COMBUSTION FLAMES AND APPLICATIONS

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COMBUSTION BASICS

You will learn about:

- Fuel properties
- Combustion calculations
- Air/fuel ratio and excess air
- Flame temperatures
- Applications

Combustion…

Is a rapid combination of oxygen and fuel that results in the release of heat

Fuel, air and an ignition source are key requirements for combustion to occur

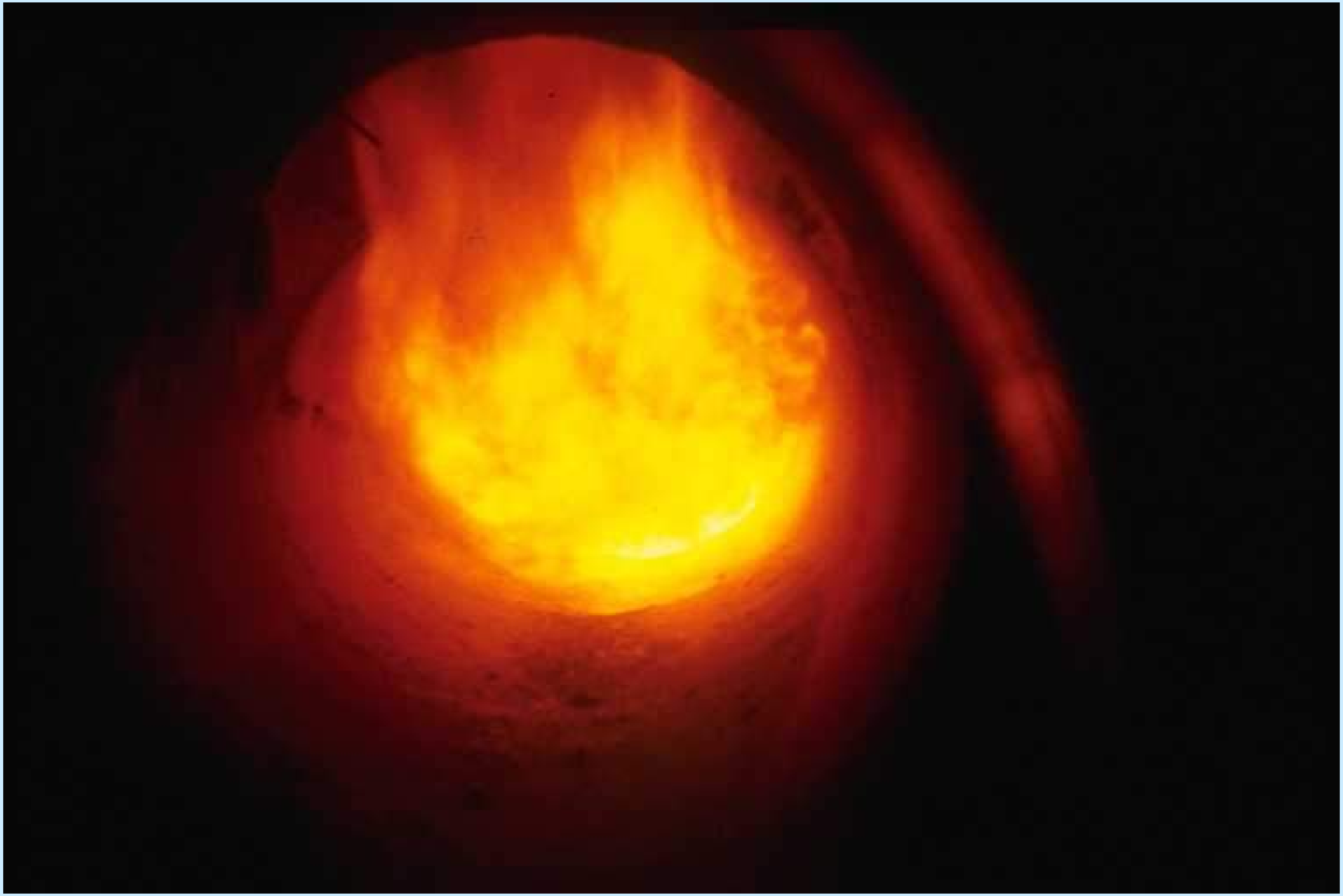
The Three T’s

Always keep in mind the 3 T’s of combustion:

- **Time**
- **Temperature**
- **Turbulence**

If all three exist in adequate amounts, plus the right amount of oxygen, good combustion will occur

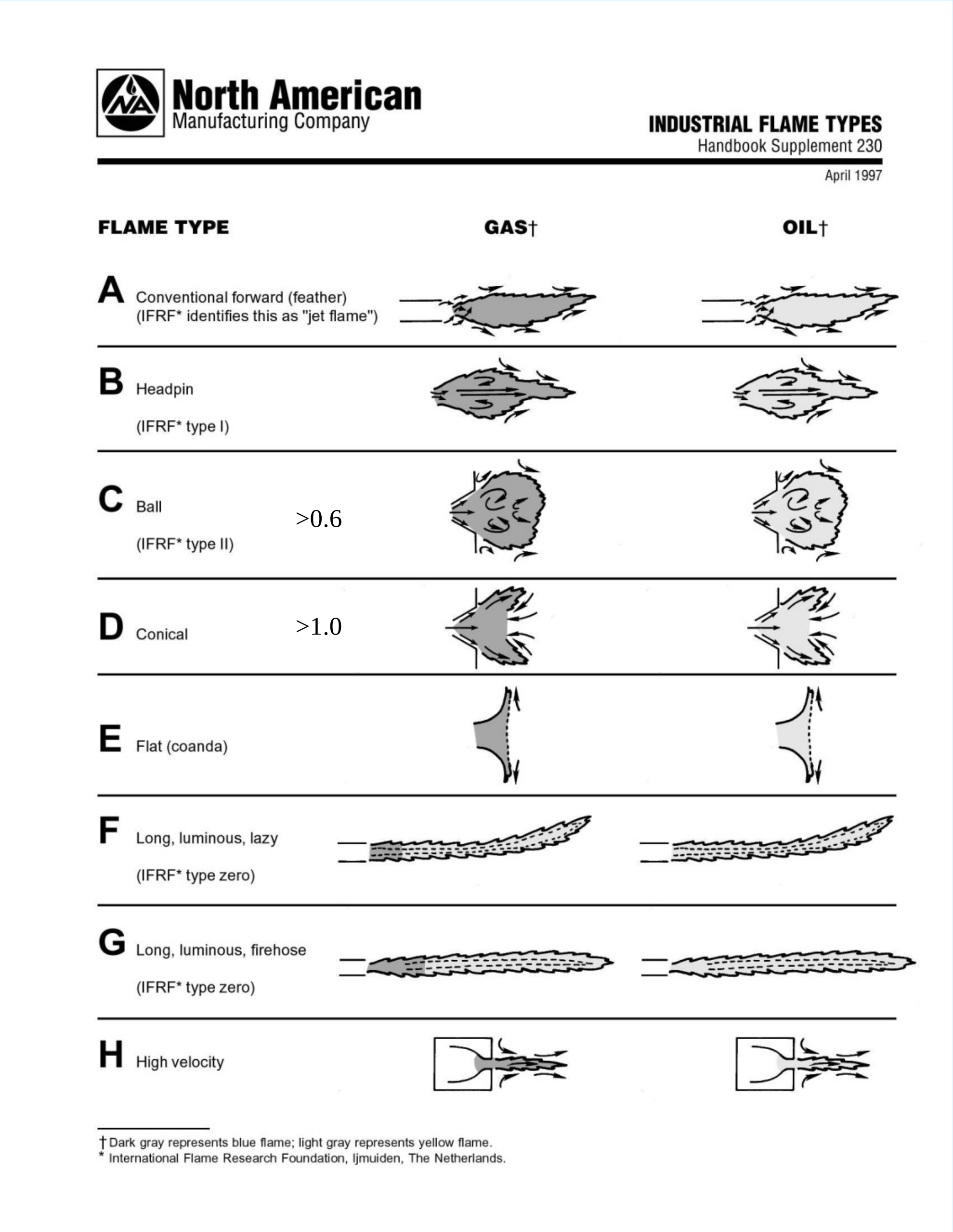
Flame from Batch Kiln Test



Burner Flame Types

There are no bad burners – but they can be misapplied, and be the wrong burner for a particular end use

Burners have the means to mix fuel and air, a point of attachment, and source of ignition



North American
Manufacturing Company

INDUSTRIAL FLAME TYPES
Handbook Supplement 230
April 1997

FLAME TYPE		GAS†	OIL†
A Conventional forward (feather) (IFRF* identifies this as "jet flame")			
B Headpin (IFRF* type I)			
C Ball (IFRF* type II)	>0.6		
D Conical	>1.0		
E Flat (coanda)			
F Long, luminous, lazy (IFRF* type zero)			
G Long, luminous, firehose (IFRF* type zero)			
H High velocity			

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† Dark gray represents blue flame; light gray represents yellow flame.
* International Flame Research Foundation, Ijmuiden, The Netherlands.

Common Fuels

- Natural gas
- Propane (LPG)
- Fuel oils (Nos. 1 through 6)
- Coal, coke, and wood
- Wastes—solid, liquid, sludge, and VOCs

Products of Combustion

- The two fundamental products of the reaction are CO_2 and H_2O
- N_2, and O_2 vary with excess air level
- Other products may include, SO_2, SO_3, NOx, HCl, HF, HBr and others, depending on the composition of the fuel and level of oxygen

Shortcuts and Rules of Thumb

Conversion of moles to volume:

1 lb mole of any gas = 378.7 scf at standard conditions
(60 ºF and 14.7 psia)

To find gas density: 1 mole of methane weighs 16 lb
So the density of methane = 16 / 378.7 = 0.042 lb/scf

Shortcuts and Rules of Thumb

For combustion air volume:
1+(XS air%/100) x (Btu / hr input)] / 6,000 = scfm combustion air

where factor (1 + XS air/100) is 1.0 at 0% XS air, and 2.0 at 100% XS air

For combustion air mass:
1+(XS air%/100) x 765 is lb air required to burn 1 MM Btu of fuel

Example:

A 10 MM Btu/hr burner running at 50% XS air requires:

[(1 + 50/100) x (10,000,000)] / 6,000 = 2505 scfm air
or
10 x (1 + 50/100) x 765 = 11,475 lb/hr air

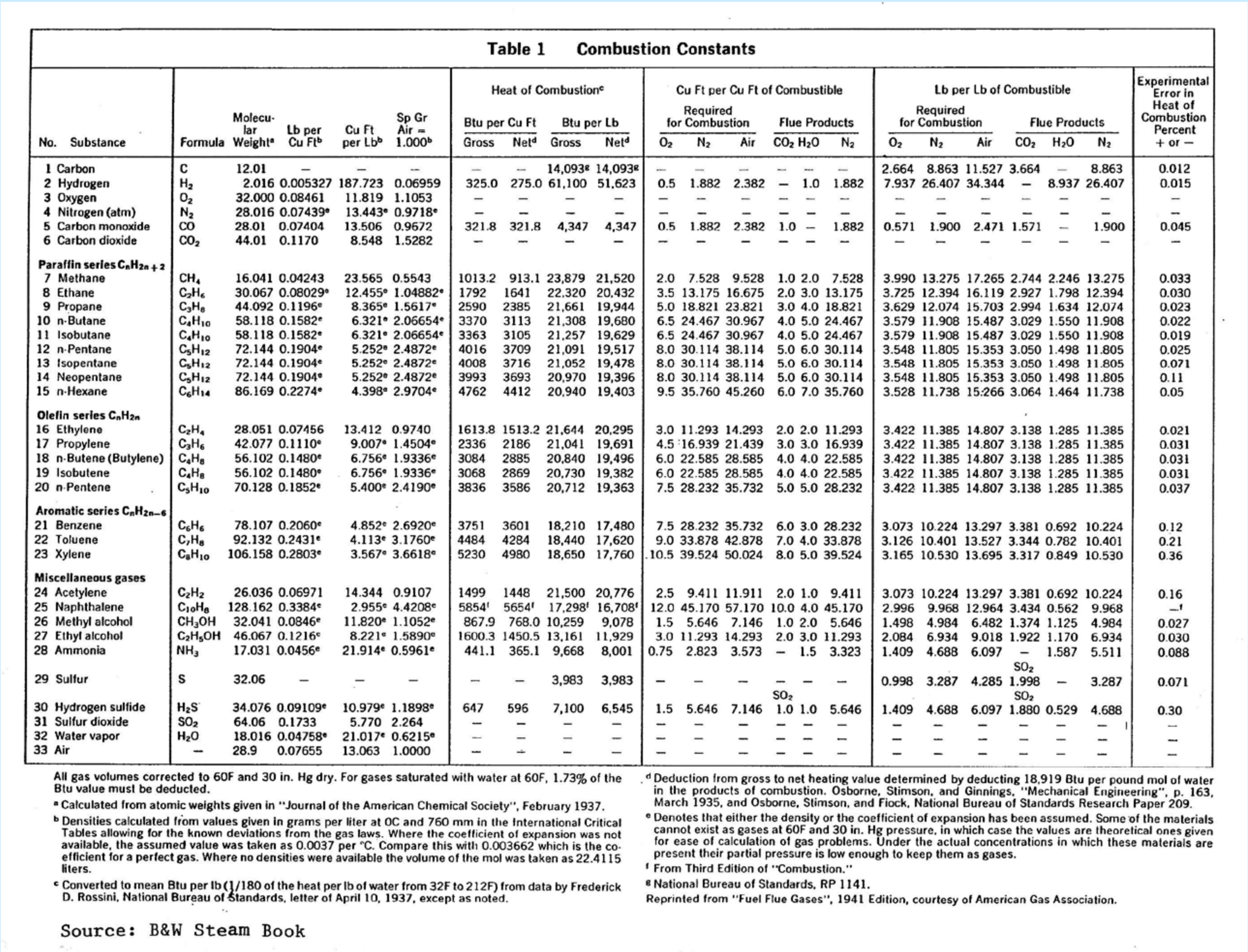


Table 1 Combustion Constants

No.	Substance	Formula	Molecular Weight[a]	Lb per Cu Ft[b]	Cu Ft per Lb[b]	Sp Gr Air = 1.000[b]	Heat of Combustion[c]				Cu Ft per Cu Ft of Combustible						Lb per Lb of Combustible						Experimental Error in Heat of Combustion Percent + or −
							Btu per Cu Ft		Btu per Lb		Required for Combustion			Flue Products			Required for Combustion			Flue Products			
							Gross	Net[d]	Gross	Net[d]	O_2	N_2	Air	CO_2	H_2O	N_2	O_2	N_2	Air	CO_2	H_2O	N_2	
1	Carbon	C	12.01	—	—	—	—	—	14,093[g]	14,093[g]	—	—	—	—	—	—	2.664	8.863	11.527	3.664	—	8.863	0.012
2	Hydrogen	H_2	2.016	0.005327	187.723	0.06959	325.0	275.0	61,100	51,623	0.5	1.882	2.382	—	1.0	1.882	7.937	26.407	34.344	—	8.937	26.407	0.015
3	Oxygen	O_2	32.000	0.08461	11.819	1.1053	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
4	Nitrogen (atm)	N_2	28.016	0.07439[e]	13.443[e]	0.9718[e]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5	Carbon monoxide	CO	28.01	0.07404	13.506	0.9672	321.8	321.8	4,347	4,347	0.5	1.882	2.382	1.0	—	1.882	0.571	1.900	2.471	1.571	—	1.900	0.045
6	Carbon dioxide	CO_2	44.01	0.1170	8.548	1.5282	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Paraffin series C_nH_{2n+2}																						
7	Methane	CH_4	16.041	0.04243	23.565	0.5543	1013.2	913.1	23,879	21,520	2.0	7.528	9.528	1.0	2.0	7.528	3.990	13.275	17.265	2.744	2.246	13.275	0.033
8	Ethane	C_2H_6	30.067	0.08029[e]	12.455[e]	1.04882[e]	1792	1641	22,320	20,432	3.5	13.175	16.675	2.0	3.0	13.175	3.725	12.394	16.119	2.927	1.798	12.394	0.030
9	Propane	C_3H_8	44.092	0.1196[e]	8.365[e]	1.5617[e]	2590	2385	21,661	19,944	5.0	18.821	23.821	3.0	4.0	18.821	3.629	12.074	15.703	2.994	1.634	12.074	0.023
10	n-Butane	C_4H_{10}	58.118	0.1582[e]	6.321[e]	2.06654[e]	3370	3113	21,308	19,680	6.5	24.467	30.967	4.0	5.0	24.467	3.579	11.908	15.487	3.029	1.550	11.908	0.022
11	Isobutane	C_4H_{10}	58.118	0.1582[e]	6.321[e]	2.06654[e]	3363	3105	21,257	19,629	6.5	24.467	30.967	4.0	5.0	24.467	3.579	11.908	15.487	3.029	1.550	11.908	0.019
12	n-Pentane	C_5H_{12}	72.144	0.1904[e]	5.252[e]	2.4872[e]	4016	3709	21,091	19,517	8.0	30.114	38.114	5.0	6.0	30.114	3.548	11.805	15.353	3.050	1.498	11.805	0.025
13	Isopentane	C_5H_{12}	72.144	0.1904[e]	5.252[e]	2.4872[e]	4008	3716	21,052	19,478	8.0	30.114	38.114	5.0	6.0	30.114	3.548	11.805	15.353	3.050	1.498	11.805	0.071
14	Neopentane	C_5H_{12}	72.144	0.1904[e]	5.252[e]	2.4872[e]	3993	3693	20,970	19,396	8.0	30.114	38.114	5.0	6.0	30.114	3.548	11.805	15.353	3.050	1.498	11.805	0.11
15	n-Hexane	C_6H_{14}	86.169	0.2274[e]	4.398[e]	2.9704[e]	4762	4412	20,940	19,403	9.5	35.760	45.260	6.0	7.0	35.760	3.528	11.738	15.266	3.064	1.464	11.738	0.05
	Olefin series C_nH_{2n}																						
16	Ethylene	C_2H_4	28.051	0.07456	13.412	0.9740	1613.8	1513.2	21,644	20,295	3.0	11.293	14.293	2.0	2.0	11.293	3.422	11.385	14.807	3.138	1.285	11.385	0.021
17	Propylene	C_3H_6	42.077	0.1110[e]	9.007[e]	1.4504[e]	2336	2186	21,041	19,691	4.5	16.939	21.439	3.0	3.0	16.939	3.422	11.385	14.807	3.138	1.285	11.385	0.031
18	n-Butene (Butylene)	C_4H_8	56.102	0.1480[e]	6.756[e]	1.9336[e]	3084	2885	20,840	19,496	6.0	22.585	28.585	4.0	4.0	22.585	3.422	11.385	14.807	3.138	1.285	11.385	0.031
19	Isobutene	C_4H_8	56.102	0.1480[e]	6.756[e]	1.9336[e]	3068	2869	20,730	19,382	6.0	22.585	28.585	4.0	4.0	22.585	3.422	11.385	14.807	3.138	1.285	11.385	0.031
20	n-Pentene	C_5H_{10}	70.128	0.1852[e]	5.400[e]	2.4190[e]	3836	3586	20,712	19,363	7.5	28.232	35.732	5.0	5.0	28.232	3.422	11.385	14.807	3.138	1.285	11.385	0.037
	Aromatic series C_nH_{2n-6}																						
21	Benzene	C_6H_6	78.107	0.2060[e]	4.852[e]	2.6920[e]	3751	3601	18,210	17,480	7.5	28.232	35.732	6.0	3.0	28.232	3.073	10.224	13.297	3.381	0.692	10.224	0.12
22	Toluene	C_7H_8	92.132	0.2431[e]	4.113[e]	3.1760[e]	4484	4284	18,440	17,620	9.0	33.878	42.878	7.0	4.0	33.878	3.126	10.401	13.527	3.344	0.782	10.401	0.21
23	Xylene	C_8H_{10}	106.158	0.2803[e]	3.567[e]	3.6618[e]	5230	4980	18,650	17,760	10.5	39.524	50.024	8.0	5.0	39.524	3.165	10.530	13.695	3.317	0.849	10.530	0.36
	Miscellaneous gases																						
24	Acetylene	C_2H_2	26.036	0.06971	14.344	0.9107	1499	1448	21,500	20,776	2.5	9.411	11.911	2.0	1.0	9.411	3.073	10.224	13.297	3.381	0.692	10.224	0.16
25	Naphthalene	$C_{10}H_8$	128.162	0.3384[e]	2.955[e]	4.4208[e]	5854[f]	5654[f]	17,298[f]	16,708[f]	12.0	45.170	57.170	10.0	4.0	45.170	2.996	9.968	12.964	3.434	0.562	9.968	—[f]
26	Methyl alcohol	CH_3OH	32.041	0.0846[e]	11.820[e]	1.1052[e]	867.9	768.0	10,259	9,078	1.5	5.646	7.146	1.0	2.0	5.646	1.498	4.984	6.482	1.374	1.125	4.984	0.027
27	Ethyl alcohol	C_2H_5OH	46.067	0.1216[e]	8.221[e]	1.5890[e]	1600.3	1450.5	13,161	11,929	3.0	11.293	14.293	2.0	3.0	11.293	2.084	6.934	9.018	1.922	1.170	6.934	0.030
28	Ammonia	NH_3	17.031	0.0456[e]	21.914[e]	0.5961[e]	441.1	365.1	9,668	8,001	0.75	2.823	3.573	—	1.5	3.323	1.409	4.688	6.097	—	1.587	5.511	0.088
29	Sulfur	S	32.06	—	—	—	—	—	3,983	3,983	—	—	—	—	—	—	0.998	3.287	4.285	SO_2 1.998	—	3.287	0.071
30	Hydrogen sulfide	H_2S	34.076	0.09109[e]	10.979[e]	1.1898[e]	647	596	7,100	6,545	1.5	5.646	7.146	SO_2 1.0	1.0	5.646	1.409	4.688	6.097	SO_2 1.880	0.529	4.688	0.30
31	Sulfur dioxide	SO_2	64.06	0.1733	5.770	2.264	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
32	Water vapor	H_2O	18.016	0.04758[e]	21.017[e]	0.6215[e]	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
33	Air	—	28.9	0.07655	13.063	1.0000	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

All gas volumes corrected to 60F and 30 in. Hg dry. For gases saturated with water at 60F, 1.73% of the Btu value must be deducted.

[a] Calculated from atomic weights given in "Journal of the American Chemical Society", February 1937.

[b] Densities calculated from values given in grams per liter at 0C and 760 mm in the International Critical Tables allowing for the known deviations from the gas laws. Where the coefficient of expansion was not available, the assumed value was taken as 0.0037 per °C. Compare this with 0.003662 which is the coefficient for a perfect gas. Where no densities were available the volume of the mol was taken as 22.4115 liters.

[c] Converted to mean Btu per lb (1/180 of the heat per lb of water from 32F to 212F) from data by Frederick D. Rossini, National Bureau of Standards, letter of April 10, 1937, except as noted.

[d] Deduction from gross to net heating value determined by deducting 18,919 Btu per pound mol of water in the products of combustion. Osborne, Stimson, and Ginnings, "Mechanical Engineering", p. 163, March 1935, and Osborne, Stimson, and Fiock, National Bureau of Standards Research Paper 209.

[e] Denotes that either the density or the coefficient of expansion has been assumed. Some of the materials cannot exist as gases at 60F and 30 in. Hg pressure, in which case the values are theoretical ones given for ease of calculation of gas problems. Under the actual concentrations in which these materials are present their partial pressure is low enough to keep them as gases.

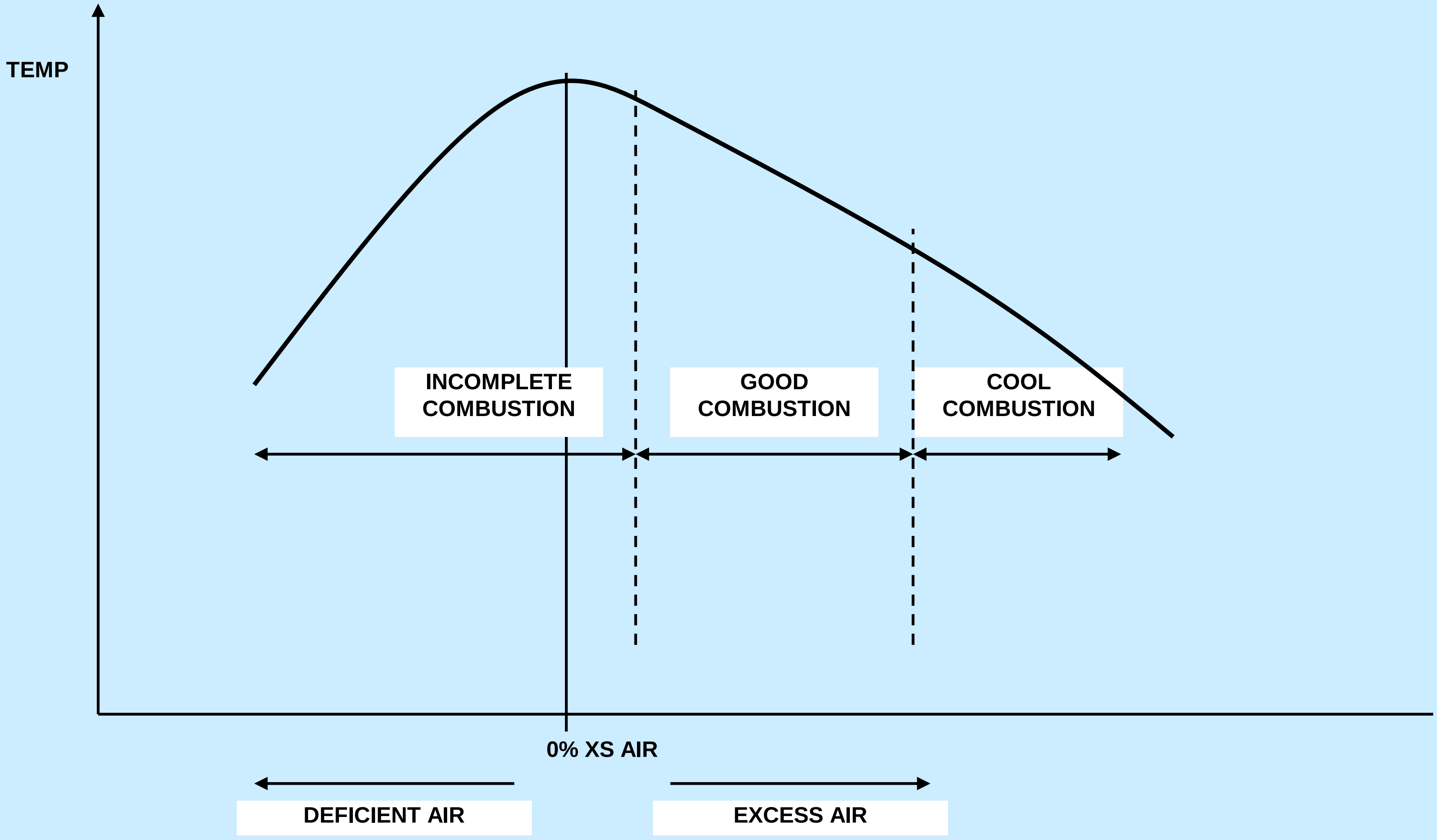
[f] From Third Edition of "Combustion."

[g] National Bureau of Standards, RP 1141.

Reprinted from "Fuel Flue Gases", 1941 Edition, courtesy of American Gas Association.

Source: B&W Steam Book

Temperature vs. Air to Fuel Ratio



Adiabatic Flame Temperature

(at zero % heat loss)

Q = M x C_p x temperature difference, or

Temperature difference = Q / (M X C_p)

Where Q = Btu

M = Mass, lb of combustion products

C_p = Specific heat of combustion products, Btu/lb-F

1 mole CH_4, 16 lb X <u>LHV</u> 21,520 Btu / lb = Q = 344,320 Btu

At 100% XS air M = 565 lb for products of combustion

Temperature difference = 344,320 / (565 lb X 0.282) = 2,161ºF

where 0.282 is approximate integrated heat capacity at this temp

With 60ºF base temperature at standard conditions:

AFT = 60 + temperature difference = 60 + 2,161 = 2,221ºF

Alternate Routes to Adiabatic Flame Temperature

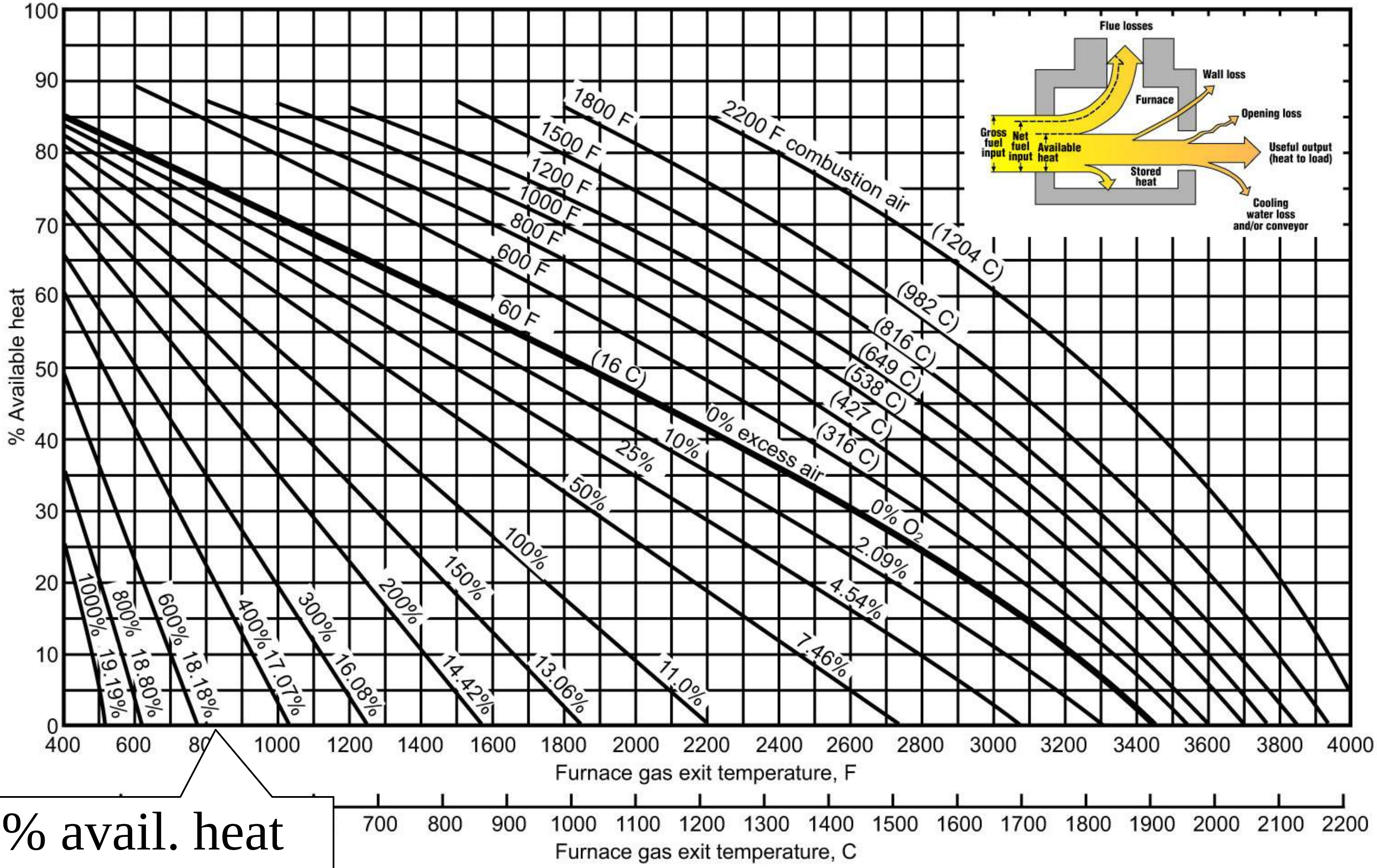
Use flame temperature vs. excess air graphs

Caution: C_p varies with gas temperature and gas type

- For greater accuracy, use integrated heat capacities of gases via equations or tables (See Table)
- At high temperatures, dissociation of CO_2 and H_2O reduce the actual temperature achieved, as does loss to furnace walls

All graphs are scaled to permit interpolation using a millimeter scale.

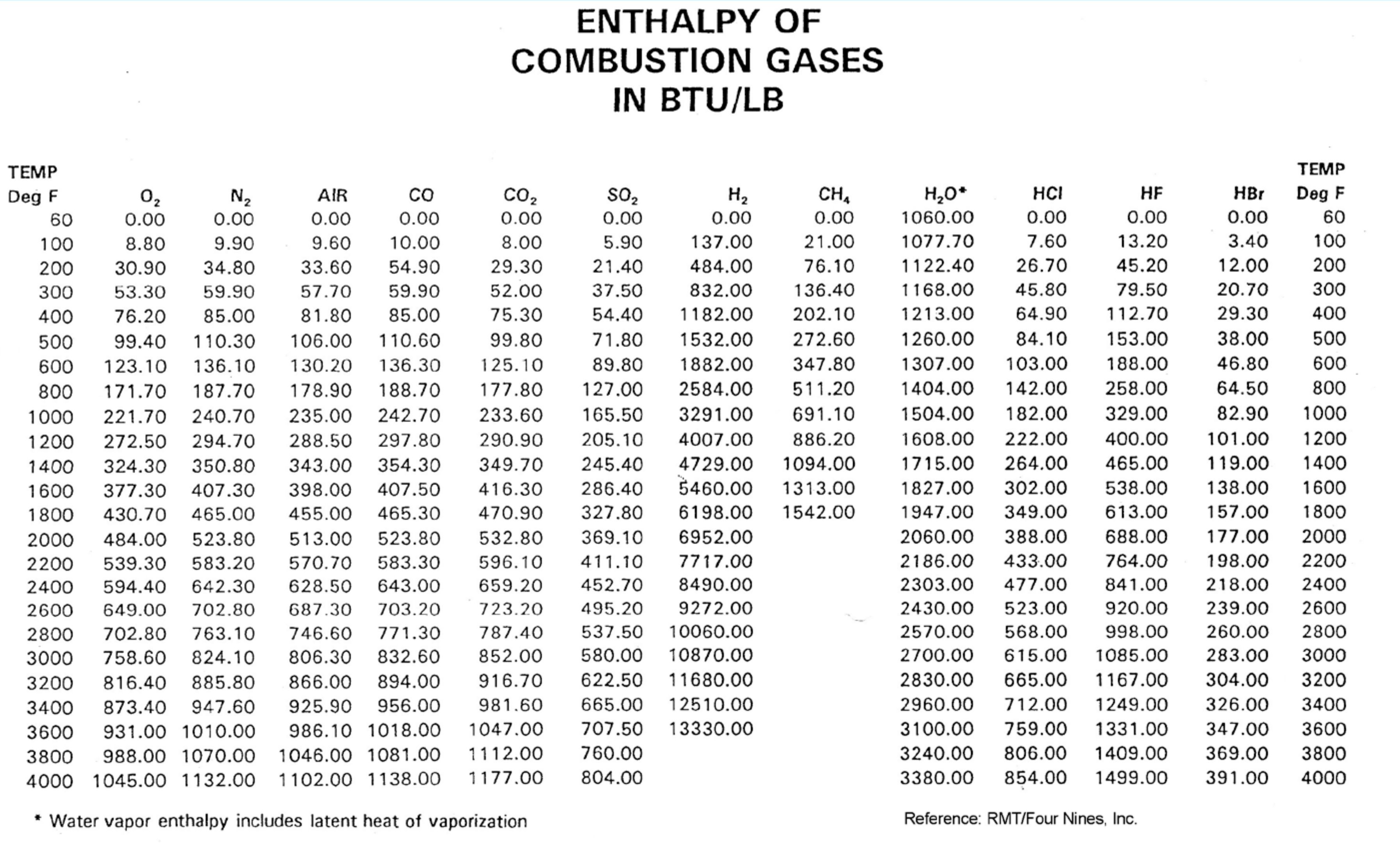
All hot air curves are based on 10% excess air.
All excess air curves are based on 60 F (16 C) combustion air.



0% avail. heat line shows AFT

Reference: North American, "Percent Available Heat With Preheated Air", Handbook Supplement 155a, Feb. 2001

Used with permission of NAMfg



ENTHALPY OF COMBUSTION GASES IN BTU/LB

TEMP Deg F	O_2	N_2	AIR	CO	CO_2	SO_2	H_2	CH_4	H_2O*	HCl	HF	HBr	TEMP Deg F
60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1060.00	0.00	0.00	0.00	60
100	8.80	9.90	9.60	10.00	8.00	5.90	137.00	21.00	1077.70	7.60	13.20	3.40	100
200	30.90	34.80	33.60	54.90	29.30	21.40	484.00	76.10	1122.40	26.70	45.20	12.00	200
300	53.30	59.90	57.70	59.90	52.00	37.50	832.00	136.40	1168.00	45.80	79.50	20.70	300
400	76.20	85.00	81.80	85.00	75.30	54.40	1182.00	202.10	1213.00	64.90	112.70	29.30	400
500	99.40	110.30	106.00	110.60	99.80	71.80	1532.00	272.60	1260.00	84.10	153.00	38.00	500
600	123.10	136.10	130.20	136.30	125.10	89.80	1882.00	347.80	1307.00	103.00	188.00	46.80	600
800	171.70	187.70	178.90	188.70	177.80	127.00	2584.00	511.20	1404.00	142.00	258.00	64.50	800
1000	221.70	240.70	235.00	242.70	233.60	165.50	3291.00	691.10	1504.00	182.00	329.00	82.90	1000
1200	272.50	294.70	288.50	297.80	290.90	205.10	4007.00	886.20	1608.00	222.00	400.00	101.00	1200
1400	324.30	350.80	343.00	354.30	349.70	245.40	4729.00	1094.00	1715.00	264.00	465.00	119.00	1400
1600	377.30	407.30	398.00	407.50	416.30	286.40	5460.00	1313.00	1827.00	302.00	538.00	138.00	1600
1800	430.70	465.00	455.00	465.30	470.90	327.80	6198.00	1542.00	1947.00	349.00	613.00	157.00	1800
2000	484.00	523.80	513.00	523.80	532.80	369.10	6952.00		2060.00	388.00	688.00	177.00	2000
2200	539.30	583.20	570.70	583.30	596.10	411.10	7717.00		2186.00	433.00	764.00	198.00	2200
2400	594.40	642.30	628.50	643.00	659.20	452.70	8490.00		2303.00	477.00	841.00	218.00	2400
2600	649.00	702.80	687.30	703.20	723.20	495.20	9272.00		2430.00	523.00	920.00	239.00	2600
2800	702.80	763.10	746.60	771.30	787.40	537.50	10060.00		2570.00	568.00	998.00	260.00	2800
3000	758.60	824.10	806.30	832.60	852.00	580.00	10870.00		2700.00	615.00	1085.00	283.00	3000
3200	816.40	885.80	866.00	894.00	916.70	622.50	11680.00		2830.00	665.00	1167.00	304.00	3200
3400	873.40	947.60	925.90	956.00	981.60	665.00	12510.00		2960.00	712.00	1249.00	326.00	3400
3600	931.00	1010.00	986.10	1018.00	1047.00	707.50	13330.00		3100.00	759.00	1331.00	347.00	3600
3800	988.00	1070.00	1046.00	1081.00	1112.00	760.00			3240.00	806.00	1409.00	369.00	3800
4000	1045.00	1132.00	1102.00	1138.00	1177.00	804.00			3380.00	854.00	1499.00	391.00	4000

* Water vapor enthalpy includes latent heat of vaporization

Reference: RMT/Four Nines, Inc.

Excess Air Example for Natural Gas

Using Table Ratios

Calculate the amount of air required for 25 percent, 50 percent and 100 percent excess air conditions for natural gas.

Answer:

Calculate the air requirements as before – then scale it up based upon the excess air requirement…

25% excess air: 17.26 lb air/lb fuel x 1.25 = 21.58 lb air

50% excess air: 17.26 lb air/lb fuel x 1.50 = 25.89 lb air

100% excess air: 17.26 lb air/lb fuel x 2.00 = 34.53 lb air

Retention Time in Afterburners or Other Combustion Chambers

Time:

- **Is a measure of the completeness of the reaction**
- **Residence Time – Length of time in the high temperature zone to allow completion of combustion reactions**

$$RT = \frac{\text{Volume of combustion chamber}}{\text{Actual Flow rate of combustion gases}}$$

- **Longer residence time needed for more difficult to burn (lower heating value) fuels**

Combustion Temperature

Temperature:

- Indicator of combustion stability
- Stable conditions exist when the temperature is in the flammability range (> 2300 F) as approximately defined by the Lower and Upper explosive Limits

COMBUSTION SAFETY

We want fuel to burn…

when and where we want it to…

and not at other times…

or other places!

Combustion system design elements:

- **BMS/Burner Management System/High temp limit**
- **Safety shut off valves, pressures switches (fuel trains)**
- **Prepurge (> 4 furnace volumes)**
- **Pilot trial for ignition (not to exceed 15 seconds)**
- **Fire eyes to monitor flame**
- **Start burner at low fire**

LEL and UEL and AIT

Lower Explosive Limit (LEL)

- **Least concentration of Volatile Organic Compound (VOC) in air (or O_2) sustaining combustion**

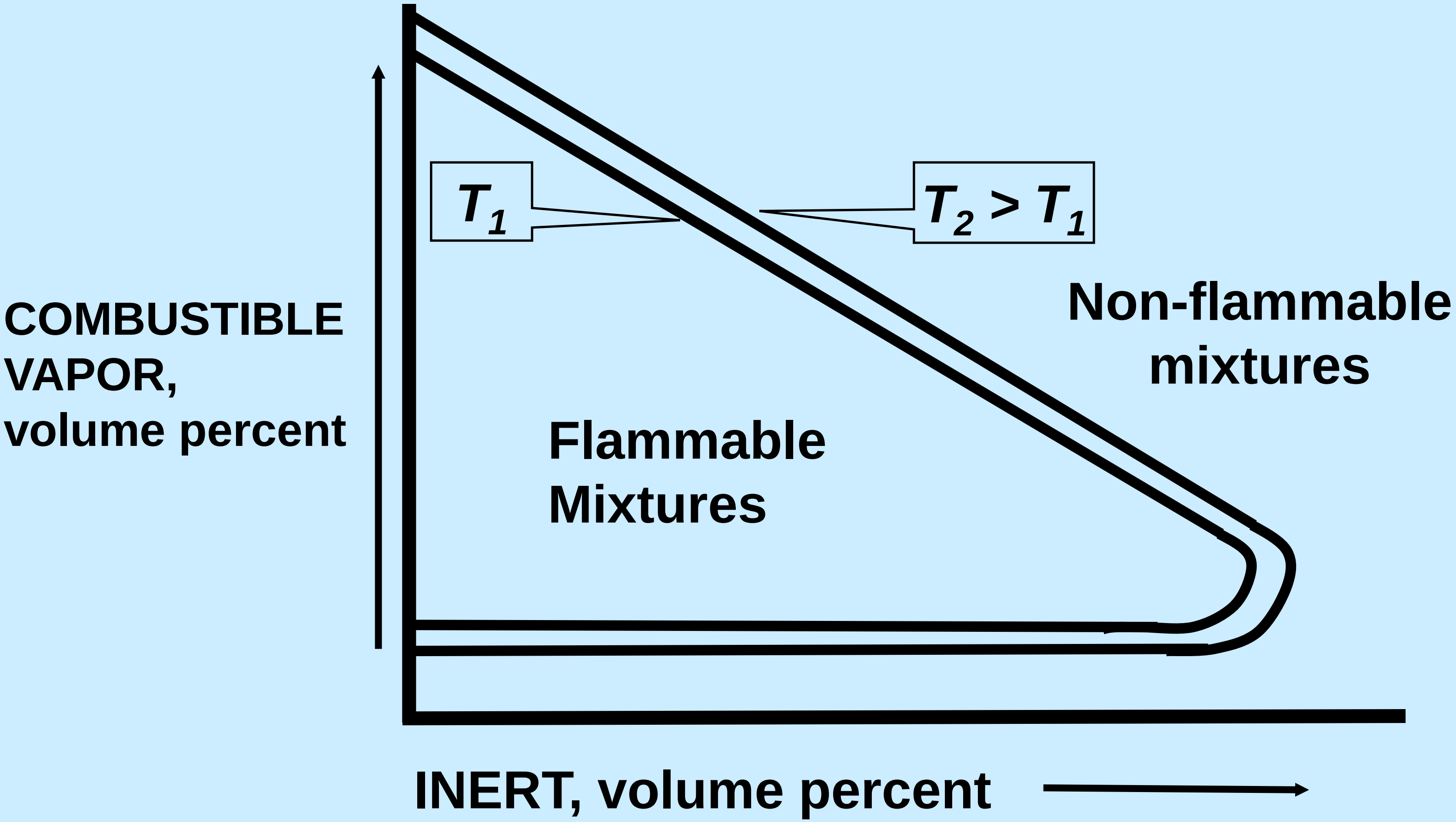
Upper Explosive Limit (UEL)

- **Highest concentration of VOC in air (or O_2) sustaining combustion**
- **See NFPA tables, reference texts**

See NFPA tables, reference texts

Limits of Flammability vs. Inert Percent in Air

% Air = 100% - % Combustible Vapor - % Inert



Computer Programs for Combustion and Heat and Mass Balances

- **Hauck E-Solutions**, Rotary dryer burner sizing, furnace sizing, emissions conversions, orifice calculations, heat transfer. Available free from http://www.hauckmfg.com/solutions/

- **HSC Software** By Outokumpu. Performs equilibrium, heat and mass balance, and chemical formula calculations. Has thousands of chemicals in the data base. Not user friendly; takes significant effort to learn. Excellent for detailed process calculations in one or more phases. http://www.outokumpu.com/hsc/brochure.htm purchase from http://www.chemsw.com/

Example Heat and Mass Balance

HEAT AND MASS BALANCE FOR THERMAL PROCESSING

By: Tom McGowan, TMTS Associates, Inc.
Filename: HTMSFMST
Date: 16-Apr-05
For:
Overview: Cocurrent kiln process
Excess air (XCS) includes leakage air.
All flow values (mass or volume) are per hour basis.
No POHC used for sizing maximum SCC burner capacity.
Propane gas is auxiliary fuel, baghouse after SCC for APC.

Major parameters entered in this line for excess air, primary and after burner temperatures

Major Parameters:

Primary Burner XCS	SCC XCS	POHC XCS	Prim. Temp	SCC Temp	Quench/Bag House Temp	Solids Chrg, lb/hr	Feed Moisture	Primary Radiatn Loss	Wet Wgt POHC
50%	25%	90%	1600	2000	400	40000	10.00%	5.00%	7.00%
		Ash temp	-150 F over gas temp				SCC Rad L	2.50%	

Stage 1, Primary Kiln Burner

Item	lb/hr	HHV MMBtuh	LHV MMBtuh	Sensible Heat MMBtuh	Flame Temp	Fuel Balance % Diff.
Auxiliary fuel	800	17.22	15.82			-0.09%
Air	18844					
Total	19644	17.22	15.82	15.82	3021	

Stage 2, Solids Injected in Primary Furnace

Item	lb/hr	HHV MMBtuh	LHV MMBtuh	Sensible Heat MMBtuh
Solids	33200			13.84
Moisture	4000		-4.24	3.08
POHC	2800	56.00	50.40	1.21
Air	76342			33.08
Total	116342	56.00	46.16	51.21

Calculations carry data from stage to stage for heat and mass

Example Heat and Mass Balance

```
Primary Chamber Outlet Gas Stream Plus Clean Ash
                                       HHV         LHV     Sensible
Item                       lb/hr    MMBtuh      MMBtuh  Heat MMBtuh
Total gas                 102786                              44.53
Total solids               33200                              13.84
Rad. loss                                        -3.66
Total input                                      58.32        58.38

Stage 3, Primary Chamber Outlet Gas Stream
                                                           Sensible SCC Inlet                      XCS air or
Item                       lb/hr                        Heat MMBtuh  Gas temp                         O2, dry
Total gas                 102786
Solids                                                         0.00                                       80%
Total                     102786                              44.53      1600                            9.4%

Page 2, Heat and Mass Balance for Hazardous Waste Incineration

Stage 4, Secondary Combustion Chamber
                                       HHV         LHV     Sensible     Flame      Scfm      Acfm
Item                       lb/hr    MMBtuh      MMBtuh  Heat MMBtuh      Temp                                      Fuel
Total inlet gas           102786                 44.53                                                          Balance
Auxiliary fuel              2000     43.05       39.55                                                          % Diff.
POHC in SCC                    0      0.00        0.00                                                           -0.89%
Air                        39258
Rad. loss                                        -2.91
Total                     144043                              81.91      3331     30356    143606
Total, stage 1-3+4                               81.18
```

Flows are calculated too for sizing fans and ducts

Oxygen/excess air calculated also

Properties of Selected Fuels

- **No. 2 Fuel Oil, 141,000 Btu/gal; 19,567 Btu/lb**
- **No. 6 Fuel Oil, 150,000 Btu/gal; 18,266 Btu/lb**
- **Bituminous Coal, Illinois, 13,390 Btu/lb; 35%VM, 56%FC + ash**
- **Wood, dry, 8,500 Btu/lb; 78%VM, 20%FC, + ash**
- **Wood, 50% MC (moisture content) wet basis, 4,250 Btu/lb**

Properties of Selected Fuels

- **Gasoline 127,000 Btu/gal; 20,800 Btu/lb; AIT 536°F; LEL 1.4%; UEL 7.6%; flash point, -50°F**
- **Natural gas, 1012 Btu/scf; 23,875 Btu/lb; AIT 1170°F; LEL 5%; UEL 15%**

Ref: North American Combustion Handbook

Metals In Combustion

- **Metals are neither created nor destroyed**
- **Oxides, chlorides, and sulfates of metals may be formed**
- **Fate varies with type of combustor and APC**
- **Low boiling point metals exit as vapors**
- **Some metals/salts form fine fume when condensed, e.g., P2O5**
- **Non-mercury/non-volatile metals easy to remove via baghouse or IWS**
- **Mercury requires carbon treatment in baghouse or condensing IWS**

How to Estimate Temperatures

Refractories and alloys have a characteristic color

(Ref: Marks ME Handbook, based on emissivity of iron and steel)

Color	**Temp, F**
Dark red	1050
Dark cherry red	1175
Cherry red	1375
Orange	1650
Light orange	1725
Yellow	1825
White	2200

Too hot to keep fingers on steel, >120F

Radiant heat noticeable/uncomfortable on skin, >400F

References

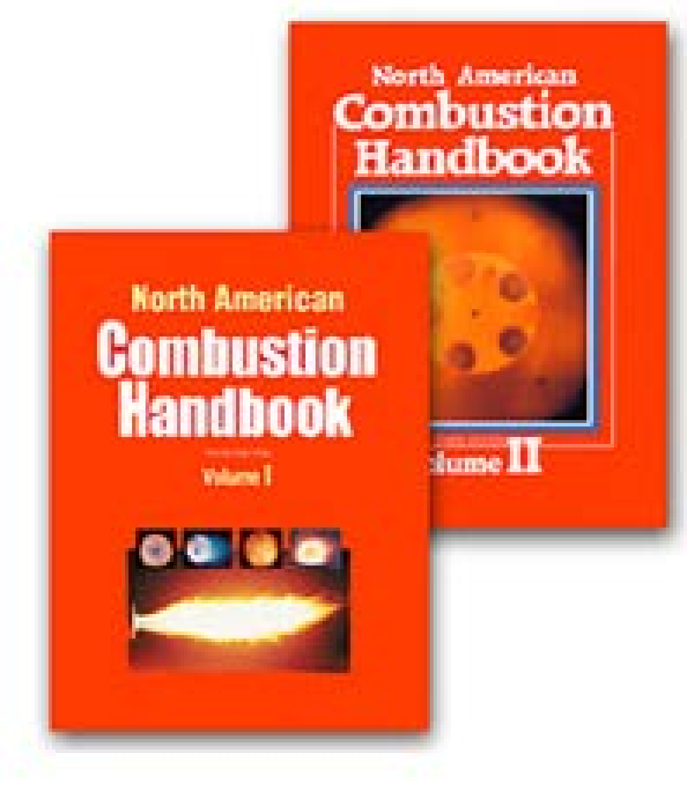
North American Combustion Handbook - 2 Volumes

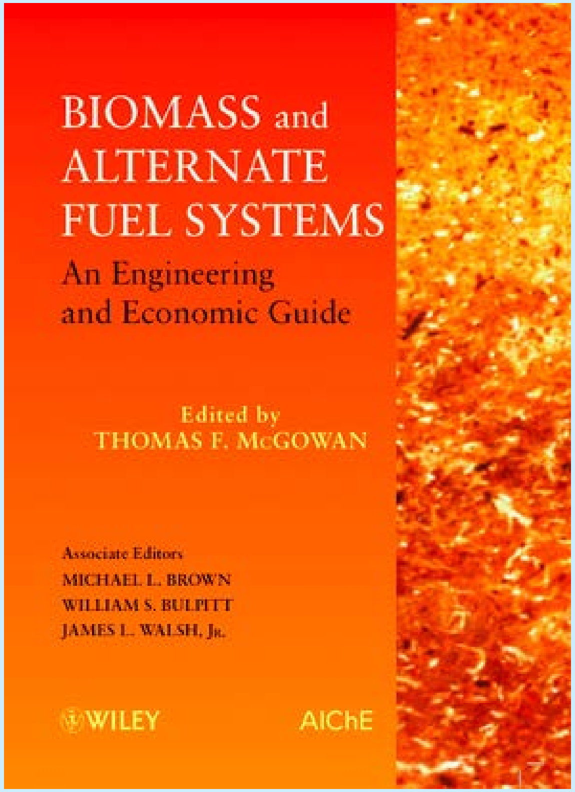
Order form: http://combustion.fivesgroup.com/publications/handbooks.html

Biomass and Alternate Fuel Systems:

An Engineering and Economic Guide

Order form: http://www.tmtsassociates.com/literature/book.html





BIOMASS and
ALTERNATE
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An Engineering
and Economic Guide

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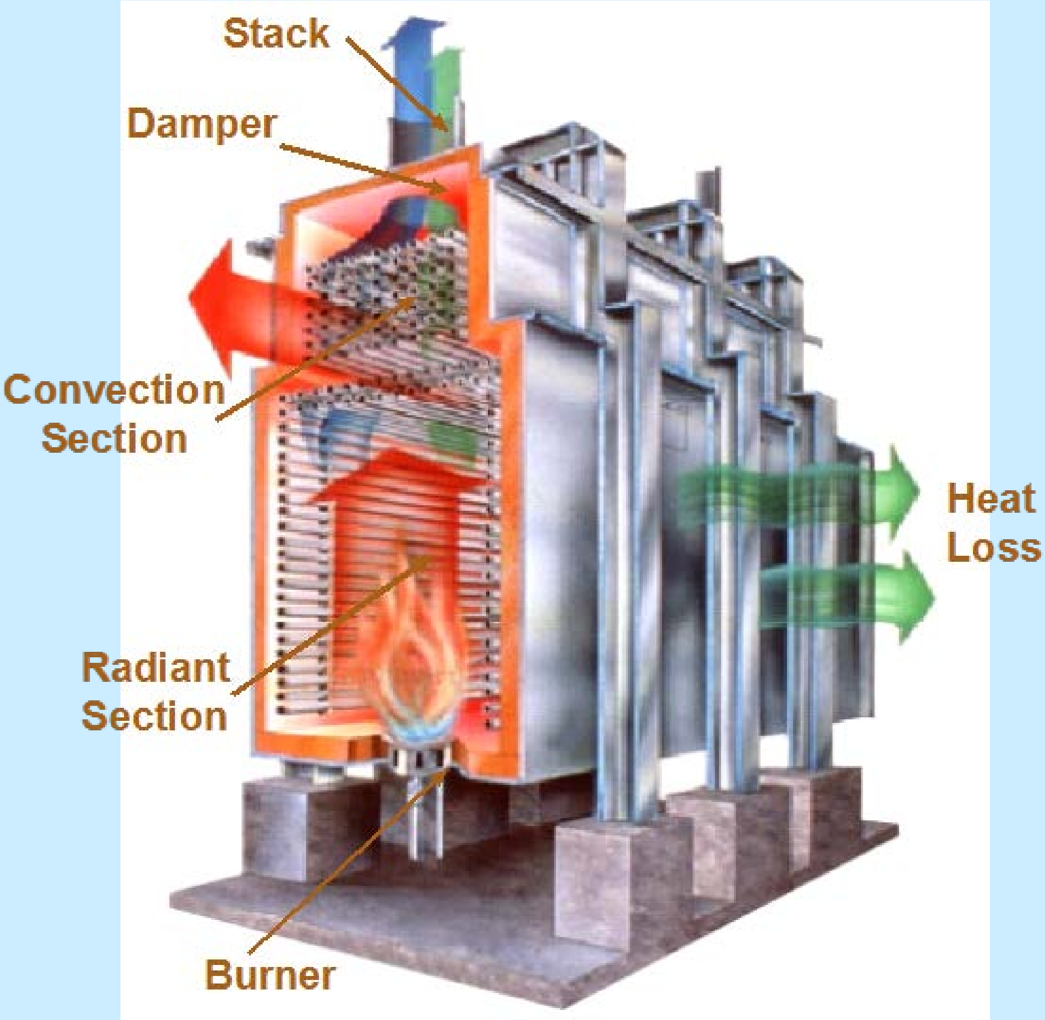
Combustion Applications

Refinery Furnaces – Heaters - Reformers

Refinery Heater Cross-section



Heater Burners & Pipe Rack

Courtesy John Zink

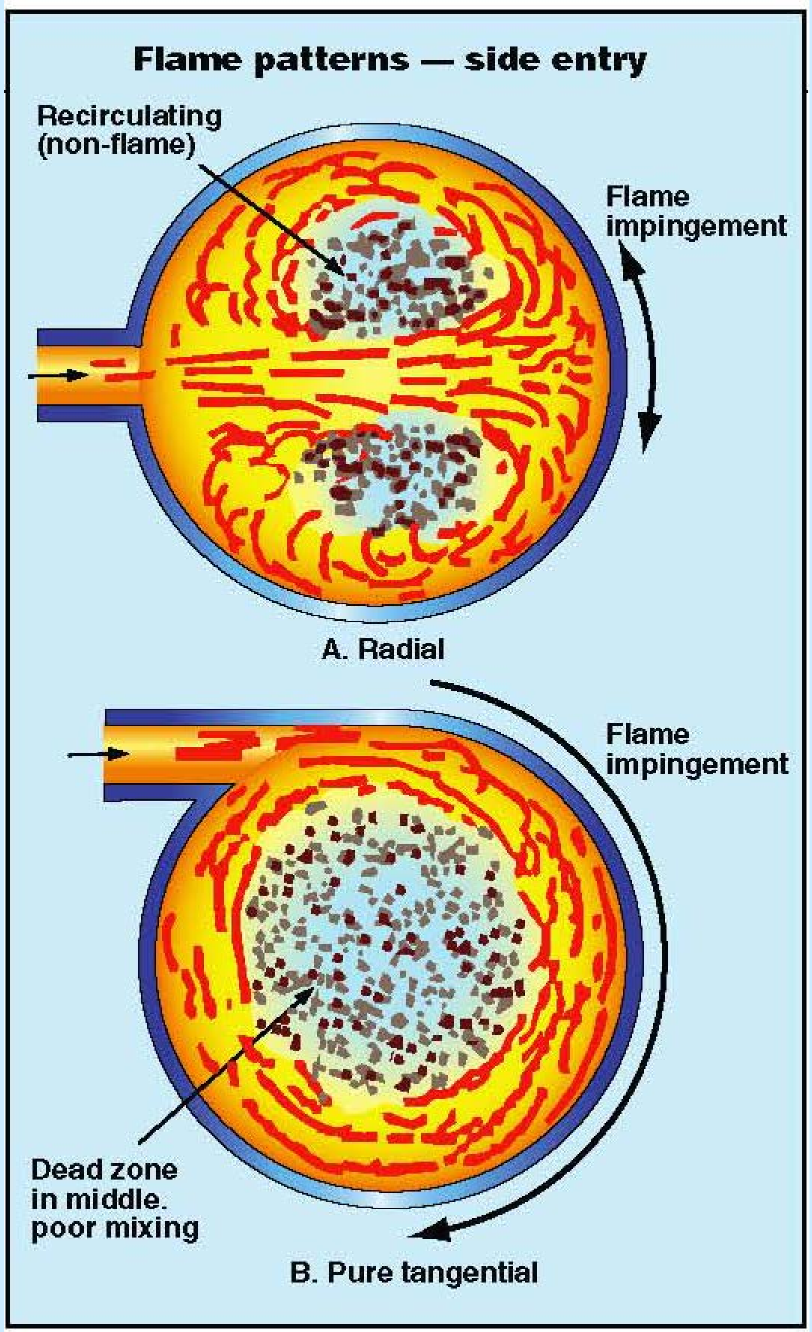
Steel Mill Arc Furnace Produces CO –

Application Requiring a Direct Thermal Oxidizer

Direct Thermal Oxidizer

Direct Thermal Oxidizer with 4 Auxiliary Burners

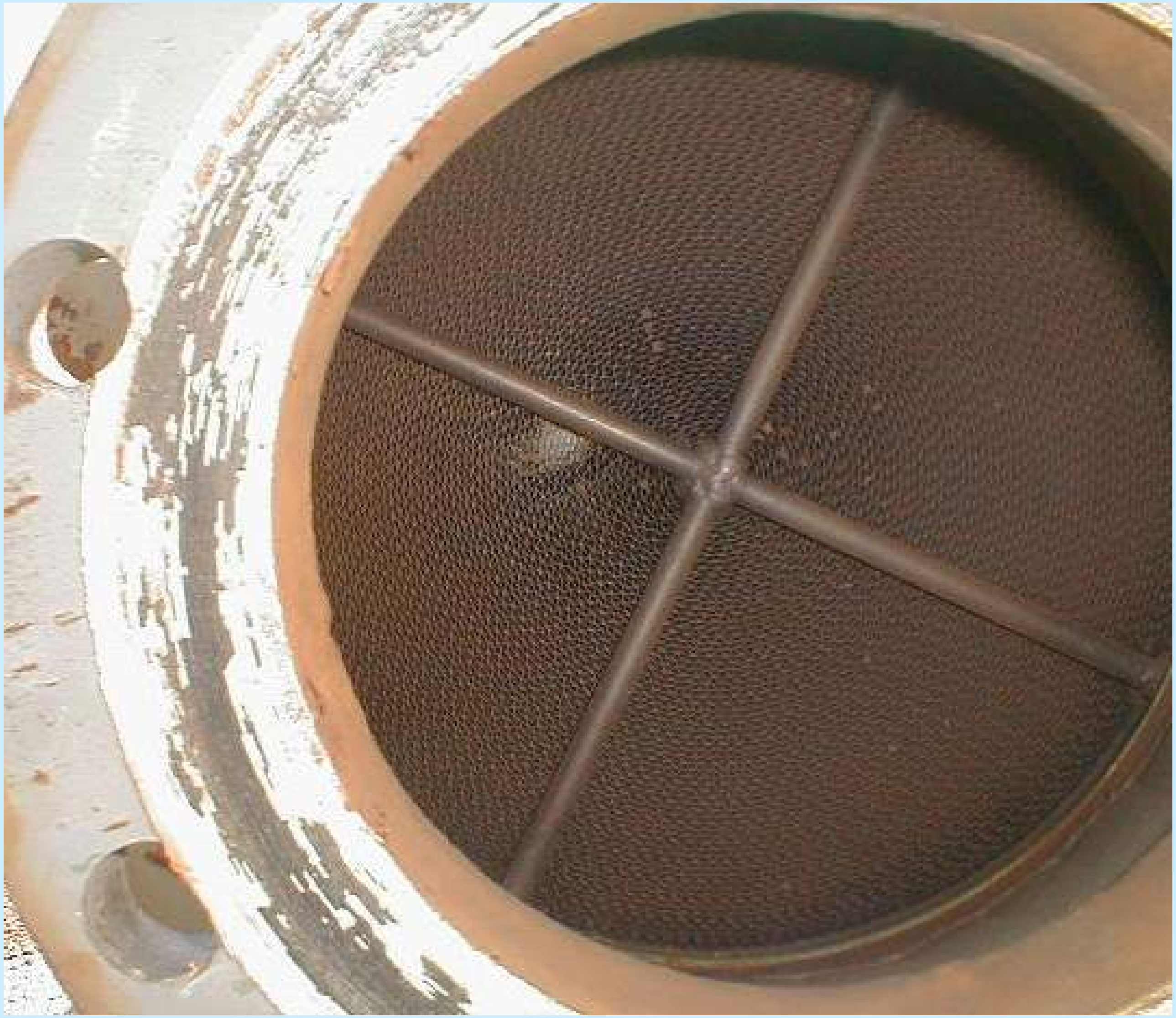
Oxidizer Fluid Dynamics – Mixing of waste Gas and Flame



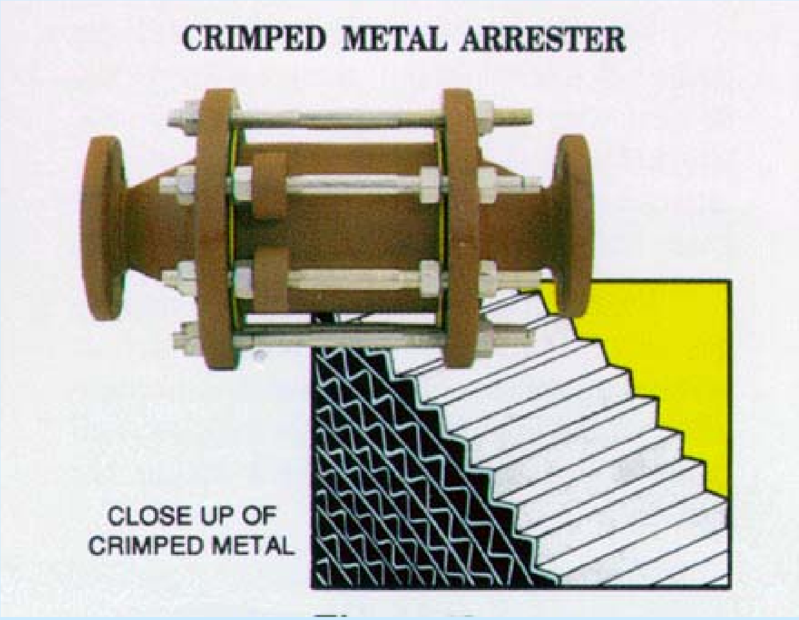
Safety Options for Oxidizers

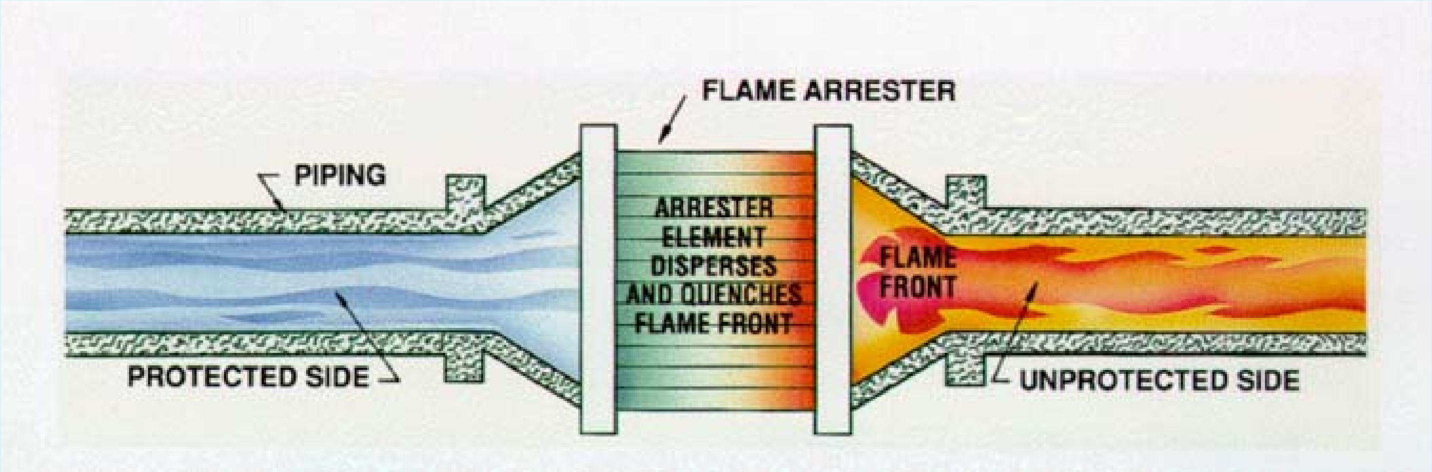
- Liquid seal tanks used for flares
- Flame arrestors
- LOC (limiting oxygen concentration approach) per NFPA 69 and NFPA 86, to prevent ignition by running rich
- Less than 25% LEL, or up to 50% LEL via upgraded controls

Crimped Metal Flame Arrestor



Crimped Metal Flame Arrestor





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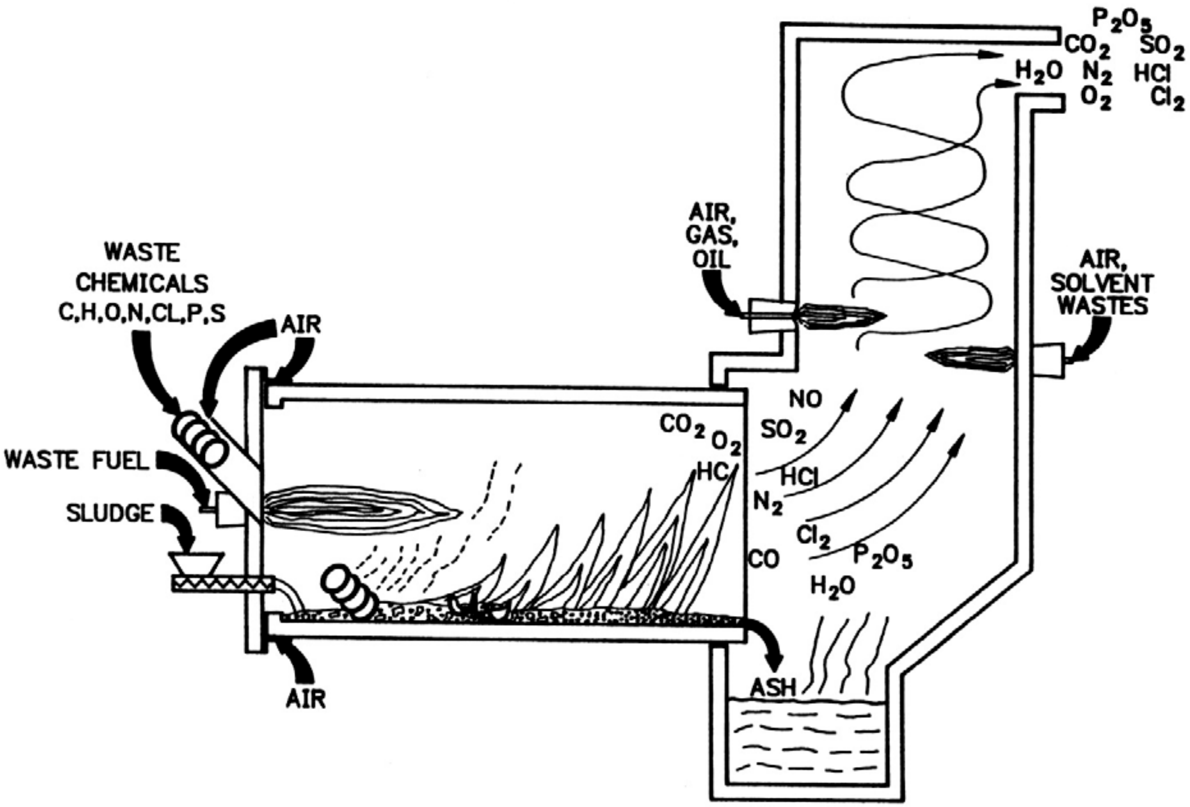
Rotary Kiln With Afterburner

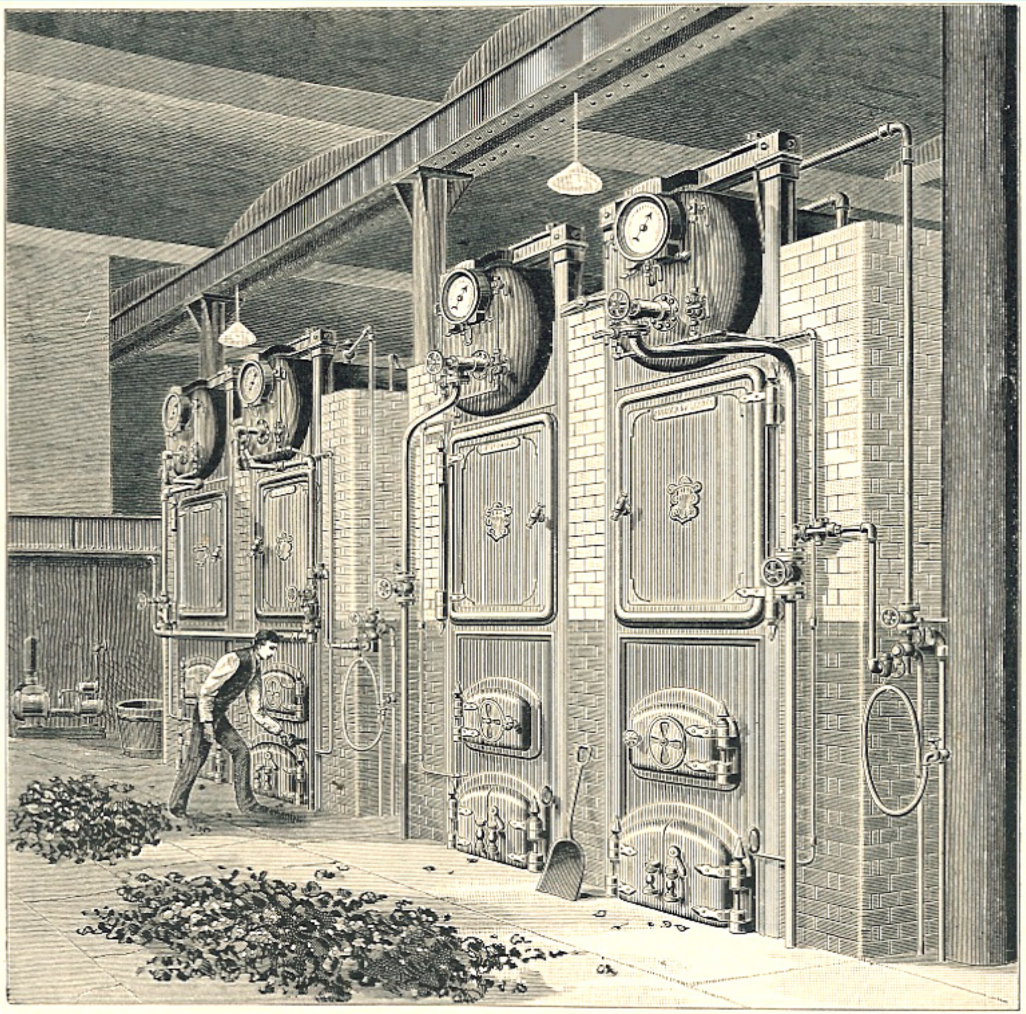


Rotary kiln—afterburner.

7.5’ x 45’ High Temperature Rotary Kiln

Steam Boilers Go Way Back...

360 hp Coal Boiler in London for Power Production, 1888



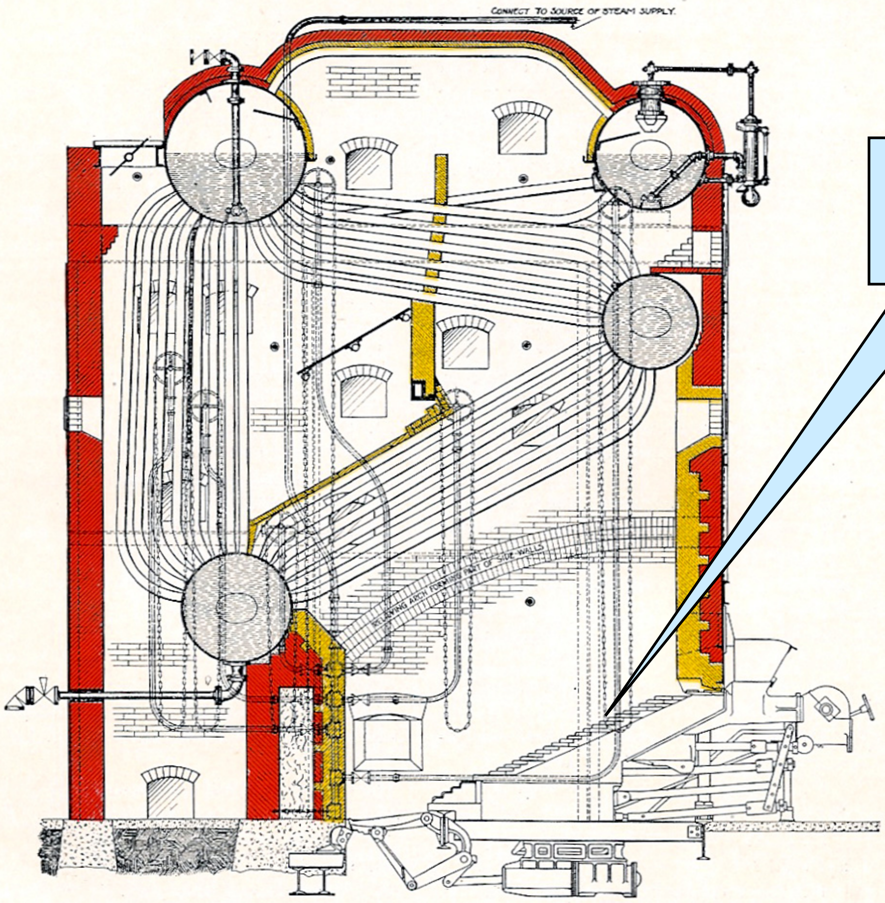
Babcock & Wilcox Boilers at the Chelsea Electricity Supply Company's Station, Chelsea, Eng. 360 H. P. Erected 1888-9.
The Brush Electrical Engineering Co., Limited, London, Contractors.

Reference: Steam, Its Generation and Use, Babcock & Wilcox, NY, 1892,

Four Drum Boiler for Coal Firing

With Sloped Reciprocating Stoker Grate

(Similar Grates Still in Use for MSW and Wood firing)

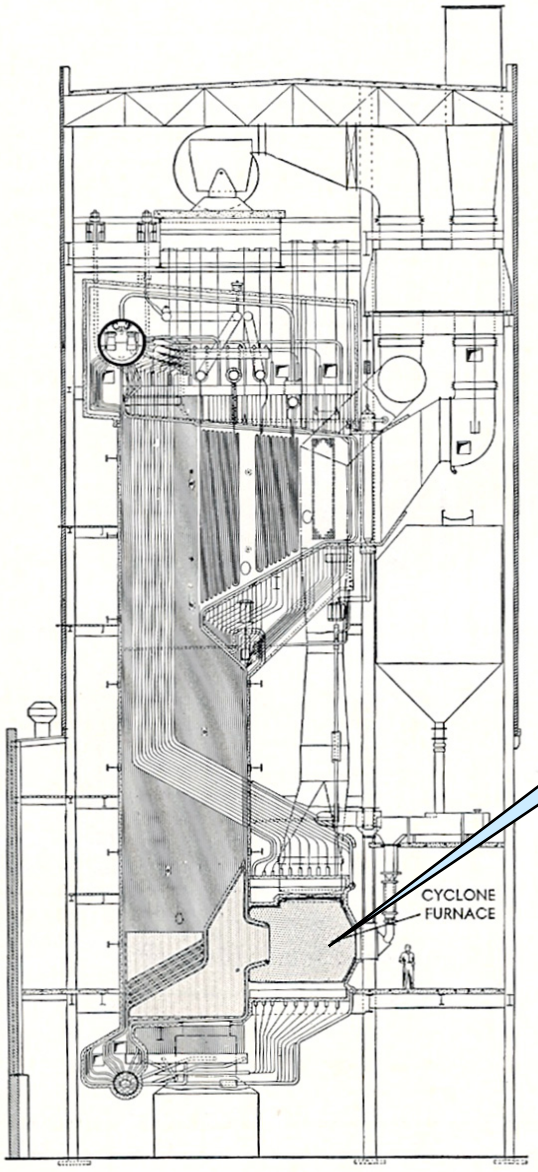


SECTIONAL SIDE ELEVATION,
KIDWELL BOILER, WITH TAYLOR UNDERFEED STOKER AND DIAMOND SOOT BLOWER

Sloped grates

Reference: The Kidwell Two Flow Ring-Circuit Water Tube Boiler, Kidwell Boiler Company, Milwaukee, WI, 1923

Modern Radiant Boiler with Cyclone Furnace for Coal Firing

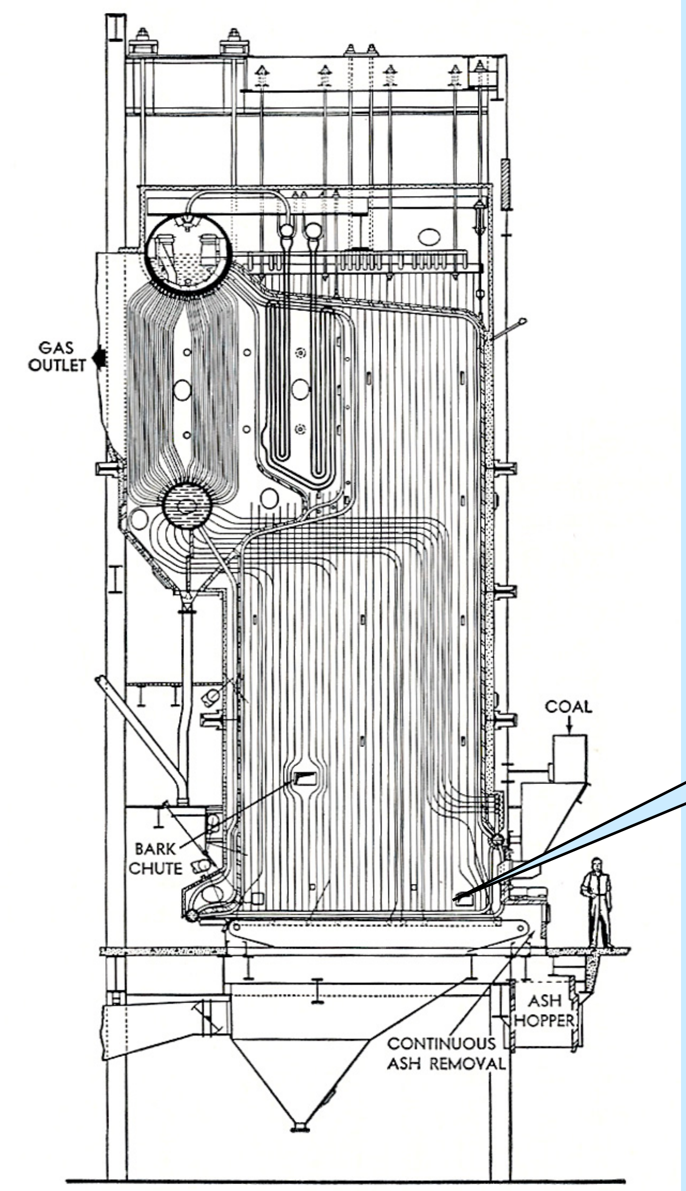


Cyclone Furnace

A Radiant boiler with Cyclone Furnaces adapted to burn hogged fuel with coal

Reference**: Steam, Its Generation and Use, Babcock & Wilcox Company, NY 1963**

Large Industrial High-Pressure Water Tube Boiler for Coal or Wood Firing

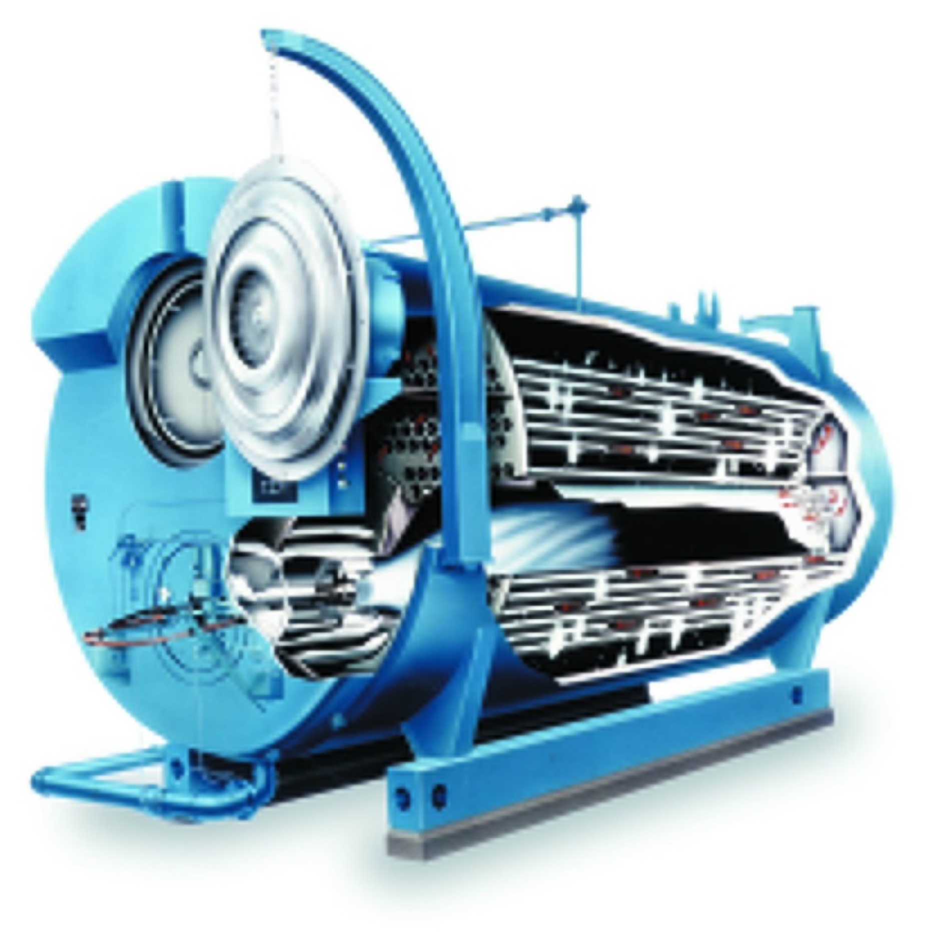


A Two-Drum Stirling boiler with spreader stoker for coal and/or wood firing

Horizontal Chain Grate

Reference: Steam, Its Generation and Use, Babcock & Wilcox Company, NY 1963

Scotch Marine Fire Tube Boiler for Gas & Oil



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Heat Recovery

- Gas-to-gas heat for air preheat
- Waste heat boiler downstream of combustor
- HX used more where fuel costs are high
  - Economics – equipment, maintenance cost vs. fuel savings.
  - Is there a use for the recovered heat?
  - Temperatures (air to air HX unreliable above 1500ºF, in dusty streams)

Shell and Tube Heatexchangers – Shell Side

Shell and Tube Heat Exchangers – Tube Side

Heat Recovery via Waste Heat Boilers

- Use hot gases produced by another process
- Economics usually poor < 5 MM Btu/hr
- Efficiency ~ 60-70% vs. 80%+ for standard boilers

Questions???