalpy

Temp (F°)	J/g-mol
1000	26020
1500	36230
2000	46913
2500	58054

Required Enthalpy Data (J/mole)				
Temp (F°)	CO_2	H_2O	O_2	N_2
1000	23335	62529	16196	15606
1500	37655	73719	25566	24515
2000	52762	85702	35279	33721
2500	68600	98480	45325	43217

Step 9: Convert enthalpy from J/mol to J/g waste (heat value of waste)

Temp (F°)	J/g Waste
1000	4244
1500	5909
2000	7651
2500	9468

*assuming 100 g of waste

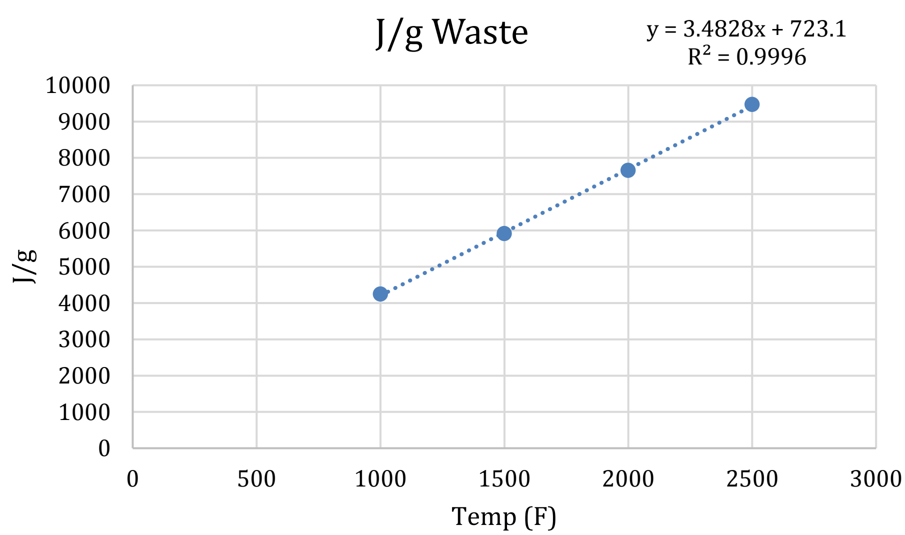
Step 10:

Case A: No Losses

Energy in Flue Gas:	12571	J/g
Temperature:	3402	F°

Case A: 20% Losses

Efficiency:	80	
Energy in Flue Gas:	10058	J/g
Temperature:	2680	F°



(b) The mass of carbon emitted in the flue gas (assuming 100% combustion efficiency) is a result o the CO_2 from waste combustion plus the CO_2 in the added air. It is determined in step 7. Convert the total CO_2 to mass of carbon:

$$= 2.58\, moles\ CO_2 \times \frac{1\ mole\ C}{mole\ CO_2} \times \frac{12\ g}{mole\ C} = 31\ g\ C$$

100 g of waste combusted, therefore:

0.31 g C/g waste combusted is emitted in the flue gas

(c)

Excess Air Calculations

% excess air supplied: 25%

Step 11A: calculate Extra Air = 3.37 moles of air

Step 11B: Flue Gas Composition

	Flue Gas (0% EA)	Air Supply for EA	Total	Percent
CO_2	2.582	0.001	2.583	13.131
H_2O	3.195	0.042	3.238	16.456
O_2	0	0.696	0.696	3.540
N_2	10.527	2.626	13.154	66.853
SO_2	0.0038	0.000	0.0038	0.0193
	16.309	3.366	19.675	100

Step 12: Calculate Flue Gas Enthalpy

Temp (F°)	J/mol
1000	24360.902
1500	34369.862
2000	44823.884
2500	55710.498

Temp	CO_2	H_2O	O_2	N_2
1000	23335	62529	16196	15606
	37655	73719	25566	24515
	52762	85702	35279	33721
	68600	98480	45325	43217

Step 13: Convert enthalpy from J/mol to J/g Waste (assuming 100 g of waste)

Temp (F°)	J/g Waste
1000	4793.169
1500	6762.498
2000	8819.396
2500	10961.410

Step 14: Flue Gas Temperature

Case A: No Losses

Energy in Flue Gas:	12572.202	J/g
Temperature:	2902	F°

Case A: 20% Losses

Efficiency:	80	
Energy in Flue Gas:	10057.762	J/g
Temperature:	2291	F°

(d) The mass of carbon increases slightly due to the additional CO_2 in the added air stream (by 0.001 moles). This difference is too small to make a difference in the calculations, so the answer is the same as part b.

9.

Determine moles of O_2 required

Component	Weight (g)	Molecular Weight	Moles (g-mole)	Moles O_2 Required (g-mole)
Carbon	34.00	12.0	2.833	2.833
Hydrogen	5.00	1.0	5.000	1.250
Oxygen	27.00	16.0	1.6875	-0.844
Nitrogen	0.31	14.0	0.022	0
Sulfur	0.10	32.1	0.003	0.003
Water	18.00	18.0	1.000	0.000
Inerts	15.59			
Totals	100			

Associated Combustion Reactions

$C + O_2 \rightarrow CO_2$ *(assume all C goes to CO_2)

$4H + O_2 \rightarrow 2H_2O$

$2O \rightarrow O_2$

$2N \rightarrow N_2$

$S + O_2 \rightarrow SO_2$

Amount O_2 required to 100 g of waste (g-moles) = 3.24

Step 4: Combustion Products – Flue Gas Composition

Component	Moles Going In (g-mole)
Carbon	2.8333
Hydrogen	5.0000
Oxygen	1.6875
Nitrogen	0.0221
Sulfur	0.0031
Water	1.0000
Ash	

Combustion Product	
Component	Moles (g-mole)
CO_2	2.8333
H_2O	3.5000
O_2	0.0000
N_2	0.0111
SO_2	0.0030

Step 5: Moles of air required/100g of waste

Air Composition	
Component	Mole Fraction
CO_2	0.0003
N_2	0.7802
O_2	0.2069
H_2O	0.0126

Moles Air required for 100g waste = 15.673 g-moles (Answer to Part a)

Step 6: Composition of supplied Air

Component	g-Mol
CO_2	0.0047
N_2	12.2279
O_2	3.2427
H_2O	0.1974
	15.6728

Step 7: Flue Gas Composition

	Moles Flue Gas			
Components	Comb. Products	Air Supply	Total	Percent
CO_2	2.83	0.0047	2.838	15.11
H_2O	3.50	0.2000	3.700	19.69
O_2	0.00	0.0000	0.000	0.00
N_2	0.01	12.2300	12.240	65.18
SO_2	0.00	0.0000	0.000	0.02
Sum:	6.35	12.4300	18.780	100.00

Answers to part b:

$$= 2.84\ moles\ CO_2 \times \frac{1\ mole\ C}{Mole\ CO_2} \times \frac{12\ g}{mole\ C} = 34\ g\ C$$

100g of waste is combusted, therefore:
0.34 g C/g waste combusted is emitted in the flue gas