Basics of Combustion, Fuels and Air Pollutants

for

Virtual AIChE Local Chapter

April 25, 2013

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Combustion Basics Includes material from J.J.Santoleri's Drexel University Incineration Course at Drexel University

You will learn about:

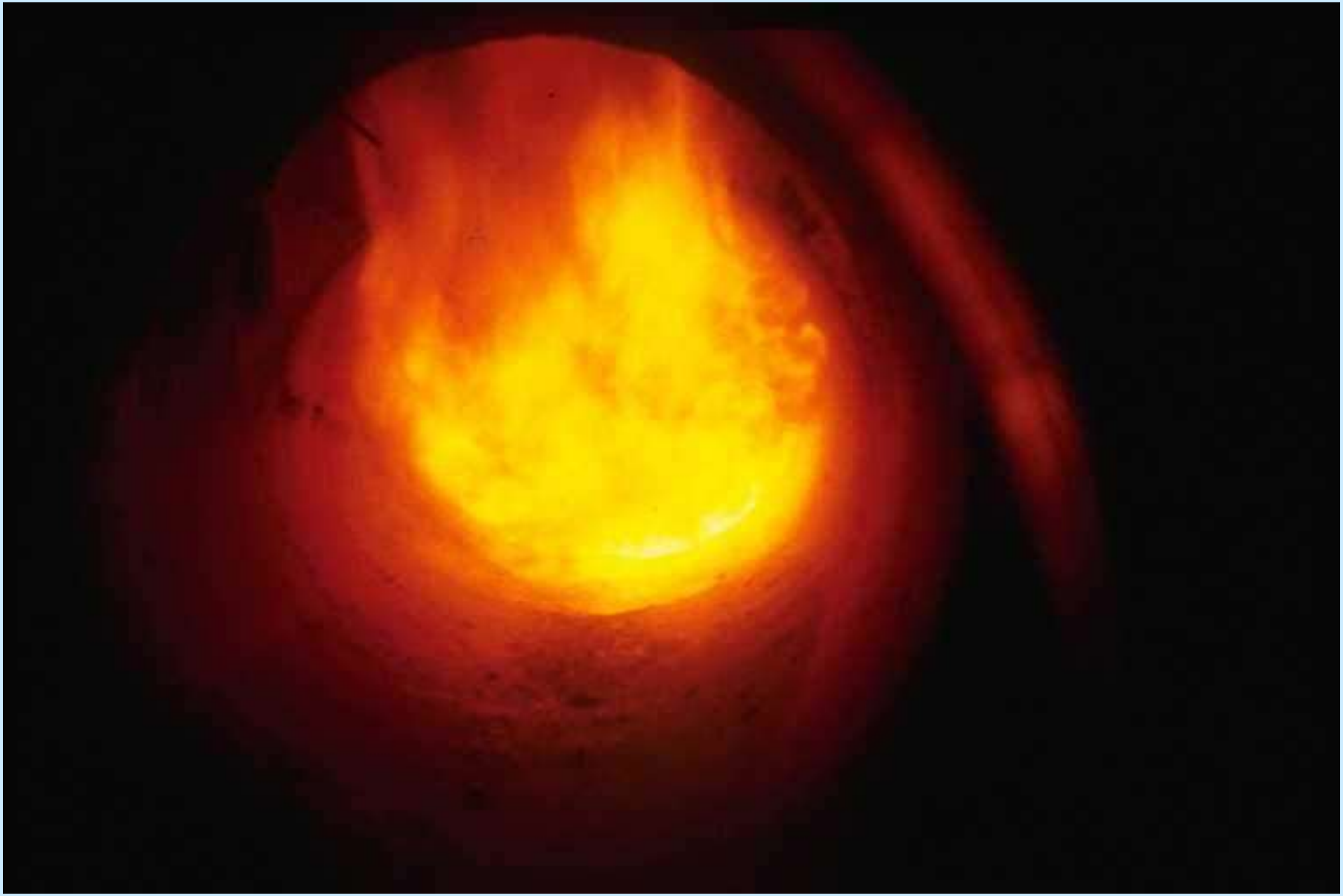
- Fuel properties
- Combustion calculations
- Air/fuel ratio and excess air
- Flame temperatures
- Combustion generated air pollution

COMBUSTION BASICS

- Combustion Reactions
- The Three T's

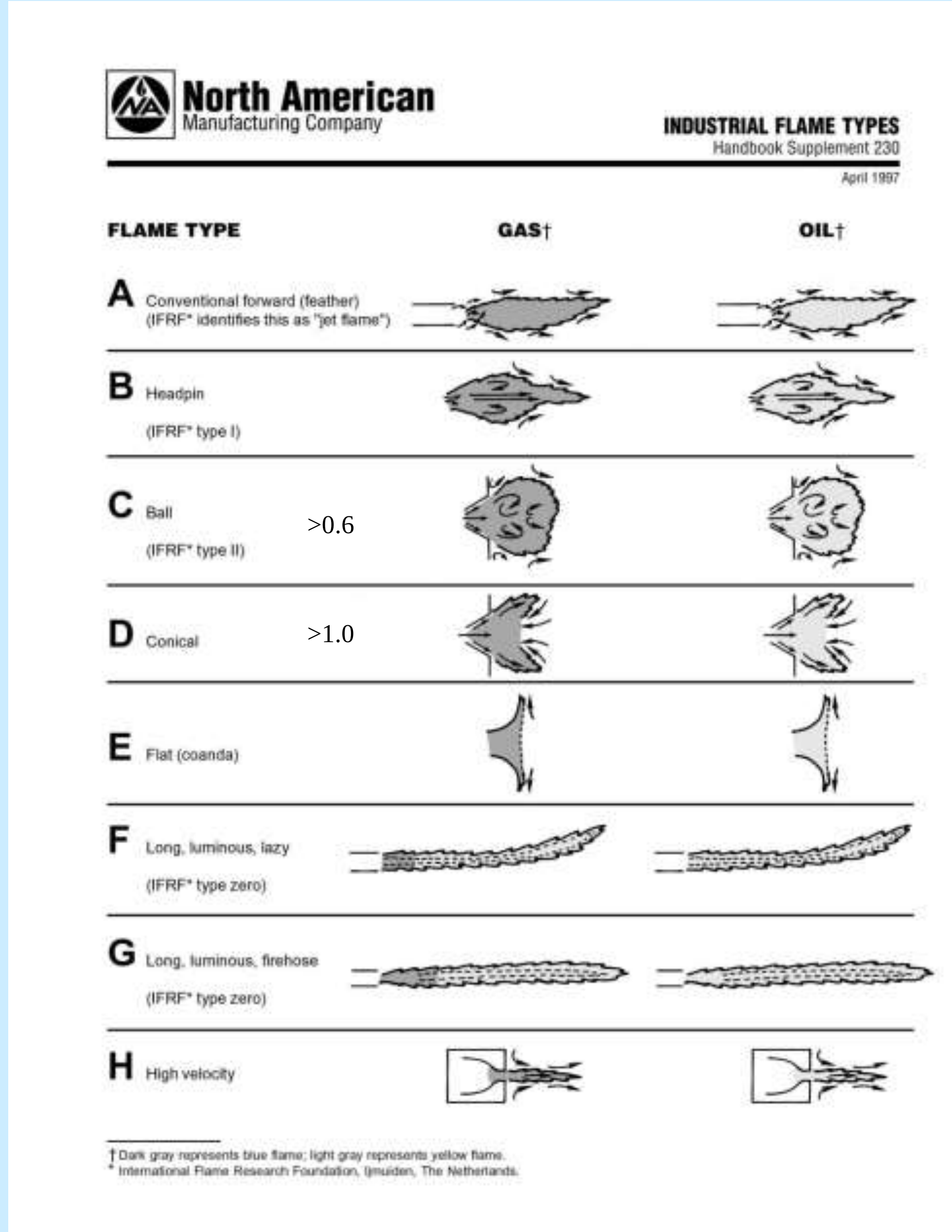
  (Time, Temperature and Turbulence)
- The Ideal Gas Law

Flame from Batch Kiln Test



Flame Types

It can be said there are no bad burners – but they can be misapplied, and be the wrong burner for a particular application



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			

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

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Some terms and their definitions used in this section are:

- HHV: Higher heating value of a fuel in Btu/lb, also known as gross heating value.
- LHV: Lower heating value of a fuel. Equal to HHV - latent heat of vaporization of water formed from hydrogen in the fuel or moisture in the fuel. Also known as net heating value.
- XS air: Excess air percent. This is the amount of air exceeding that required to completely combust the fuel.
- TA: Theoretical Air = Stoichiometric air = 0% XS air, the exact amount of air needed to burn a fuel.
- ppm: Parts per million; for gases, on volume basis.

TERMINOLOGY

- ppmvd: ppm, by volume, dry basis, water excluded.
- acfm: Actual cubic feet per minute of a gas at measured temperature and pressure.
  acfm = scfm x ((T°F+460)/520) x (14.7/P in psia)
- scfm: Standard cubic feet per minute of gas (@ 60°F, 14.7 psia)
- dscfm: Dry scfm (scfm less water vapor).
- AFT: Adiabatic flame temperature.
- Available heat: The percent of heat input to a combustion system that can be transferred to the load (furnace, boiler, air heater or incinerator) at a given exit flue gas temperature.

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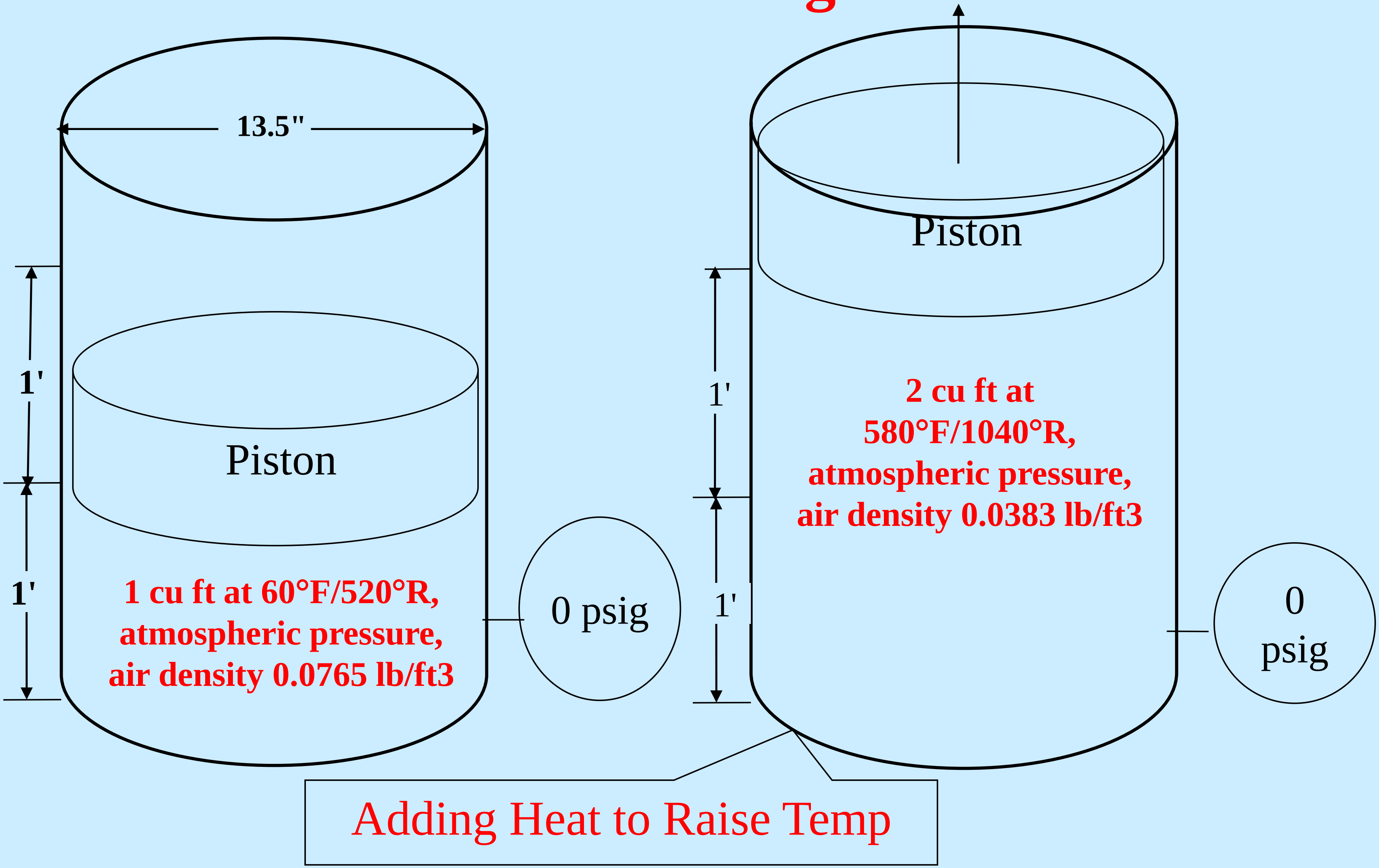
Visualize Temperature and Volume Change



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Combustion Reactions

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

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

Common Fuels

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

Basic Combustion Calculations

(With oxygen as the oxidizer)

Carbon	C	+	O_2	→	CO_2
Mols	1		1		1
Wt.	12		32		44
Lb/lb fuel	1		2.66		3.66

Heat released: 14,100 Btu/lb of fuel

Hydrogen	H_2	+	$1/2O_2$	→	H_2O
Mols	1		1/2		1
Wt.	2		16		18
Lb/lb fuel	1		8		9

Heat released: 61,100 Btu/lb of fuel

Basic Combustion Calculations

The Stoichiometric Ratio is the ratio of oxygen to fuel that is required to complete perfect combustion with no unused fuel or oxygen = 0% XS Air.

Methane with 0% excess air as the oxidizer

Input

Methane	CH_4	+2	$(O_2$	+	$3.76N_2)$	→
Mols	1		2		7.52	
Wt.	16		64		211	
Lb/lb fuel	1		4		13.2 (Air =17.2)	

Output

	CO_2	+	$2H_2O$	+	$7.52N_2$	Totals
Mols	1		2		7.52	10.5
Wt.	44		36		211	291
Lb/lb fuel	2.74		2.25		13.2	18.2
Vol. %, wet	9.5 (= 1/10.5)		19.0		71.5	
Vol. %, dry	11.7 (= 1/8.5)		N/A		88.3	
Wt. %	15.1 (= 44/291)		12.4		72.5	

Heat released: 23,879 Btu/lb of fuel higher heating value

Basic Combustion Calculations

Note: Some excess air is used to compensate for less-than-ideal situations, and to help assure that adequate oxygen is available for complete combustion. In some cases, it's needed to limit temperature, such as for dryers.

(Methane with 100% excess air)

Input

Methane	CH_4	+2 x 2	(O_2	+	$3.76N_2$)	→
Mols	1		2 x 2		2 x 7.52	
Wt.	16		2 x 64		2 x 211	
Lb/lb fuel	1		2 x 4		2 x 13.2	(Air = 34.4)

Output

	CO_2	+	$2H_2O$	+	$15.0N_2$	$+ 2O_2$	Totals
Mols	1		2		2 x 7.53	2	20
Wt.	44		36		2 x 211	64	565
Lb/lb fuel	2.74		2.25		2 x 13.2	4	35.4
Vol. %, wet	5		10		75	10	
Vol. %, dry	5.54		N/A		83.3	11.1	
Wt. %	7.8		6.4		74.5	11.3	

(Note: A mole of any gas = 378.7 ft3 at standard conditons)

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] Btu per Cu Ft Gross	Btu per Cu Ft Net[d]	Btu per Lb Gross	Btu per Lb Net[d]	Cu Ft per Cu Ft of Combustible: Required for Combustion O_2	N_2	Air	Flue Products CO_2	H_2O	N_2	Lb per Lb of Combustible: Required for Combustion O_2	N_2	Air	Flue Products CO_2	H_2O	N_2	Experimental Error in Heat of Combustion Percent + or −
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 Flock, 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

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	

Calculations carry data from stage to stage for heat and mass

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

Example Heat and Mass Balance

Primary Chamber Outlet Gas Stream Plus Clean Ash

Item	lb/hr	HHV MMBtuh	LHV MMBtuh	Sensible 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

Item	lb/hr	Sensible Heat MMBtuh	SCC Inlet Gas temp	XCS air or 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

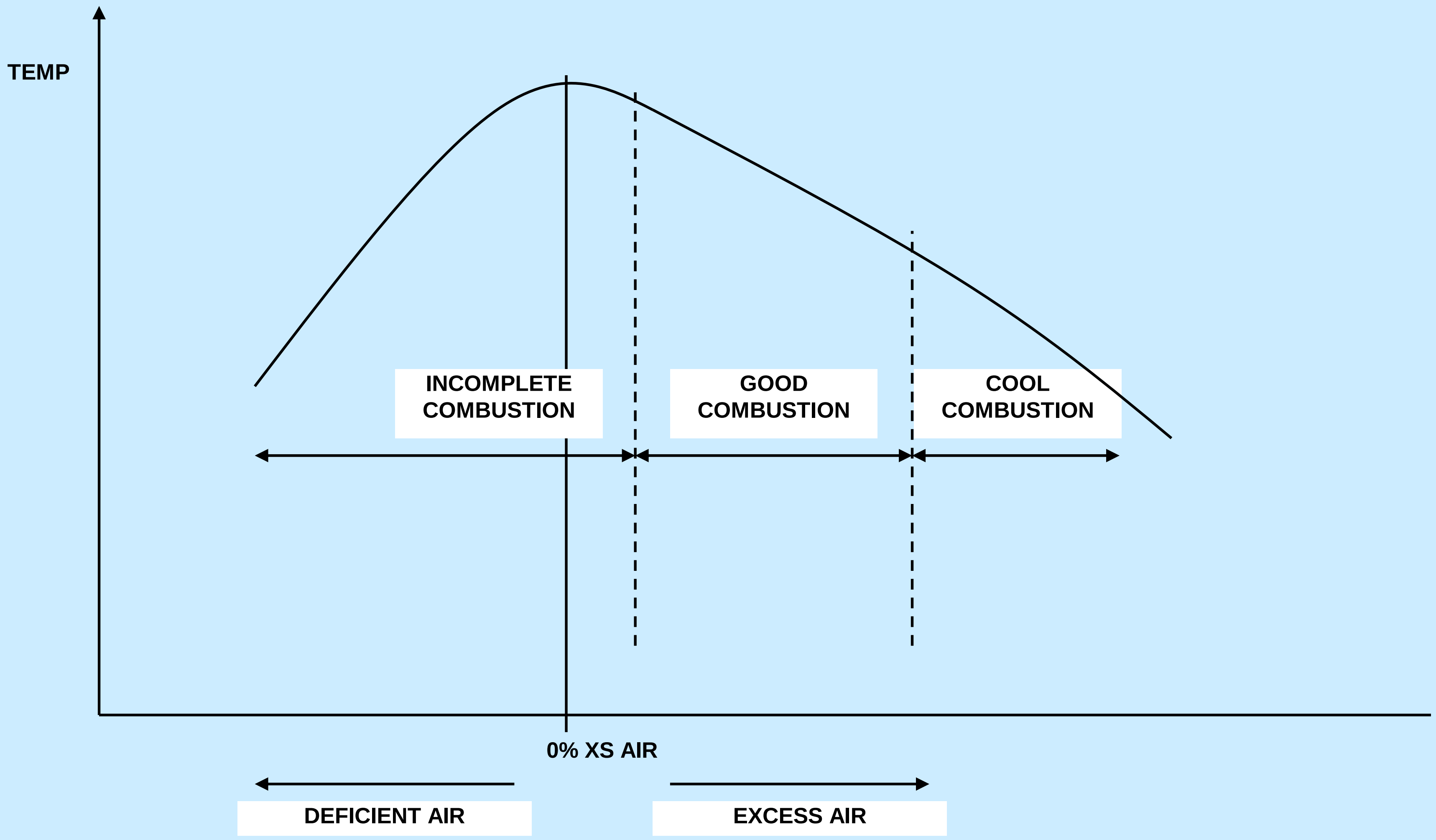
Stage 4, Secondary Combustion Chamber

Item	lb/hr	HHV MMBtuh	LHV MMBtuh	Sensible Heat MMBtuh	Flame Temp	Scfm	Acfm	Fuel Balance % Diff.
Total inlet gas	102786		44.53					
Auxiliary fuel	2000	43.05	39.55					
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

Temperature vs. Air to Fuel Ratio



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Adiabatic Flame Temperature

(at zero % heat loss)

$Q = M \times C_p \times$ temperature difference, or

Temperature difference = $Q / (M \times C_p)$

Where Q = Btu

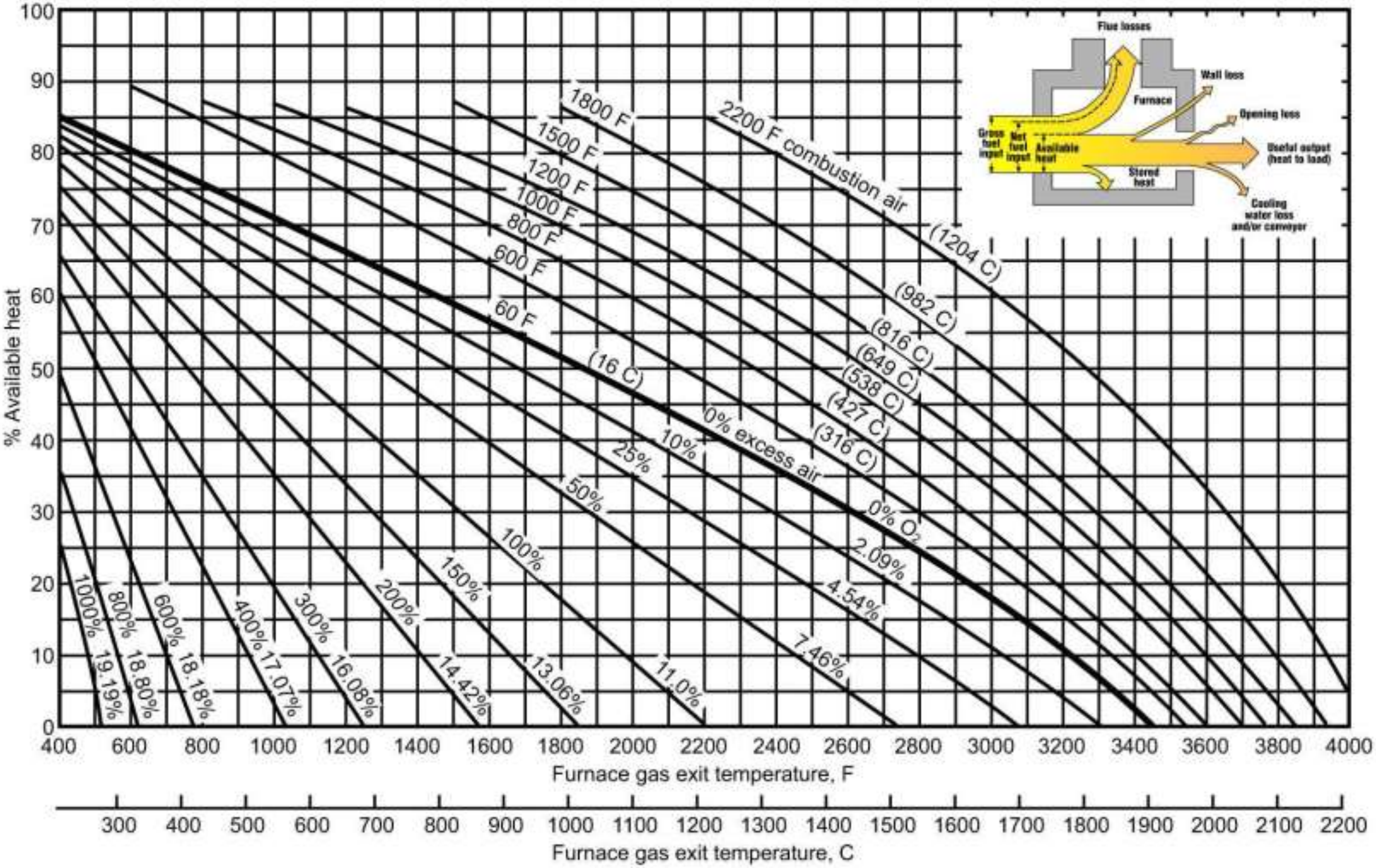
M = Mass, lb of combustion products

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

For methane at 100% XS Air, AFT ~ 2200F/1200C

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.



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

Used with permission of NAMfg

Products and Byproducts 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 CO, VOCs/HAPs, Semi Vols, SO_2, SO_3, NOx, HCl, HF, HBr and others, depending on the composition of the fuel and level of oxygen

Retention Time in Afterburners used to destroy CO and VOCs/HAPs/Semi Vol

- **Retention Time (RT): Length of time in the high temperature zone to complete the combustion reactions**

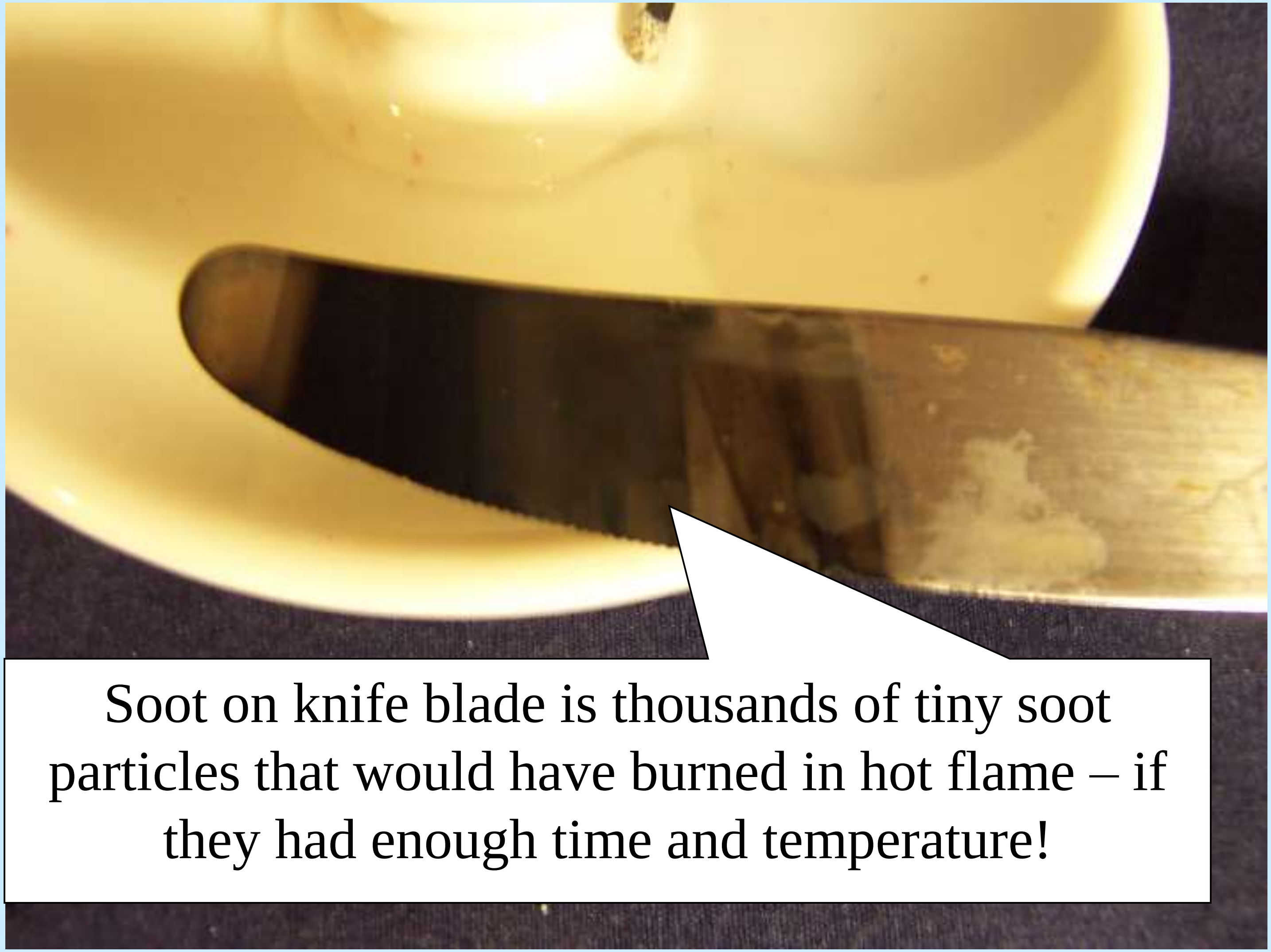
$$RT = \frac{\text{Volume of combustion chamber}}{\text{Actual Flow rate of combustion gases}}$$

- **Use longer retention time for more difficult to burn fuels**

Learning from a Candle…

Except for carbon and metals, solids turn into gases before they burn! Remember the 3 T's!

Quenching a Flame



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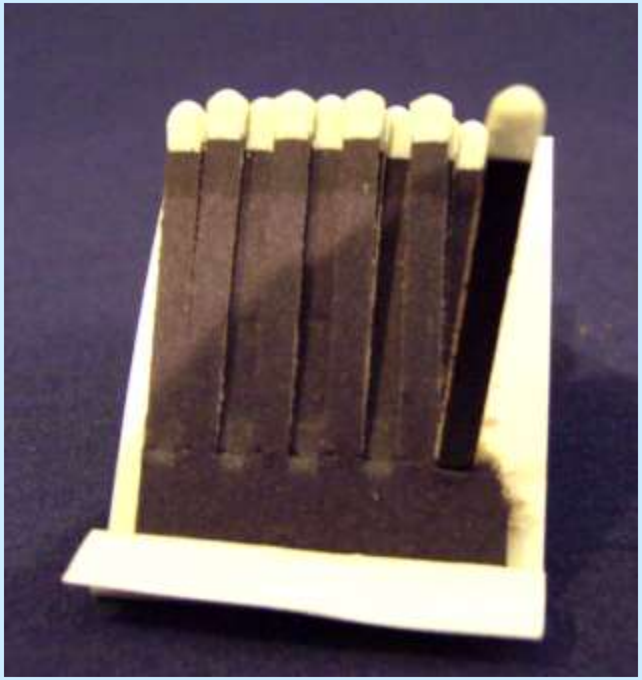
Pyrophoric Materials

The heat from a bit of friction on the scratch block is enough to reach AIT, the autoignition temperature.
The sulfur and phosphorous mixture is pyrophoric and burns easily.



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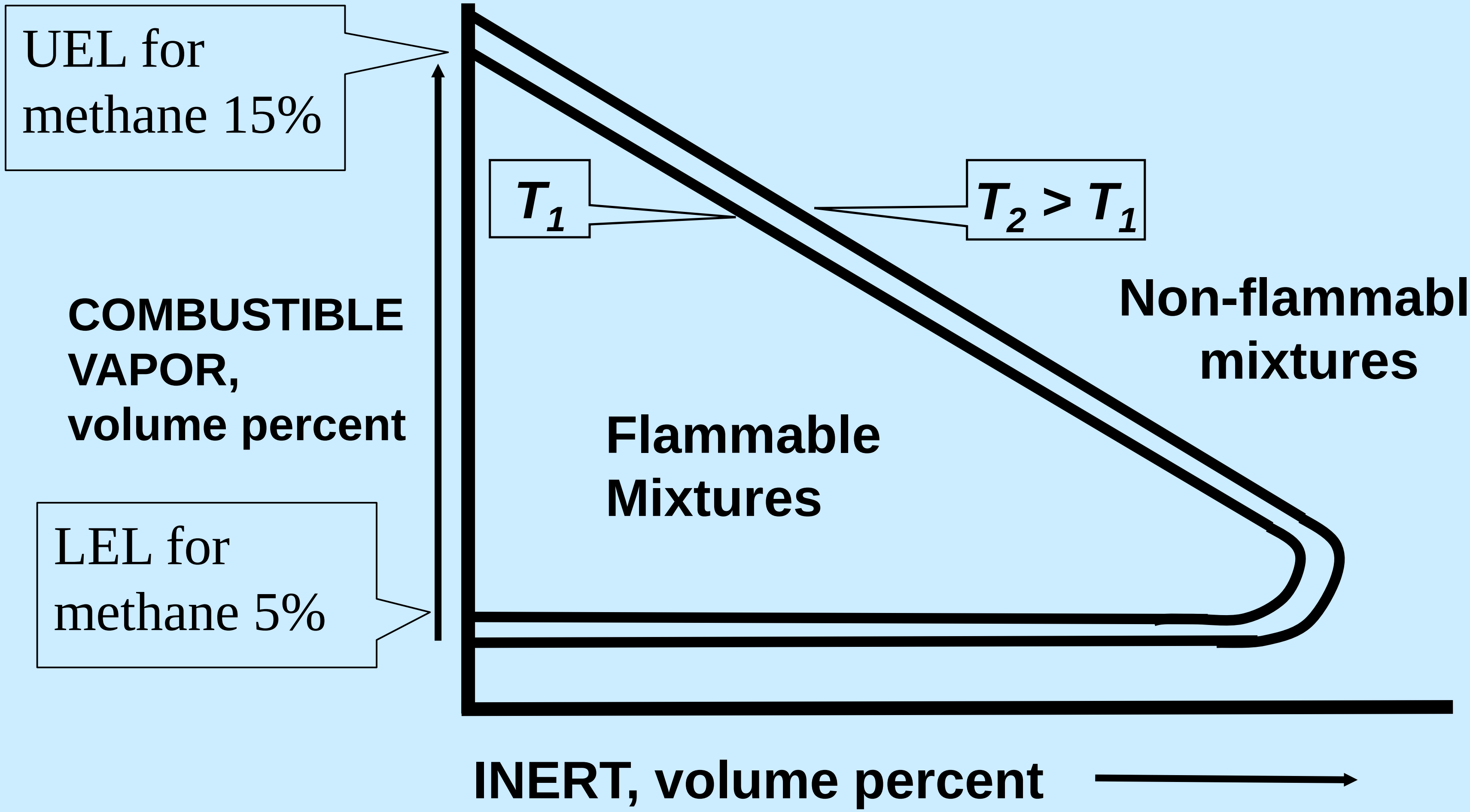
Limits of Flammability vs. Inert Percent in Air

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



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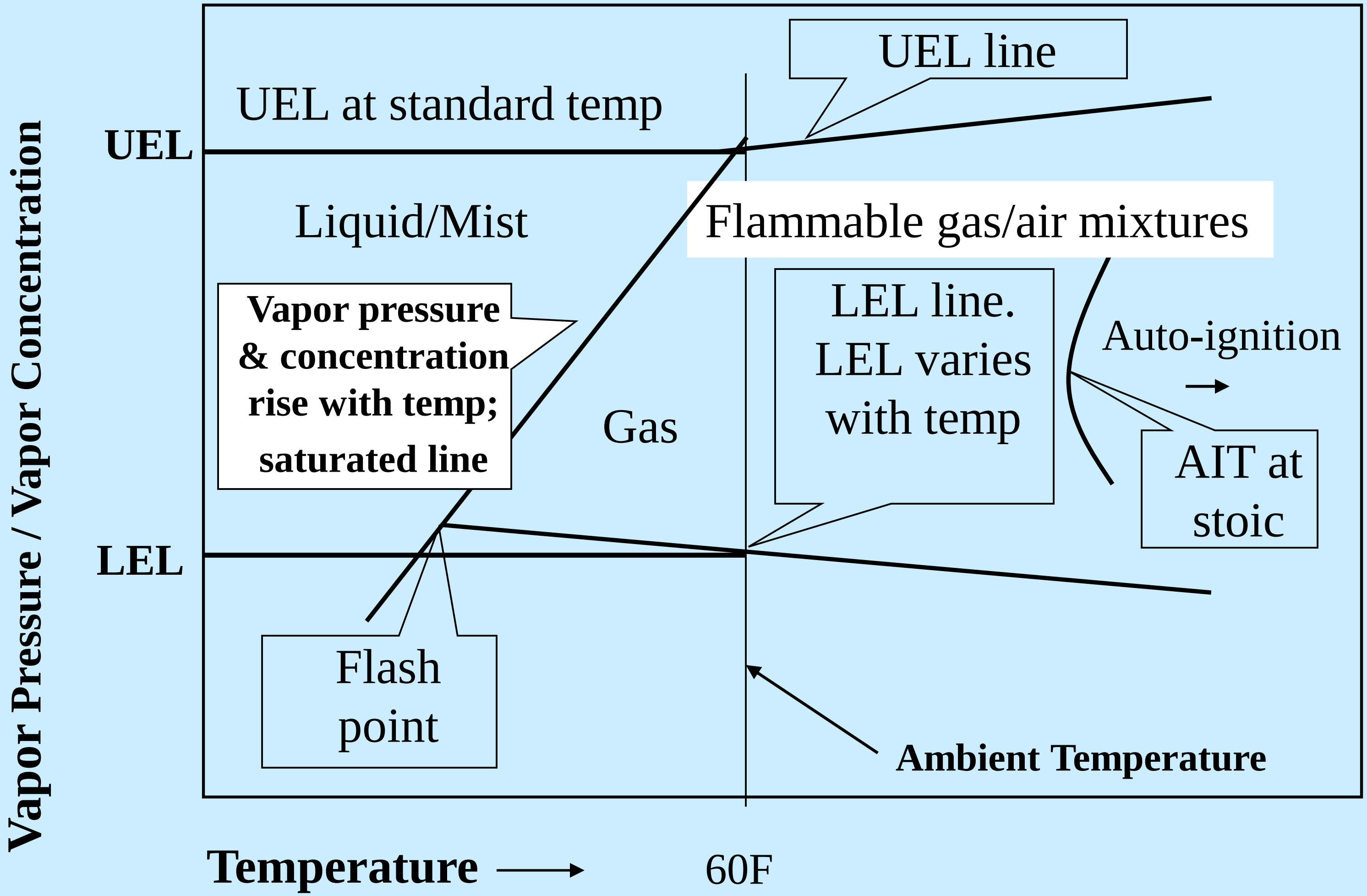
Limits of Flammability vs. Temperature



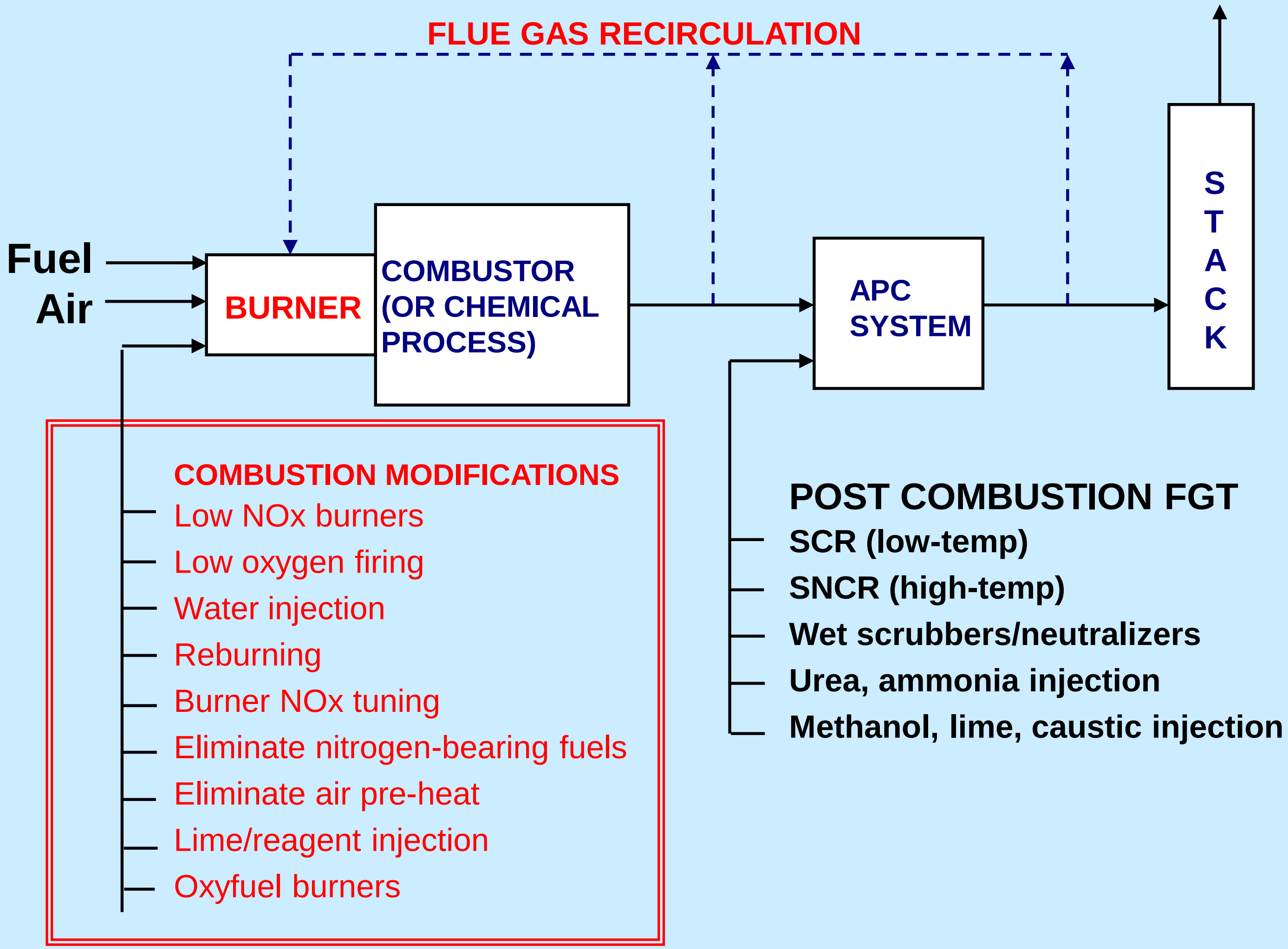
Hexane LEL =1.1%, UEL = 7.5% at 60F; Flash Point = -7°F AIT at Stoic. = 437°F

Ref: Graph adapted from US Bureau of Mines Bulletin 627; numerical data from NFPA 325M

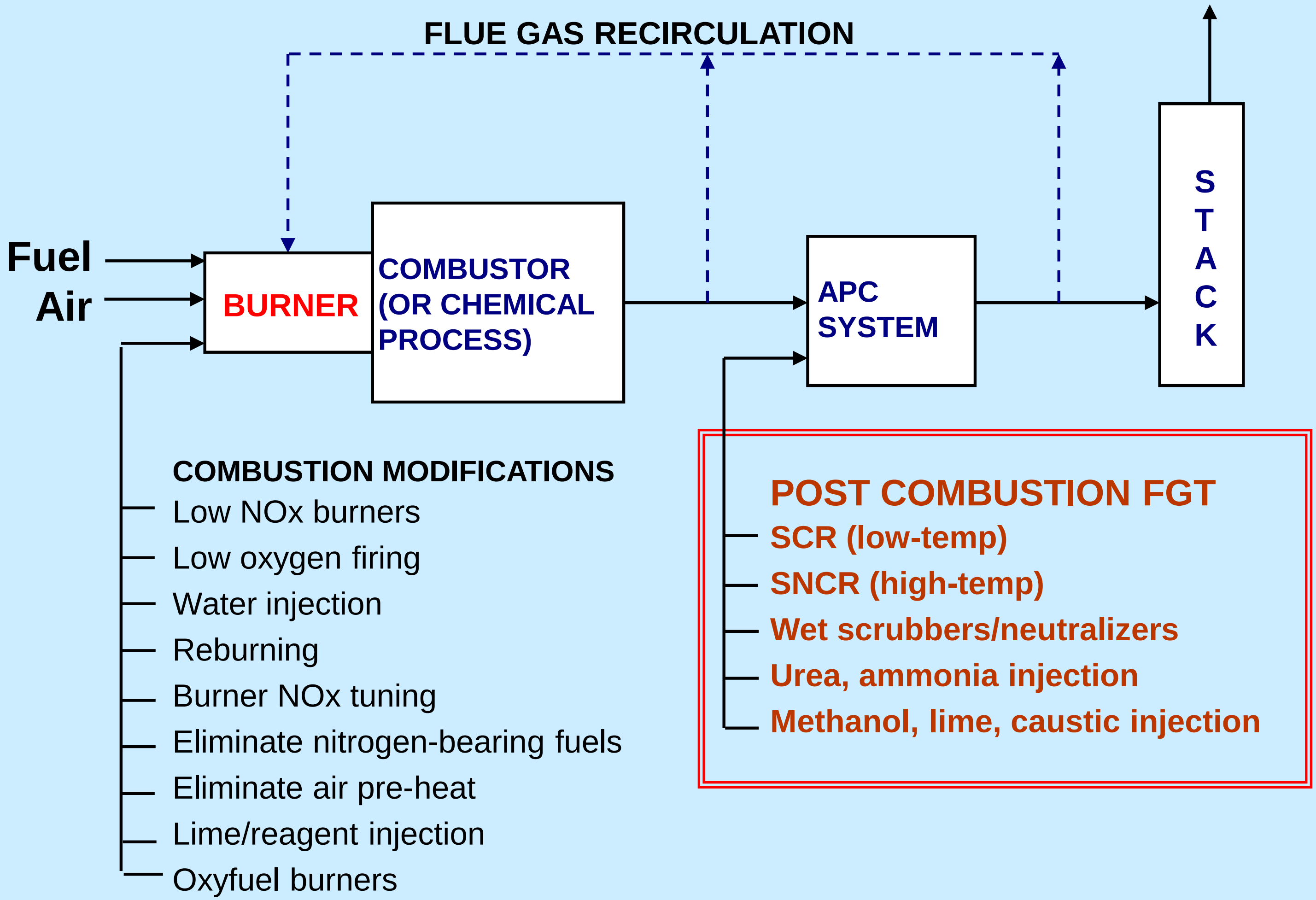
Air Pollutants from Combustion and Control Strategy

- **CO - better mixing, higher temp, catalyst**
- **NOx - low NOx burners, SCR, SNCR, FGR, Low O2, water injection, lower fuel bound N2, etc.**
- **VOCs - oxidizers, catalysts, carbon, zeolites**
- **Acid gas - e.g., HCl -- wet or dry scrubber**
- **Dioxins - >1600F/870C; fast quench, carbon, etc.**
- **PM - Baghouse, ESPs**
- **Metals – Baghouse, ESPs; for Hg, carbon or IWS**
- **CO2 - Greenhouse gas - use more efficient process**

NOx Control Technologies
Post Combustion Flue Gas Treatment



NOx Control Technologies
Post Combustion Flue Gas Treatment



Some Combustion References

- **North American Combustion Handbook, 2 volumes:**

http://www.namfg.com/comb-handbook/gra49.pdf

- **B&W Steam Book**

http://www.babcock.com/library/steam.html

- **Biomass and Alternate Fuel Systems: An Engineering and Economic Guide**

http://tinyurl.com/Amazon-biomass-book

- **Papers and Literature on TMTS website**

www.tmtsassociates.com