

Basics of Combustion, Fuels and Air Pollutants

for

Virtual AIChE Local Chapter

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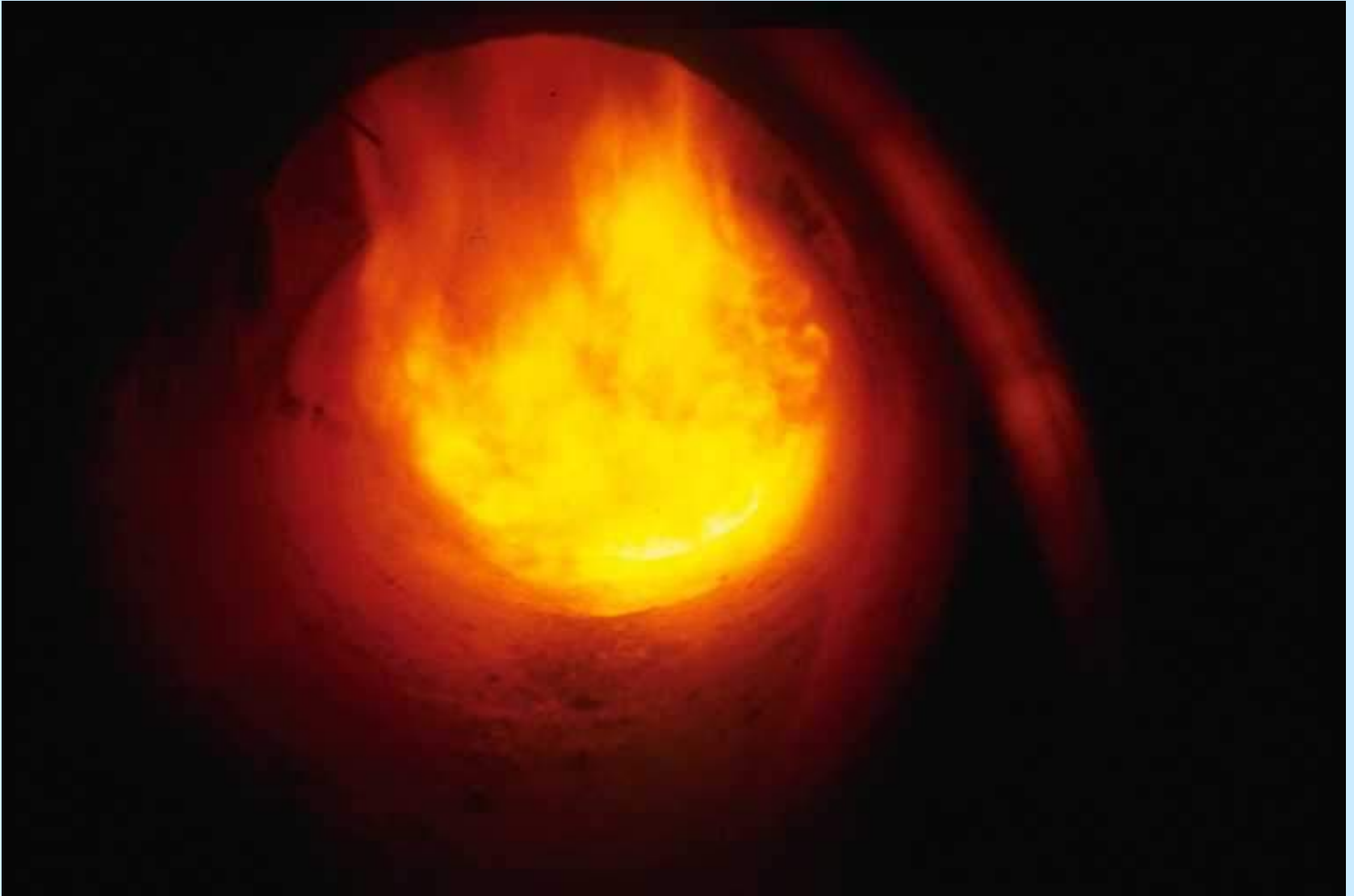
You will learn about:

- **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



| 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 (IFRF* type II) | >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.

TERMINOLOGY

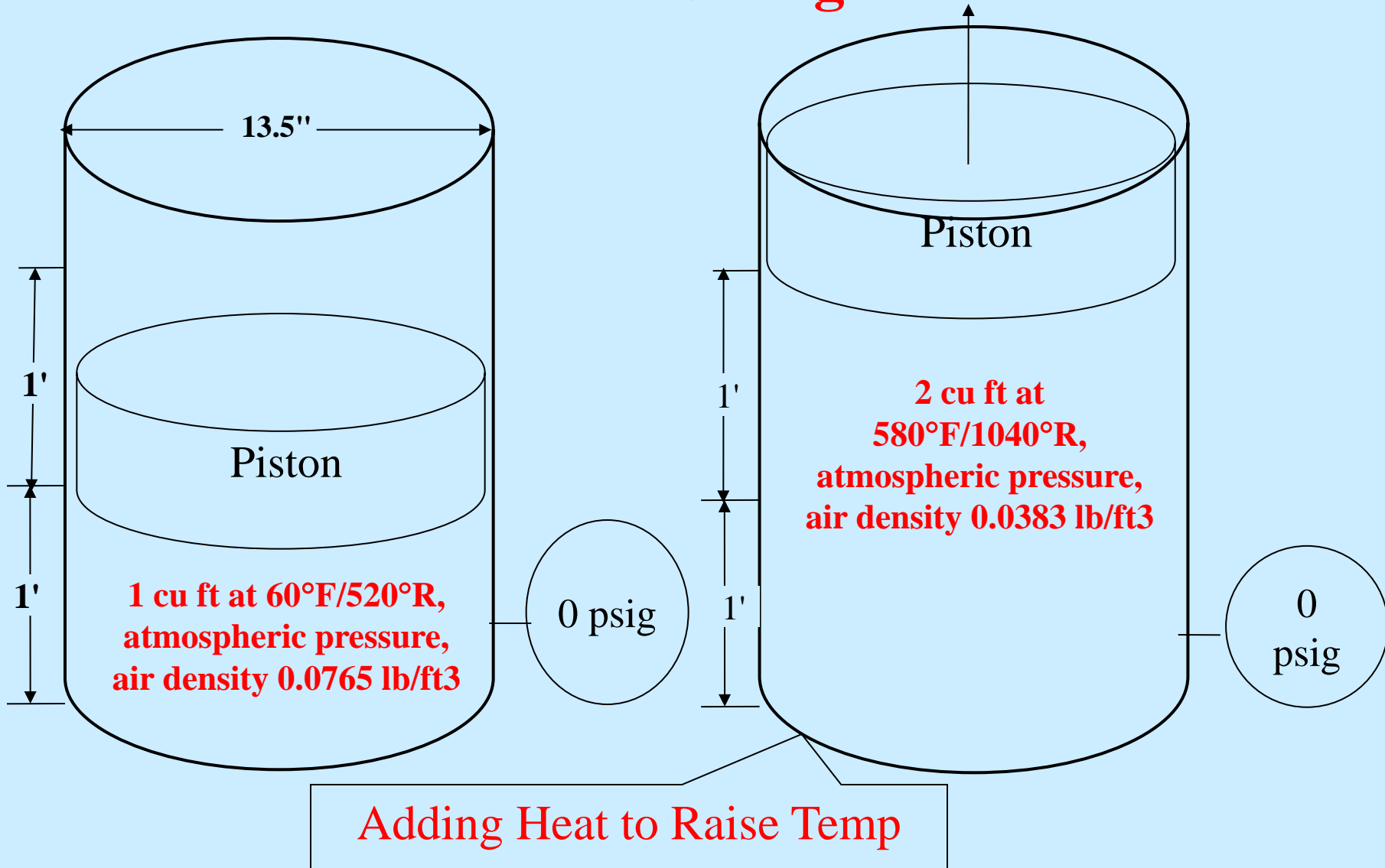
Some terms and their definitions used in this section are:

- **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.
$$\text{acfm} = \text{scfm} \times ((T^{\circ}\text{F}+460)/520) \times (14.7/P \text{ in psia})$$
- 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.

Visualize Temperature and Volume Change



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 ₂ O |
| 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 | CH₄ | +2 | (O₂ | + | 3.76N₂) | → | |
| Mols | 1 | | 2 | | 7.52 | | |
| Wt. | 16 | | 64 | | 211 | | |
| Lb/lb fuel | 1 | | 4 | | 13.2 | | (Air =17.2) |

Output

| | | | | | | | |
|--------------------|------------------------|----------|------------------------|----------|--------------------------|--|---------------|
| | CO₂ | + | 2H₂O | + | 7.52N₂ | | 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 | CH₄ | +2 x 2 | (O₂ | + 3.76N₂) | → | |
| 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

| | | | | | | | |
|--------------------|-----------------------|----------|------------------------|----------|--------------------------|-------------------------|---------------|
| | CO₂ | + | 2H₂O | + | 15.0N₂ | + 2O₂ | 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 | | | | 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 ₂ O | N ₂ | O ₂ | N ₂ | Air | CO ₂ | H ₂ O | N ₂ | | |
| 1 | Carbon | C | 12.01 | — | — | — | — | — | 14,093 ^e | 14,093 ^e | — | — | — | — | — | — | 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 ₂ H 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 ₃ H 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 ₄ H 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 ₄ H 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 ₅ H 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 ₅ H 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 ₅ H 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 ₆ H 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 ₂ H 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 ₃ H 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 ₄ H 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 ₄ H 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 ₅ H 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 ₆ H 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 ₇ H 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 ₈ H 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 ₂ H 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 | — ^g | |
| 26 | Methyl alcohol | CH ₃ OH | 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 ₂ H ₅ OH | 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 | 3.233 | 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 | — | 3.287 | 0.071 | |
| 30 | Hydrogen sulfide | H ₂ S | 34.076 | 0.09109 ^e | 10.979 ^e | 1.1898 ^e | 647 | 596 | 7,100 | 6,545 | 1.5 | 5.646 | 7.146 | 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 ₂ O | 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 0.003652 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: | | | Quench/Bag | Solids Chrg, | Feed | Primary | WetWgt |
|--------------------|----------|----------|------------|--------------|-----------|----------------|--------|
| Primary Burner XCS | SCC XCS | POHC XCS | House Temp | b/hr | Moisture | Radiation Loss | POHC |
| 50% | 25% | 90% | 400 | 40000 | 10.00% | 5.00% | 7.00% |
| | Ash temp | | -150 F | overgas temp | SCC Rad L | 2.50% | |

Stage 1, Primary Kiln Burner

| Item | b/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 | b/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

| Item | b/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

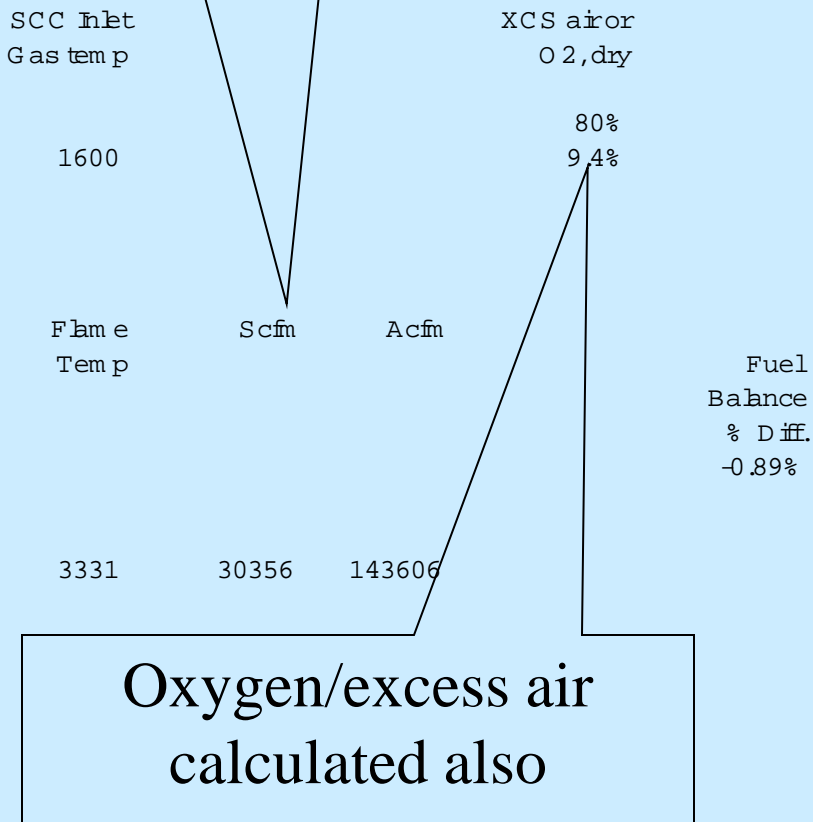
| Item | b/hr | Sensible Heat MMBtuh | SCC Inlet Gas temp | XCS air or O ₂ , dry |
|-----------|--------|----------------------------|-----------------------|------------------------------------|
| Total gas | 102786 | | | |
| Solids | | 0.00 | | 80% |
| Total | 102786 | 44.53 | 1600 | 9.4% |

Page 2, Heat and Mass Balance for Hazardous Waste Incineration

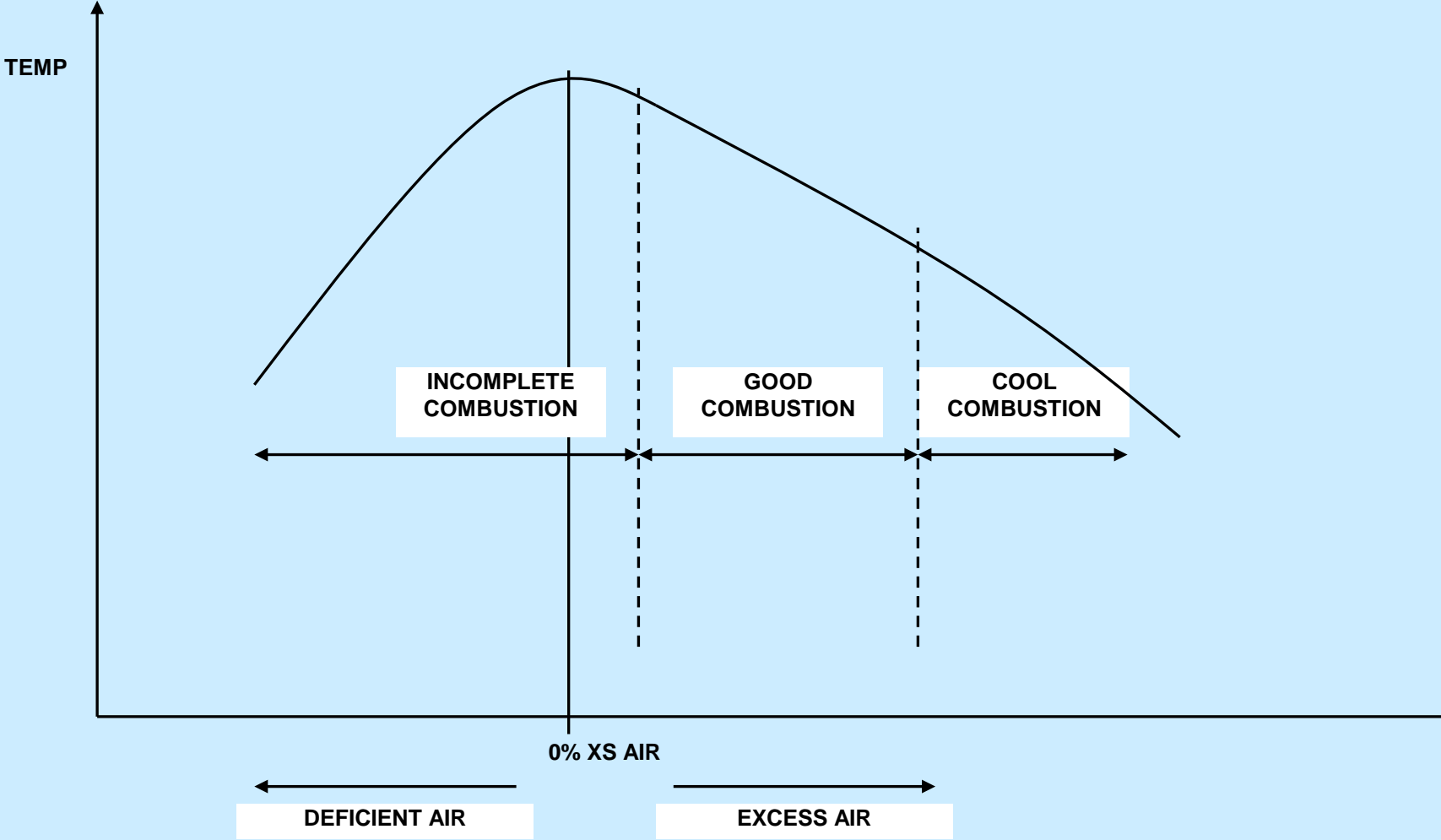
Stage 4, Secondary Combustion Chamber

| Item | b/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



Temperature vs. Air to Fuel Ratio



Adiabatic Flame Temperature

(at zero % heat loss)

$Q = M \times C_p \times \text{temperature difference, or}$

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

Where $Q = \text{Btu}$

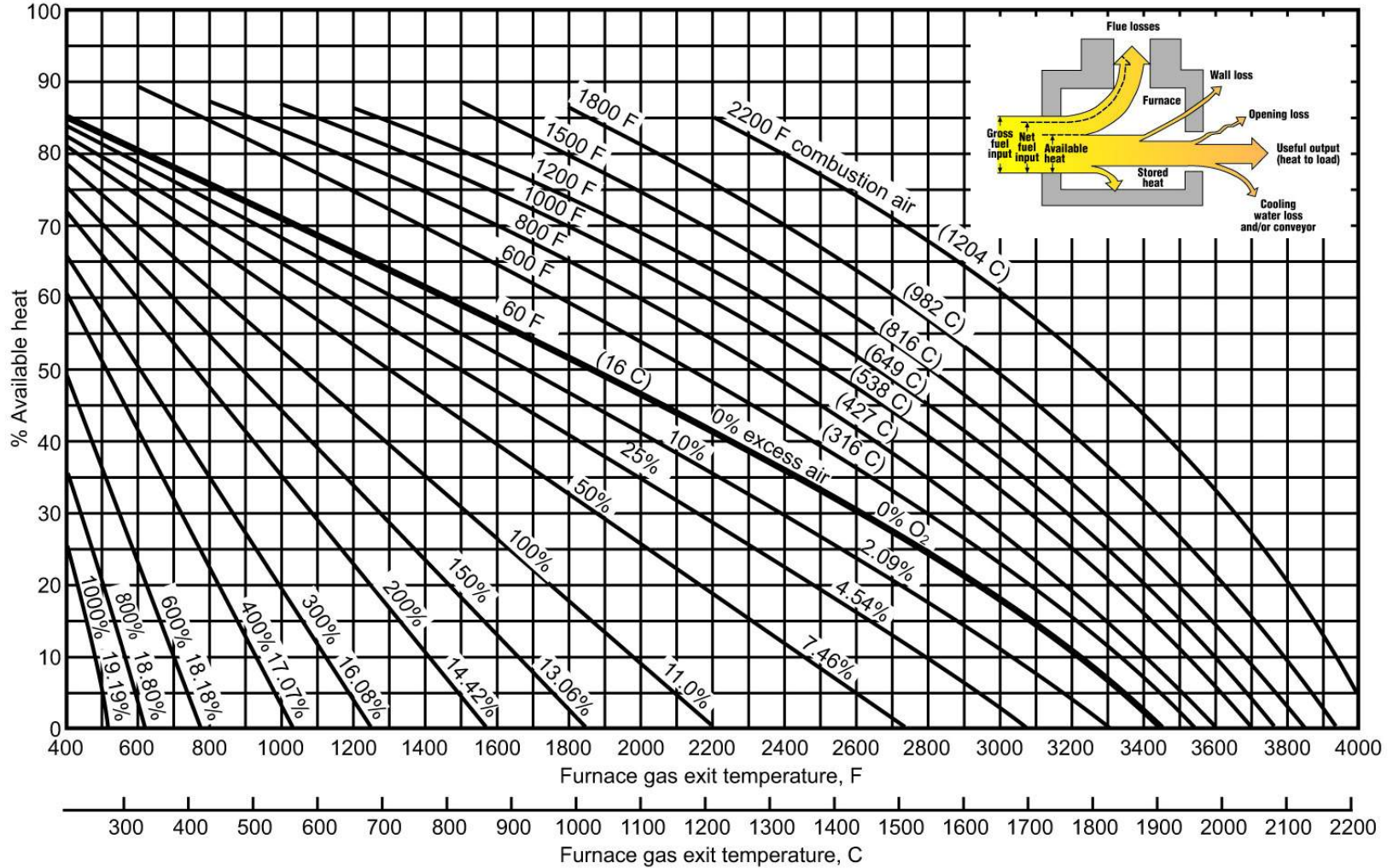
$M = \text{Mass, lb of combustion products}$

$C_p = \text{Specific heat of combustion products, Btu/lb-F}$

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 , NO_x , 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

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

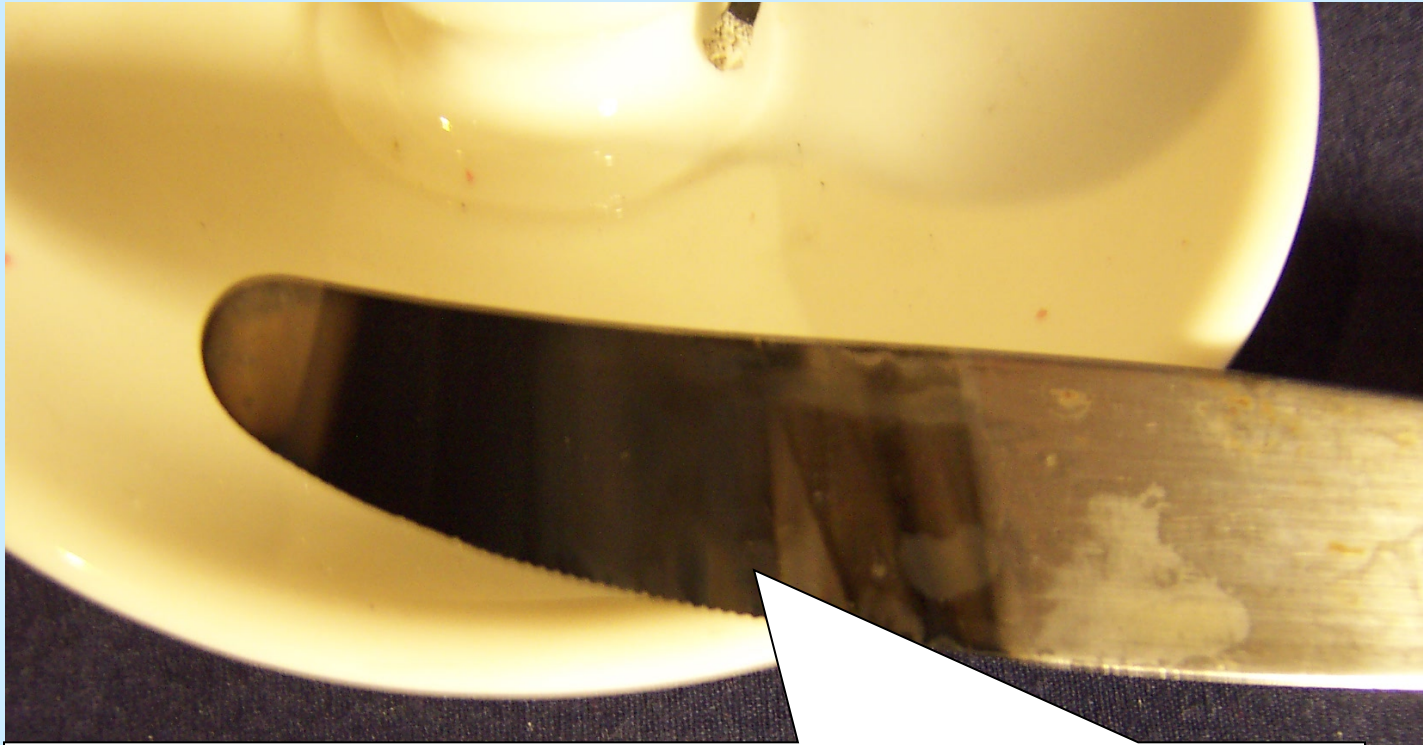
- Use longer retention time for more difficult to burn fuels

Learning from a Candle...

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



Quenching a Flame

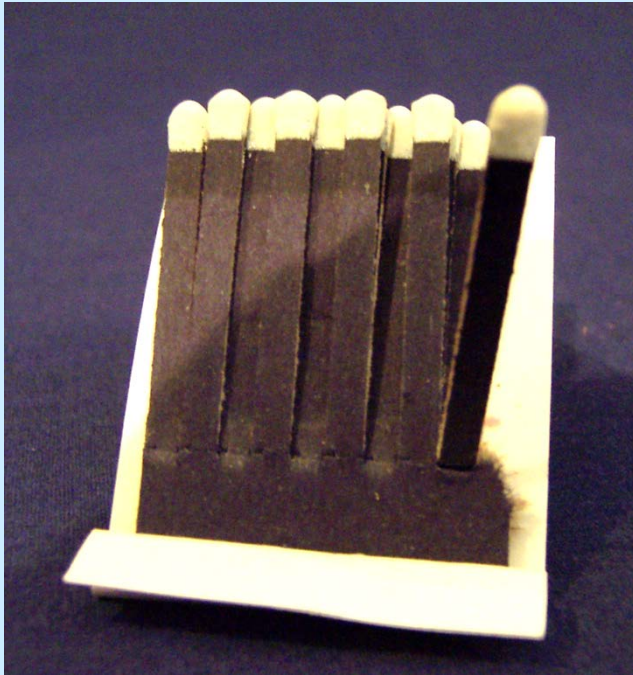


Soot on knife blade is thousands of tiny soot particles that would have burned in hot flame – if they had enough time and temperature!

Pyrophoric Materials

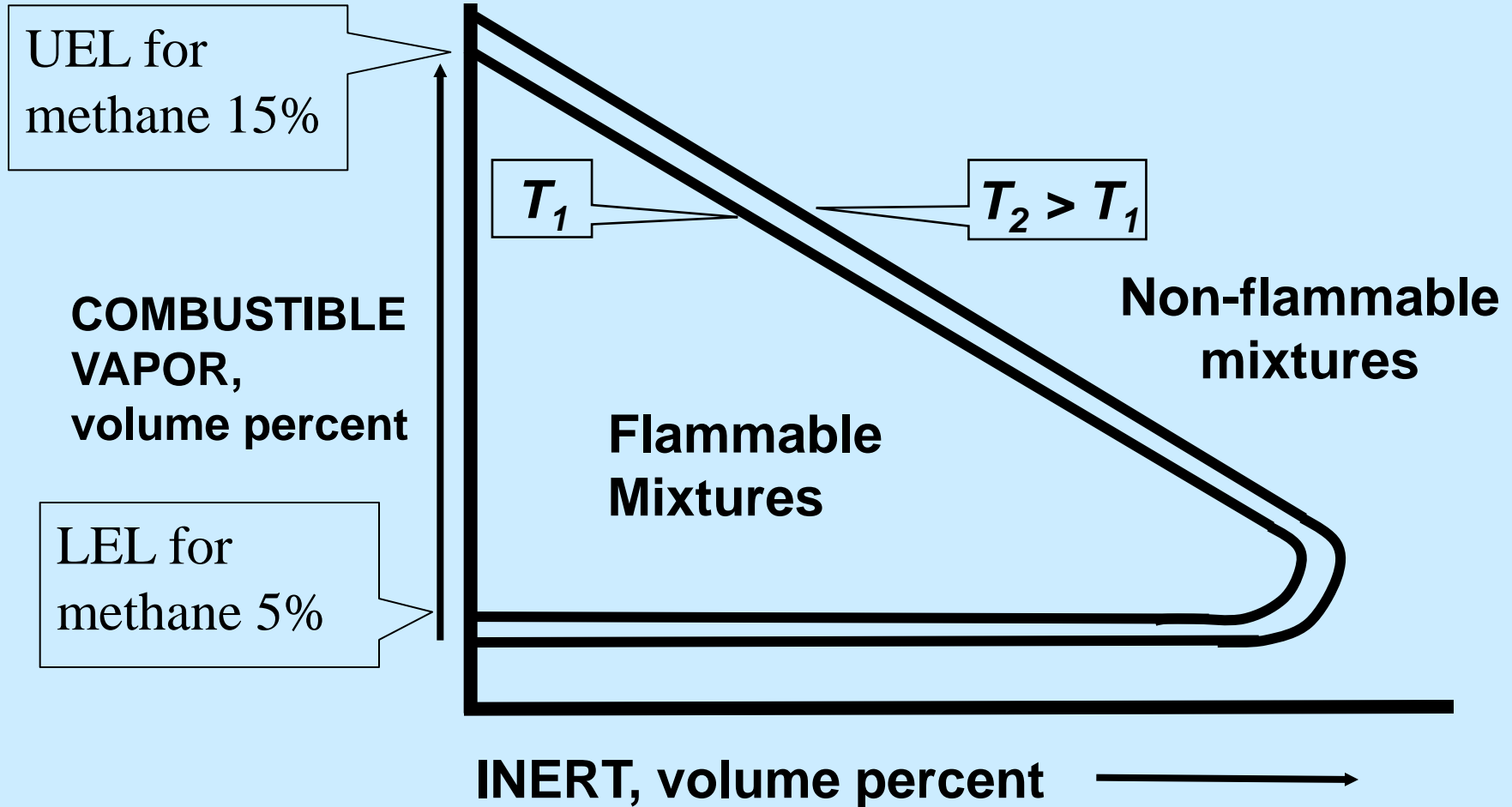
The heat from a bit of friction on the scratch block is enough to reach AIT, the autoignition temperature.

The sulfur and phosphorous mixture is pyrophoric and burns easily.

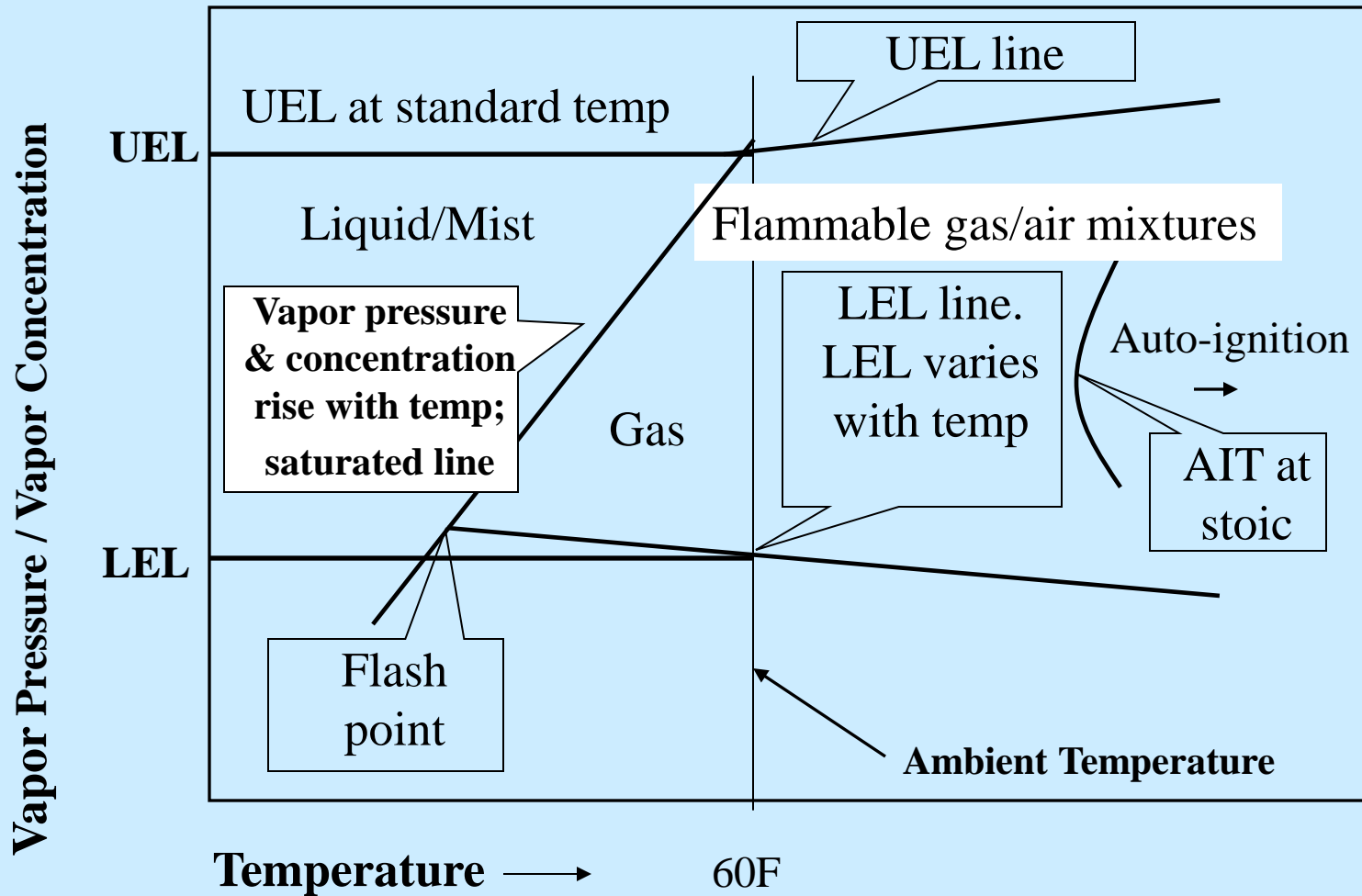


Limits of Flammability vs. Inert Percent in Air

$$\% \text{ Air} = 100\% - \% \text{ Combustible Vapor} - \% \text{ Inert}$$



Limits of Flammability vs. Temperature



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

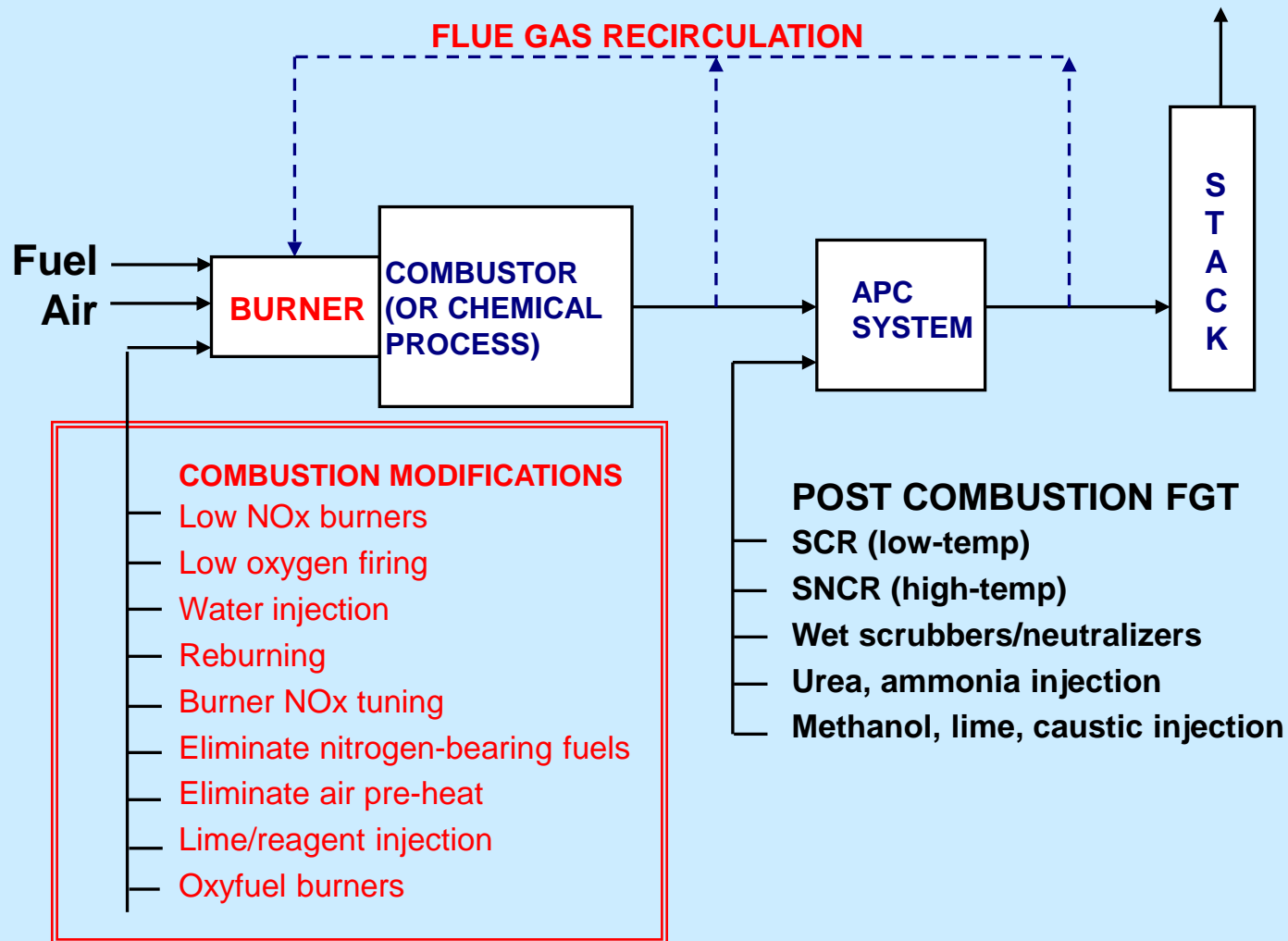
Ref: Graph adapted from US Bureau of Mines Bulletin 627; numerical data from NFPA 325M

Air Pollutants from Combustion and Control Strategy

- **CO - better mixing, higher temp, catalyst**
- **NO_x - low NO_x 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**

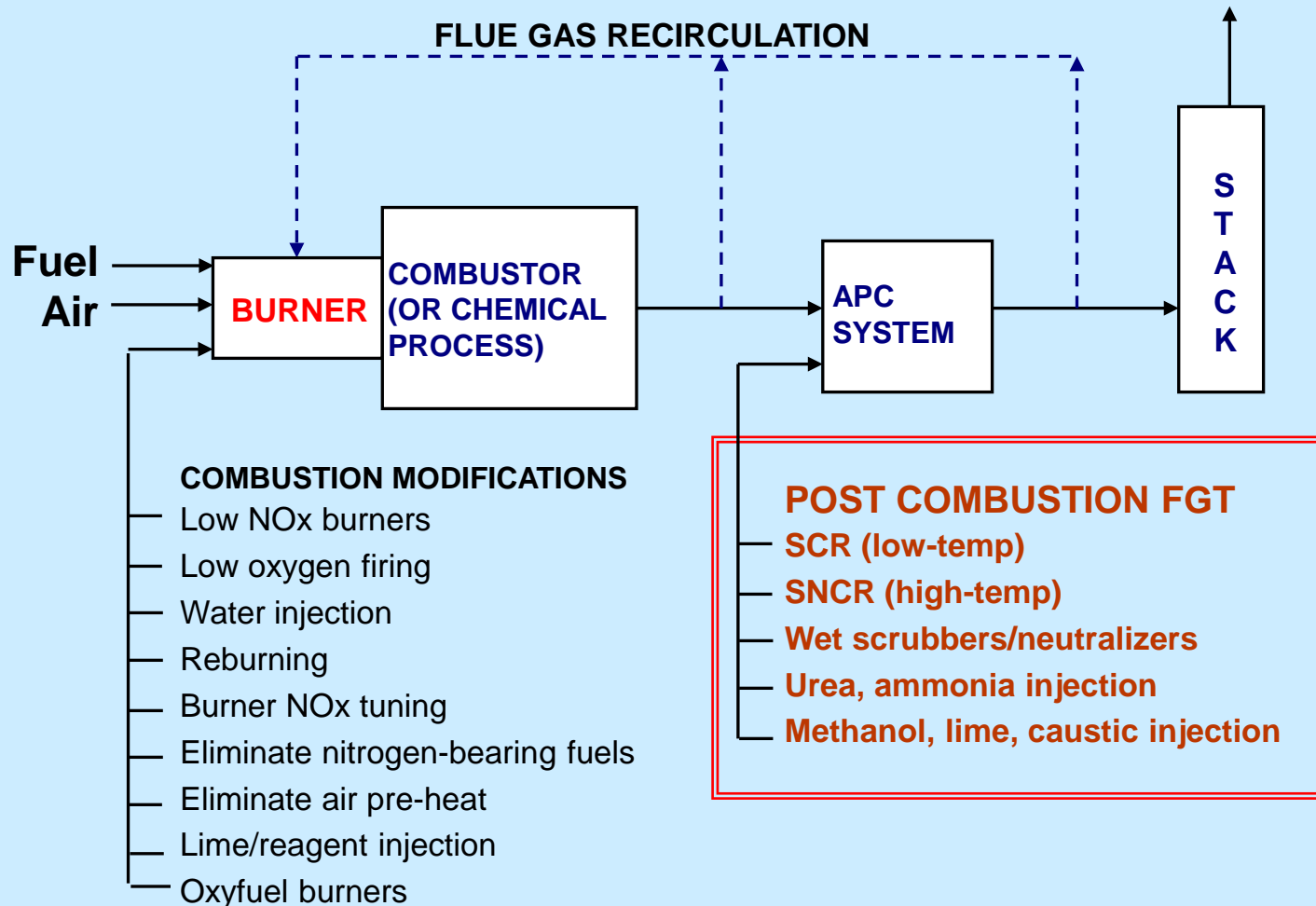
NOx Control Technologies

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