Heat and Material Balances for Nonautogenous Wastes

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INTRODUCTION

The incineration of nonautogenous (will not sustain combustion) wastes is becoming increasingly prevalent as more stringent water quality regulations are being enacted and enforced and land available for waste disposal is becoming increasingly difficult to find.

An understanding of the parameters affecting combustion temperatures and auxiliary fuel usage will aid both the designer and user of incinerators in choosing those items, which collectively form the incinerator system, that will give optimum performance at minimum cost.

The purpose of this paper is to provide the reader with a method of making heat and material balances on nonautogenous wastes. The method of solution is applicable where:

1) Auxiliary fuel is mixed directly with the waste in the combustion chamber.

2) Auxiliary fuel is supplied by a fuel burner preheating the combustion air.

3) Auxiliary fuel is supplied by a fuel burner serving as an after-burner for the combustion products from the incinerator.

The solutions obtained only approximate a real system. Items such as heat losses to surroundings, water vapor present in the air, heat of compression in combustion air, and others have not been included in the calculations. The values to be placed on these items are usually determined by the specific type of equipment used to perform the operation and judgment of the designer. However, the results of these calculations do enable the designer to graphically display them in such a manner as to indicate the optimum mode of operation.

These calculations have been carried out past the usual significant figures in order to facilitate bookkeeping when making the heat and material balances.

TERMINOLOGY

The following terminology is generally used in describing the physical characteristics of waste sludges.

1. Total Solids (TS) – the percentage, by weight, of the solid fraction of the waste sludge.

NOTE: Unless specifically stated, the liquid fraction is assumed to be water.

2. Volatile Solids (VS) – the percentage, by weight, of the combustible fraction of the Total Solids (TS). Includes fixed carbon. The remaining solids are assumed to be ash.

3. Heating Value (HHV) – can be expressed either as:

(a) Btu's/lb. TS
(b) Btu's/lb. VS
(c) Btu's/lb. Sludge (Total Solids plus water)

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NOTE: Bomb Calorimeter results are usually reported as Btu's/lb. TS

CALCULATIONS

For the example calculation presented here, we shall use 100 lb. Total Solids as a calculation base. We shall also assume that the waste sludge has the following analysis:

Total Solids	22% TS
Volatile Solids	80% VS

Ultimate Analysis of Volatile Solids

Carbon	50%
Hydrogen	7%
Oxygen	39%
Nitrogen	4%
	100%
Btu's/lb. VS	9,500

Let us also assume that we will incinerate the sludge with only 30% Excess Air to minimize auxiliary fuel usage and burn at 1650°F. to insure complete deodorization.

From the preceeding we can now determine the feed to the incinerator.

$$100 \text{ lb. TS} \times \frac{80 \text{ lb. VS}}{100 \text{ lb. TS}} = 80 \text{ lb. VS}$$

50% C x 80 lb. VS = 40.00 lb. Carbon

7% H x 80 lb. VS = 5.60 lb. Hydrogen

39% O x 80 lb. VS = 31.20 lb. Oxygen

4% N x 80 lb. VS = 3.20 lb. Nitrogen

80.00 lb. VS — 80.00 lb. VS

$$100 \text{ lb. TS} \times \frac{(100 - 22) \text{ lb. } H_2O}{22 \text{ lb. TS}} = 354.50 \text{ lb. } H_2O$$

$$100 \text{ lb. TS} \times \frac{(100 - 80) \text{ lb. Ash}}{100 \text{ lb. TS}} = 20.00 \text{ lb. Ash}$$

454.50 lb. Sludge

COMBUSTION OF VOLATILE SOLIDS

$$40.00 \text{ lb. C} \times \frac{32 \text{ lb. O}}{12 \text{ lb. C}} = 106.67 \text{ lb. Oxygen}$$

$$5.60 \text{ lb. H} \times \frac{16 \text{ lb. O}}{2 \text{ lb. H}} \qquad 44.80$$

151.47

Oxygen available in VS -31.20

120.27 lb. Stoichiometric Oxygen

0.30 x 120.27 — 36.08 lb. Excess Oxygen

156.35 lb. Oxygen for Combustion

$$156.35 \times \frac{76.85 \text{ lb. N}}{23.15 \text{ lb. O}} \qquad 519.03 \text{ lb. Nitrogen}$$

675.38 lb. Combustion Air

Combustion Products

$$40.00 \text{ lb. C} \times \frac{44 \text{ lb. } CO_2}{12 \text{ lb. C}} = 146.67 \text{ lb. } CO_2$$

$$5.60 \text{ lb. H} \times \frac{18 \text{ lb. } H_2O}{2 \text{ lb. H}} = 50.40 \text{ lb. } H_2O$$

Nitrogen in air 519.03 lb.		
Nitrogen in VS 3.20		
522.23 lb.	=	522.23 lb. N_2
Excess Oxygen		36.08 lb. O_2
		755.38 lb. Flue Gas

Calculation Check

Input

Volatile Solids	80.00 lb.
Combustion Air	675.38 lb.
	755.38 lb.

Output

Flue Gas	755.38 lb.

COMBUSTION OF AUXILIARY FUEL

Natural Gas:

76% Carbon	0.044/lb./ft.^{3}
24% Hydrogen	1,003 Btu's/ft.^{3}
22,800 Btu's/lb.	

Combustion of 1 lb. Natural Gas at 30% XS Air.

$0.76 \text{ lb. C} \times \frac{32 \text{ lb. O}}{12 \text{ lb. C}}$	=	2.03 lb. Oxygen
$0.24 \text{ lb. H} \times \frac{16 \text{ lb. O}}{2 \text{ lb. H}}$	=	1.92 lb.
	=	3.95 lb. Stoichiometric Oxygen
0.30 x 3.95		1.19 lb. XS Oxygen
		5.14 lb. Combustion Oxygen
$5.14 \text{ lb. O} \times \frac{76.85 \text{ lb. N}}{23.15 \text{ lb. O}}$	=	17.06 lb. Nitrogen
		22.20 lb. Combustion Air

Combustion Products

$0.76 \text{ lb. C} \times \frac{44 \text{ lb. } CO_2}{12 \text{ lb. C}}$	=	2.79 lb. CO_2
$0.24 \text{ lb. H} \times \frac{18 \text{ lb. } H_2O}{2 \text{ lb. H}}$	=	2.16 lb. H_2O
Excess Oxygen		1.19 lb. O_2
Nitrogen in combustion air		17.06 lb. N_2
		23.20 lb. Flue Gas

Calculation Check

Input

1.00 lb.	Natural Gas
22.20 lb.	Combustion Air
23.20 lb.	

Output

23.20 lb. Flue Gas

HEAT AND MATERIAL BALANCE

Enthalpy of combustion products at 1650°F.

Carbon Dioxide	CO_2	419 Btu's/lb.
Water (Including Heat of Vaporization)	H_2O	1839
Nitrogen	N_2	417
Oxygen	O_2	386
Ash	Ash	413

Btu Output from Sludge (Volatile Solids, Water, and Ash) @ 1650°F.

146.67 lb.	CO_2	x	419 Btu's/lb.	=	61,455 Btu's
50.40 lb.	H_2O	x	1839	=	92,686
522.23 lb.	N_2	x	417	=	217,777
36.08 lb.	O_2	x	386	=	13,927
354.50 lb.	H_2O	x	1839	=	651,926
20.00 lb.	Ash	x	413	=	8,260
					1,046,031 Btu's

Btu Output from 1 lb. Natural Gas @ 1650°F.

2.79 lb.	CO_2	x	419	=	1,169 Btu's
2.16 lb.	H_2O	x	1839	=	3,972
17.06 lb.	N_2	x	417	=	7,114
1.19 lb.	O_2	x	386	=	459
					12,714 Btu's

Determination of Natural Gas requirements

Let X equal the pounds of Natural Gas required

Input

80.00 lb. VS x 9,500 Btu's/lb. VS =	760,000 Btu's
X lb. Natural Gas x 22,800 Btu's/lb. =	22,800X Btu's

Output

Sludge	1,046,031 Btu's
Natural Gas	12,714X

Input		Output
760,000 + 22,800X	=	1,046,031 + 12,714X
10,086X	=	286,031
X	=	28.36 lb. Natural Gas

Total Air Requirements

For combustion of VS — 675.38 lb.

For combustion of Natural Gas

$$28.36 \text{ lb. gas} \times \frac{22.20 \text{ lb. air}}{1.00 \text{ lb. gas}} = 629.59$$

1,304.97 lb. air

Combustion Products from Natural Gas

28.36 lb. gas	x	2.79 lb. CO_2/lb. gas	=	79.12 lb. CO_2
28.36 lb. gas	x	2.16 lb. H_2O/lb. gas	=	61.26 lb. H_2O
28.36 lb. gas	x	1.19 lb. O_2/lb. gas	=	33.75 lb. O_2
28.36 lb. gas	x	17.06 lb. N_2/lb. gas	=	483.82 lb. N_2

Total Weight of Combustion Products (Sludge + Natural Gas)

225.79 lb. CO_2

466.16 lb. H_2O

69.83 lb. O_2

1,006.05 lb. N_2

1,767.83 lb. Flue Gas/100 lb. TS

Calculation Check

Input

Air	1,304.97 lb.
Sludge	454.50 lb.
Natural Gas	28.36 lb.
	1,787.83 lb.

Output

Flue Gas	1,767.83 lb.
Ash	20.00 lb.
	1,787.83 lb.

FLUE GAS VOLUMES

$$V = \frac{mRT}{p}$$

V = ft.^{3}

P = lbf./ft.^{2}

m = lbm.

R = ft.-lbf./lbm.°R

T = °R

CO_2	R = 35.10 ft.-lbf./lbm. °R
H_2O	R = 85.76
N_2	R = 55.15
O_2	R = 48.28

For the example calculation:

T = 1650 + 460 = 2110°R

P = 14.7 lbf./in.^{2} x 144 in.^{2}/ft.^{2} = 2116.8 lbf./ft.^{2}

$$V = \frac{2110.0}{2116.8} \times m \times R = 0.99679 \times m \times R$$

CO_2	0.99679	x	225.79	x	35.10	=	7,900 ft.^{3}	=	7.42%
N_2	0.99679	x	1,006.05	x	55.15	=	55,306	=	51.97%
O_2	0.99679	x	69.83	x	48.28	=	3,361	=	3.16%
H_2O	0.99679	x	466.16	x	85.76	=	39,850	=	37.45%
							106,417 ft.^{3}		100.00%

On a dry basis (Orsat Analysis)

CO_2	7,900 ft.^{3}	=	11.87%
N_2	55,306	=	83.08%
O_2	3,361	=	5.05%
	66,567 ft.^{3}		100.00%

DISCUSSION

In order to cover a wide range of input conditions, a computer program was developed to perform the calculations described in this paper. Listed below are the parameters used in these calculations.

Btu/lb. VS	6,350; 9,500; 12,500
% TS	10; 15; 20; 25; 30; 35
% VS	60; 70; 80
% XS Air	40; 60; 80; 100; 120
Temperature °F.	1,400; 1,500; 1,600; 1,700; 1,800

Thirteen hundred and fifty (1,350) separate heat and material balances were made. Several graphs showing the results of these calculations are included in the appendix of this paper. With the aid of graphs such as these, the designer can evaluate alternatives to a particular incineration problem.

ENTHALPY OF FLUE GASES ABOVE 80°F

RANGE 1400°F. to 1800°F.

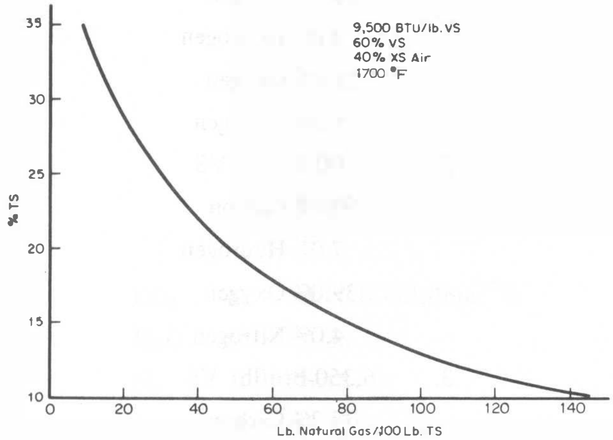
CO_2	h = 0.30325 T	–	81.1 Btu/lb.
N_2	h = 0.28550 T	–	54.3 Btu/lb.
O_2	h = 0.26478 T	–	50.7 Btu/lb.
H_2O	h = 0.57133 T	+	898.7 Btu/lb.
	(including 1048.6 Btu/lb. heat of vaporization)		
Ash	h = 0.25 T	–	20 Btu/lb.

T = Temperature °F.

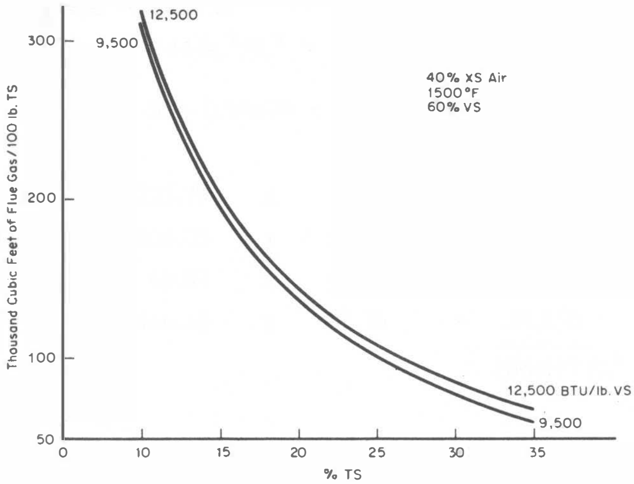
ANALYSIS OF VOLATILE SOLIDS

1. 12,500 Btu/lb. VS
   - 65.0% Carbon
   - 9.0% Hydrogen
   - 21.0% Oxygen
   - 5.0% Nitrogen
2. 9,500 Btu/lb. VS
   - 50.0% Carbon
   - 7.0% Hydrogen
   - 39.0% Oxygen
   - 4.0% Nitrogen
3. 6,350 Btu/lb. VS
   - 38.2% Carbon
   - 7.3% Hydrogen
   - 54.4% Oxygen
   - 0.1% Nitrogen

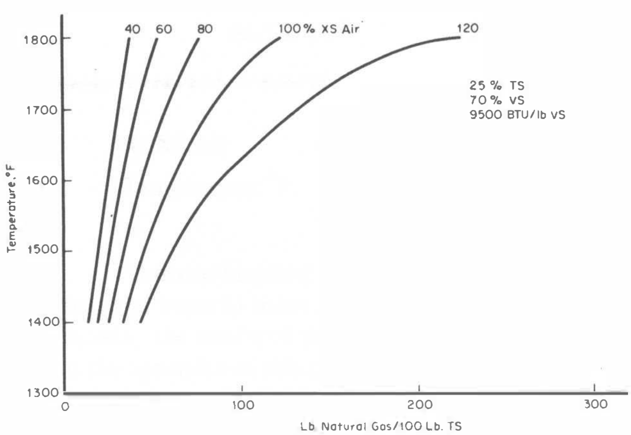
APPENDIX



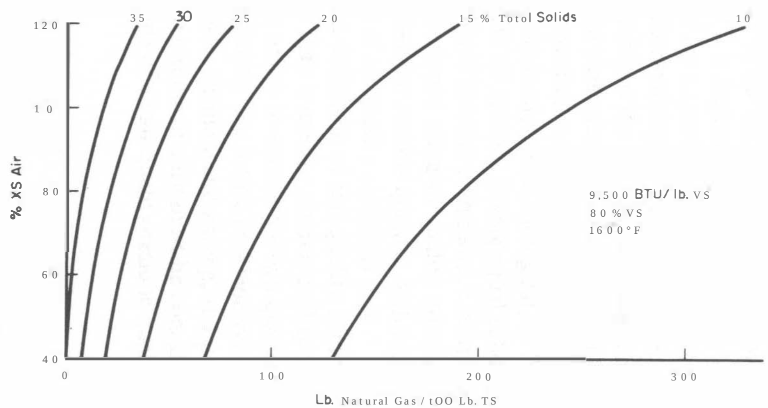
9,500 BTU/lb. VS
60% VS
40% XS Air
1700 °F
% TS
35
30
25
20
15
10
0
20
40
60
80
100
120
140
Lb. Natural Gas/100 Lb. TS



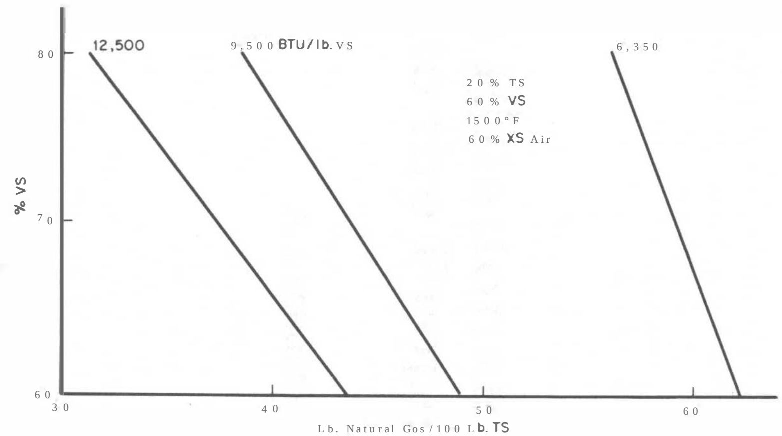
12,500
9,500
40% XS Air
1500 °F
60% VS
Thousand Cubic Feet of Flue Gas/100 lb. TS
300
200
100
50
12,500 BTU/lb. VS
9,500
0
10
15
20
25
30
35
% TS



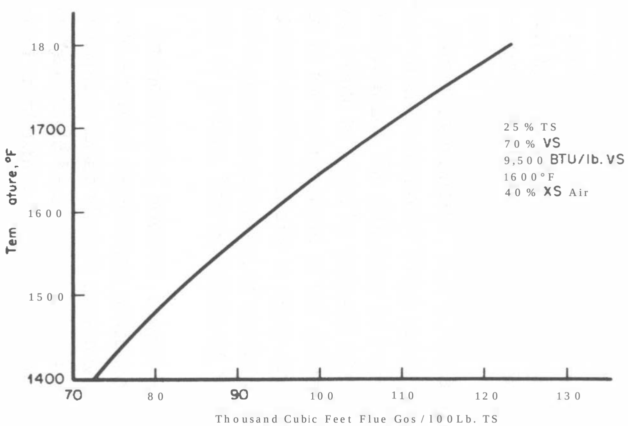
40
60
80
100% XS Air
120
25 % TS
70 % VS
9500 BTU/lb VS
Temperature, °F
1800
1700
1600
1500
1400
1300
0
100
200
300
Lb. Natural Gas/100 Lb. TS



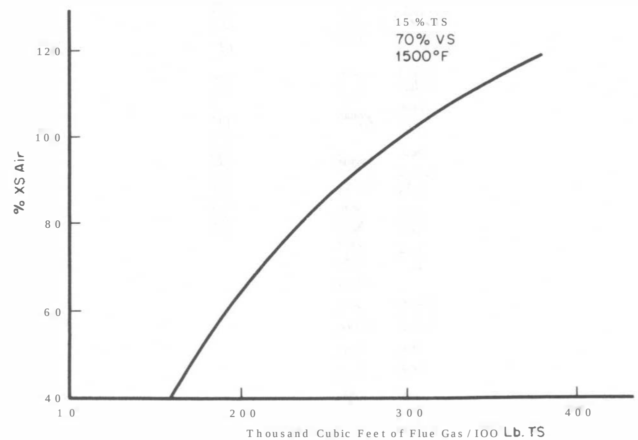
35
30
25
20
15 % Totol Solids
10
120
10
80
60
40
% XS Air
0
100
200
300
Lb. Natural Gas / tOO Lb. TS
9,500 BTU/ lb. VS
80 % VS
1600°F



12,500
9,500 BTU/lb. VS
6,350
20 % TS
60 % VS
1500°F
60 % XS Air
80
70
60
% VS
30
40
50
60
Lb. Natural Gos / 100 Lb. TS



18 0
1700
1600
1500
1400
Tem ature, °F
70
80
90
100
110
120
130
Thousand Cubic Feet Flue Gos / 100 Lb. TS
25 % TS
70 % VS
9,500 BTU/lb. VS
1600°F
40 % XS Air



15 % TS
70% VS
1500°F
120
100
80
60
40
% XS Air
10
200
300
400
Thousand Cubic Feet of Flue Gas / IOO Lb. TS