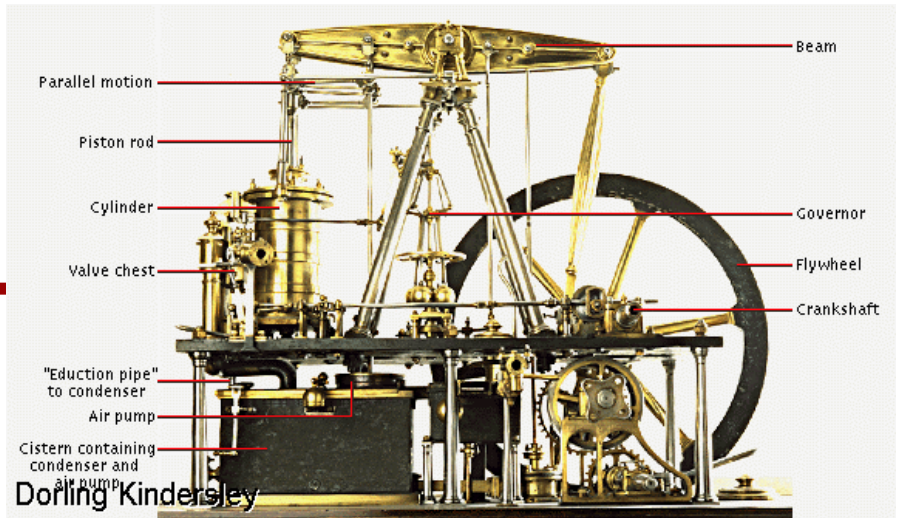


Boilers



Motivation



- Boilers, were a major part of the Industrial Revolution beginning about 1700. They are major consumers of industry and building energy consumption today.
- Industry: boilers are used for power generation, process heat (e.g., refineries, petrochemicals, paper mills, tire manufacturing, etc.) and heating.
- In buildings, boilers are used for steam primary heat, terminal reheat systems, water heating and absorption chillers.

DEUTSCHE BABCOCK



CK



DB RILEY, INC.

BTM **BRYAN
BOILERS**

Since 1916 *Subsidiary of Bryan Steam Corporation*

ABB



nebraska boiler company

DIVISION OF NATIONAL DYNAMICS CORPORATION



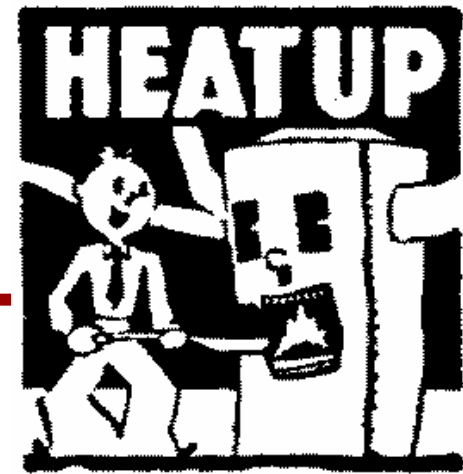
E N G L I S H

ENGLISH BOILER & TUBE, INC.

ME 416/516

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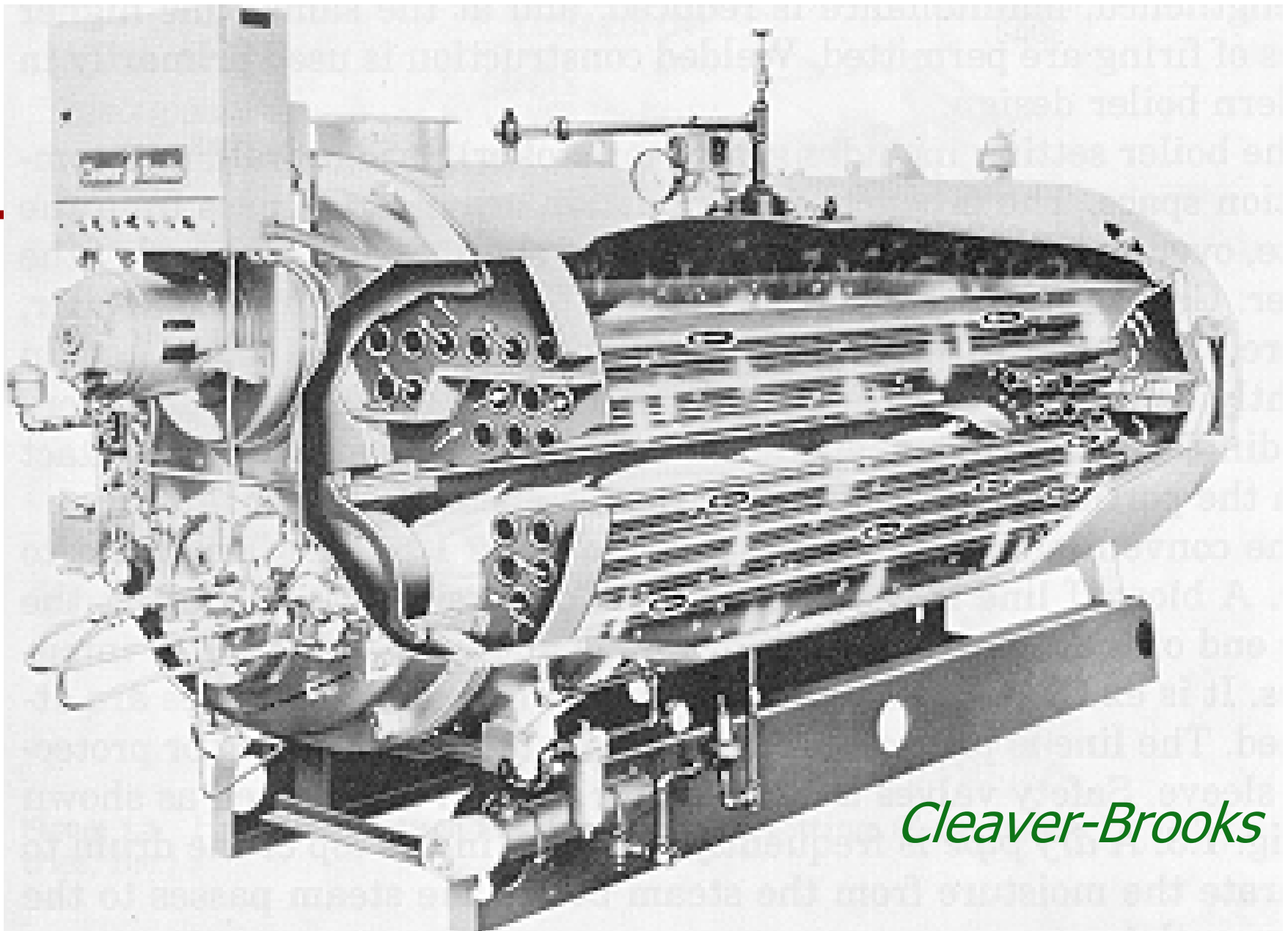
Introduction



- There is a tremendous variation in boiler design and size- ranging from home heating size of capacity less than 100 lbm/hr of steam to utility boilers in excess of 10 million lbm/hr.
- The focus here will be on boilers sized in between these two extremes, which is also where there is the greatest diversity of design.
- In order of increasing capacity, three boiler types are the fire-tube, water-tube and waterwall boilers.

Fire-Tube Boiler (~1800)

- The fire tube boiler, the oldest design, is made so the products of combustion pass through tubes surrounded by water in a shell.
- The furnace/flame volume can either be inside or external to the shell that contains the water.
- The upper steam capacity of fire tube boilers is about 20,000 lbm/hr, and the peak pressure obtainable is limited by their large shells to about 300 psi.
- Fire-tube boilers are used for heating systems.

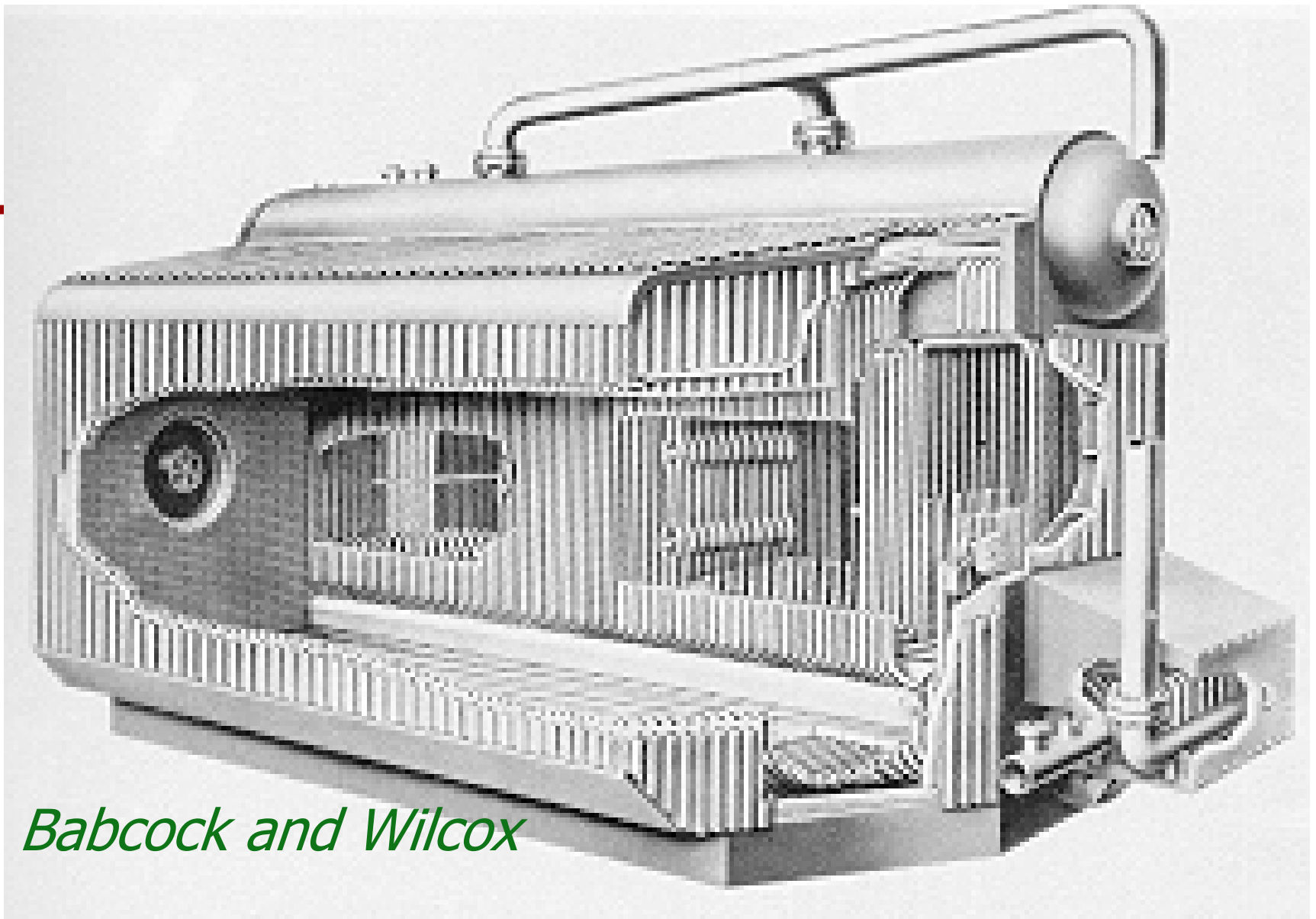


Cleaver-Brooks

Horizontal, four-pass, forced-draft fire-tube boiler

Water-Tube Boiler (1867)

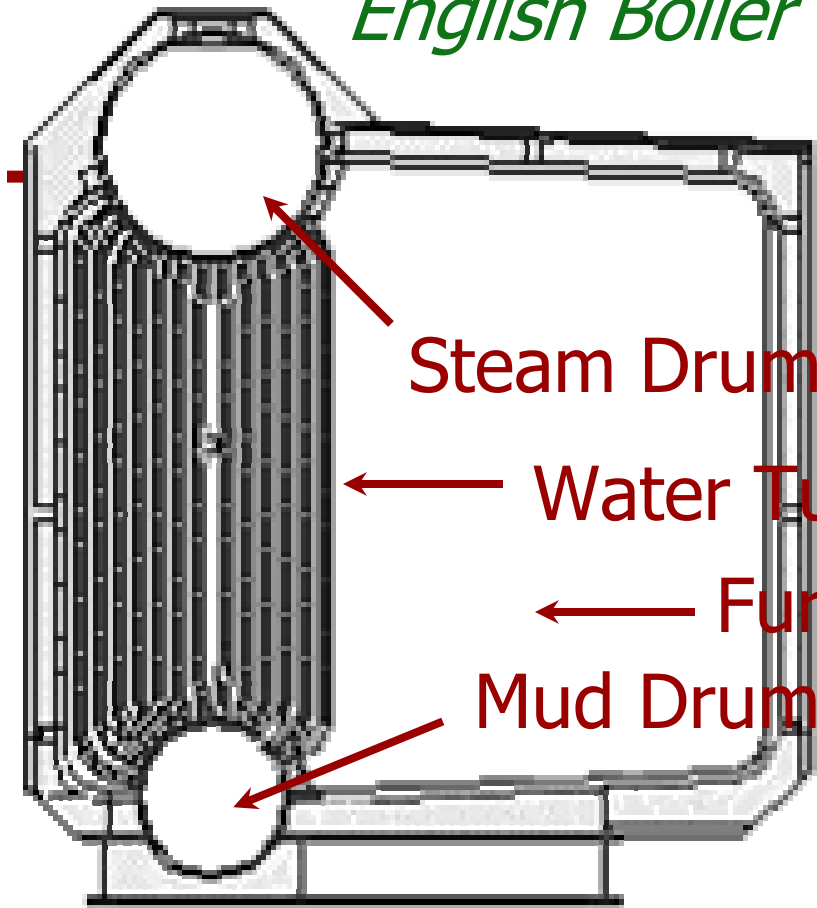
- A water-tube boiler is one in which the products of combustion pass around the outside and heat tubes containing the water.
- The water tube diameter is much smaller than the shell diameter of a fire-tube boiler, so much higher pressures can be obtained, well over 2000 psi.
- The furnace and boiler tube area must be surrounded by a heavily insulated refractory wall to prevent heat transfer through the boiler walls. The refractory lining is a high maintenance item.



Babcock and Wilcox

Type FM integral-furnace package boiler

English Boiler Co.



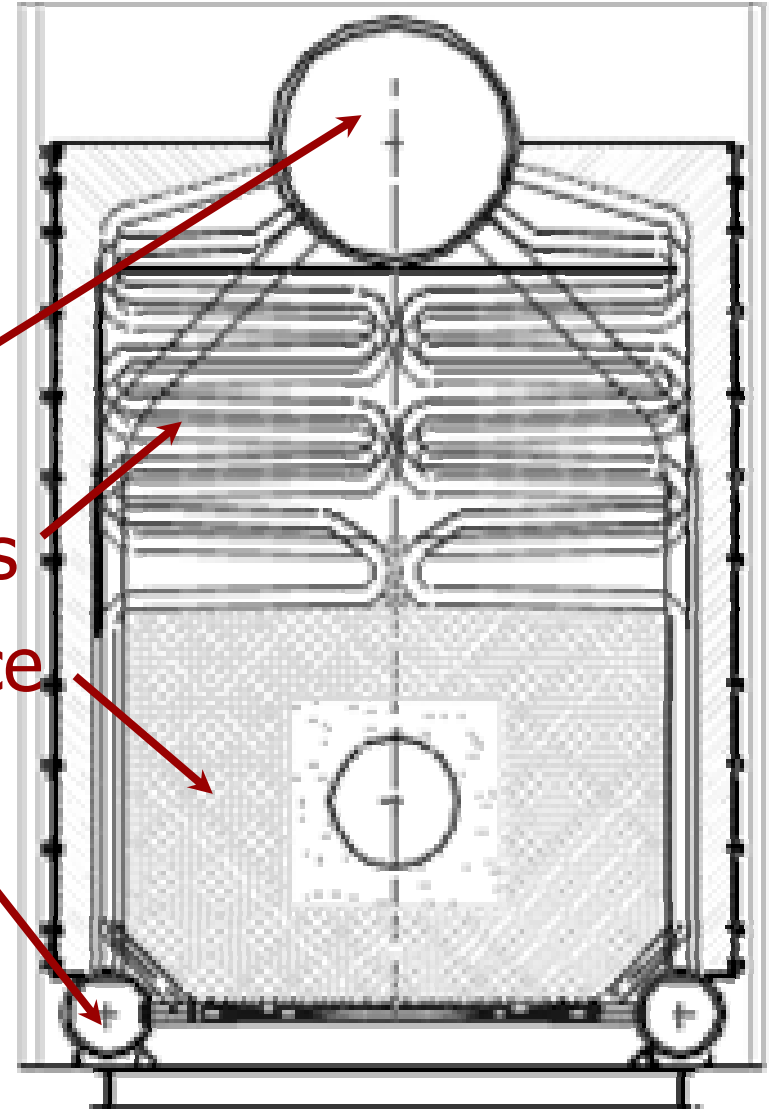
Steam Drum

Water Tubes

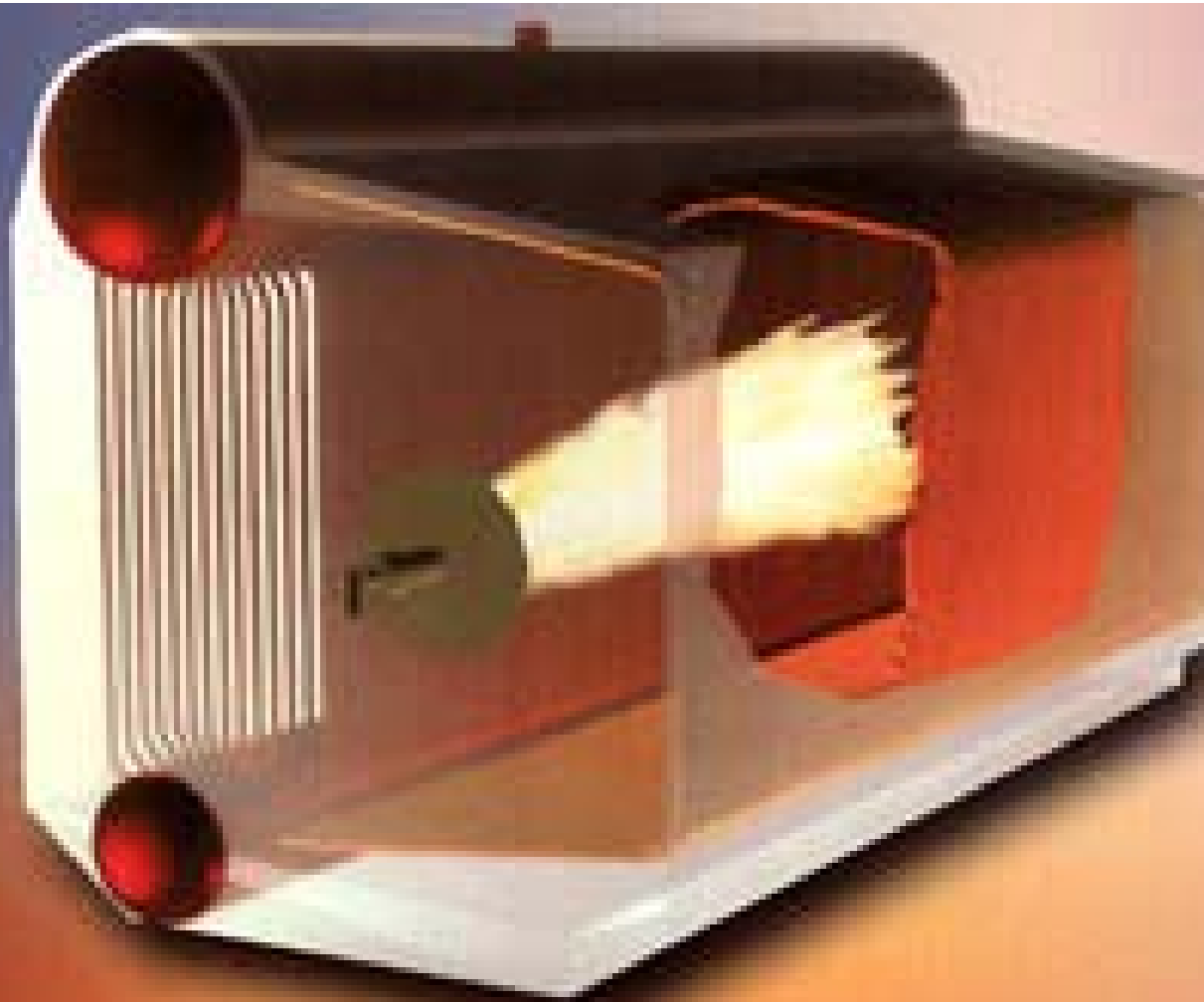
Furnace

Mud Drum

"D-type" water-tube boiler



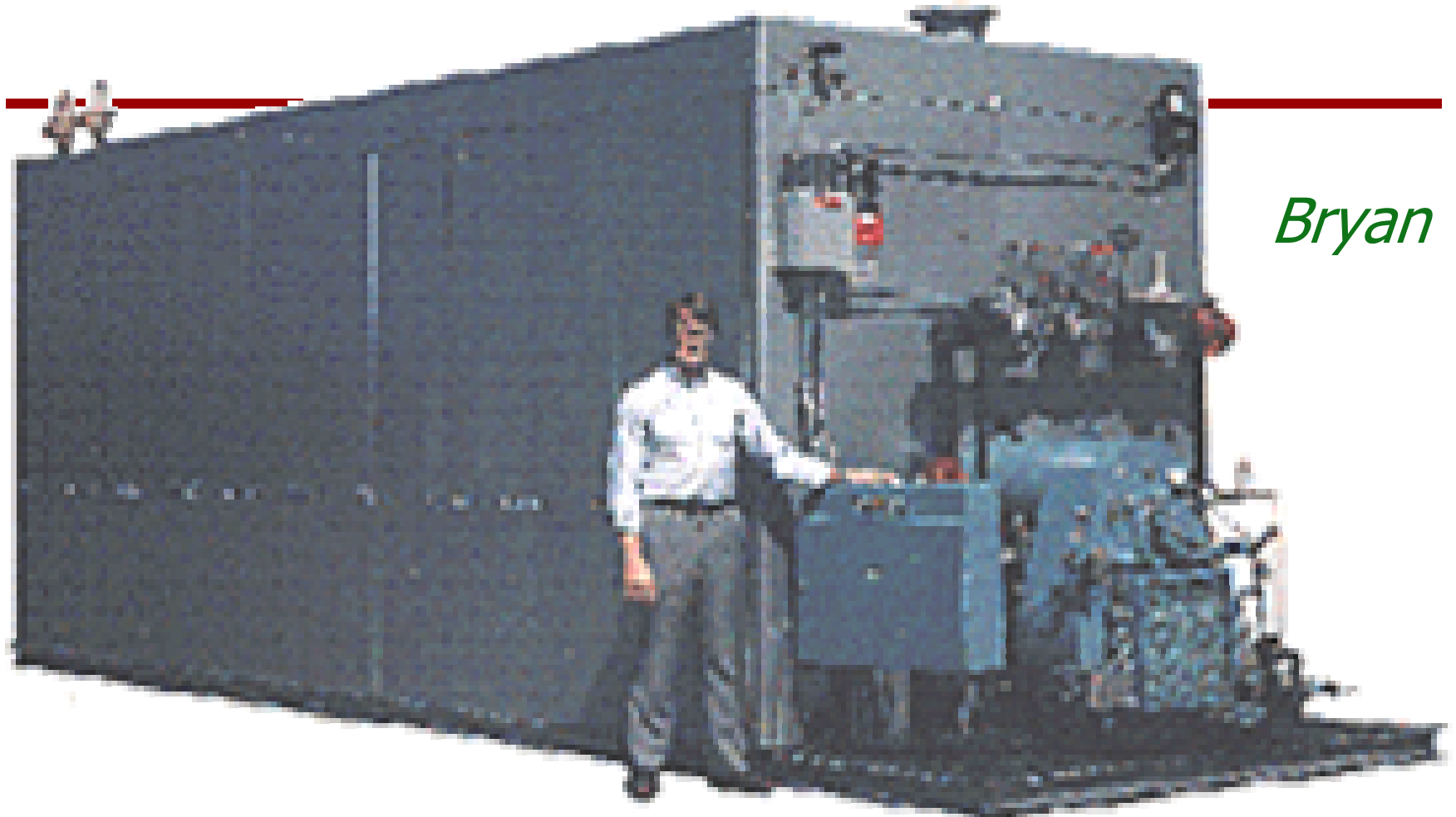
"Flex-tube" water-tube boiler



ABB

"D-type" water-tube boiler

ME 416/516



Bryan

Exterior of small water-tube package boiler

Package Boiler

- All but the largest boilers used for heating and industrial purposes are packaged boilers.
- They are factory-built and shipped whole or in modular components to the customer.
- Many are constructed in an elongated shape that will fit through large building doors with minimal field adjustment required.

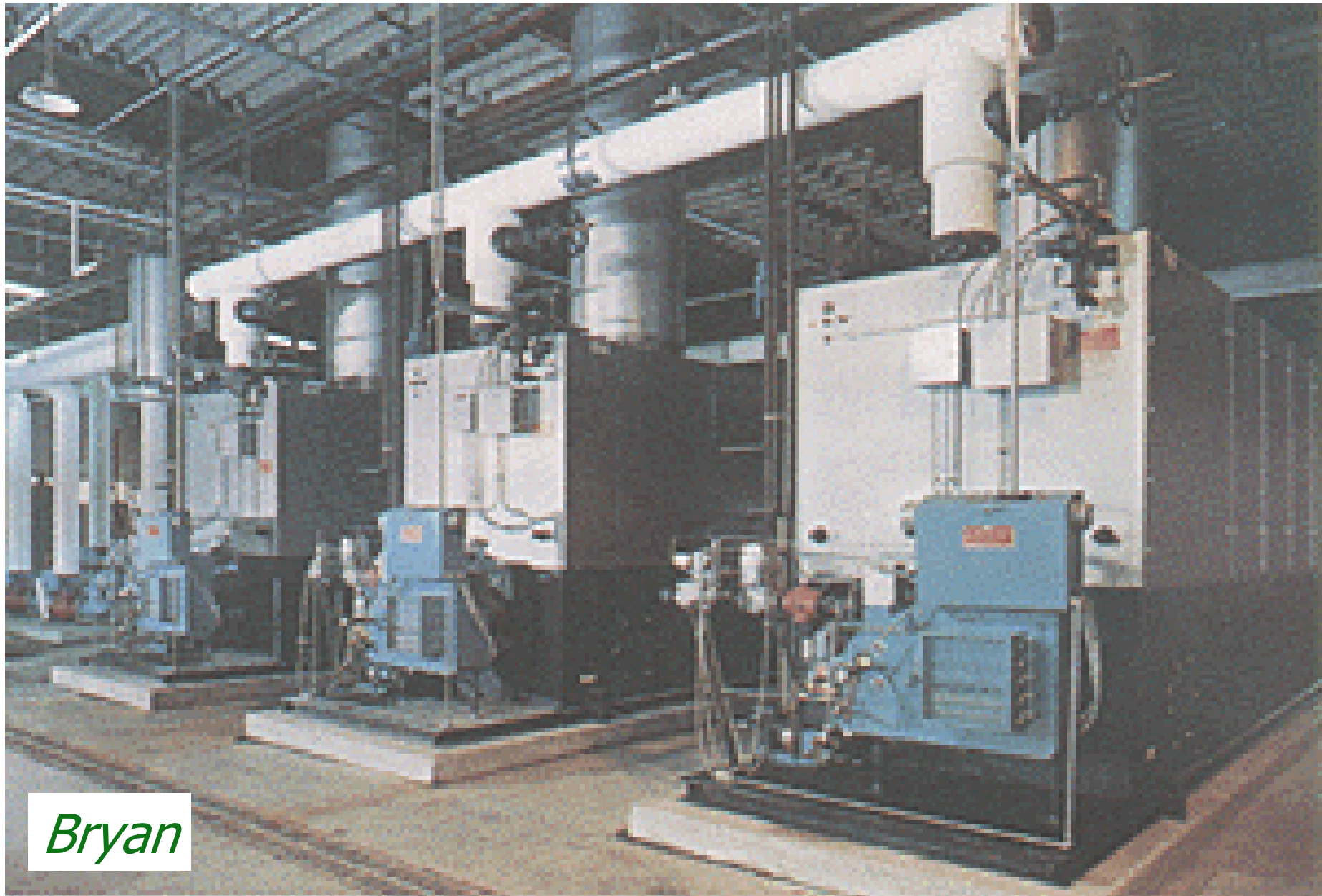


Riley

Water-tube package boiler under construction

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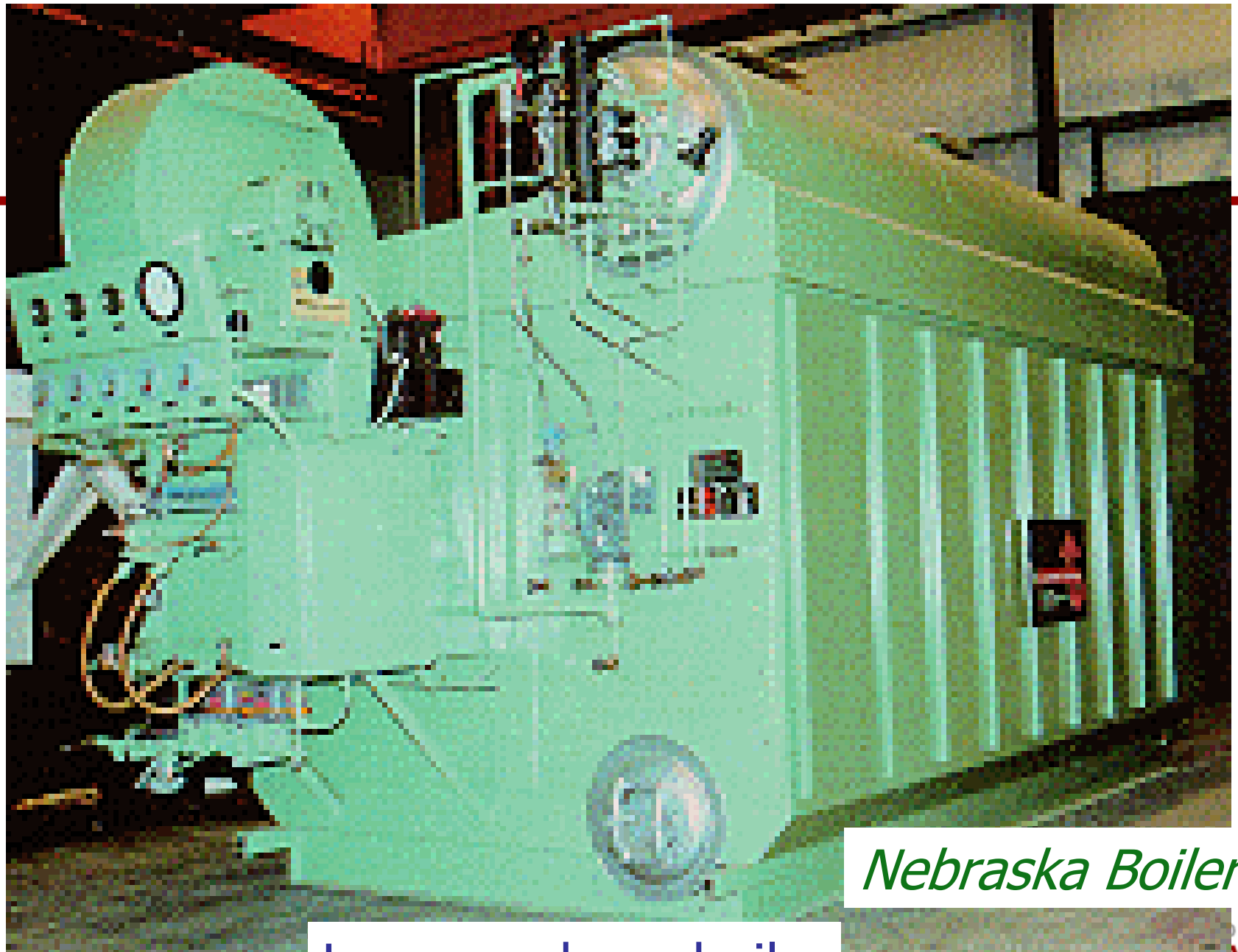
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Bryan

ME 416/516 Large package boiler installation

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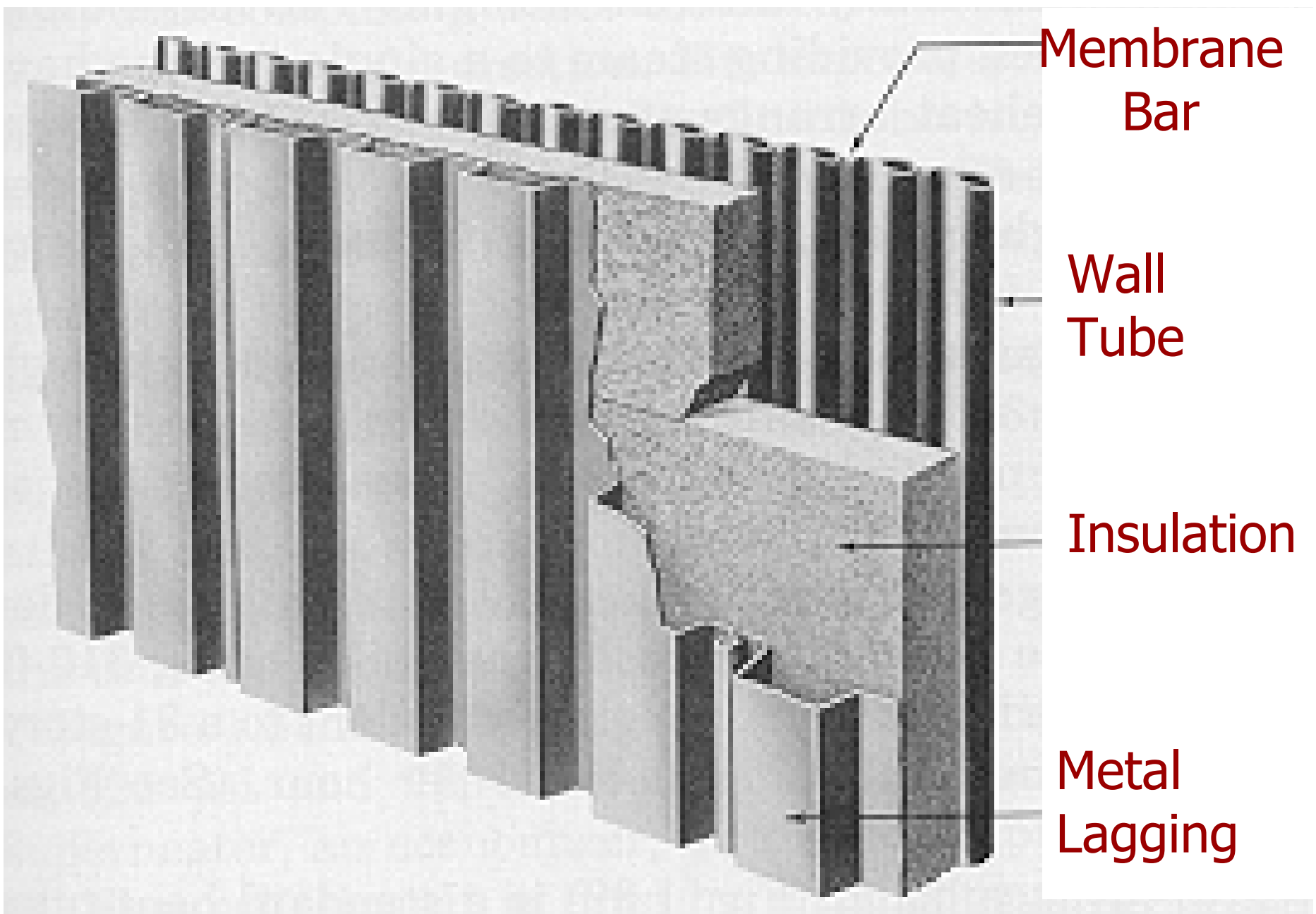
Large package boiler

Nebraska Boilers

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ENGINEERING

Waterwall Boiler

- All large and many intermediate-sized boilers are water-tube boiler with a boiler section that consists of closely-spaced water tubes covering the furnace wall.
- The waterwall boiler design allows much lighter, less expensive walls by having the waterwalls form an integral part of the boiler wall so that the wall is water cooled.
- If so equipped, the superheater and reheater are separate sections hanging above the main furnace volume.



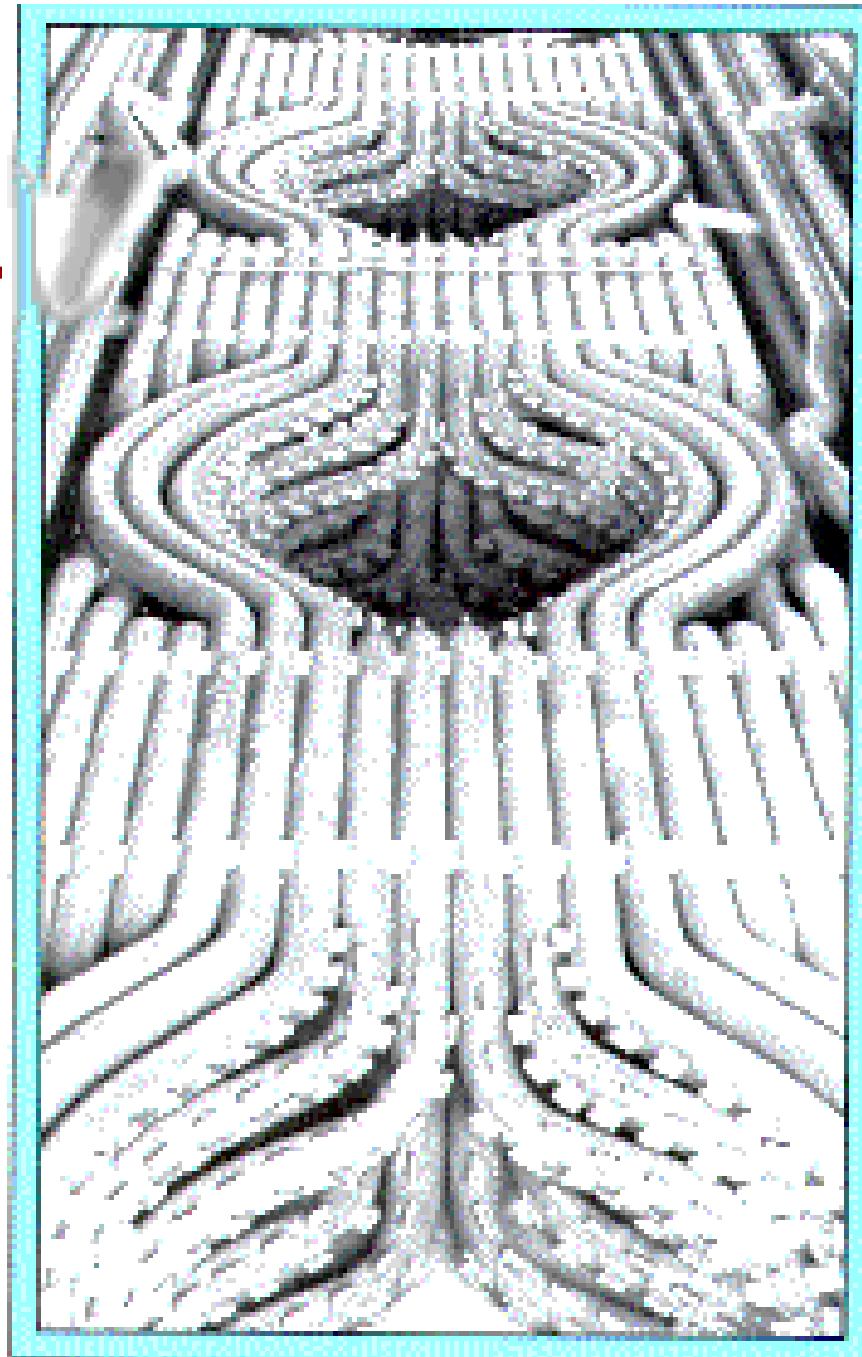
Membrane
Bar

Wall
Tube

Insulation

Metal
Lagging

Waterwall under construction



Cyclone
Scrubbers

Stirling Boiler- A
small waterwall
boiler for burning
solid material
such as bark,
chips or coal.

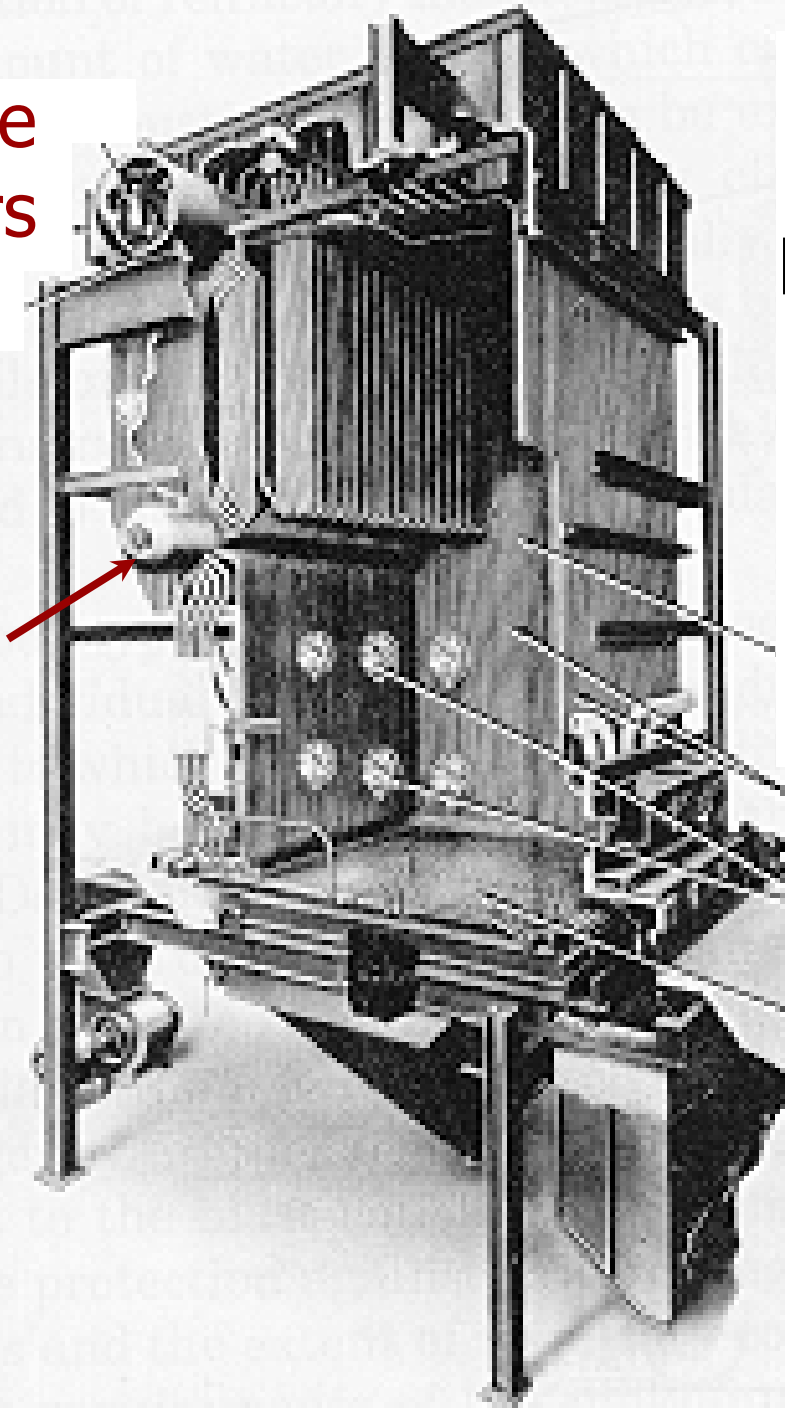
Steam Drum

Superheater

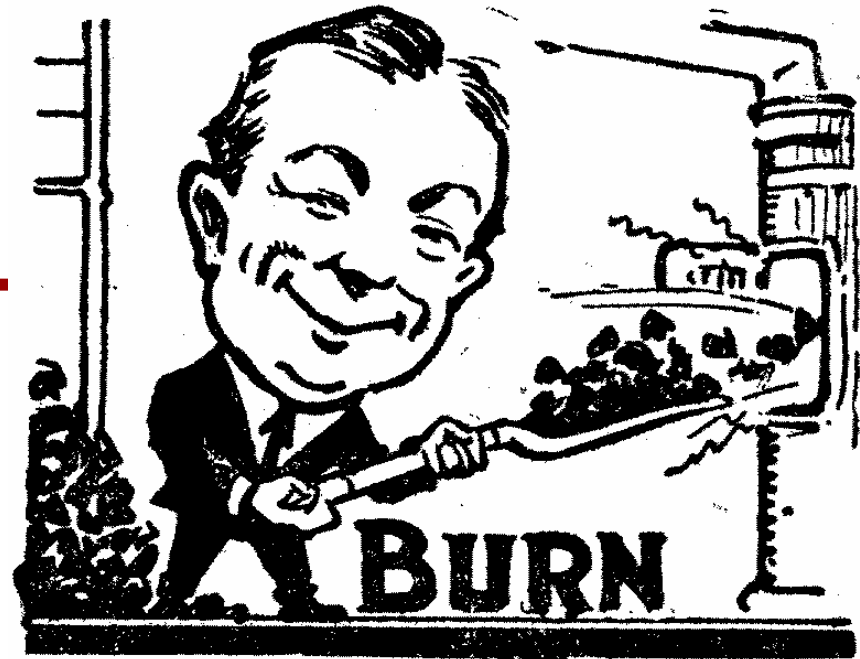
Waterwalls

Aux. Burners

Spreader Stoker



Combustion in Boilers



- There are four important factors that control combustion in boiler furnace:

1. Air supply- Need adequate air for complete combustion.

- The rating (capacity) of a boiler can be increased by supplying additional air (think of the effect of bellows on a small fire).
- Too much air can result in excessive stack losses.

Combustion Factors

2. Mixing of fuel and air- fuel and air molecules must be brought into close proximity in order for combustion to occur.
- The larger the fuel "particles" the greater the difficulty in achieving good mixing-
 - easiest for gaseous fuels,
 - more difficult for liquid fuels and pulverized solids,
 - most difficult for stoker coal, bark or large trash clumps.

Combustion Factors

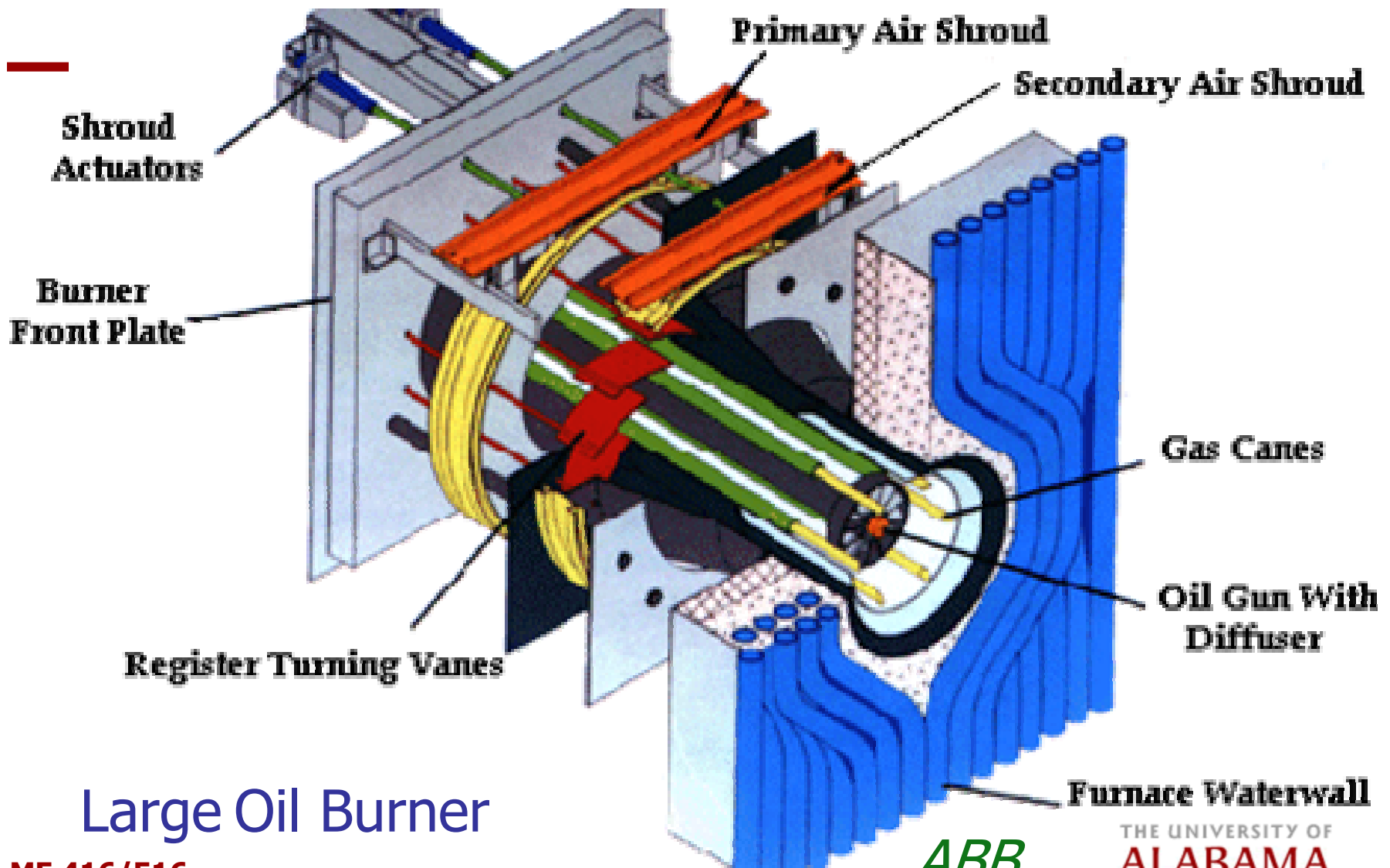
3. Temperature- all combustion reactions proceed exponentially more rapidly with increasing T
- Temperatures too low:
 - incomplete combustion, waste fuel
 - unburned hydrocarbons and soot emissions greatly increased
 - Temperatures too high:
 - equipment failure, metal strength drops off quickly at high T
 - NO_x emissions greatly increased.

Combustion Factors

4. Combustion time- fuel "particles" must be given sufficient time (*residence time*) in the furnace to achieve complete combustion.
- Like fuel/air mixing, the required residence time is least for gases and most for large solid fuels:
 - Gases and fine liquid sprays- 10 - 20 ms burnout
 - Pulverized fuel (coal, sawdust)- 1 s burnout
 - Stoker coal, bark, wood waste, trash- 10's of minutes

Fuel Considerations

- Natural gas and fuel oil burners. The fuel is brought to a burner at elevated pressure and jetted (gas) or sprayed (oil) into the furnace. Relatively simple and low cost.



Large Oil Burner

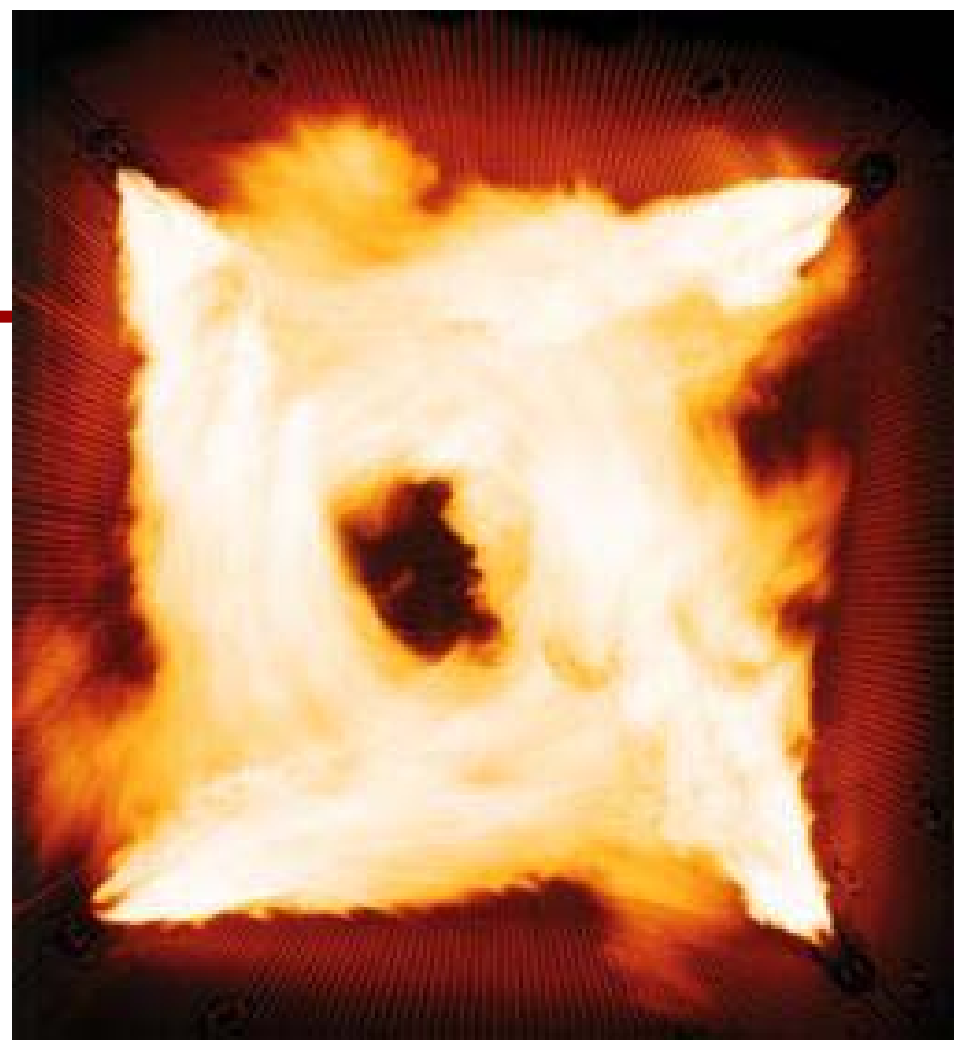
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Coal/Solid Fuel Firing

- There are a considerable number of ways to feed coal in use, including, hand-fired boilers, chain or traveling grate stokers, vibrating grate stokers, underfeed stokers, spreader stoker, pulverized coal boilers, cyclone boilers and fluidized bed boilers.



Tangential-fired coal furnace

Stoker Boilers

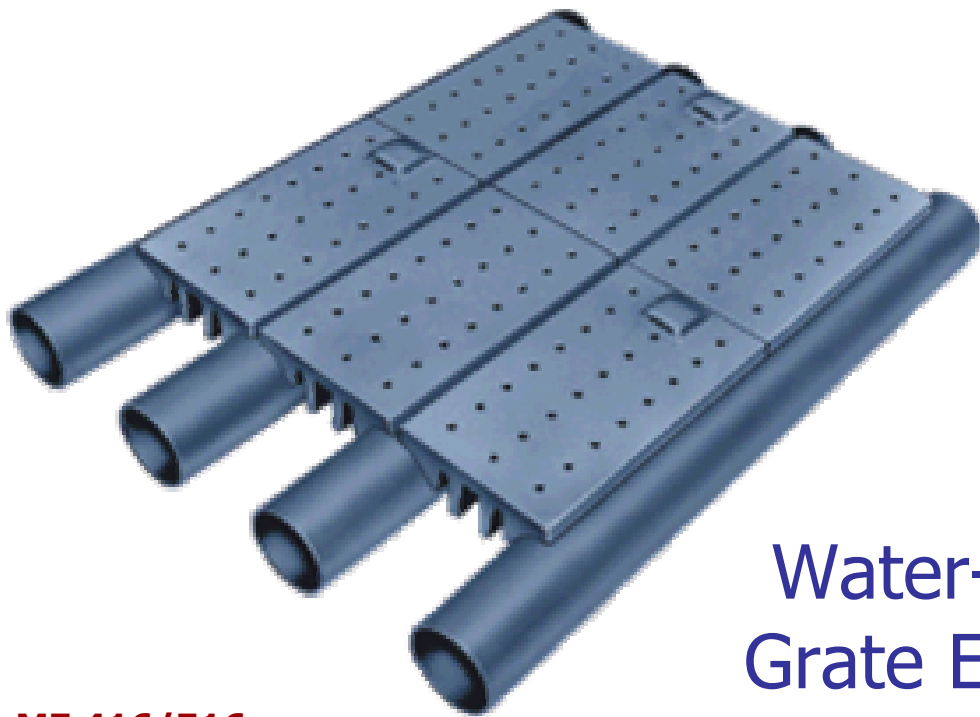
- The term stoker implies a boiler that automatically feeds (or "stokes") the boiler.
- Stoker coal size is typically 1.25 inches maximum with less than 30% under 0.25 inches.

Traveling or Chain Grate Stokers

- Traveling or chain grate stokers feed coal out onto a rotating metal belt that supports the fire.
- Coal is fed from a hopper.
- Grate speed is automatically controlled to maintain desired steam pressure.
- Burning progresses as the belt moves from front to back of furnace.
- Combustion is essentially complete at the back end of belt, and ash is dumped off into an ashpit there.



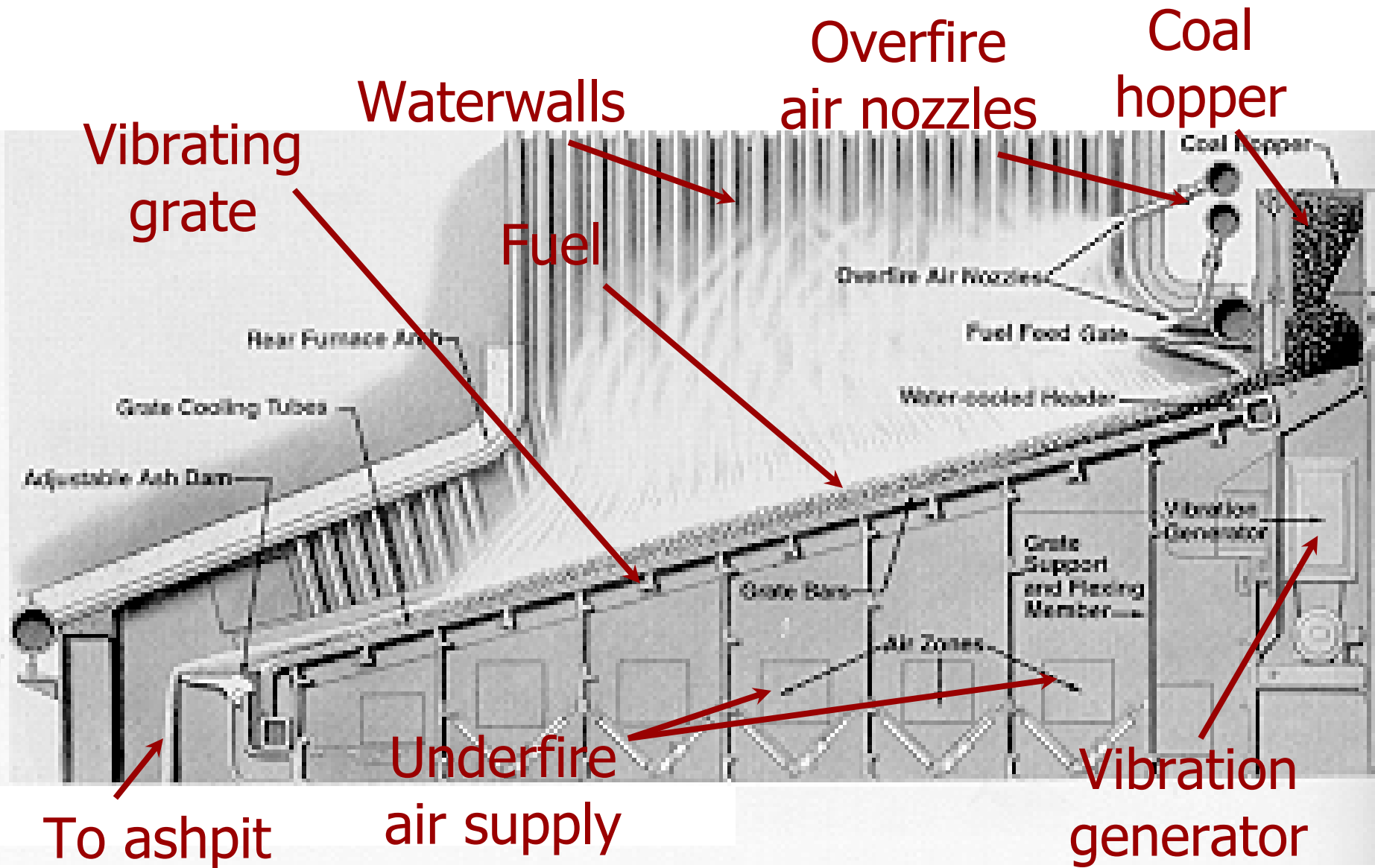
Traveling
Grate



Water-Cooled
Grate Elements

Vibrating Grate Stoker

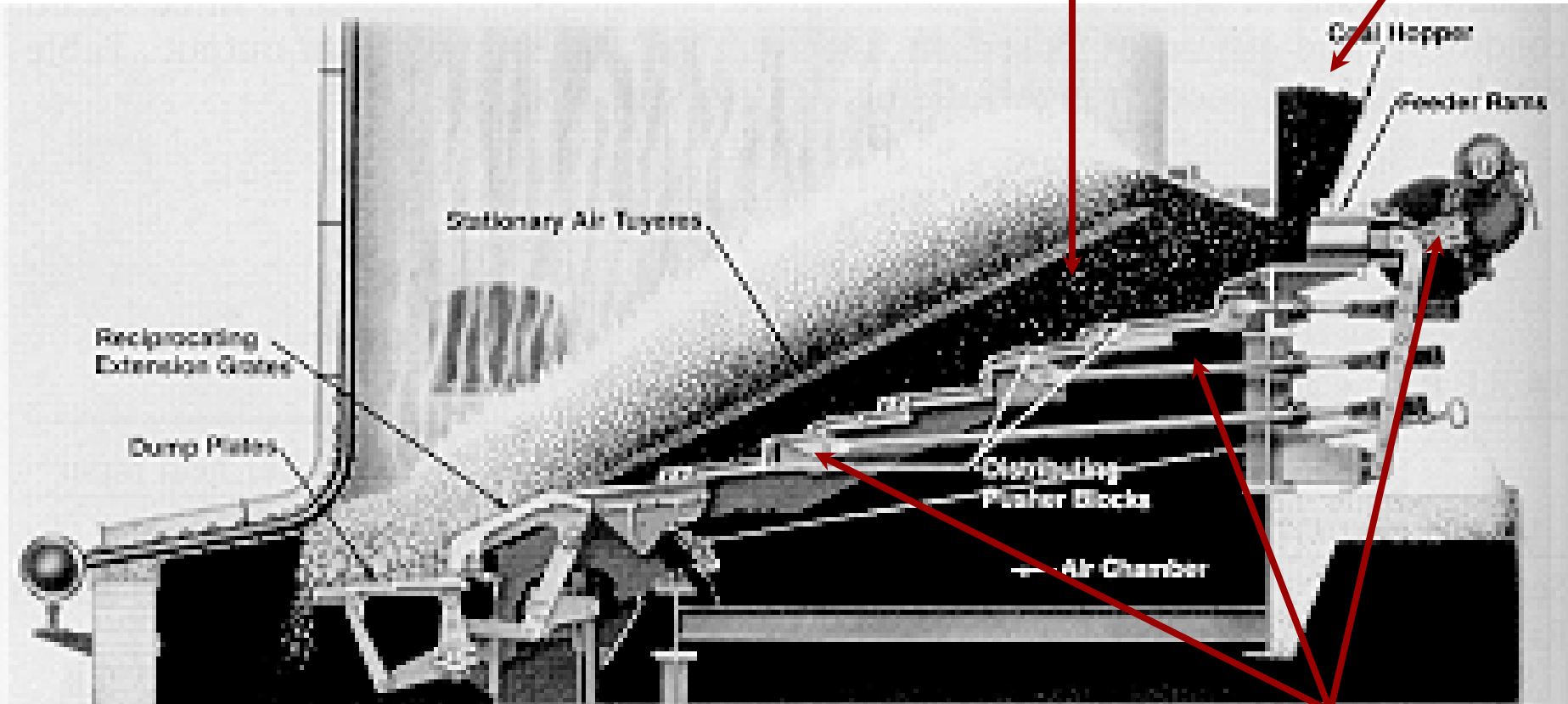
- Vibrating grate stoker is similar to a traveling grate, except that instead of being on a continuous loop, grate sections are sloped downward and periodically vibrate to cause fuel particle movement from front to back.
- Vibration frequency is controlled to obtain desired steam pressure/ heat output.



Water-Cooled Vibrating Grate Boiler

Underfeed Stokers

- So named because they use rams to force the coal up underneath the burning fuel bed.
- Grates are designed to flex up and down to break up fuel bed and prevent "clinker" formation.
- Action of feed rams and fuel bed flexing cause fuel to move from front to back of furnace.
- Underfeed stokers range in size from small home heating boilers to large industrial size.
- Underfeed stokers are very good at burning high volatile coal with a high turn-down ratio.



Feeder rams
and actuator

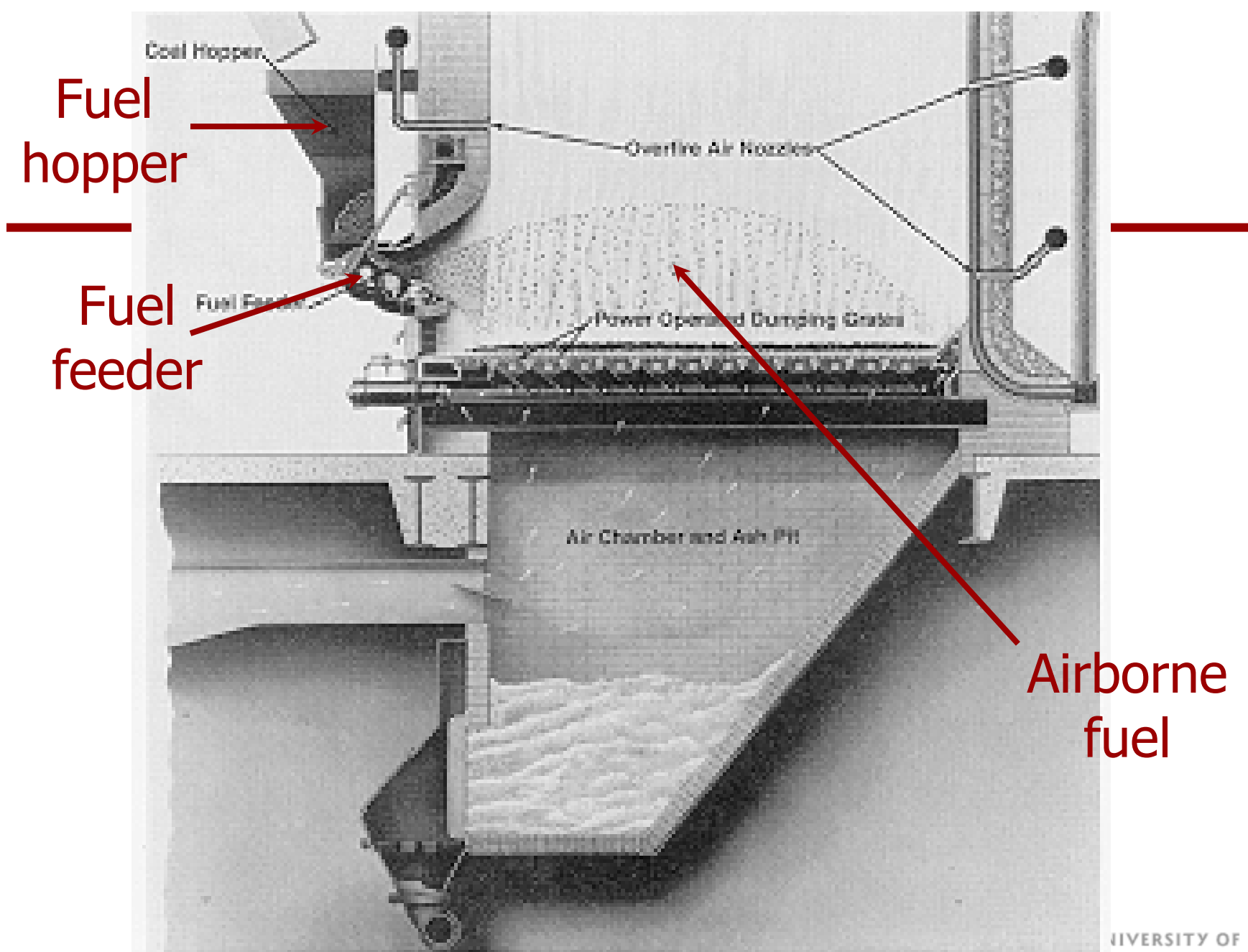
Underfeed Stoker Boiler

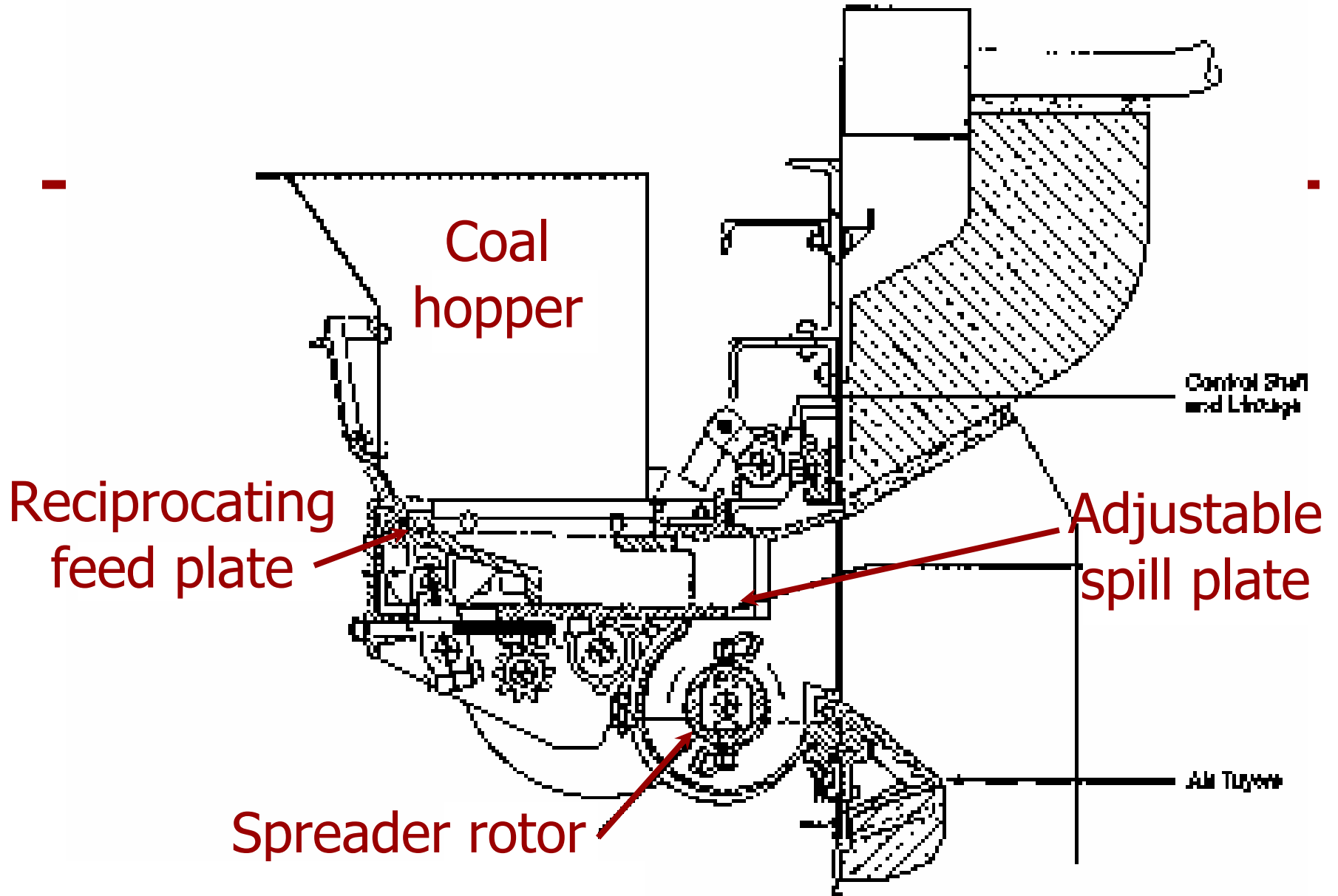
Spreader Stokers

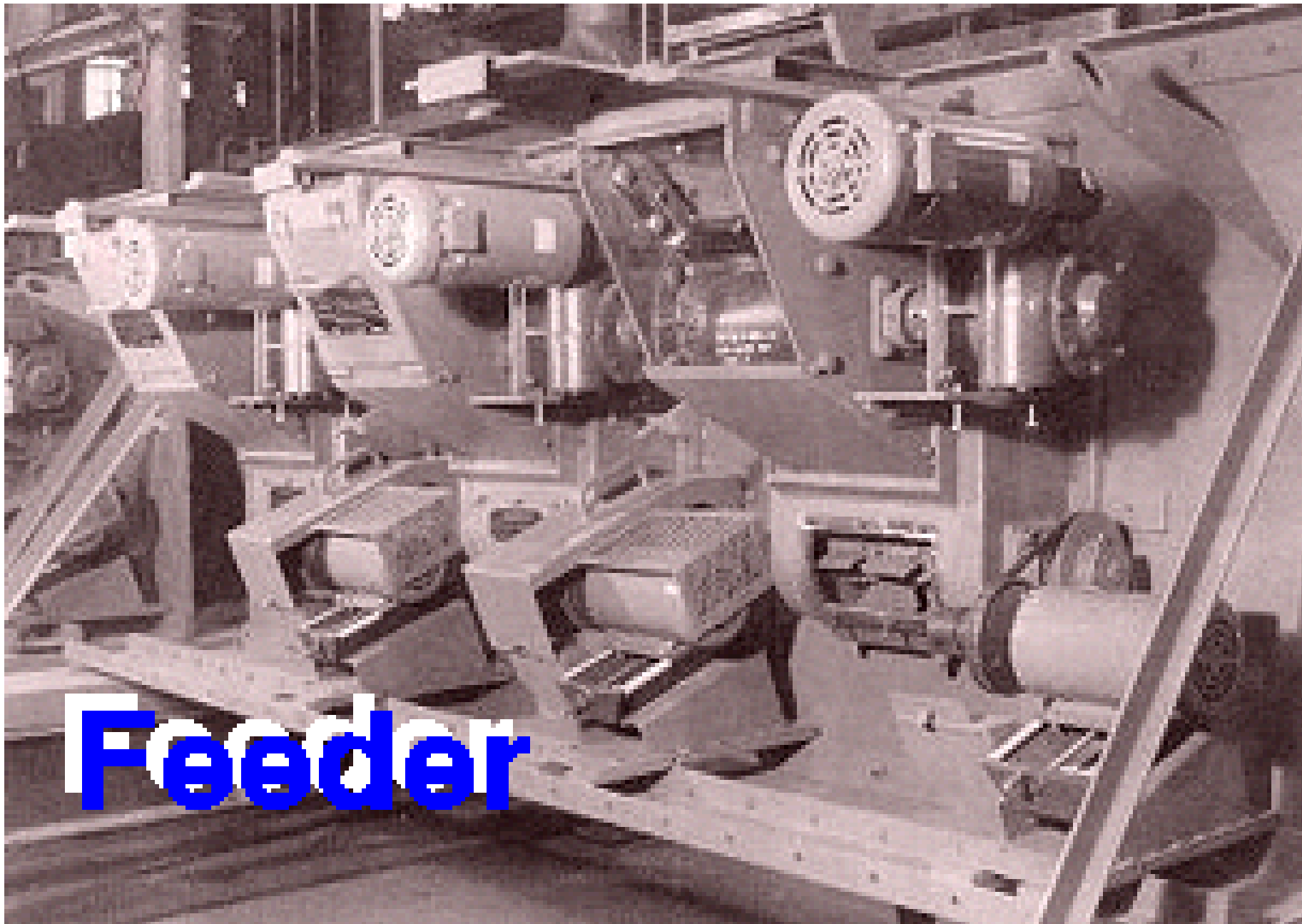
- Fed by a rotating bladed wheel that throws the coal out over the grate.
- Spreaders stokers are more expensive than other stokers in small sizes, and are more expensive than pulverized coal boilers in large sizes (over 500,000 lbm/hr of steam) but are very common in the intermediate (large industrial) size range.
- Compared to previous stokers, more fuel burning occurs in suspension- that is, in the air as the fine particles are slung out over the fuel bed.

Spreader Stokers (Cont'd)

- Because of feeding method, more small particles and fly ash are carried up with the exhaust.
- Particles trapped up in boiler, economizer, air preheater and dust collectors are recycled for better combustion efficiency and reduced particulate emissions.
- Grates are of several types. Some are traveling or vibrating to move fire from back to front of furnace and dump ash over the front into an ashpit. Others grates periodically are turned over to collect ash.







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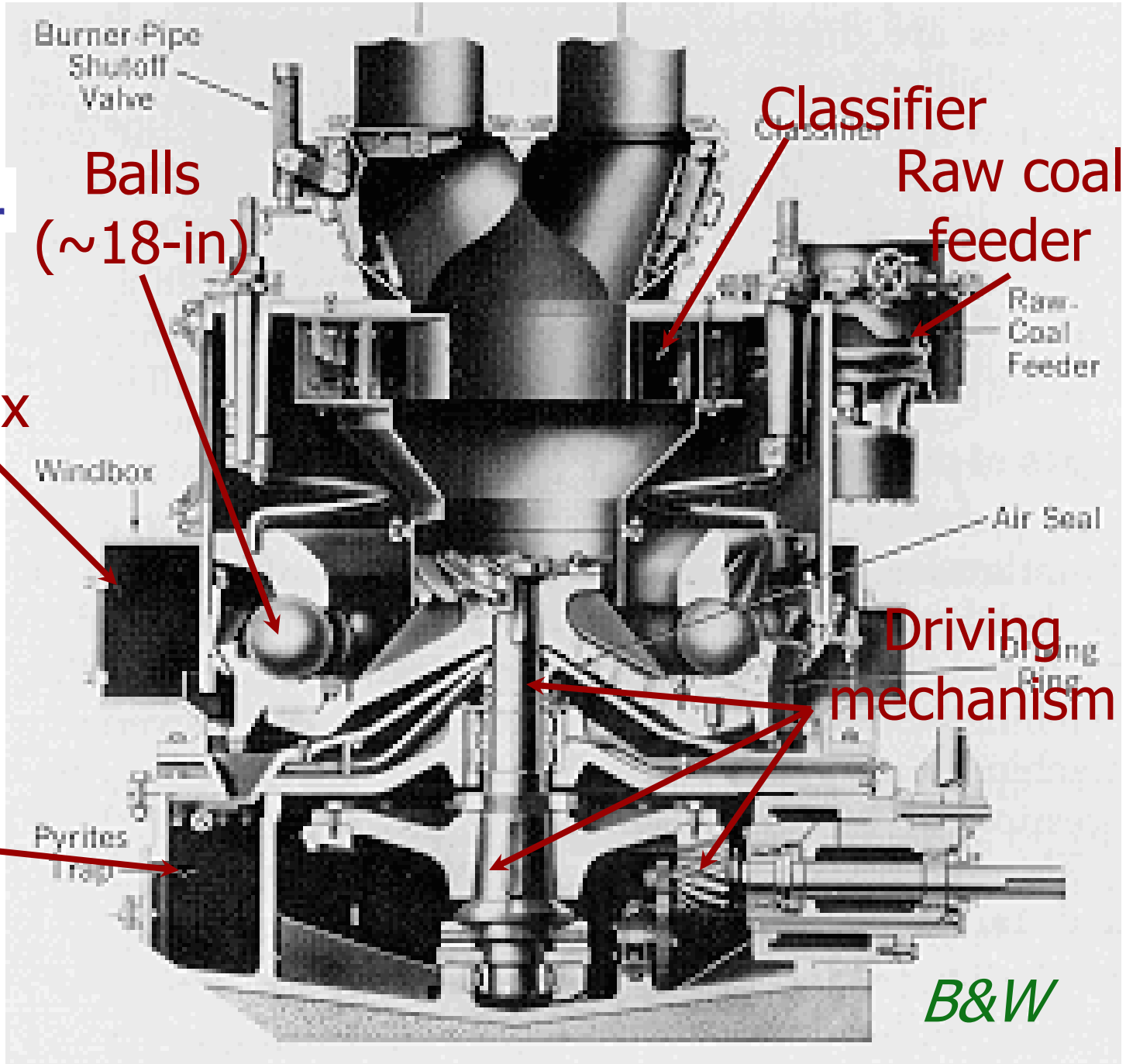
Coal Feeders

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Pulverized Fuel Boilers

- Pulverized coal boilers fire finely powdered coal, typically with an average particle size of about 25 μm (0.001 in). Coal burns in suspension, like the combustion in an oil- or gas-fired boiler.
- Coal is pulverized in some type of large mill
- Pulverized coal is fired out into the furnace volume using burners that look somewhat like oil or gas burners.

Ball Mill Coal Pulverizer



Roller Mill Coal Pulverizer

PC outlet

Coal feed inlet

DB Riley

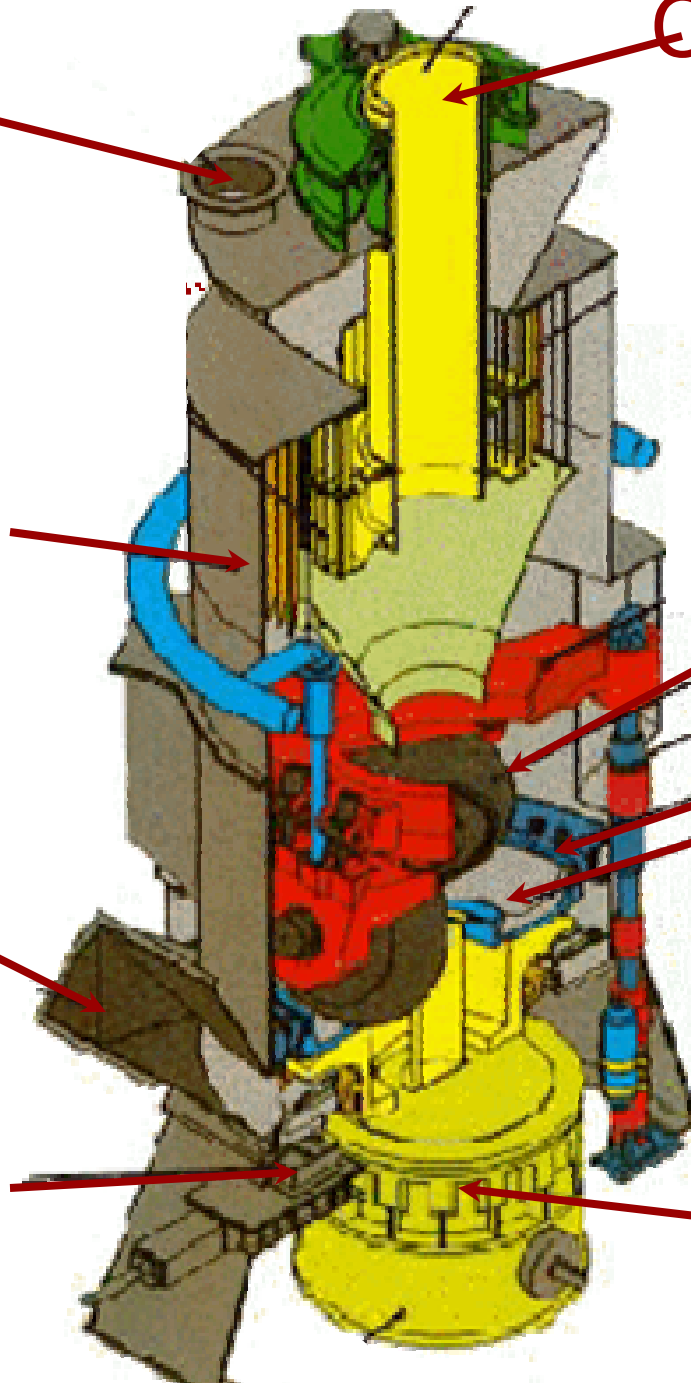
Classifier housing

Grinding roller
Nozzle ring
Grinding table

Primary air inlet

Rejects hopper

Planetary gear drive



Secondary air register door

Windbox

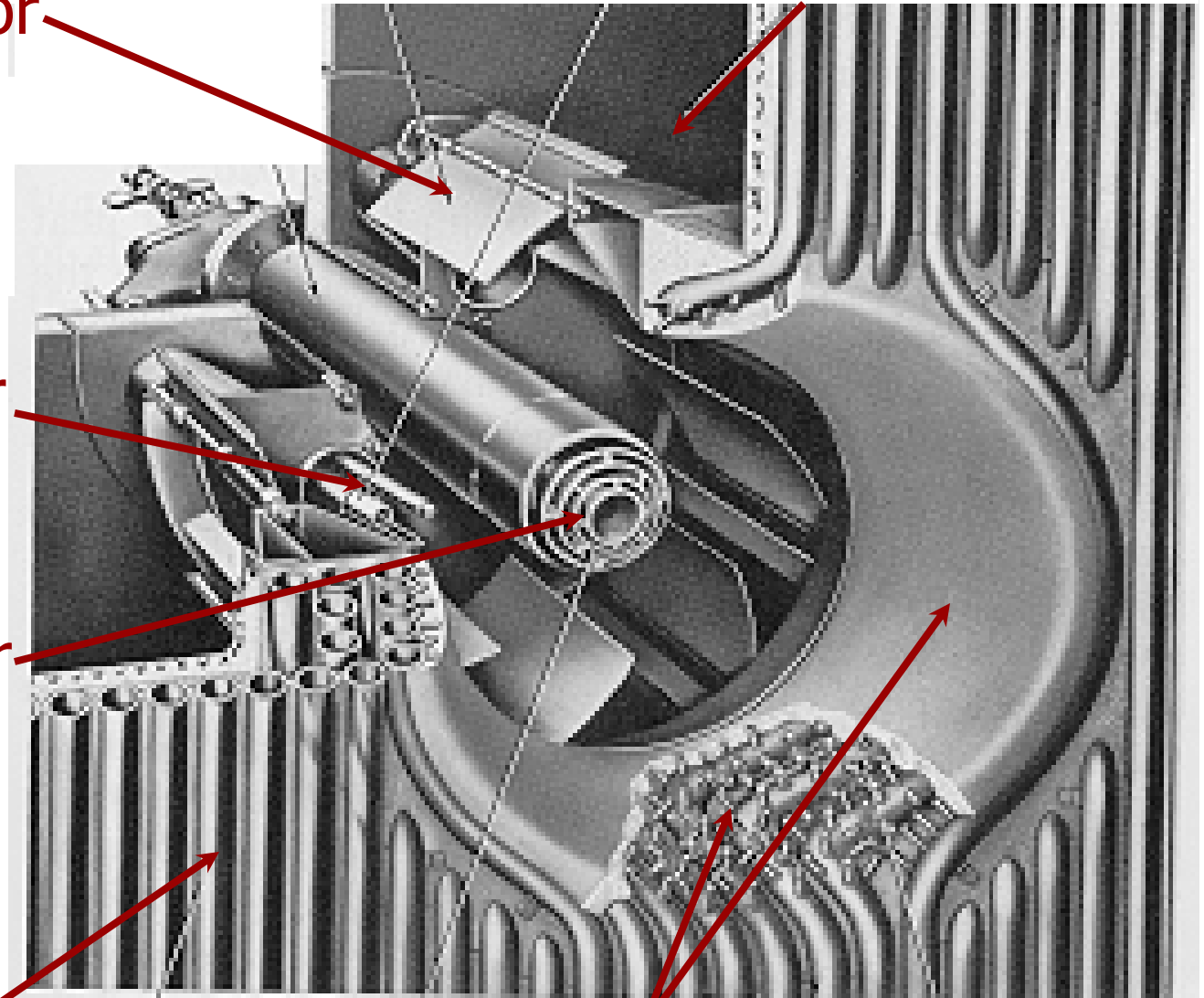
Pulverized Coal Burner

Oil/gas lighter

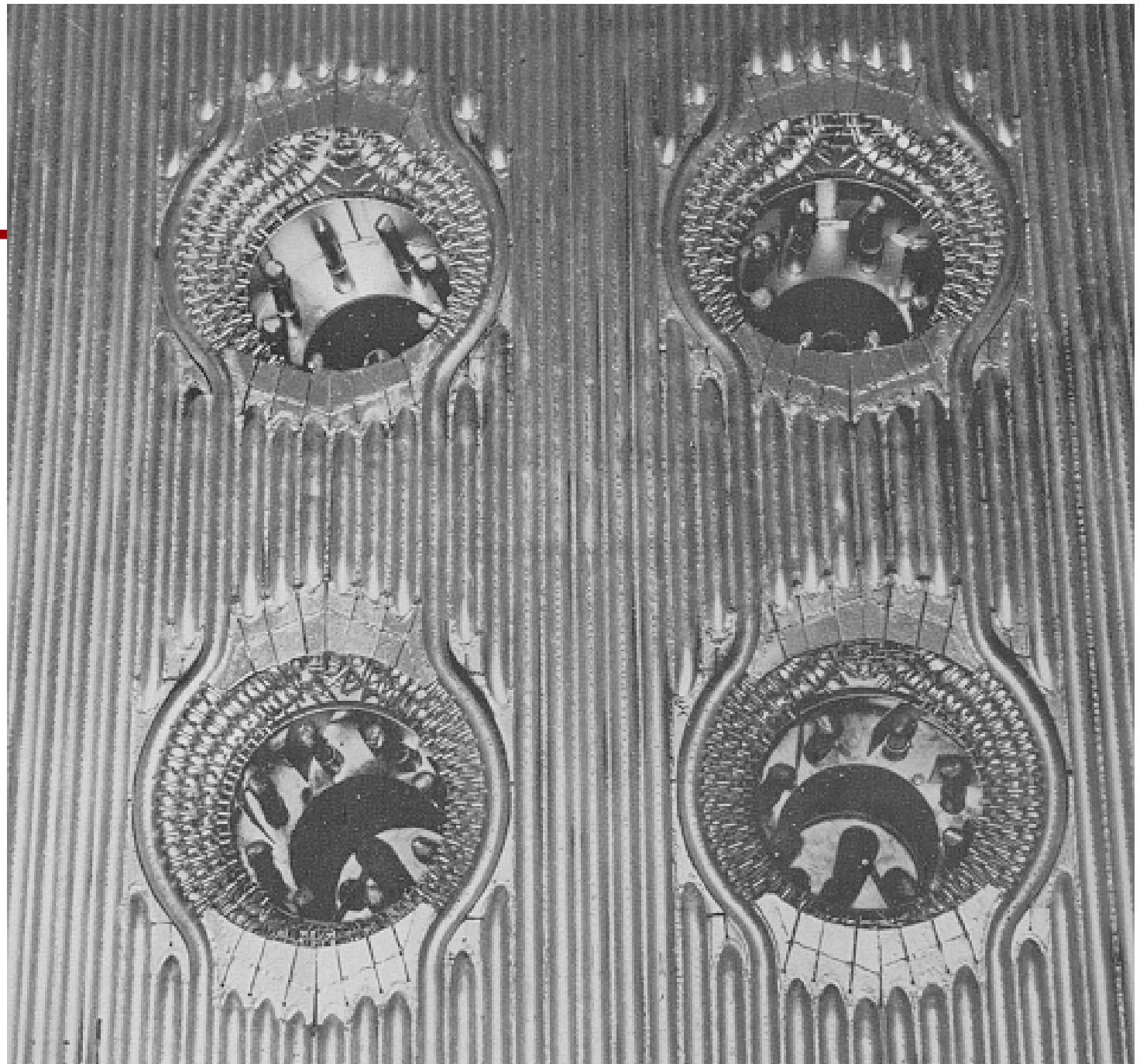
Coal impeller

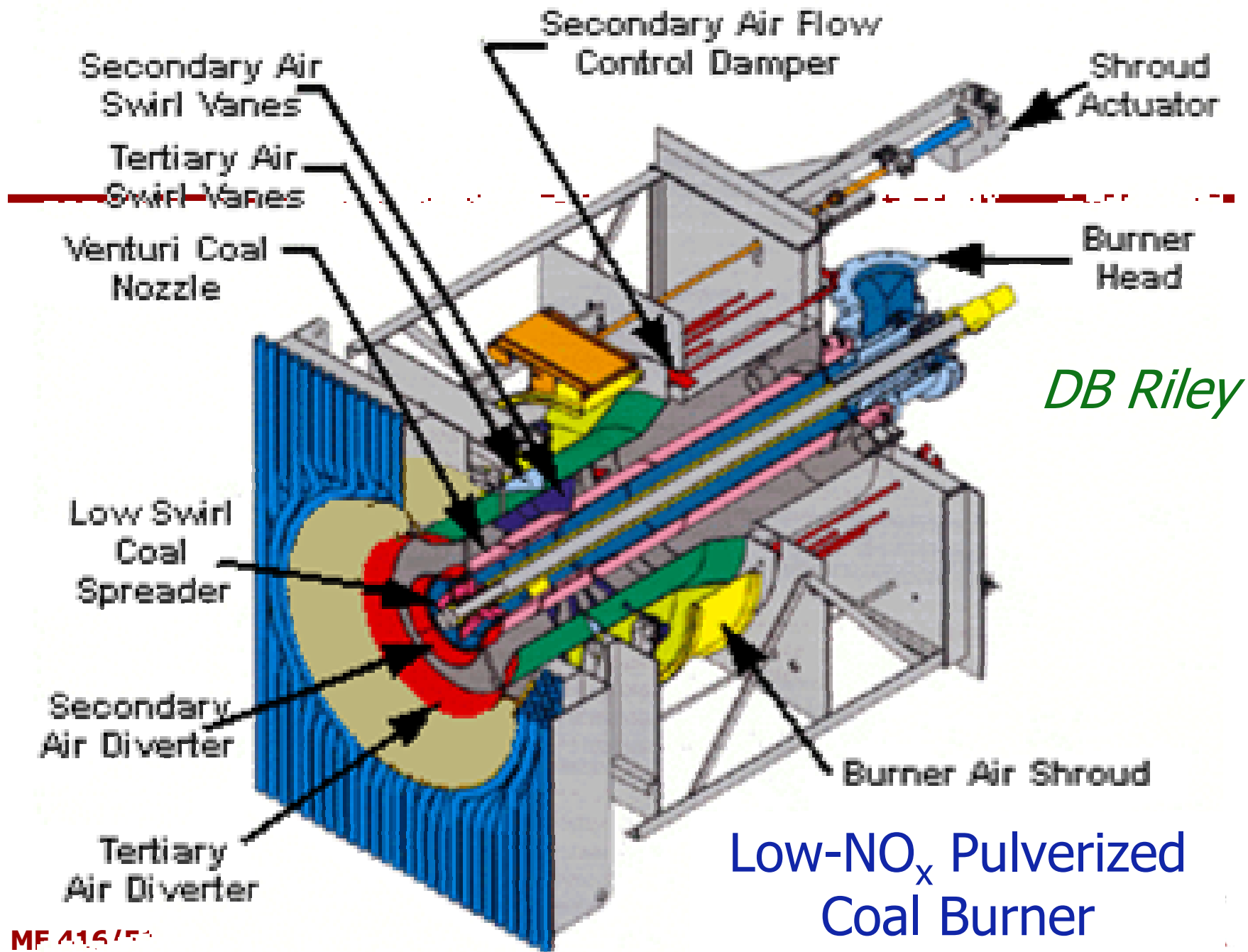
Waterwall

Refractory throat with studded tubes



Water- wall With Four Burners





PC vs. Stoker Boilers: Advantages/Disadvantages

- Advantages of PC vs. stoker boilers:
 - much quicker response to changing loads
 - lower excess air/higher efficiency
 - easily adaptable to automatic control
 - can burn wide variety of coals
- Disadvantages of PC vs. stoker boilers:
 - more expensive (at least for smaller capacities)
 - require more skilled personnel
 - require better emission control (particulates)
 - require more energy to pulverize fuel

Coal Combustion

- We have examined the combustion of fuels for which we have a molecular formula, e.g., C_3H_8 or CH_4
- Coal is characterized by a mass based formula resulting from an **ultimate analysis**.
- Ultimate analysis gives the elemental composition



Ultimate Analysis

- The ultimate analysis is a measurement of a coal sample that yields the mass percent of each element tested, plus the percent of ash in the coal.
- The primary elements are C, H, O, N and S.
- The ash is the noncombustible portion of the coal.
- There are other elements present in lesser quantities, some of which are hazardous, such as Cl, V, and Hg, but the “CHONS” are the important elements for combustion calculations.

Conversion from a Mass to a Mole Basis

- The secret to doing coal combustion calculations is to calculate the chemical formula from the ultimate analysis data
- One standard method is to start with the assumption of 100 lbm of coal
- Recall that the relationship between mass, m , and number of moles, n , is given by the molecular weight, M , where:

$$M = m/n \quad \text{or} \quad n = m/M$$

Example: mass to mole basis

- If a coal has an ultimate analysis of H = 5%, C = 90% and Ash = 5%, find its molecular formula
- Assume a total mass of 100 lbm of coal
- The mass of carbon out of the total 100 lbm of coal is: $m_C = 0.9 * 100 = 90$ lbm carbon
- Number of moles of carbon is $n_C = m_C/M_C$, where $M_C = 12$, so $n_C = 90 \text{ lbm}/12 \text{ lbm/lbmol} = 7.5$ lbmol
- Similarly, $m_H = 5$ lbm, $n_H = m_H/M_H = 5/1 = 5$ lbmol
- We ignore the ash because it does not burn

Coal Combustion Chemistry

- Once we have the number of moles of each fuel component, we can calculate the moles of air needed for complete combustion (stoichiometric reaction) just as we did earlier
- Once we obtain the moles of air required, we can convert that to mass of air required and calculate the **air-to-fuel ratio**, A/F
- A/F is defined as the mass of air per mass of fuel for a reaction

Stoichiometry Terms

- The **stoichiometric A/F** is the A/F obtained for the stoichiometric reaction (no excess air)
- The actual A/F is higher than the A/F_{stoich} to insure complete fuel burnout
- The **stoichiometric ratio** is defined: $SR = \frac{A/F_{\text{act}}}{A/F_{\text{stoich}}}$
- The **fuel equivalence ratio** is $\Phi = 1/SR$
- Percent excess air = $100\% * (SR - 1)$
- Percent theoretical air = $100\% * SR$

Estimating Coal HHV

- A handy rule of thumb formula for estimating the higher heating value of coal is provided by the Dulong formula:

$$\text{HHV} = 14,600 \cdot C + 62,000 \cdot (H - O/8) + 4050 \cdot S$$

where HHV is the higher heating value in Btu/lbm, and C, H, O and S are the coal mass fractions of carbon, hydrogen, oxygen and sulfur, respectively, from the ultimate analysis of the coal.

Coal HHV Example

PROBLEM: A coal has an ultimate analysis of 78% carbon, 4% hydrogen, 3% oxygen, 6% sulfur, and 9% ash. Estimate the HHV of the coal.

SOLUTION: Use the Dulong formula:

$$\text{HHV} \cong 14,600 * 0.78 + 62,000 * (0.04 - 0.03/8) + 4050 * 0.06)$$

$$\text{HHV} \cong 13,900 \text{ Btu/lbm}$$

Coal Combustion Example

A coal has an ultimate analysis of C = 84%, H = 4.5%, S = 2.5% and Ash = 9%. The coal is to be burned in a boiler to raise 150,000 lbm/hr of steam using inlet water at 46

Coal Combustion Example

A coal has an ultimate analysis of C = 84%, H = 4.5%, S = 2.5% and Ash = 9%. The coal is to be burned in a boiler at 12% excess air to raise 150,000 lbm/hr of 120 psia steam using inlet water at 46°F. If the boiler efficiency is 83%, find: (a) HHV, (b) coal firing rate in lbm/hr, and (c) the air flow rate in cfm entering the boiler at 55°F.

Boiler Efficiency



Introduction

- One of the "usual suspects" in looking for efficiency improvements is the boiler.
- In smaller businesses or institutions there may be no employees adequately trained to operate and maintain boilers for efficient operation.
- In larger firms or institutions (e.g., UA?), the people who are trained are overextended and lack time for optimal boiler maintenance and improvement.

Simplified Boiler Efficiency Analysis

- The following section provides a simplified analysis method to determine the boiler efficiency.
- This method works reasonably well for fossil fuel fired boilers.



Boiler Efficiency & Losses

- **Boiler efficiency**, h_b , is the fraction of energy input that actually goes into raising steam.
- The remainder of the input energy is the boiler losses, which have the following components.
- **Carbon Loss** or **Refuse Loss** results from the presence of unburned combustible materials, mostly carbon, in the "refuse" or "bottom ash".
- **Heat Transfer Losses** result from convective and radiative losses from hot boiler exterior surfaces to the surroundings.

Blowdown Loss

- Most boilers circulate water from a steam drum above the boiler to the bottom of the boiler through unheated downcomers and back up to the steam drum via risers, which are waterwall and other water heating tubes.
- The “mud drum” lies at the lowest point in the circulation and is designed to collect sediment.
- The mud drum is periodically discharged to remove the collected sediment, a process called “blowdown”. The energy content of the water blown out is lost and reduces η_b .

Stack Losses

- **Vapor Loss**- H_2O in exhaust leaves as vapor rather than liquid, so the heat of vaporization is lost as useful energy.
- H_2O that enters with combustion air is already in vapor form and can be neglected.
- The other two sources of H_2O are the moisture content of the fuel (from the proximate analysis) and the H_2O formed from fuel hydrogen combustion.
- **CO Loss** is the unused fuel energy of exhaust, primarily from unburned CO.

Stack Losses (Cont'd)

- **Sensible Loss** is the $\dot{m} \cdot c_p \cdot \Delta T$ loss of energy from the exhaust.
- Ideally, the products of combustion could be cooled to the surroundings temperature and the fire would give up the maximum possible heat.
- For practical reasons the exhaust leaves the boiler considerably hotter than T_{surr} , so the sensible energy of the hot exhaust in excess of ambient temperature is lost.
- The sensible loss is typically the largest single boiler loss component.

Losses from Non-Coal Boilers

- These losses apply equally well to other fossil-fuel-fired boilers, including oil or natural gas, except that there may not be a refuse/carbon loss if there is negligible ash.
- Only heat transfer losses will apply directly to electric boilers. However, significant indirect losses have already occurred at the powerplant where the electricity was generated (~85% of electricity generated by Rankine cycle with steam generator).

Method for Calculating Boiler Efficiency

- Equations are presented in following slides that can be used to determine the boiler losses as Btu per lbm of coal that is fired.
- The boiler efficiency is given by:

$$\text{Efficiency (fractional)} = 1 - (\Sigma \text{ Boiler Losses in Btu/lbm})/\text{HHV}$$

Relations for Individual Boiler Losses

- **Carbon Loss:**

$$q_{\text{carb}} = 14,540 * ab / [100 * (100 - b)]$$

- a is the % of ash in the fuel
- b is the % of combustible (carbon) in dry refuse (measured). “Refuse” is the bottom ash.
- 14,540 is the heating value of carbon in Btu/lbm

$$q_{\text{rad}} = 0.1714 \times 10^{-8} * A * (T_h^4 - T_\infty^4) / \dot{m}_f$$

- 0.1714×10^{-8} is the Stefan-Boltzmann constant, σ , in Btu/hr-ft²-R⁴
- A is the area of the surface from which heat is transferred
- T_h is the hot boiler surface temperature (in degrees R)
- T_∞ is the ambient temperature (in degrees R)
- \dot{m}_f is the mass flow rate of fuel in lbm/hr

$$q_{\text{conv}} = 0.18 * A * (T_h - T_\infty)^{4/3} / \dot{m}_f$$

- $0.18 * (T_h - T_\infty)^{1/3}$ Btu/hr-ft²-F is a natural convection heat transfer coefficient for air

$$q_{\text{blow}} = \dot{m}_b * (h_b - h_c) / \dot{m}_f$$

- \dot{m}_b is the mass flow rate of blowdown water
- h_b is the enthalpy of water bled from mud drum
- h_c is enthalpy of water fed to the boiler ($h_c \cong h_f$ at boiler feedwater inlet temperature).

$$q_{\text{vap}} = 0.9 * H * (100 - M) + 10 * M$$

- H is % hydrogen in fuel from ultimate analysis
- M is % moisture in fuel from proximate analysis

$$q_{\text{sens}} = 0.24 * (1 + A/F) * (T_{\text{exh}} - T_{\text{in}})$$

- 0.24 is c_p of air in Btu/lbm-°F
- A/F is actual air/fuel ratio
- T_{exh} is exhaust T leaving boiler into stack.
- T_{in} is temperature of air entering boiler (usu. outside air temp.)

$$q_{\text{CO}} = [1.02 * (100 - M) * C * \text{CO}] / (\text{CO} + \text{CO}_2)$$

- C is % of carbon in fuel from ultimate analysis
- CO is volume % of CO in exhaust from stack gas analyzer
- CO₂ is volume % of CO₂ in exhaust from stack gas analyzer