Better Plants
U.S. DEPARTMENT OF ENERGY

VIRTUAL PROCESS HEATING INPLT
Session 1

Training Module # 2
Process Heating System Basics

Process Heating Basics

Heat Supply

Fuel Combustion, Steam, and Electricity

Process Heating Systems

Heat Demand

Heat Transfer, Process Heat Requirement, Heat Losses

Combustion Generated Emissions

(CO, UHC, and NOx)

Outline

- **Combustion Basics**
- Available Heat
- Heat Transfer
- Combustion Pollution Emissions

Process Heating Basics

- Fuels and heating value
- Stoichiometric combustion
- Flame temperature
- Available heat

Typical Fuels Used in Industrial Process Heating Equipment

Most Commonly Used Gaseous Fuels

Heating value: 800 to 1200 BTU/SCF

Examples: Natural Gas, Waste Gases, etc.

Methane - CH_4, Ethane - C_2H_6

High BTU Gaseous Fuels

Heating value: 1400+ BTU/SCF

Examples: Propane, Butane, LNG, etc.

Propane - C_3H_8, Butane - C_4H_{10}

Low BTU Gaseous Fuels

Heating value: 100 to 700 BTU/SCF

Examples: Coke Oven Gas, Blast Furnace Gas, Digester Gas, Landfill Gas, etc.

Hydrogen - H_2, Carbon Monoxide – CO,

Carbon Dioxide - CO_2, Nitrogen - N_2

Other Fuels

Examples: fuel oils, waste gases, coal, by-product fuels, other

Trace Constituents in many commonly used fuels

Hydrogen Sulfide - H_2S, Ammonia - NH_3,

Carbon Dioxide - CO_2 Nitrogen - N_2, Water Vapor - H_2O

Note: All heating values are higher (gross) heating values (Explained later)

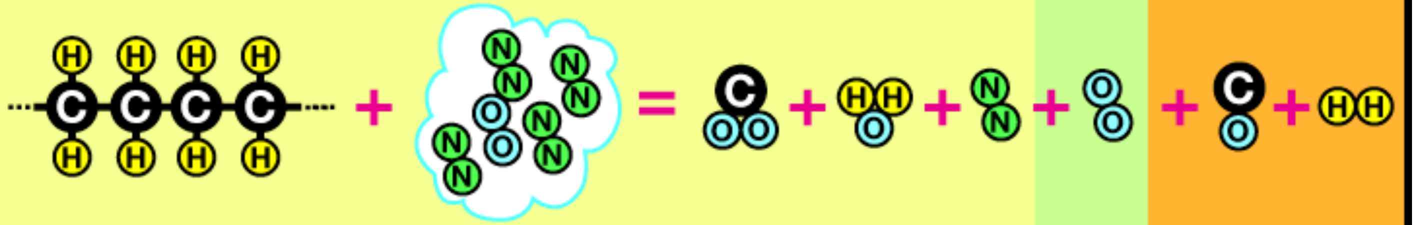
Poll Question # 1

Major elements or components of most commonly used fuels (i.e. oil, natural gas, etc.) for process heating equipment contain (select two):

A	Hydrogen	Yes!
B	Iron	
C	Water Vapor	
D	Carbon	Yes!
E	Ash	

What is Combustion?

A chemical reaction between a fuel and an oxidant above a minimum temperature.



If Stoichiometric,

Fuel (CnHm) + Air (O_2 + 3.76 N_2) = CO_2 + H_2O + N_2

If Lean (Excess Air),

Fuel (CnHm) + Air (O_2 + 3.76 N_2) = CO_2 + H_2O + N_2 + O_2

If Sub-stoichiometric (air deficient or fuel-rich),

Fuel (CnHm) + Air (O_2 + 3.76 N_2) = CO_2 + H_2O + N_2 + CO + H_2

Theoretical (Adiabatic) Flame Temperature

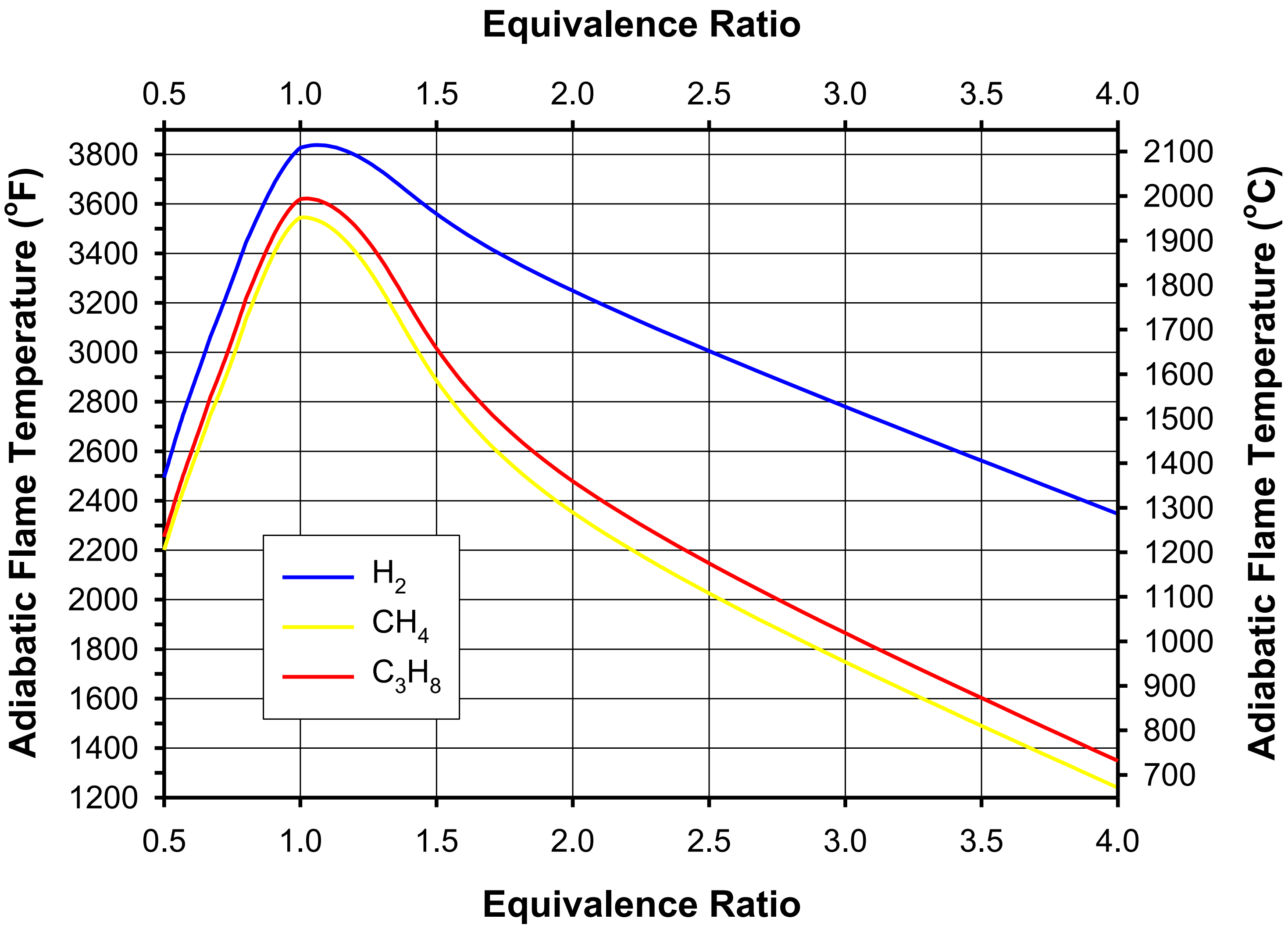
Flame temperature affects heat transfer and temperature distribution within the heating system (furnace, oven, etc.).

Flame Temp. (Deg. F)	Condition *
>5000	*NG, With 100% O_2*
3750	NG, 900˚ F Combustion Air
3610	COG - ambient air
3545	NG, 900 F Air - 20% XS Air
3460	*NG, Ambient Air*
3225	NG, 15 % XS Air
2750	*NG, 7.0:1 Air/Fuel Ratio*
2650	Blast Furnace Gas – ambient air

* Unless Specified Assume Correct Air/Fuel Ratio. Dissociation Considered

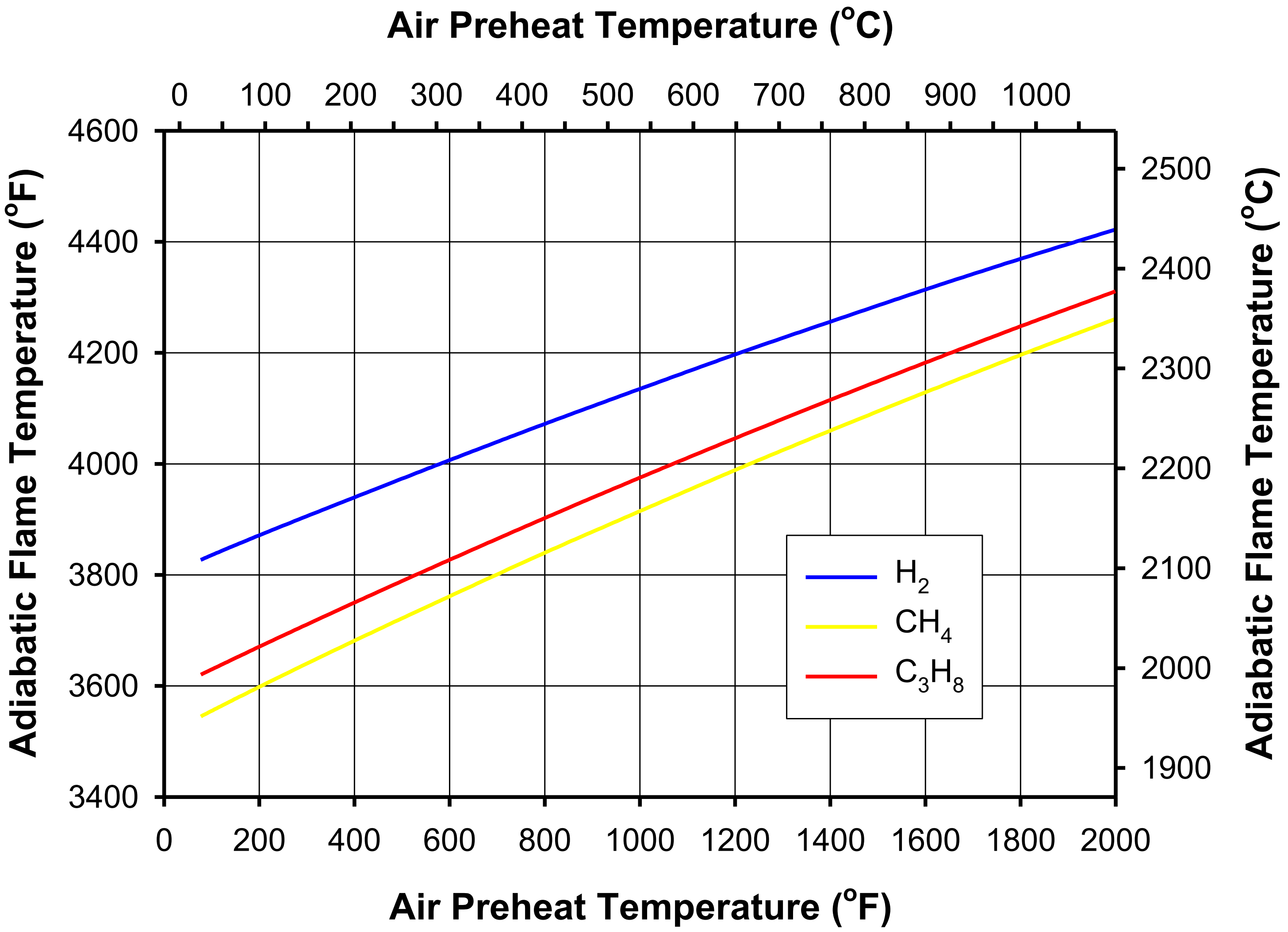
- Adiabatic flame temperature, the temperature resulting from complete combustion of a fuel-air mixture without any heat loss to the surroundings, is determined by:
  - Type of fuel
  - Type of oxidant (air, oxygen, etc.)
  - Temperature of the fuel and oxidant
  - Ratio of oxidant to fuel mass flow
- Real life flame temperatures are lower than adiabatic because flames begin losing heat before combustion is complete.

Theoretical Flame Temperature Stoichiometry (equivalence ratio) Effects

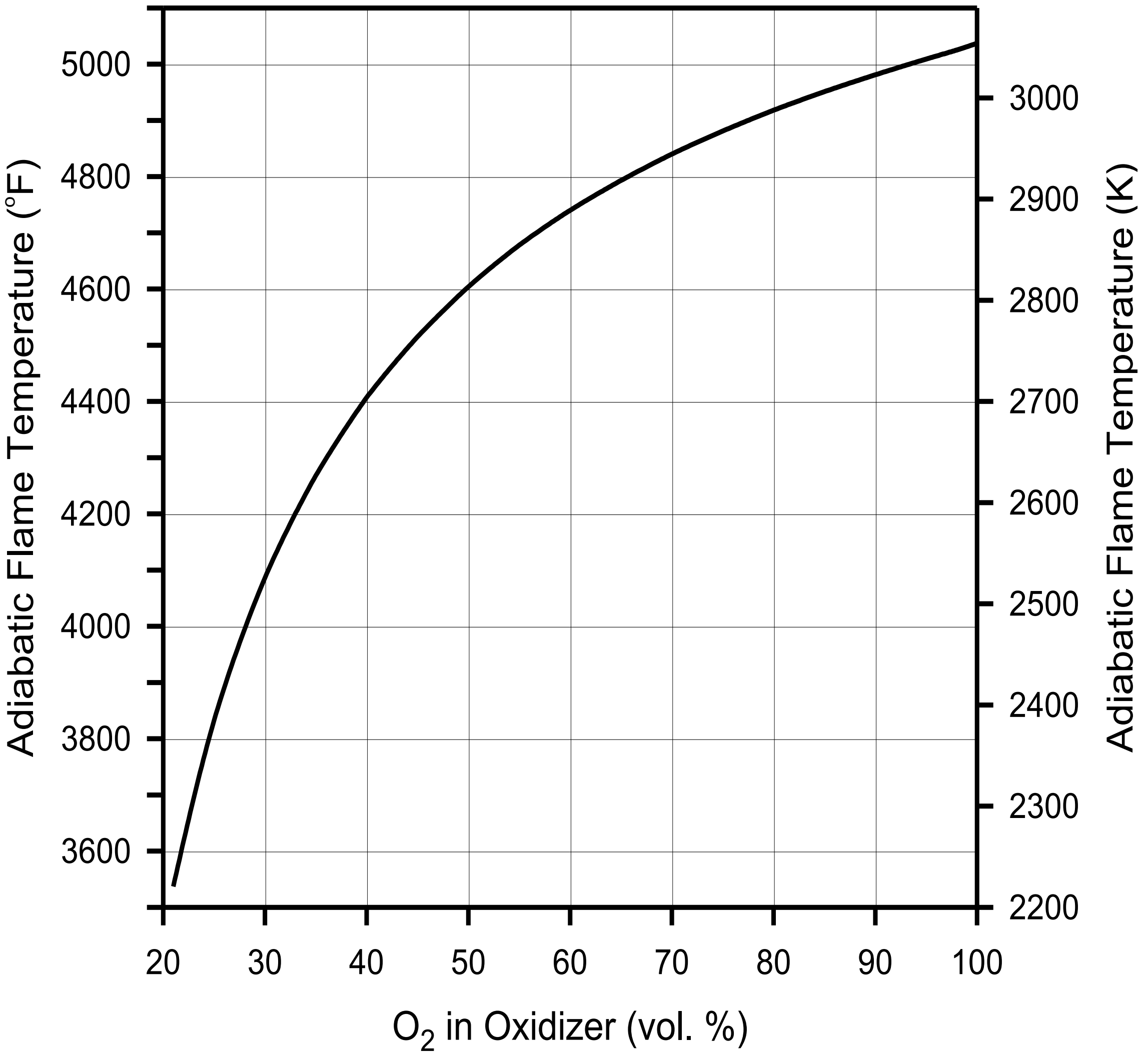


The equivalence ratio is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio.

Theoretical Flame Temperature
Air Preheat Effects



Effect of Oxygen Enhancement Flame Temperature for Natural Gas



Perfect Combustion

When fuel reacts with exactly the right amount of air, all the carbon and hydrogen atoms combine with all the oxygen to form carbon dioxide and water vapor.

$$C + O_2 \longrightarrow CO_2 + 14{,}100 \text{ Btu/lb}$$

$$2H_2 + O_2 \longrightarrow 2H_2O + 61{,}100 \text{ Btu/lb}$$

Poll Question # 2

Oxygen in products of natural gas combustion primarily depends on (select only one):

A Temperature of combustion air

B Type of metal being heated in a reheat furnace

C Furnace dimensions or size

D Excess air used for combustion

Yes!

Useful Terms Used in Combustion

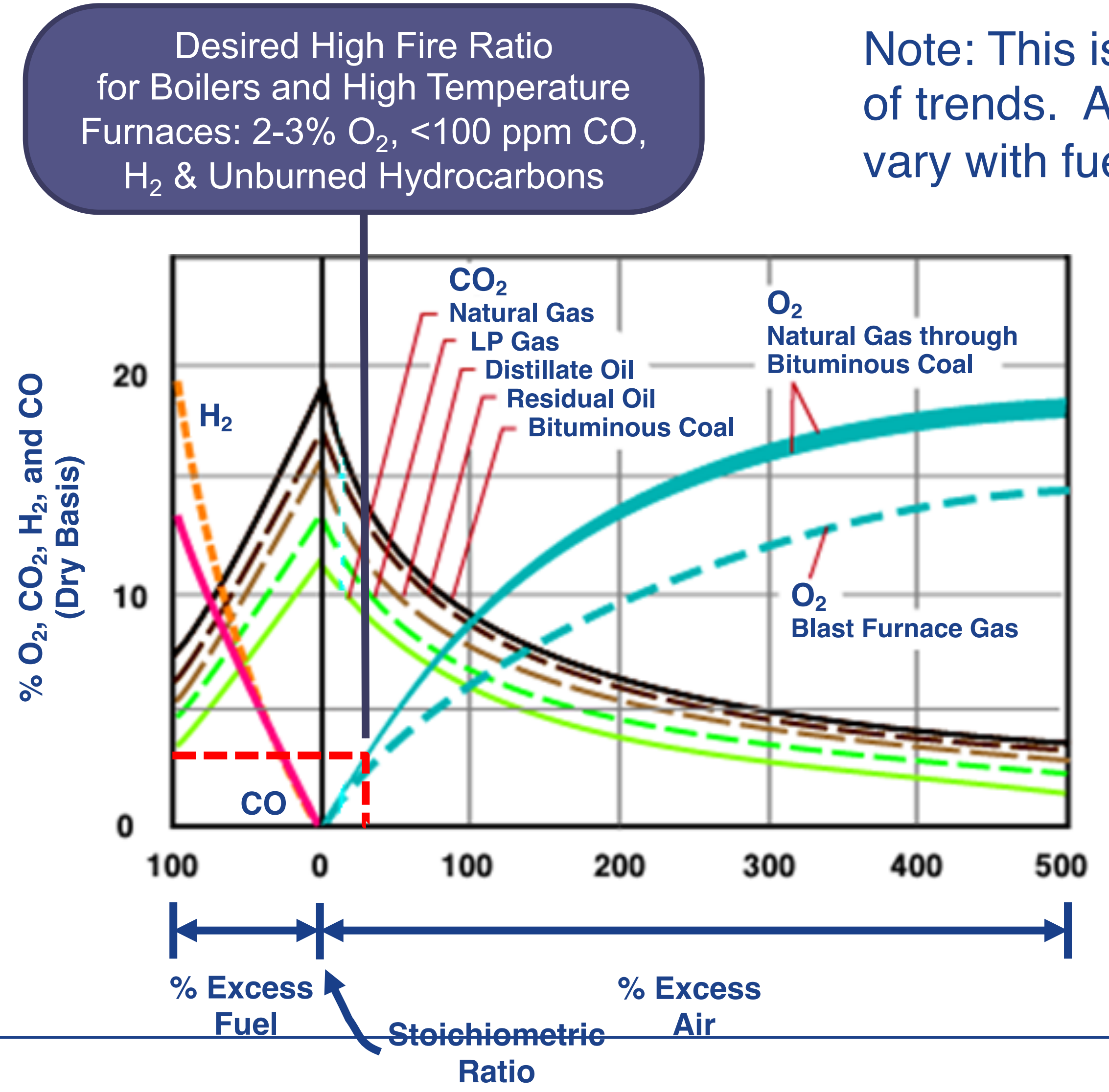
- Stoichiometric air
  - Chemically correct amount of air to burn all the fuel.

- Excess Air
  - Air supplied beyond the quantity needed for stoichiometric combustion.
  - Can usually be measured by the percentage of O_2 that remains after fuel combustion is compete.
  - Often expressed as a percentage of stoichiometric air.

Efficient Combustion

Combustion Products Analysis for Common Hydrocarbon Fuels

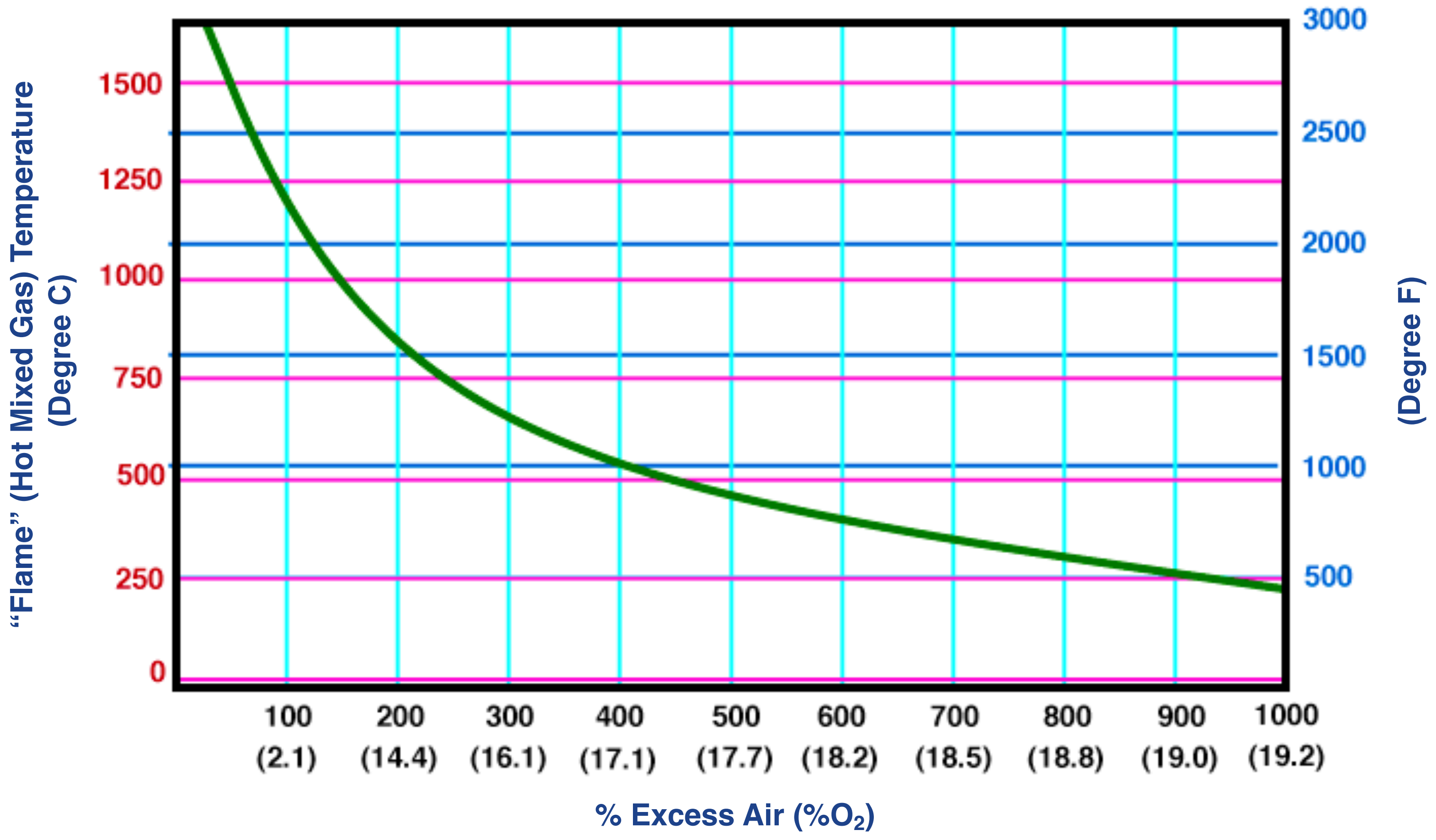
Note: This is an illustration of trends. Actual values will vary with fuel composition.



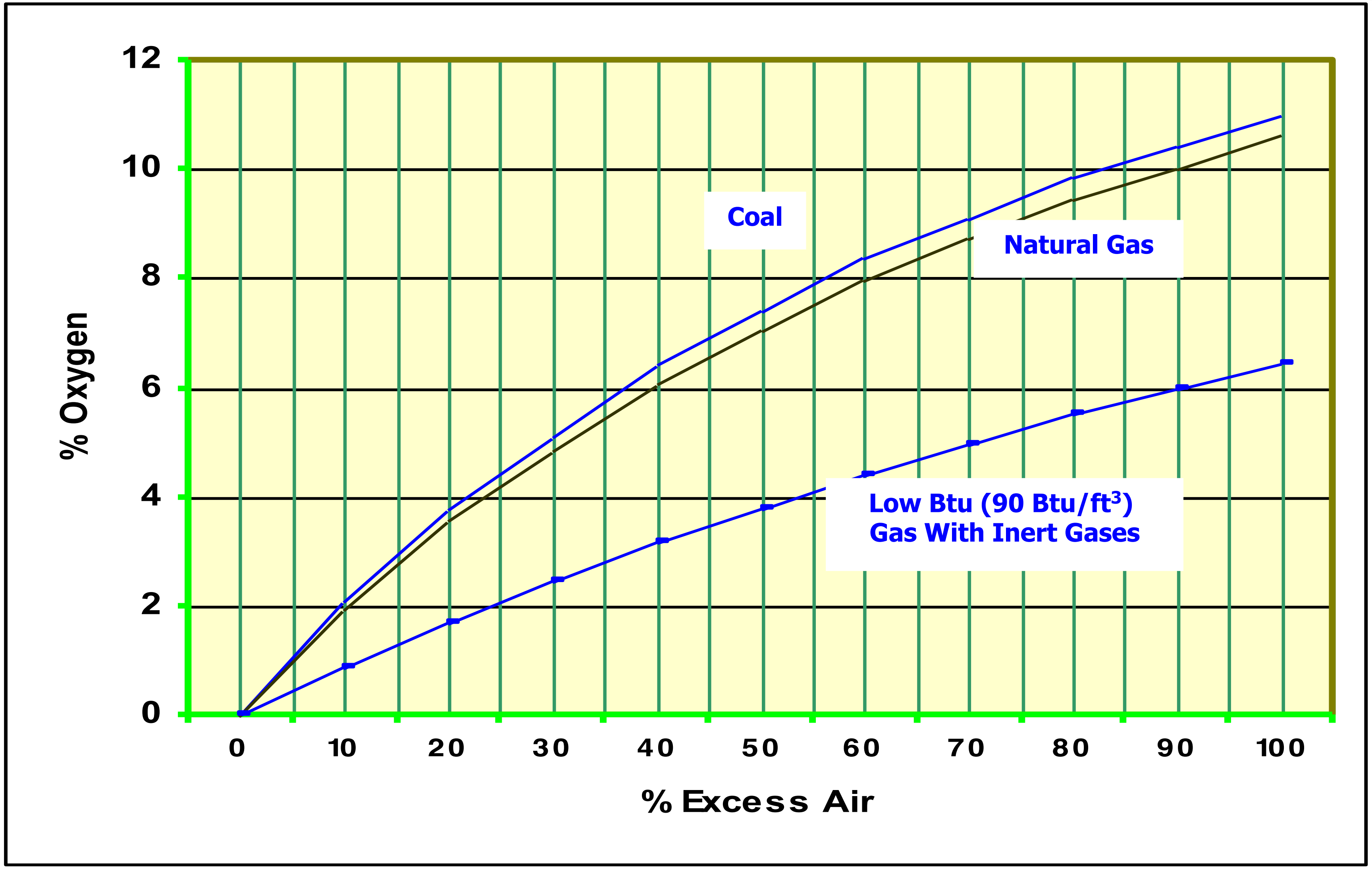
See "North American Combustion Handbook Volume 1", 3rd Edition for more information.

Effect of Excess Air (O_2) on "Flame" Temperature

For commonly used fuels:



Effect of Excess Air on Oxygen in Flue Gases (For commonly used fuels)



Efficient Combustion

Air-Fuel Ratio (By volume) for Commonly Used Fuels

Rule of Thumb

- 10 ft^3 of combustion air per 1000 Btu (higher/gross heating value) of fuel
- Exception – Fuels with high inert gases, hydrogen or CO content

Theoretical Air/Fuel Ratio for Commonly Used Fuels

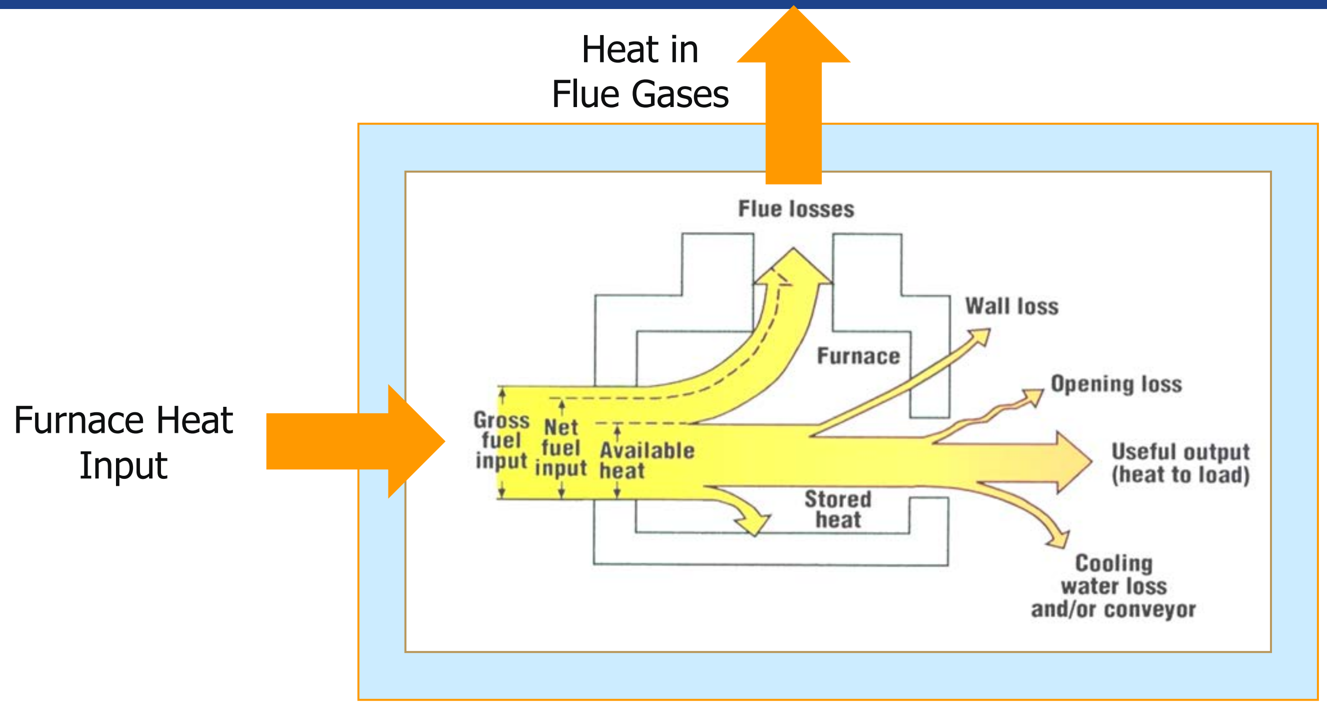
Fuel	High (Gross) Heating Value		Theoretical stoichiometric air required		
	Btu/ft^3	Btu/lb	Standard ft^3/ft^3	Standard ft^3/lb	Standard ft^3 per 1000 Btu
Natural gas - 1	1,084		10.26		9.46
Natural gas - 2	980		9.19		9.38
Hydrogen *	325		2.39		7.36
Carbon Monoxide *	322		2.39		7.43
Propane (gas)	2,520		23.93		9.49
Coke oven gas (Koppers) *	590		5.28		8.95
Producer gas *	150		1.12		7.47
Butane	3,200		31.09		9.72
Blast furnace gas *	92		0.68		7.39
No. 2 fuel oil		19,500		192.30	9.86
No. 6 fuel oil		18,300		181.82	9.94
Low ash bituminous coal		14,490		143.64	9.91
High ash bituminous coal		12,780		127.00	9.94
Lignite - wet		10,082		102.90	10.21
Lignite - dry		7,063		72.60	10.28

* Fuels that do not follow the "Rule of Thumb" that gives approximately 10 ft3 of combustion air per 1000 Btu heat release

Outline

- Combustion Basics
- **Available Heat**
- Heat Transfer
- Combustion Pollution Emissions

What is Available Heat?



$$\text{Available Heat} = \text{Heat to Load} + \text{Wall, Opening, Conveyor, and Cooling Losses} + \text{a Portion of Stored Heat}$$

$$= \text{Gross Heat Input} - \text{Flue Gas Losses}$$

$$\text{Percent Heat Available} = \frac{\text{Furnace Heat Input} - \text{Heat in Flue Gases}}{\text{Furnace Heat Input}}$$

Poll Question # 3

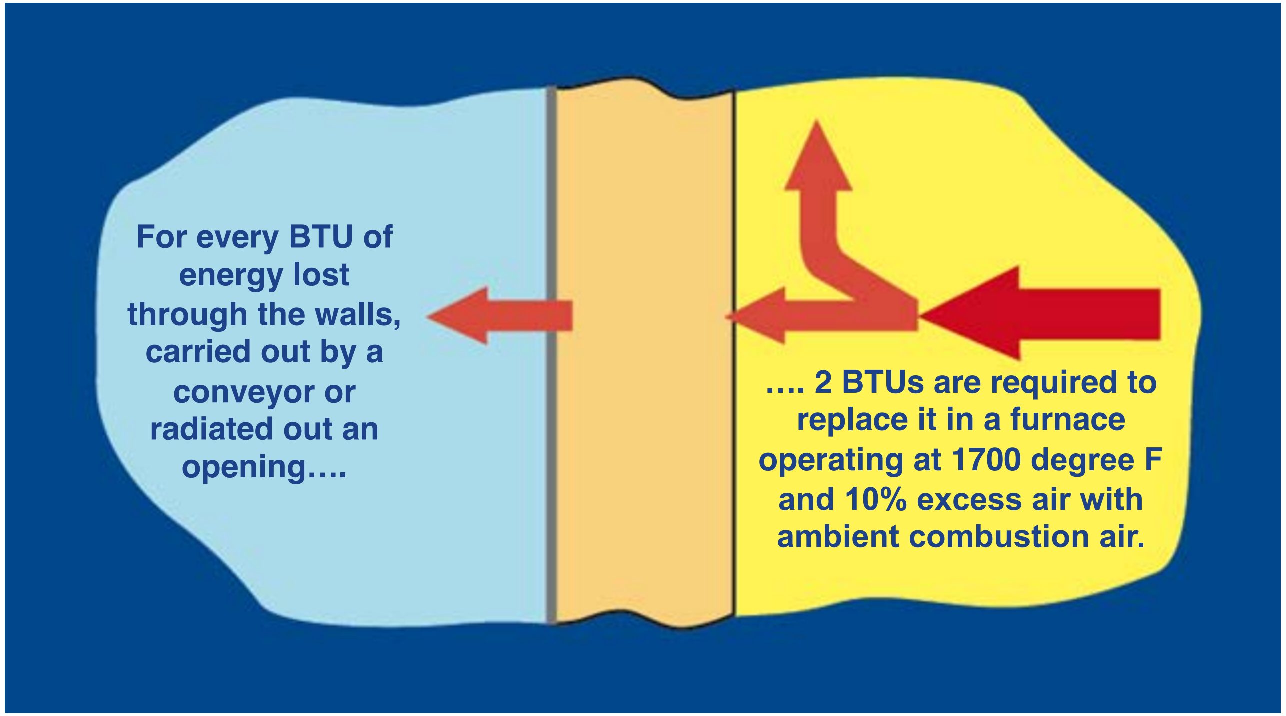
The available heat of a furnace depends on the following parameters for a furnace (select two):

A	Temperature of the fuel used	Yes!
B	NOx content of the flue gases at the stack	
C	Furnace wall thickness & type of insulation used	
D	Furnace flue gas temperature	Yes!
E	Temperature rise of the load or work in the furnace	

Effect of Available Heat

Savings are more than what we calculate!

A penny saved is a lot more valuable than a penny earned



Factors Affecting Available Heat

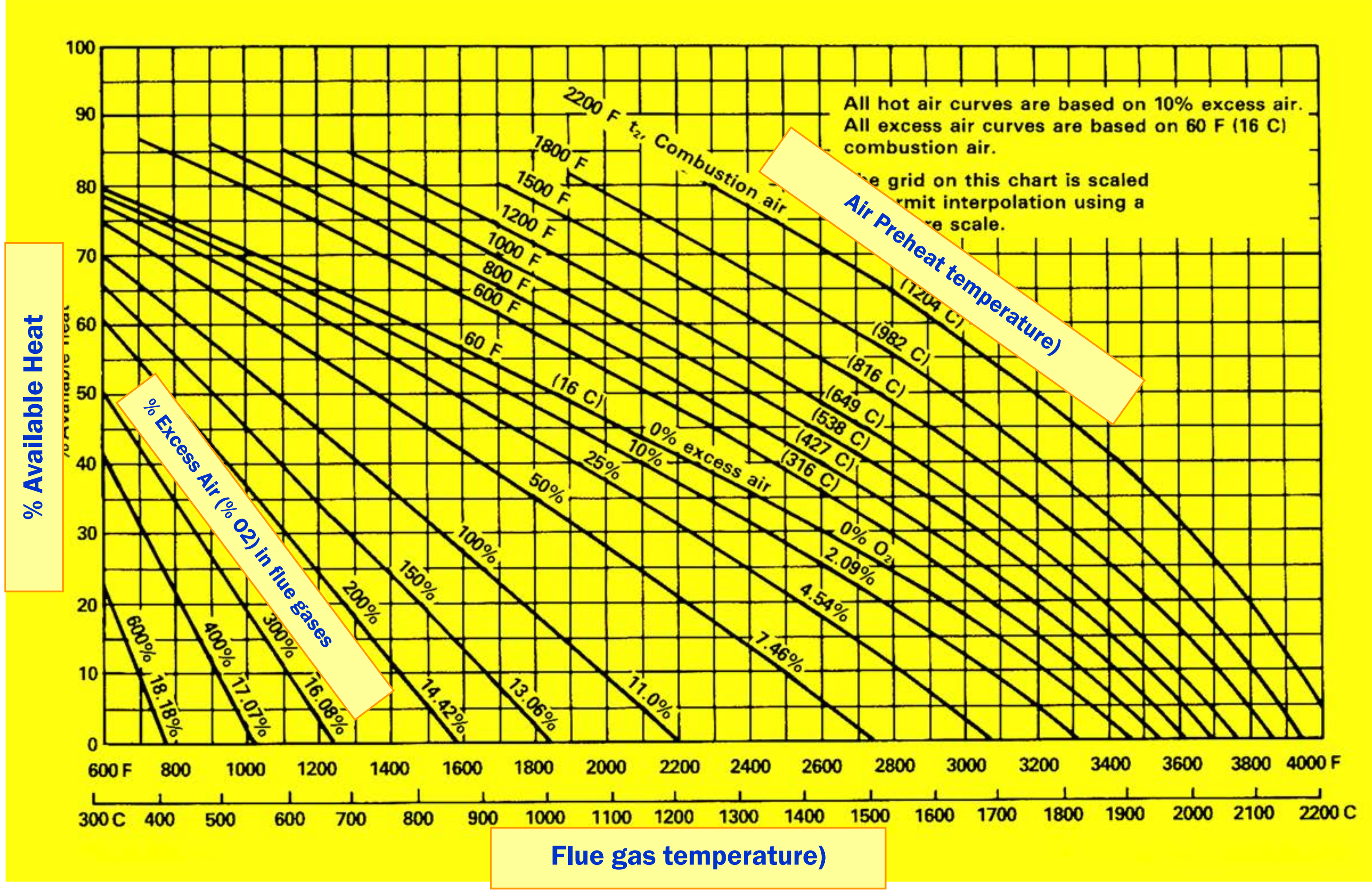
$$\Delta H = M \times C_p \times \Delta T$$

	M	C_p	ΔT
Flue Gas Temperature Heat Loss	Mass Flow of Flue Gases	Specific Heat	Temperature Rise
Determined by:	Excess Air (or Oxygen) in Flue Gases	Type of Fuel (Flue Gas Composition)	$\frac{\text{Flue Gas Temperature}}{\text{Combustion Air Temperature}}$

Factors Affecting Available Heat

(For Most Hydrocarbon Gaseous Fuels)

Percent Available Heat vs. Exhaust Gas, Air Preheat Temperatures, and % Excess Air



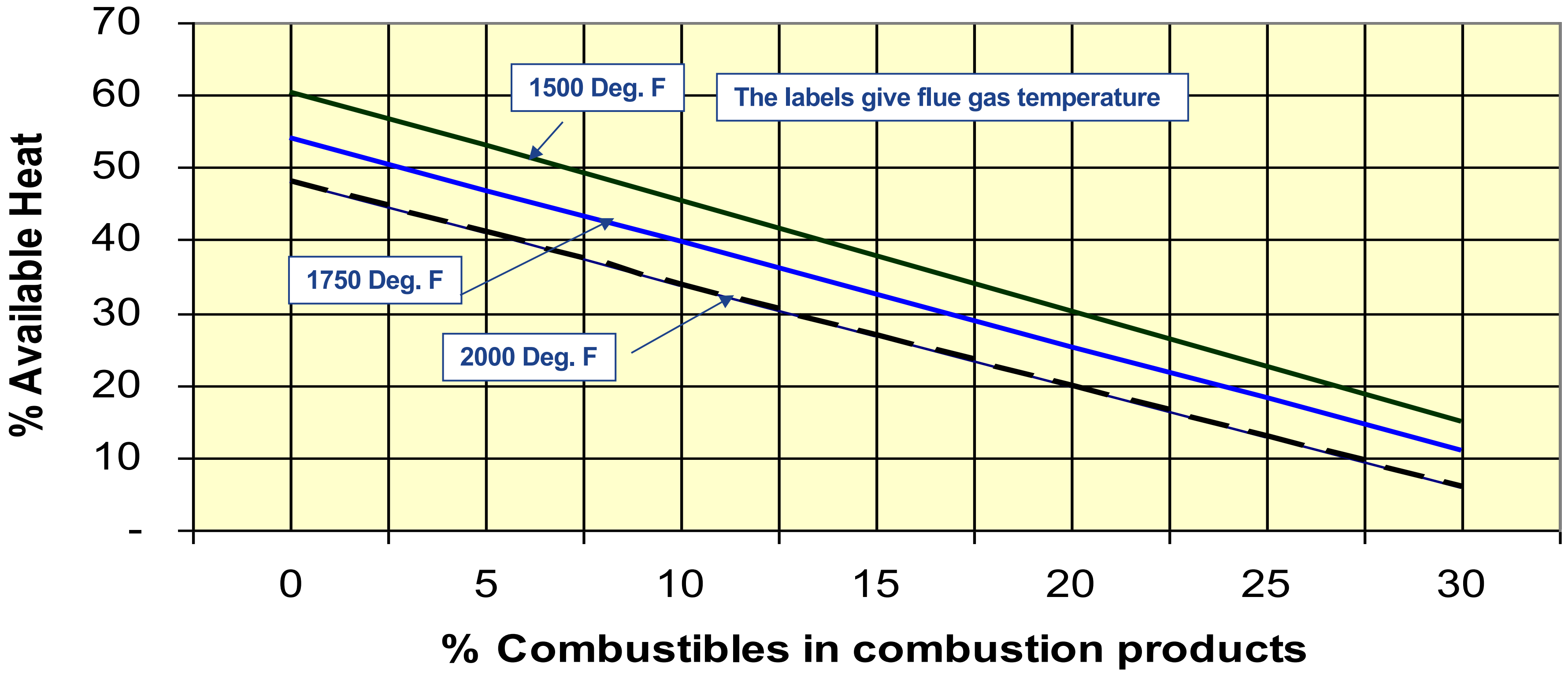
For the same ratio and exhaust temperature, available heat for LP gases and fuel oils will be 2 - 5% higher.

Products of Incomplete or Sub-stoichiometric Combustion

- Products of incomplete combustion of a fuel contain CO, H2, and other combustible gases (i.e., CH4).
- This combustion condition is considered highly dangerous due to presence of CO and other combustibles and should be avoided and corrected.
- Occasionally there may be excess oxygen present in flue gases. This condition may indicate poor mixing, incomplete combustion and/or quenching of the flame.
- In some cases, as in drying ovens where volatile vapors are mixed with combustion products, the oven exhaust gases may contain high level (>15%) of oxygen to dilute combustible organics to safe levels.
- The real danger is when small percentage of O2 is detected in presence of large (3%) concentrations of combustibles.
- Available heat for such conditions can be obtained using the figure in the next slide.

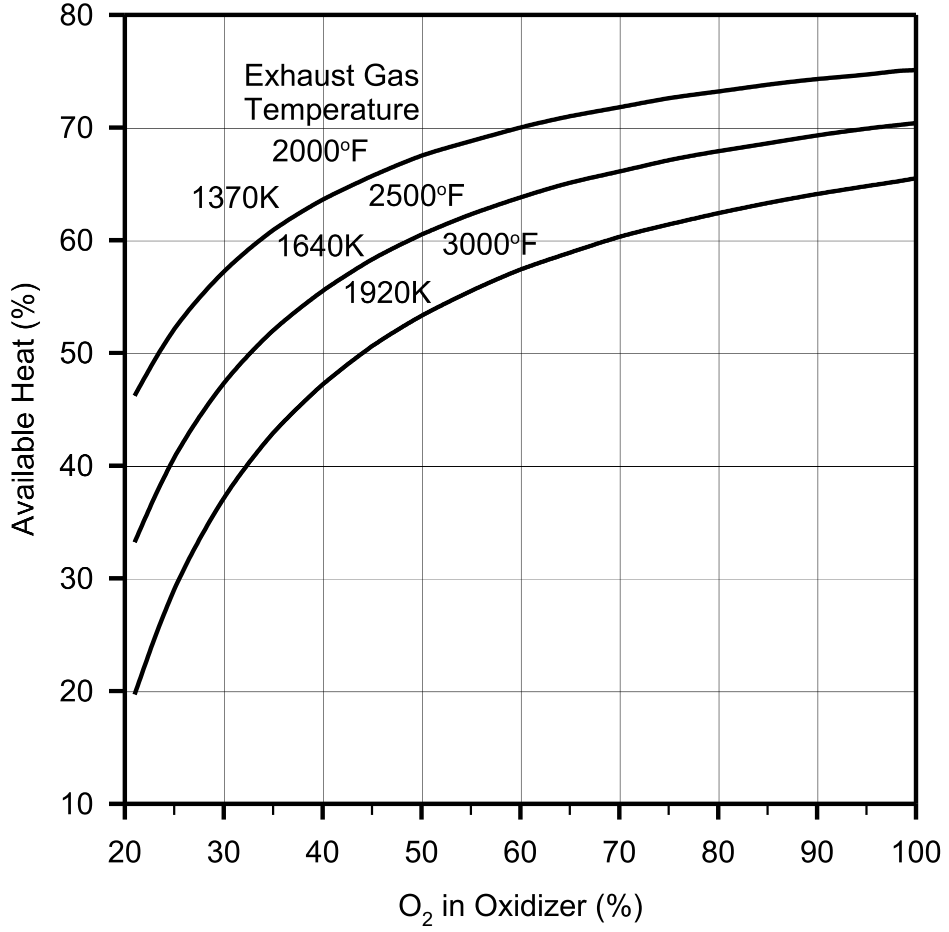
Available Heat for Sub-stoichiometric Combustion

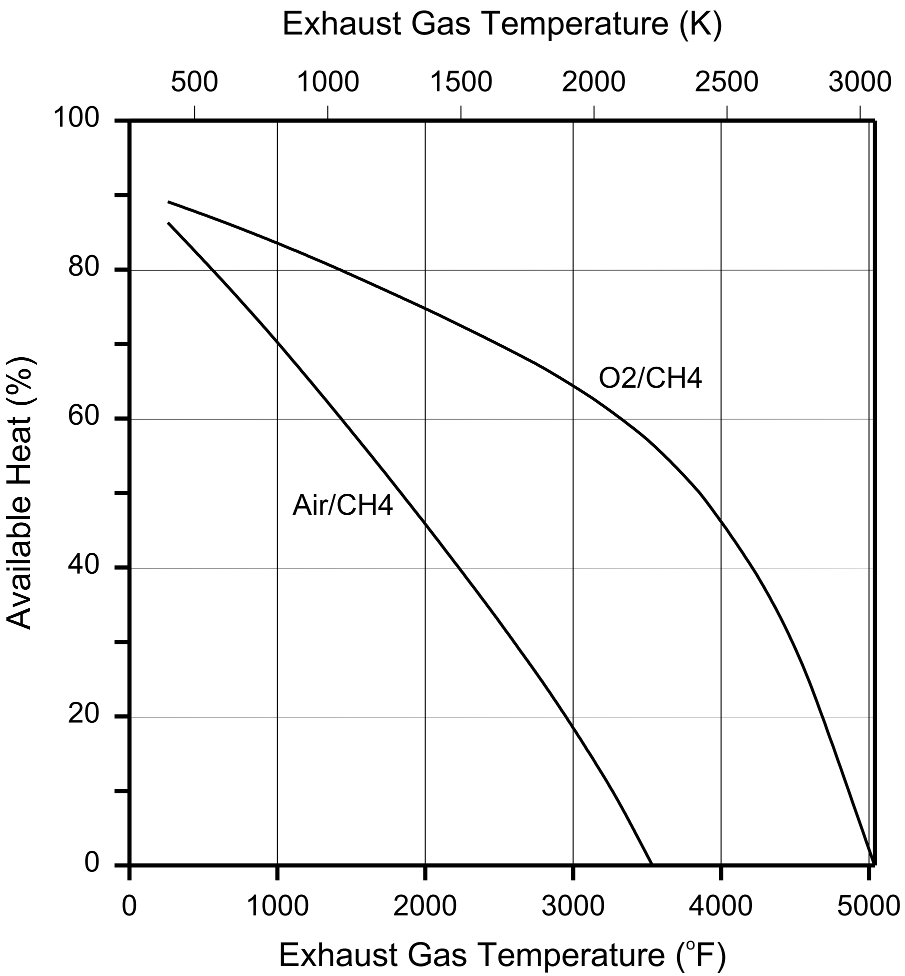
For methane (or typical US natural gas)



Available Heat for Oxy-Fuel Firing

Ambient Oxidant (air or oxygen) Temperature





Maximize Available Heat
(Minimize Exhaust Gas Losses)

$$\Delta H = M \times C_p \times \Delta T$$

Reduce Exhaust Gas Mass Flow

- Minimize excess air at all firing rates
- Reduce/control air leakage into the furnace
- Minimize dilution air in ovens
- Replace or enrich combustion air with oxygen
- Ensure complete combustion – minimize CO, H_2, and unburned hydrocarbons in exhaust

Maintain Lowest Possible Temperature Differential between Exhaust Gases & Incoming Air & Fuel

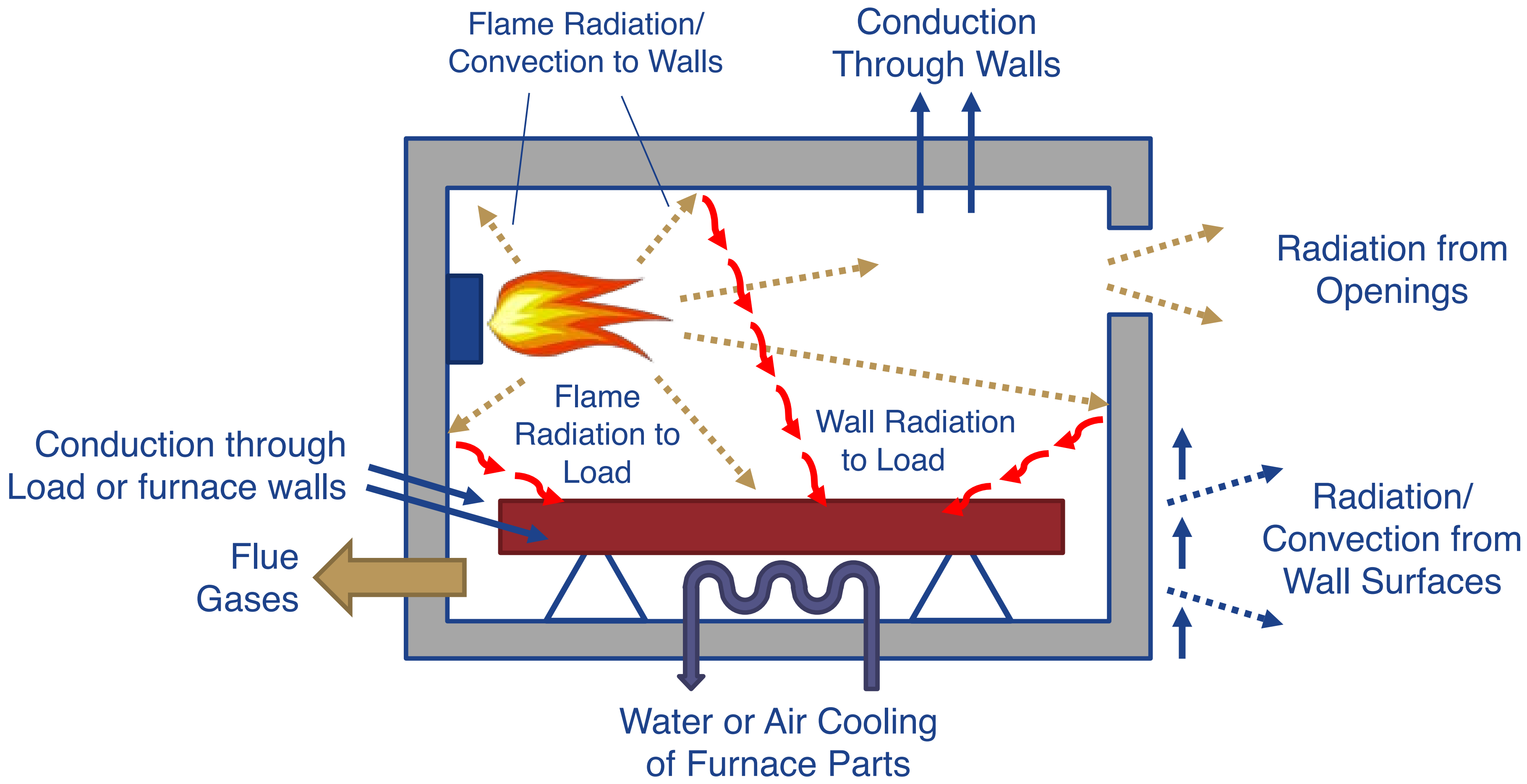
- Preheat combustion air with exhaust
- Preheat low calorific value fuels with exhaust
- Preheat incoming load materials with exhaust
- Maximize heat transfer to load
- Use lowest possible temperature control setting

Modes of Heat Transfer for Process Heating Applications

- Radiation
- Convection
- Conduction

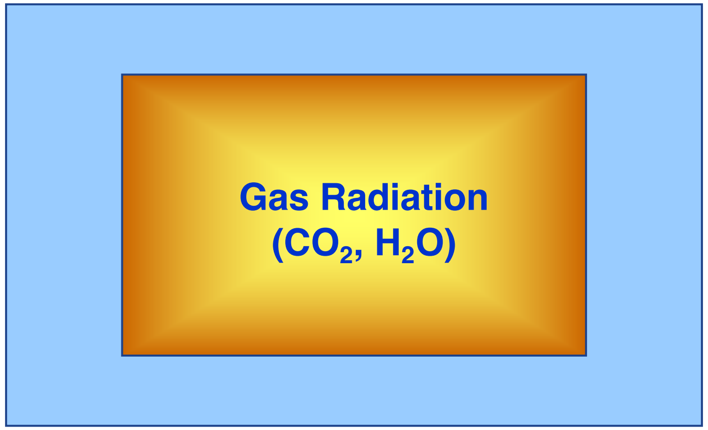
Heat Transfer in Furnaces

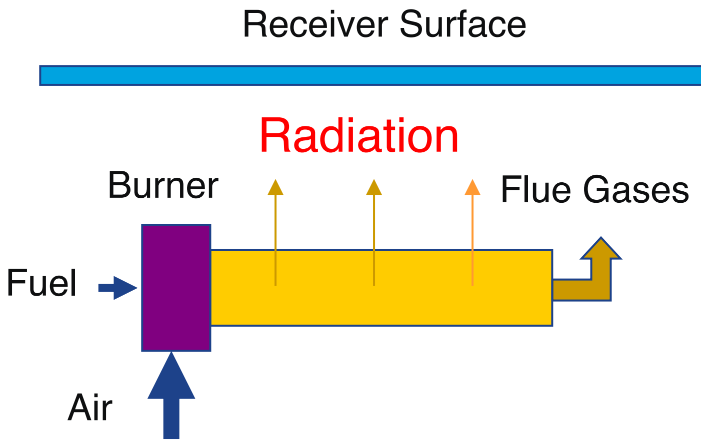
Heat transfer is everywhere and is very complex!



Radiation Heat Transfer

- Radiation is heat transfer via electromagnetic waves. The energy is converted into heat when the waves strike a surface or a body of gases. Physical contact is not necessary for heat transfer—radiation can pass through a vacuum.
- It can originate from a solid or liquid surface or from dipolar gases, such as CO_2 and H_2O, and is a very strong function of temperature.
- Radiation follows the laws of optics – it travels in straight lines, can cast shadows and can be redirected with a suitable reflector. The intensity of omnidirectional radiation decreases with the square of the distance from the source to the receiver.





Factors Affecting Radiation Heat Transfer

- Source (furnace walls, flame, load etc.) temperature
- Receiver (load, ambient surroundings, water cooled surfaces etc.) temperature
- Source emissivity
- Receiver absorptivity (equal to emissivity in most cases)
- Relative position of the source and receiver or “radiation view factor”
- Area of the receiving surface or object

Rate of Radiation Heat Transfer

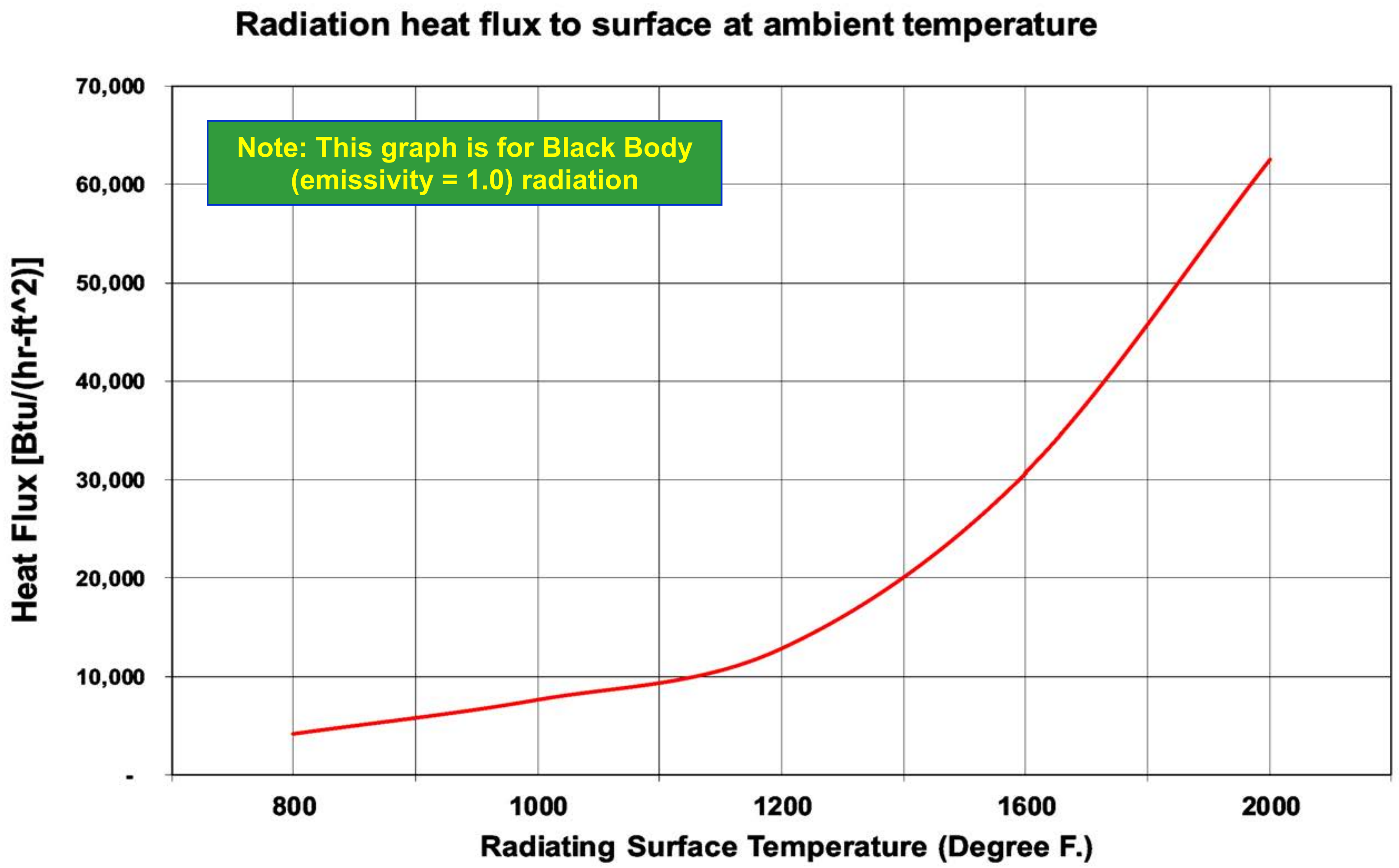
Basic Equation

$$Q = 0.1713*10^{(-8)*}E*F_a*A*(T_{source}^4 - T_{sink}^4)$$

where

Q	Rate of Heat Transfer, Btu/hour
E	Emissivity of the source surface
F_a	Factor related to arrangement (line of sight) of 2 surfaces
T_{source}	Absolute (°F + 460) temperature of radiation source
T_{sink}	Absolute (°F + 460) temperature of receiving surface
A	Surface Area, ft^2

Radiant Heat Transfer

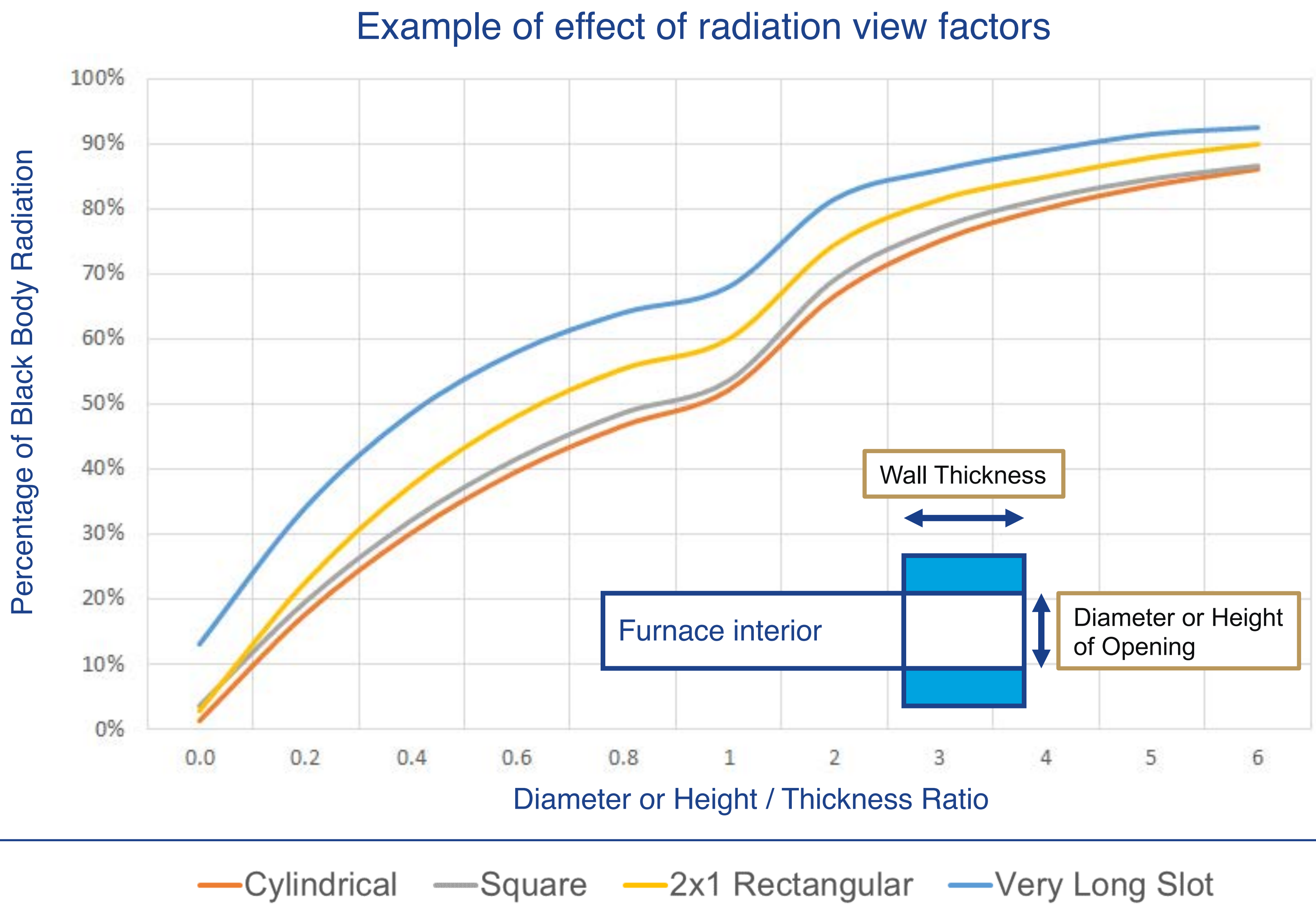


Role of Radiation in Process Heating Equipment

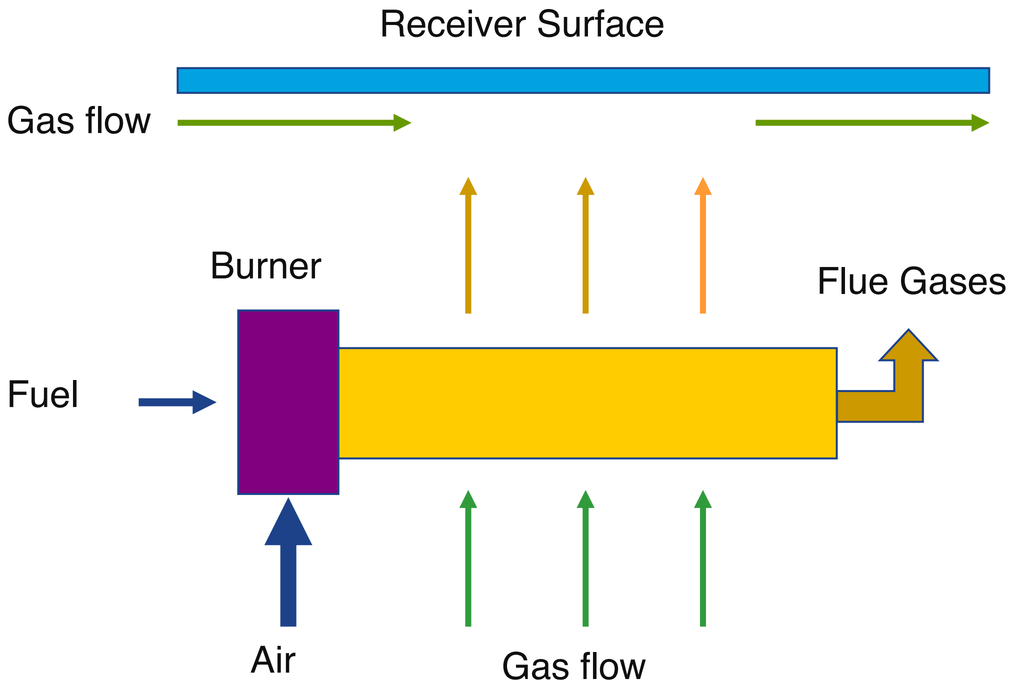
Thermal radiation controls heat transfer in many areas for a heating system operating above approximately 750°F.

- Load heating
- Wall losses
- Opening losses
- Water cooling losses
- Heat recovery (recuperation) equipment

Radiation Heat Losses from Furnace Openings



Convection Heat Transfer



Convection is heat transfer to a surface via a moving fluid (liquid or gas).

- Convection heat transfer affects temperature uniformity in a furnace or oven, and heat transfer to many areas of a furnace and heat losses from the heating system.
- Convection heat transfer is very important for ovens, dryers etc. operating below 750°F.
- However, it can affect temperature uniformity for load and other areas for high temperature processes also.

Poll Question # 4

The single most powerful factor affecting the rate of convection heat transfer from a moving gas stream to a piece of metal is (select one):

- A Surface emissivity of the metal
- B Thickness of the metal piece
- C Temp. difference between gases & metal's surface **Yes!**
- D Shape and size of the furnace

Rate of Convection Heat Transfer

Basic Equation

$$Q = h \cdot A \cdot \Delta T$$

Where:

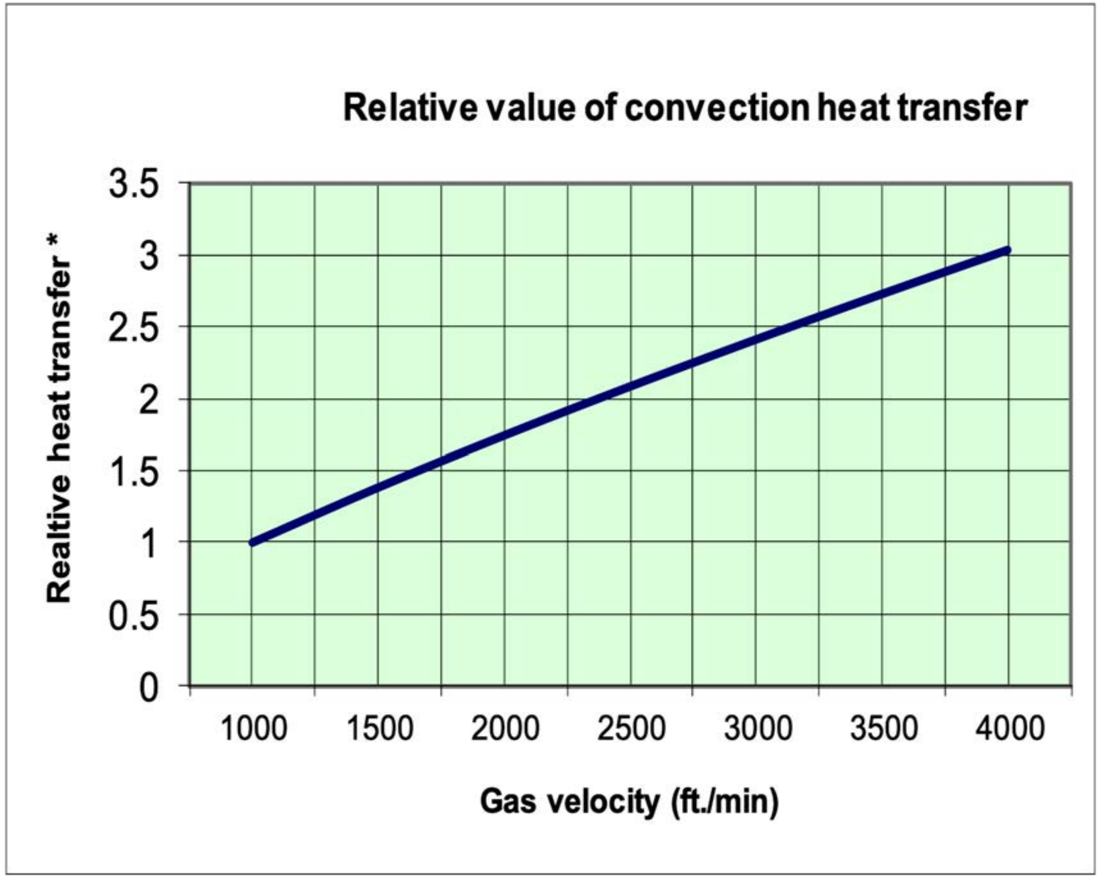
Q = Rate of heat transfer, $\mathrm{Btu/hr}$

h = Heat transfer coefficient $\left(\frac{\mathrm{Btu}}{\mathrm{hr \cdot ft^2 \cdot {}^\circ F}}\right)$

A = Surface area across which heat is transferred, ft^2

ΔT = Temperature difference $(°F)$

Convection Heat Transfer



*** ΔT (temperature difference) constant**

Convection heat transfer depends on:

- Gas velocity on or around the surface being heated (higher velocity gives higher heat transfer)
- Type of gas (Hydrogen is better than air or nitrogen)
- Gas or system pressure
- Gas or system temperature (higher temperature gives a lower convection heat transfer coefficient)

Commonly Used methods for Convection Heat Transfer in Furnaces

The following systems provide convection in increasing order

Higher Convection

- No fan or other forced convection device (natural convection)
- Use of high velocity burners
- Use of roof fan with no shrouds or distribution baffles
- Use of high volume, recirculating fan (roof, side or end) with shrouds and distribution baffles
- Use of an external recirculation fan with proper gas (air) distribution for the load
- Use of high velocity jets with direct jet impingement on the load

Poll Question # 5

Radiation heat transfer from a hot source is most effective (select only one):

A At a temperature below 300°F

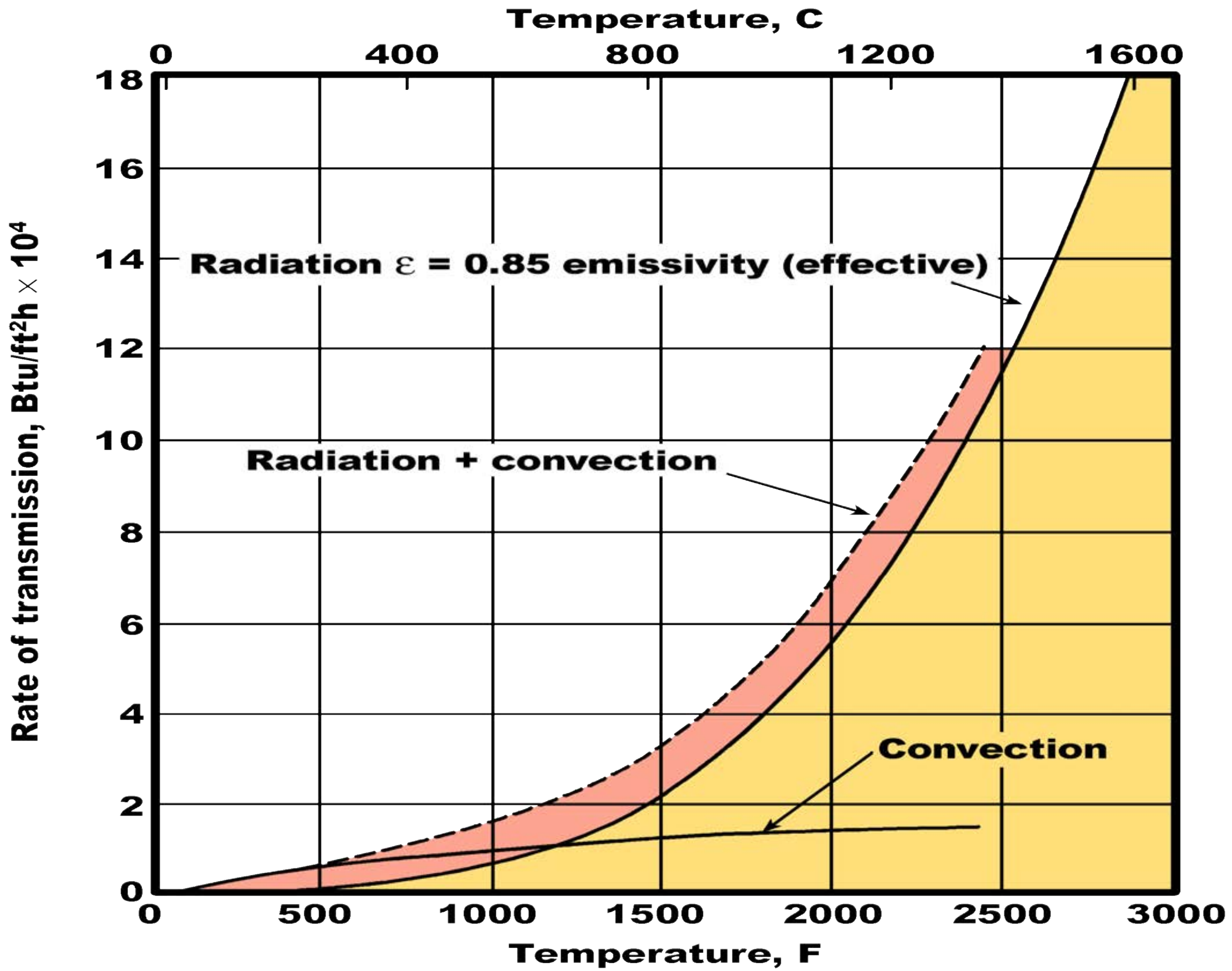
B In smaller furnaces compared to larger furnaces

C For frying of potato chips

D At a radiating temperature higher than 1400°F **Yes!**

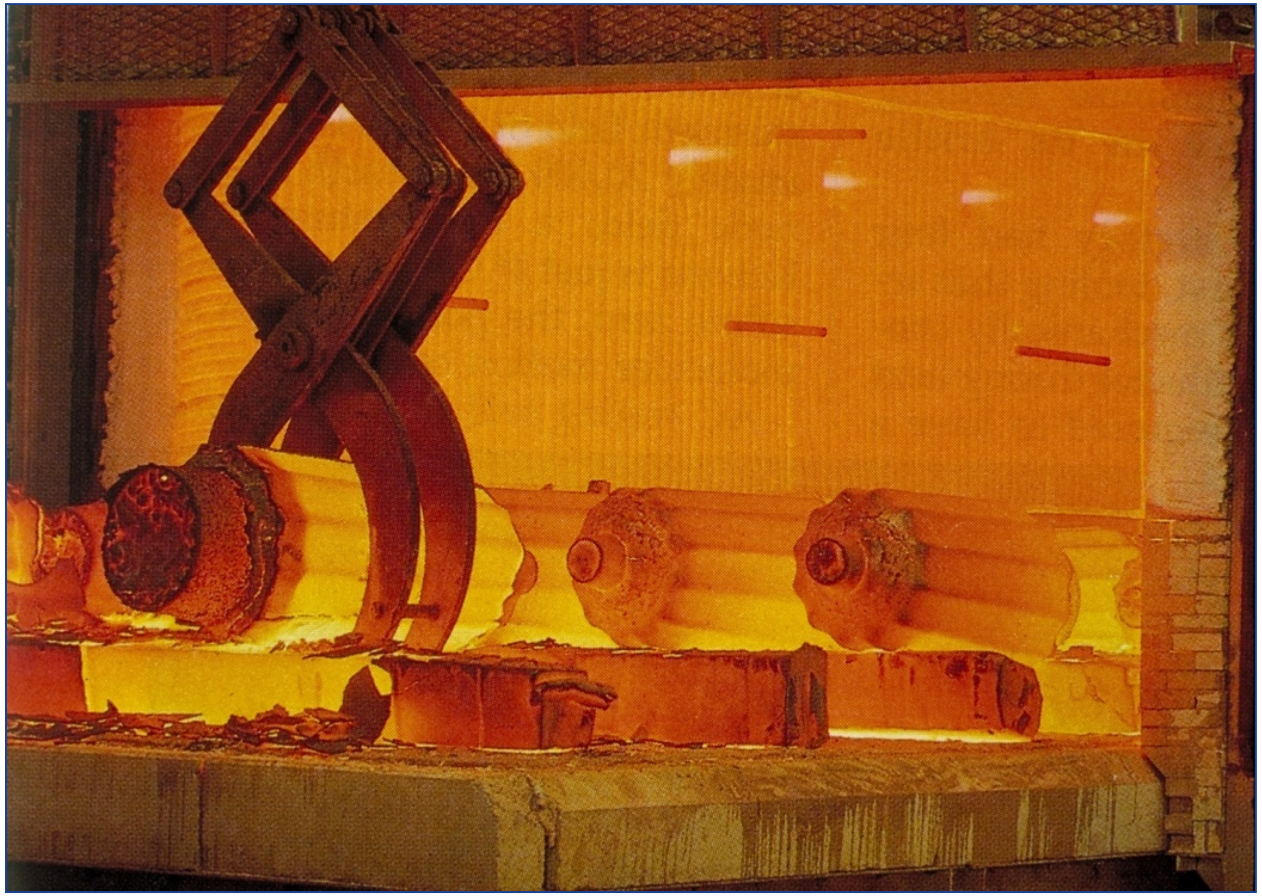
Combined Heat Transfer in Furnaces and Ovens

Putting it All Together!



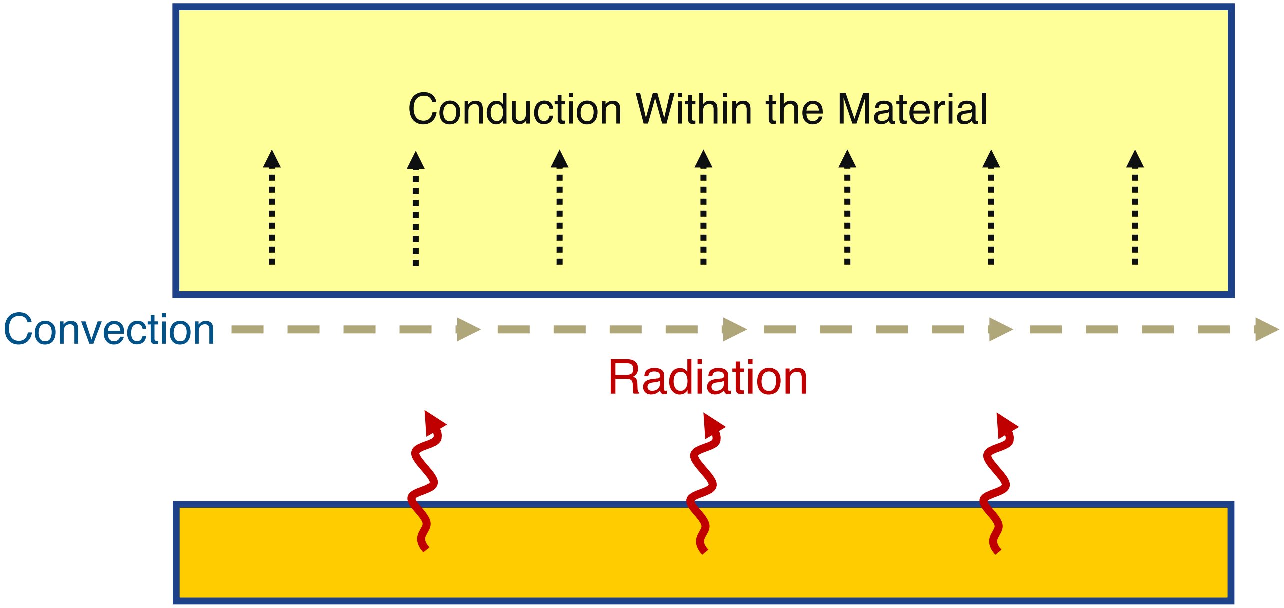
Real Life Applications in High Temperature Furnaces

Radiation Plus Some Convection



Conduction Heat Transfer

Heat transfer within a solid or liquid from one point to another or by physical contact between two materials.



Conduction Heat Transfer

Basic Equation

$$Q = k \cdot A \cdot \Delta T / \Delta X$$

where

- ***Q*** **rate of heat transfer (Btu/hr)**
- ***K*** **thermal conductivity of material [Btu-ft/(hr-ft²)]**
- ***A*** **surface area (ft²)**
- **ΔT temperature difference (ºF)**
- **Δx depth (thickness or radius) through which heat is transferred (ft)**

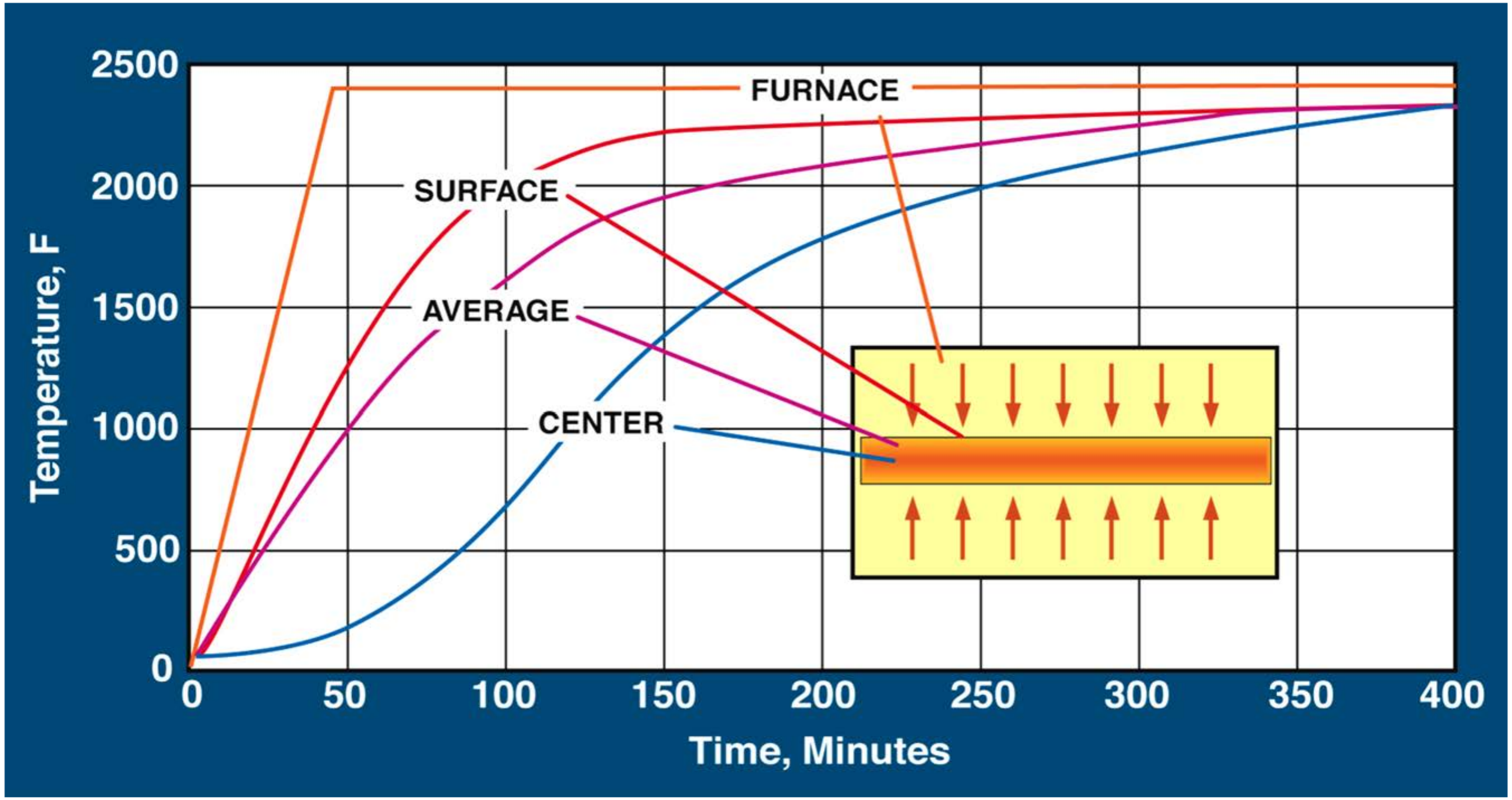
Conduction heat transfer is within the material itself.

Conduction heat transfer depends on:

- Thermal conductivity of the material
- Temperature difference between the surface and the interior or opposite surface
- Dimension (thickness, radius) of the part or particle across which the heat must travel

Typical Temperature Gradients through Load

Heating of a Thick Steel Slab



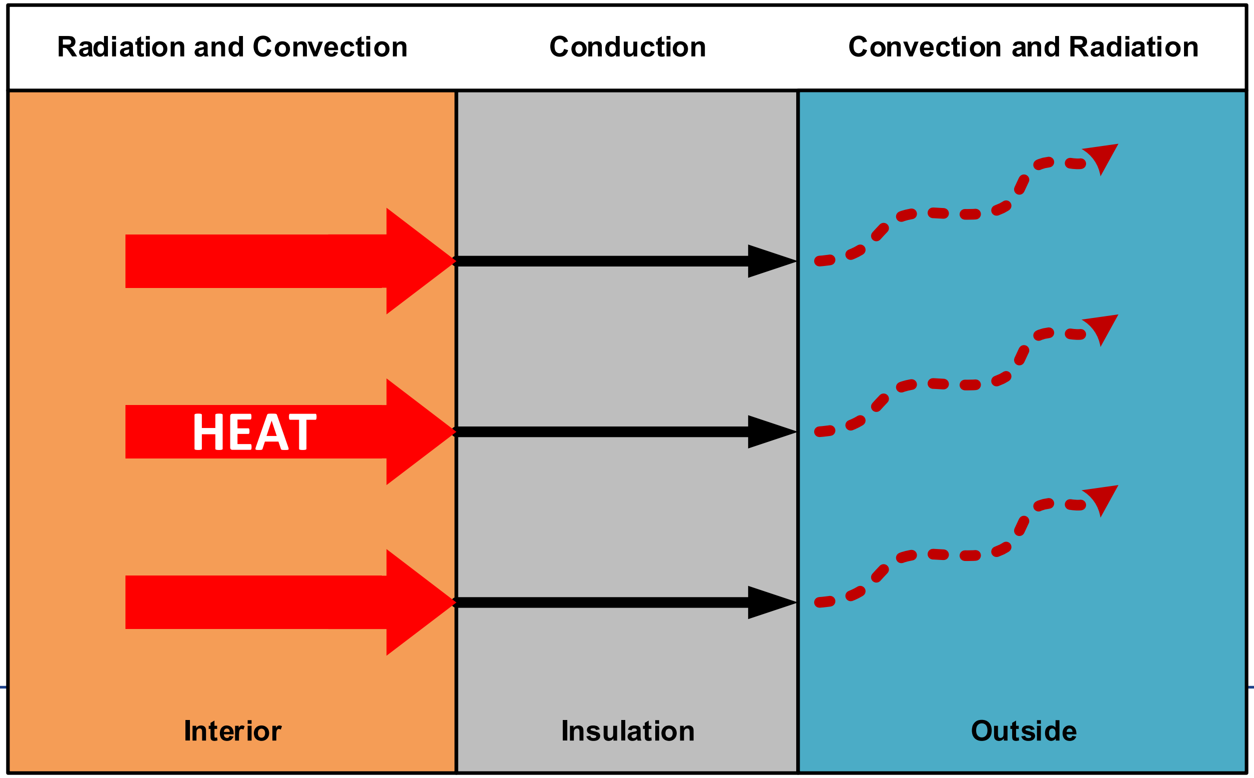
Importance of Three Modes of Heat Transfer:

Furnace wall losses depend on the following factors:

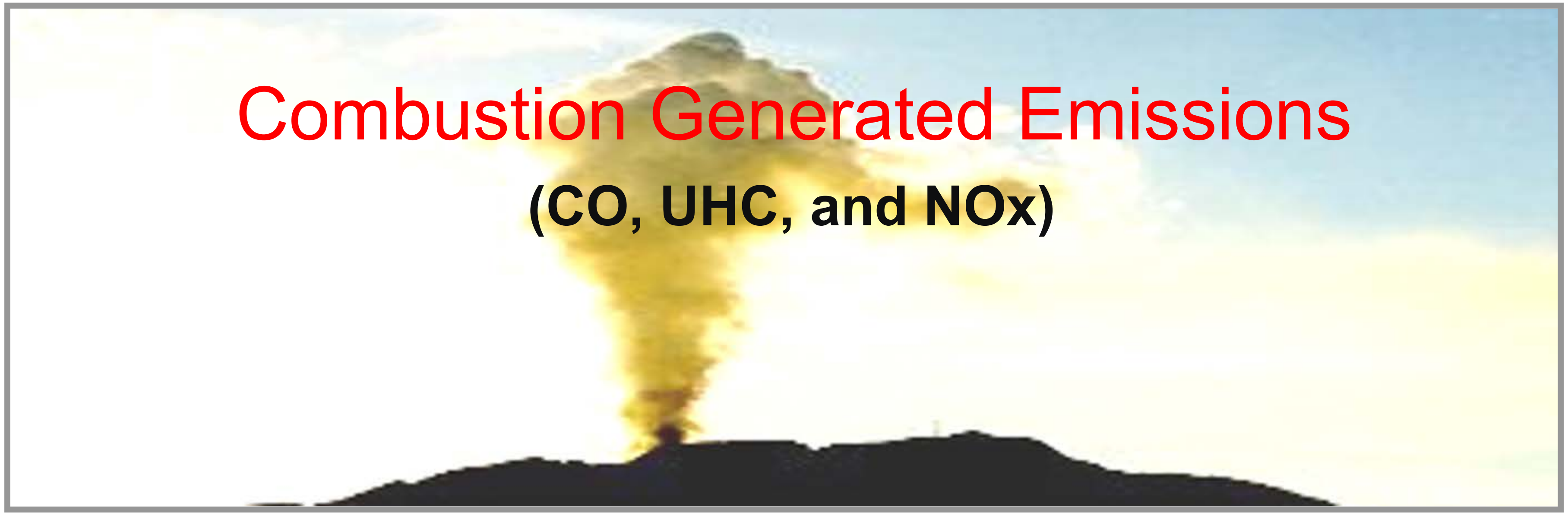
Inside temperature
Furnace atmosphere, particularly amount of hydrogen, if present.

Wall thickness
Type of insulation

Ambient temperature
Ambient wind conditions
Wall surface orientation (horizontal, vertical, facing up or down)



Process Heating Basics



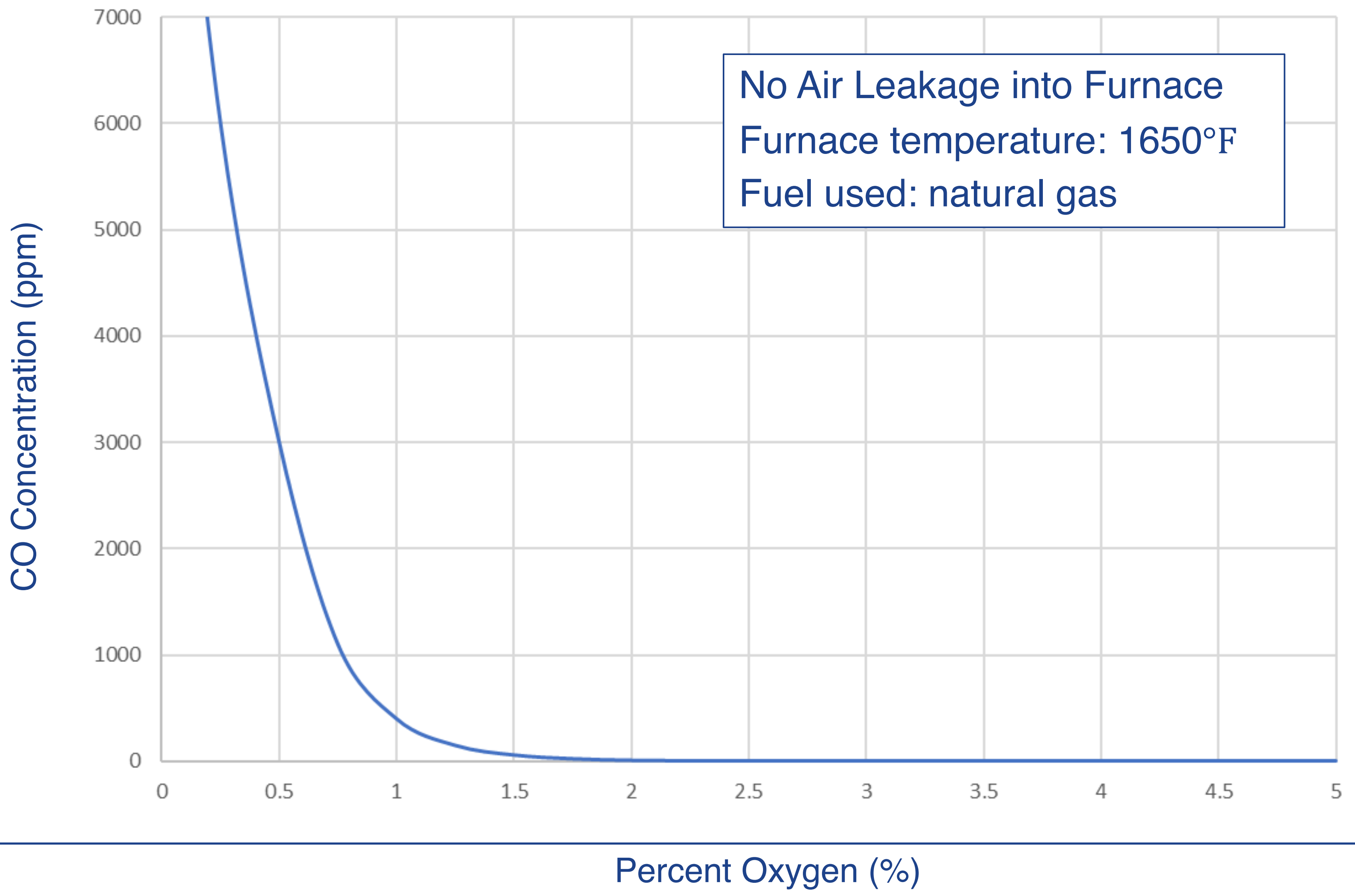
This section considers issues for most commonly used heating systems using “clean” fuels that do not contain contaminants such as sulfur, chlorine etc.

Factors Affecting CO and UHCs* Formation

- Operating Temperature of the Furnaces or Ovens
- Excess Air Operation
- Excess Fuel (Sub-stoichiometric) Operation
- Burner and Furnace Design:
  - burner mixing & turbulence characteristics
  - location of colder “quenching” surfaces relative to flame
  - furnace gas recirculation patterns

* UHC – Unburned hydrocarbons

CO Formation



Poll Question # 6

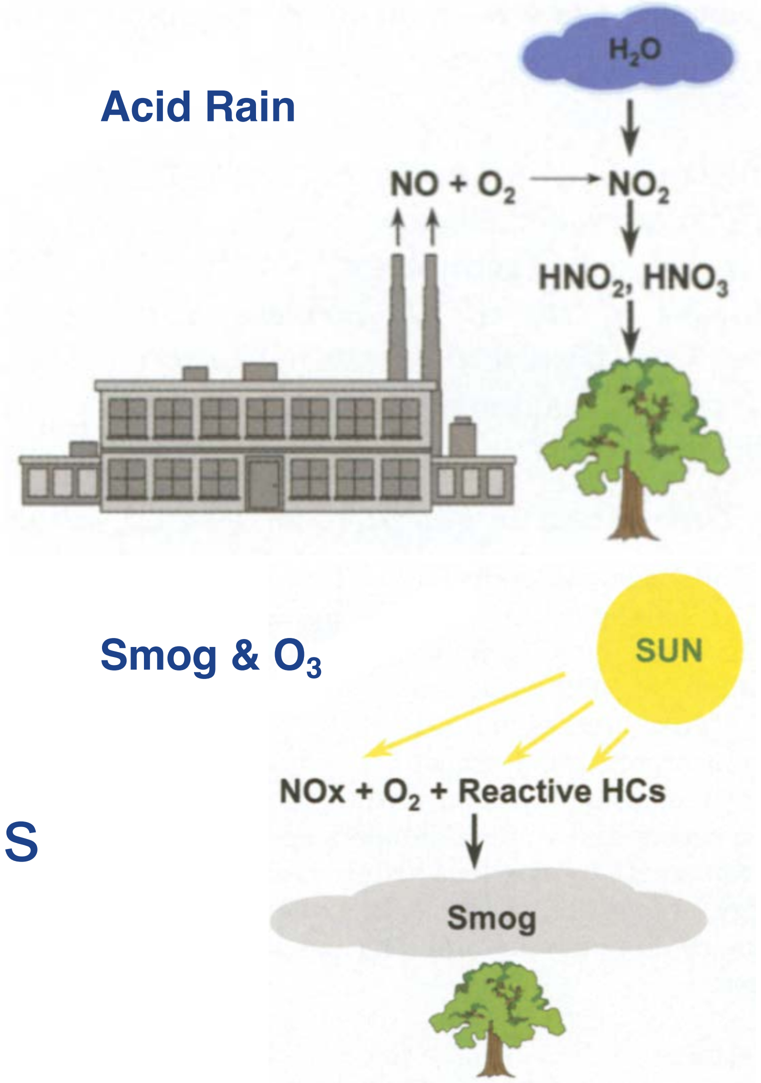
What major factors control the NOx formation (select only TWO):

A	Ambient Temperature	
B	Flame Temperature	Yes!
C	Charge material characteristics	
D	Nitrogen from fuel or other sources	Yes!

Factors Influencing NOx Formation

- Temperature
  - Flame Temperature
  - Operating Temperature
  - Fuel-air reaction (residence) time
- Oxygen Concentration in Flame Zone
- Burner design characteristics
- Nitrogen from fuel or other sources
- Combustion & furnace gas recirculation patterns

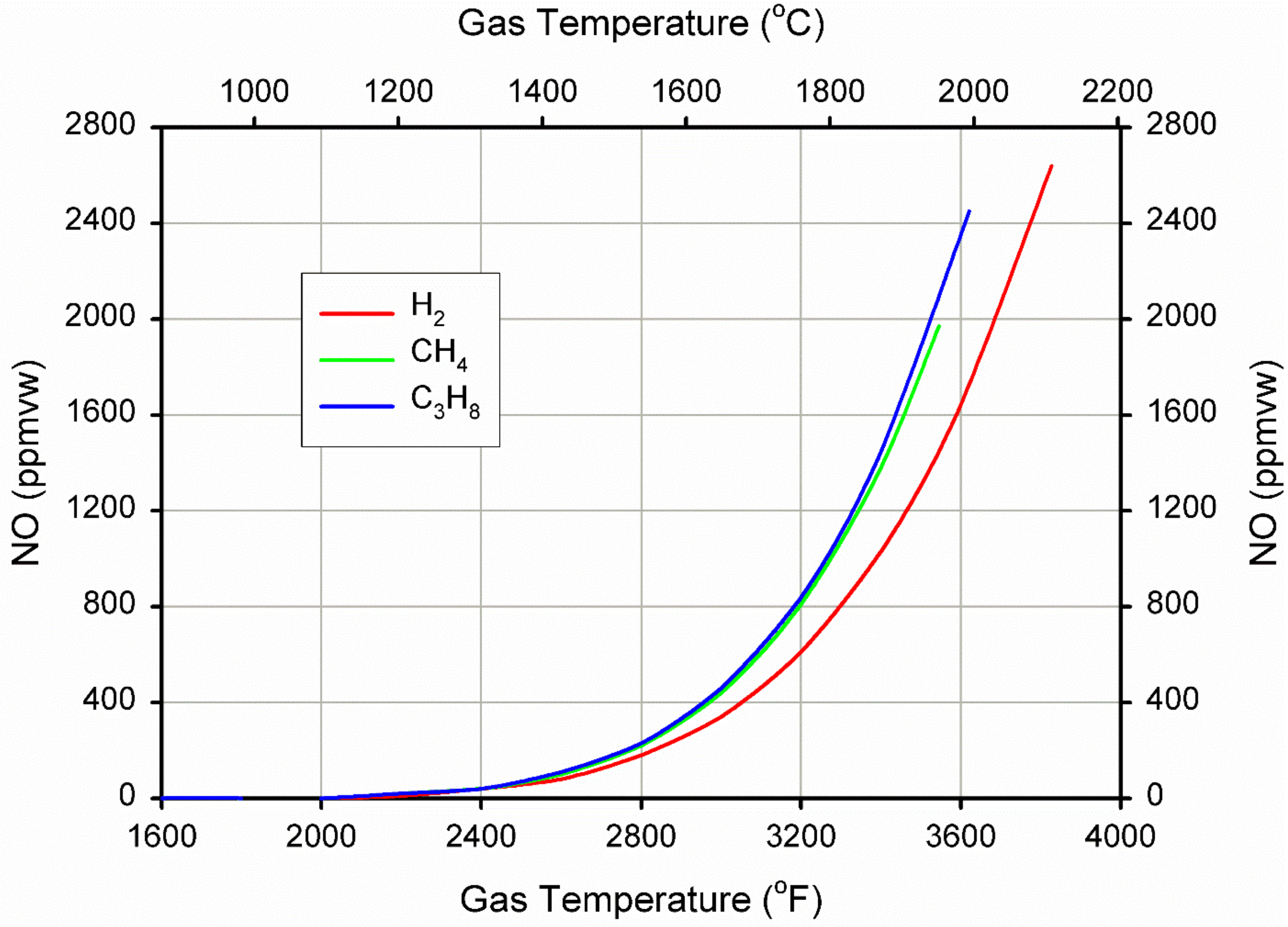
Thermal NOx   Prompt NOx   Fuel NOx



Temperature Factors for NOx Formation

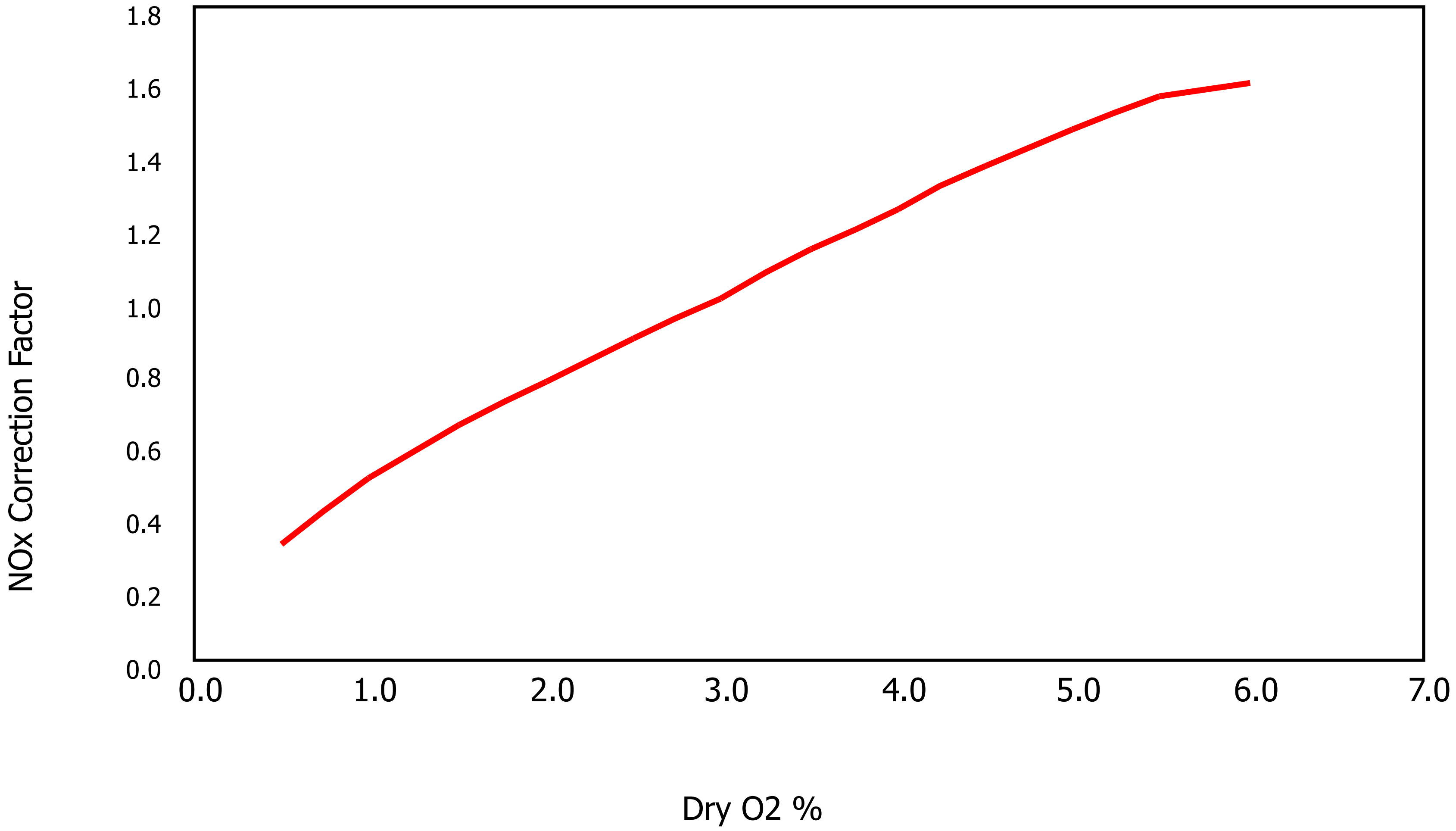
- Flame temperature - fuel composition
- Furnace temperature
- Combustion air temperature
- Burner location for multi-burner systems
- Burner firing rate
- Mixing (furnace gases and combustion products) within the furnace

NOx Formation
Flame Temperature Effects



Excess O2 Correction for NOx Emission Readings

Factors to correct Measured NOx to 3% O2 Standard



Commonly Used Methods of NOx Reduction

Table I: NOx Reduction Technologies (adapted from M. Bradford, R. Grover, P. Paul, Controlling NOx Emissions—Part 1, *Chem. Eng. Progress*, Vol. 98, No. 3, pp. 42–cv46, 2002)		
Technology	*Approximate Reduction (%)*	*Approximate Emissions (lb./MMBtu)*
Standard burners	Base Case	0.14
Low-NOx burners (LNB)	60%	0.06
Ultra-low-NOx-burners (ULNB)	80–95%	0.007–0.03
Flue gas recirculation	55%	0.025
Selective noncatalytic reduction (SNCR)	40%	0.033–0.085
Selective catalytic reduction (SCR)	90–97%	0.006–0.015

Reference - Everything you need to know about NOx: Controlling and minimizing pollutant emissions is critical for meeting air quality regulations, Charles Baukal, 2005

Acknowledgement

Information used in this presentation has been derived from several sources including web sites of equipment manufacturers, published literature and handbooks. Special thanks to Fives North American Manufacturing Company for use of number of figures from the North American Combustion Handbook.

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Questions?