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An Introduction to Boiler Design Basics

JC Foucher

ALSTOM

Summary

- History
- Thermodynamics for beginners
- Boiler design
- Utilily versus Industrial boilers
- Boiler Construction, Examples, and Troubles

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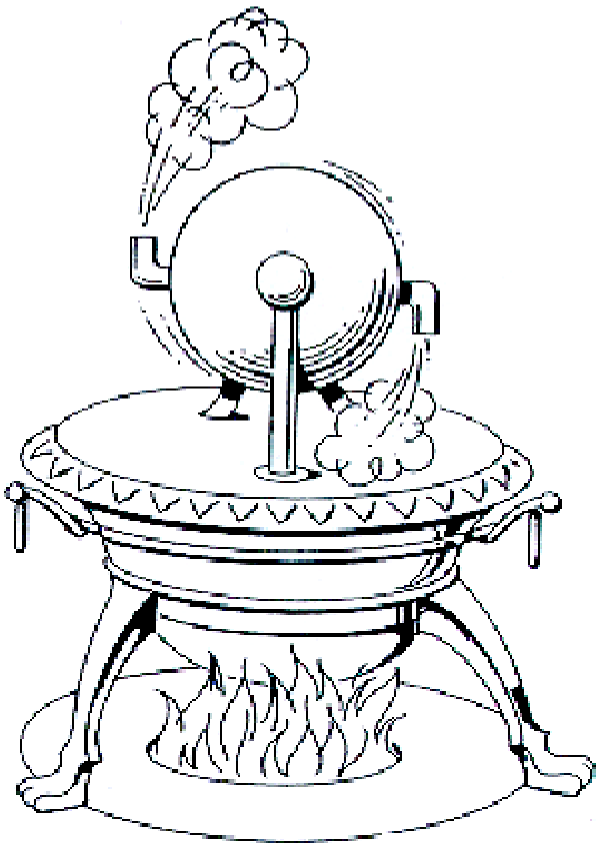
History : Steam as a resource



The most significant series of events shaping today's world is the late 17th century industrial revolution.

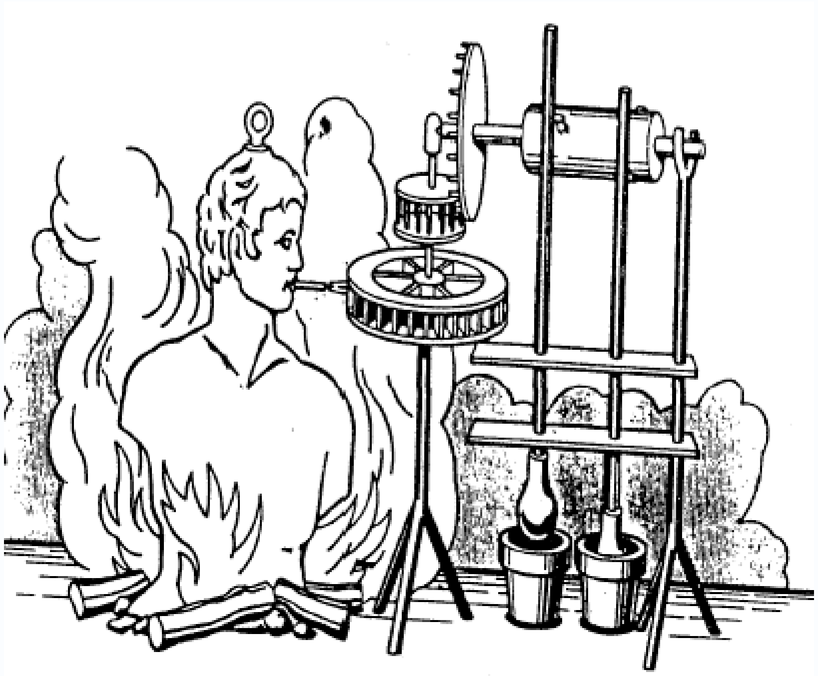
However, the first steam reaction turbine, illutrated here, has been invented in 200 BC by ***Hero*** from Greece.

Steam Technology is an old invention its future is still brilliant, based on the same fundamentals :

- *GENERATE HEAT*
- *TRANSFER THE HEAT to WATER*
- *PRODUCE STEAM and*
- *CONVERT TO ENERGY*

Source : ALSTOM Indonesia Boiler Seminar, April 2002

History :
First Application of Steam Power

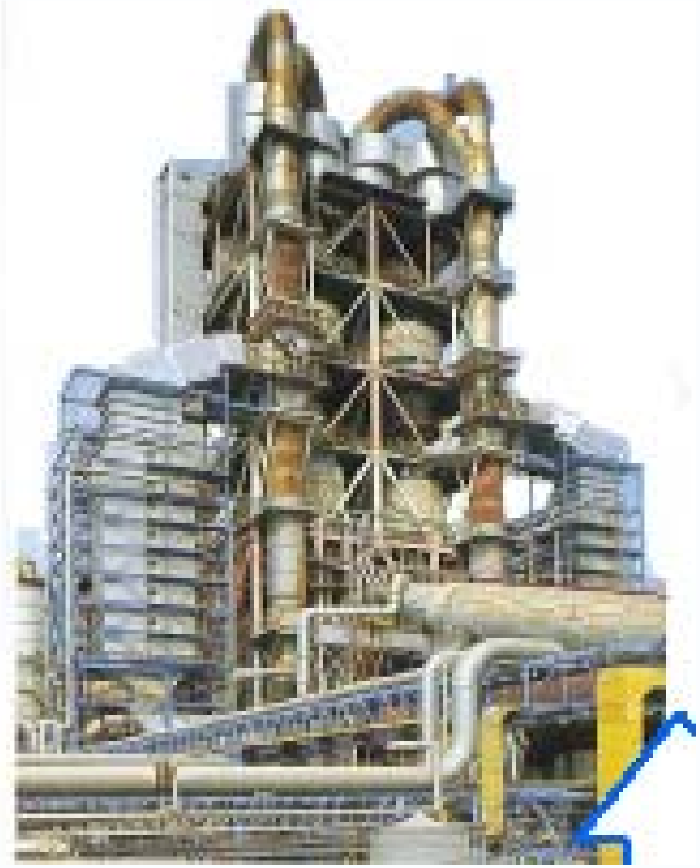


Steam Industries develop after inventors designed safe and efficient steam devices useful to man activities : ***Alexandro Branca*** from Italy invented in the 16th century a device, illustrated here, which marked the beginning of Steam Turbine Development.

It was used for milling wheat grains effortlessly.

Source : ALSTOM Indonesia Boiler Seminar, April 2002

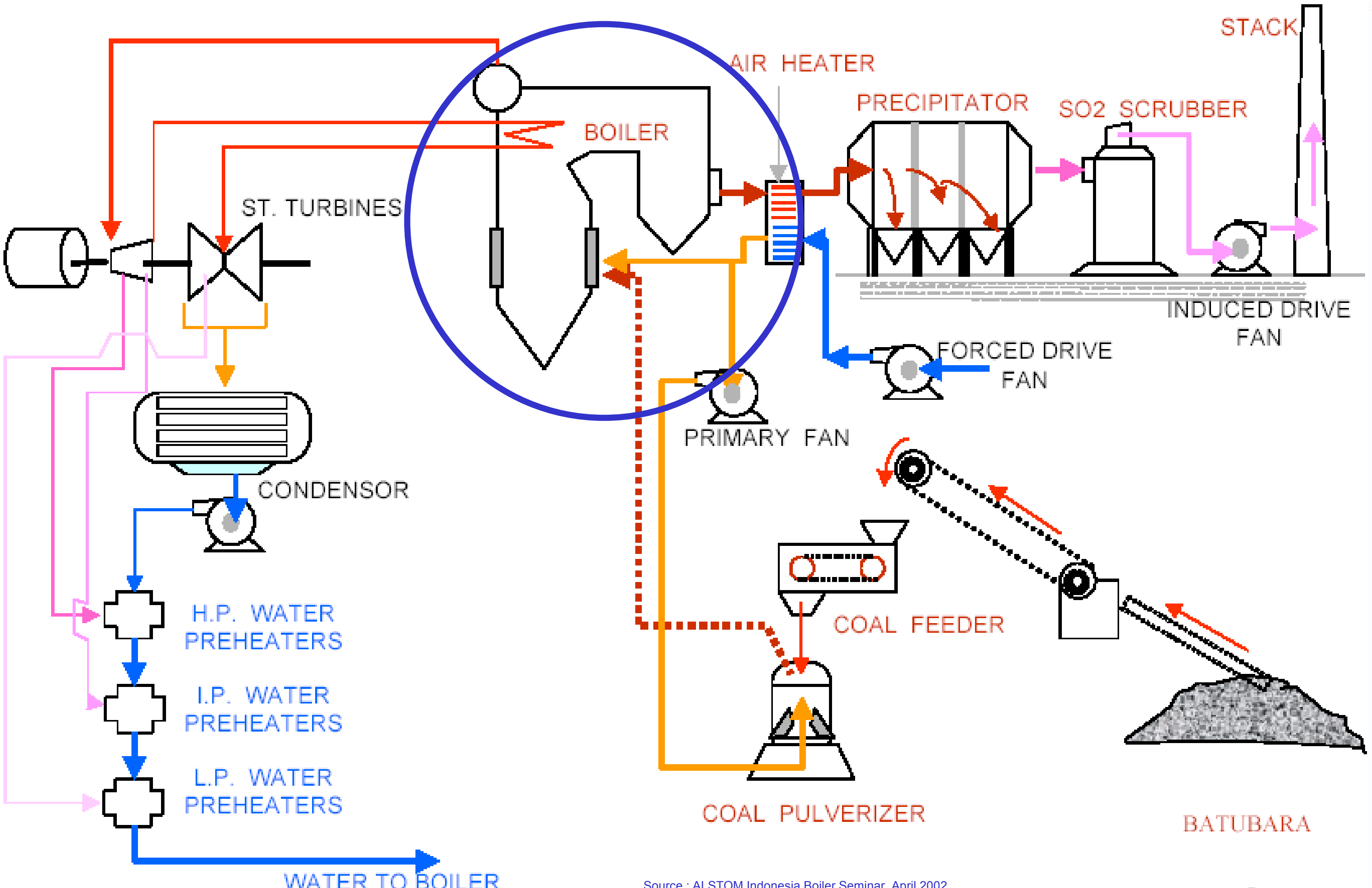
Modern Use of Steam Power



- Power Generation
- Industrial Processes
- Sea and land transportation
- District Heating
- Other special uses

Source : ALSTOM Indonesia Boiler Seminar, April 2002

A Typical Power Station



Source : ALSTOM Indonesia Boiler Seminar, April 2002

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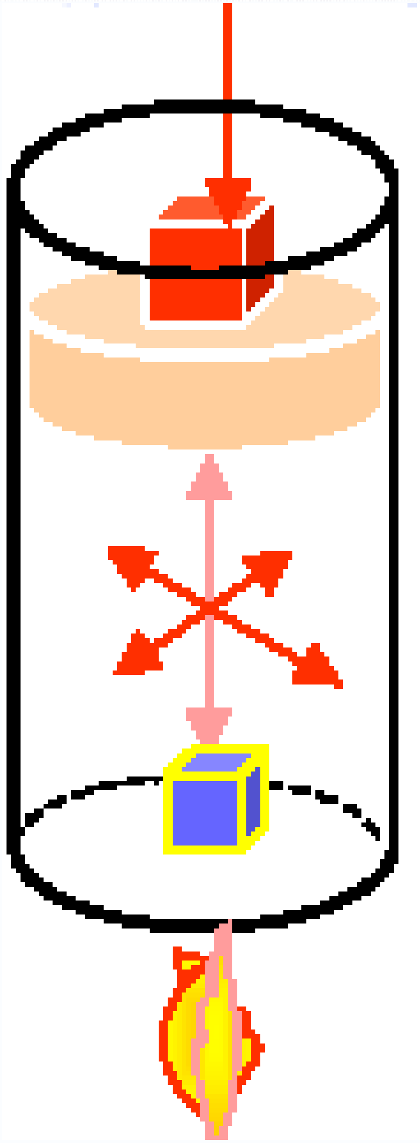
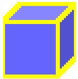
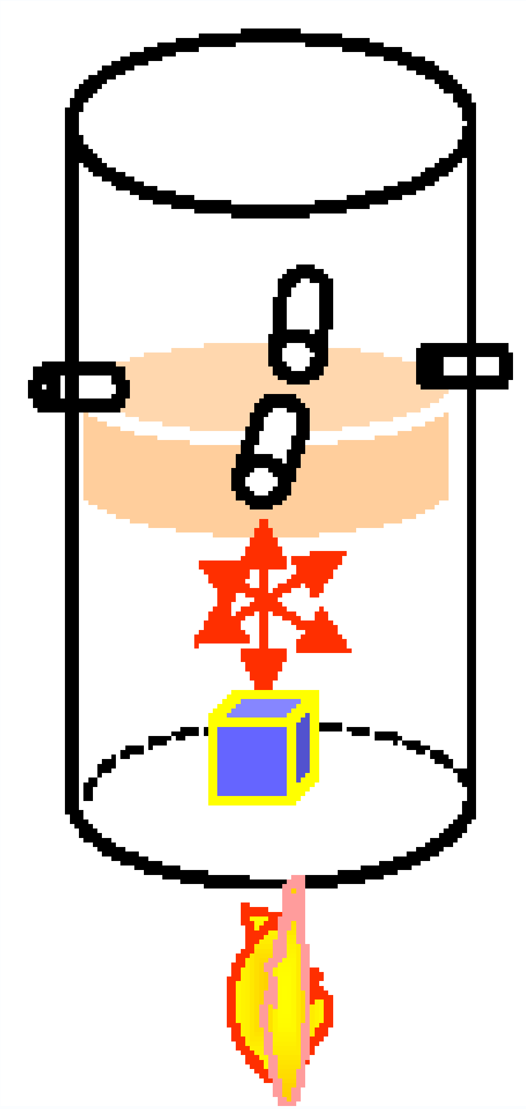
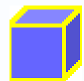


- A vessel is filled with an amount of water () and warmed at constant pressure up to boiling
- a continuing supply of heat changes water phase from liquid to gas (steam), the temperature remains constant
- result : a steam at temp. Tp, pressure Pp, volume Vp and energy stored as internal heat or enthalpy Qp
- one m³ of water is transformed under such conditions into 1700 m³ of steam

Source : ALSTOM Indonesia Boiler Seminar, April 2002

Thermodynamics for beginners - 2

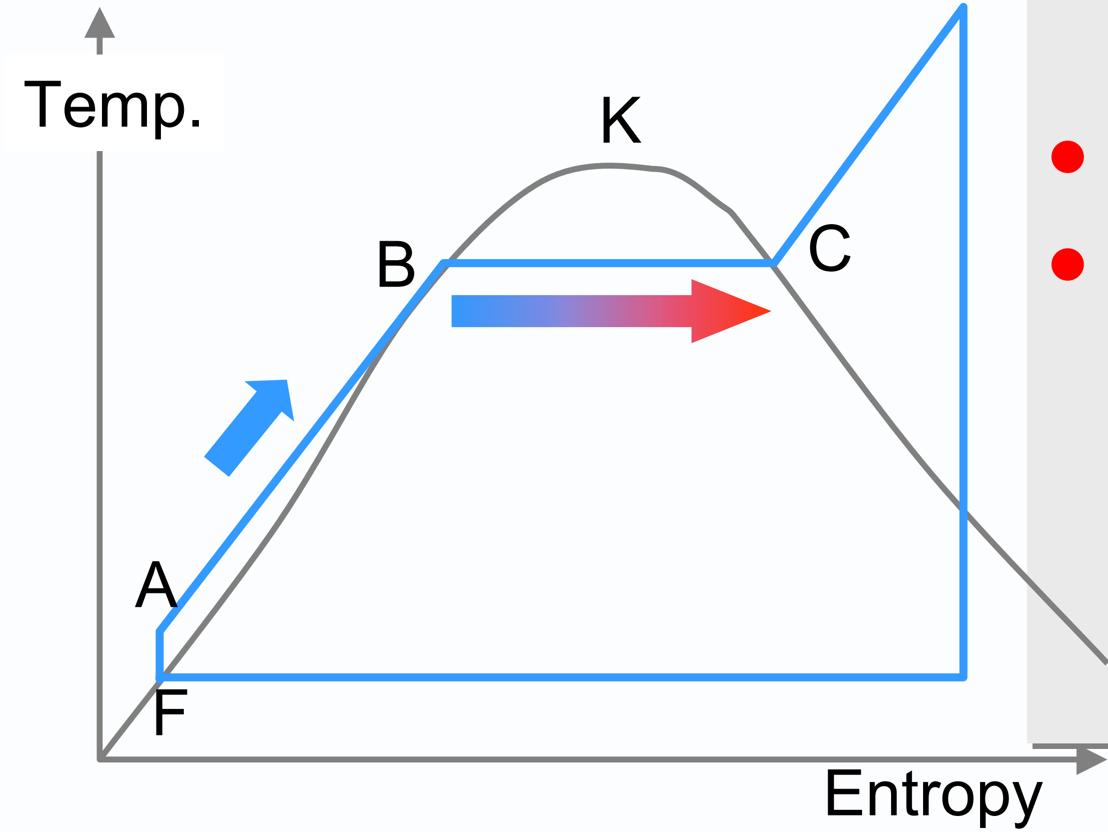


- A vessel is filled with the same water amount () and warmed at constant volume up to boiling
- a continuing supply of heat changes water phase from liquid to gas (steam),
- result :
  - steam temperature Tv >Tp,
  - pressure Pv > Pp,
  - Vv =Vp volume unchanged
  - energy stored as internal heat or enthalpy Qv > Qp

Source : ALSTOM Indonesia Boiler Seminar, April 2002

- Steam generation is a phase change or water from liquid to gas, thanks to a continuous supply of heat,
- the higher both pressure and temperature are, the higher is the energy stored in the steam,
- the steam turbine purpose is to convert this thermal energy into rotational mechanical energy
- the purpose of the generator is to convert this rotational mechanical energy into electric energy

The Water-Steam Cycle inside the boiler



- From F to A to B
  - liquid water warm-up
- B : evaporation begins
- B to C :
  - mixture of water (decreasing) and steam (increasing) called saturated steam

Source : J. Goalvoueden in Les Techniques de l 'Ingénieur, B 124

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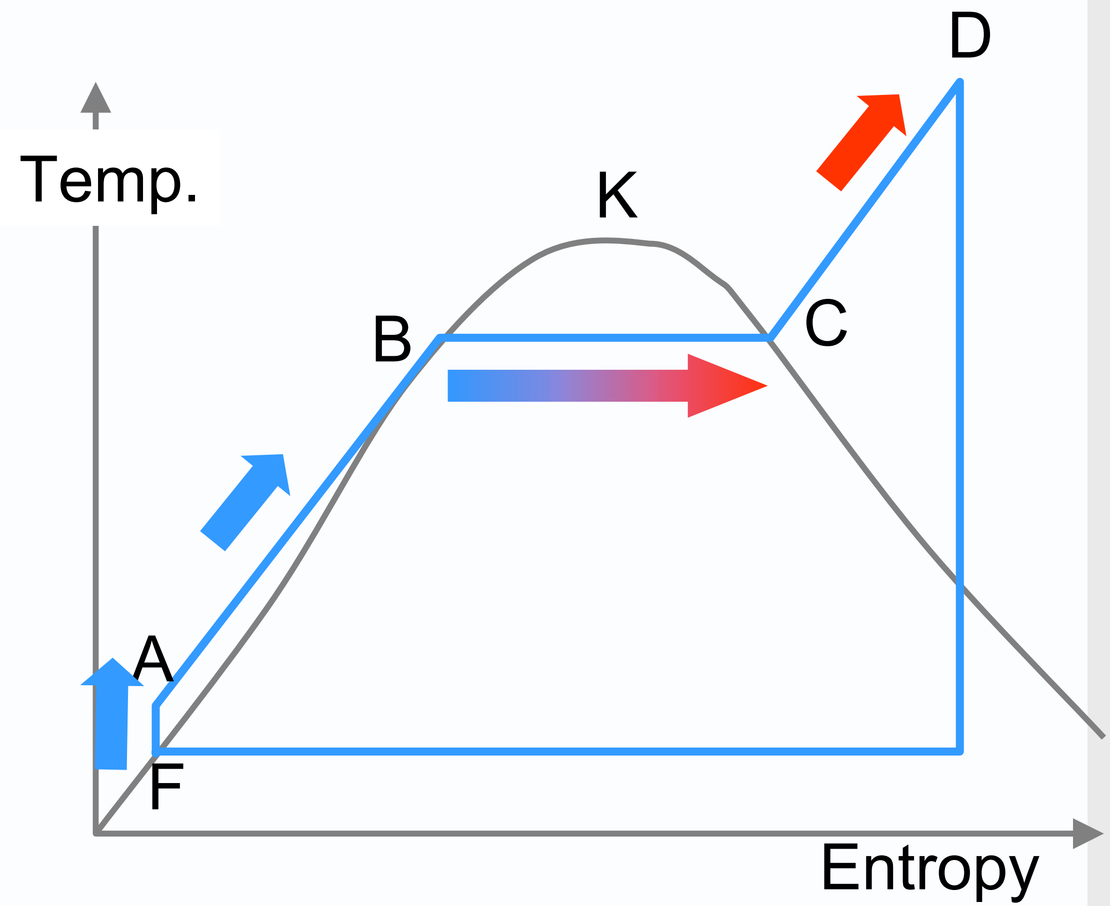
The Water-Steam Cycle inside the boiler (cont)



- C : evaporation completed, steam still saturated
- C to D
  - steam is superheated
- D
  - superheated steam sent to turbine

Source : J. Goalvoueden in Les Techniques de l 'Ingénieur, B 124

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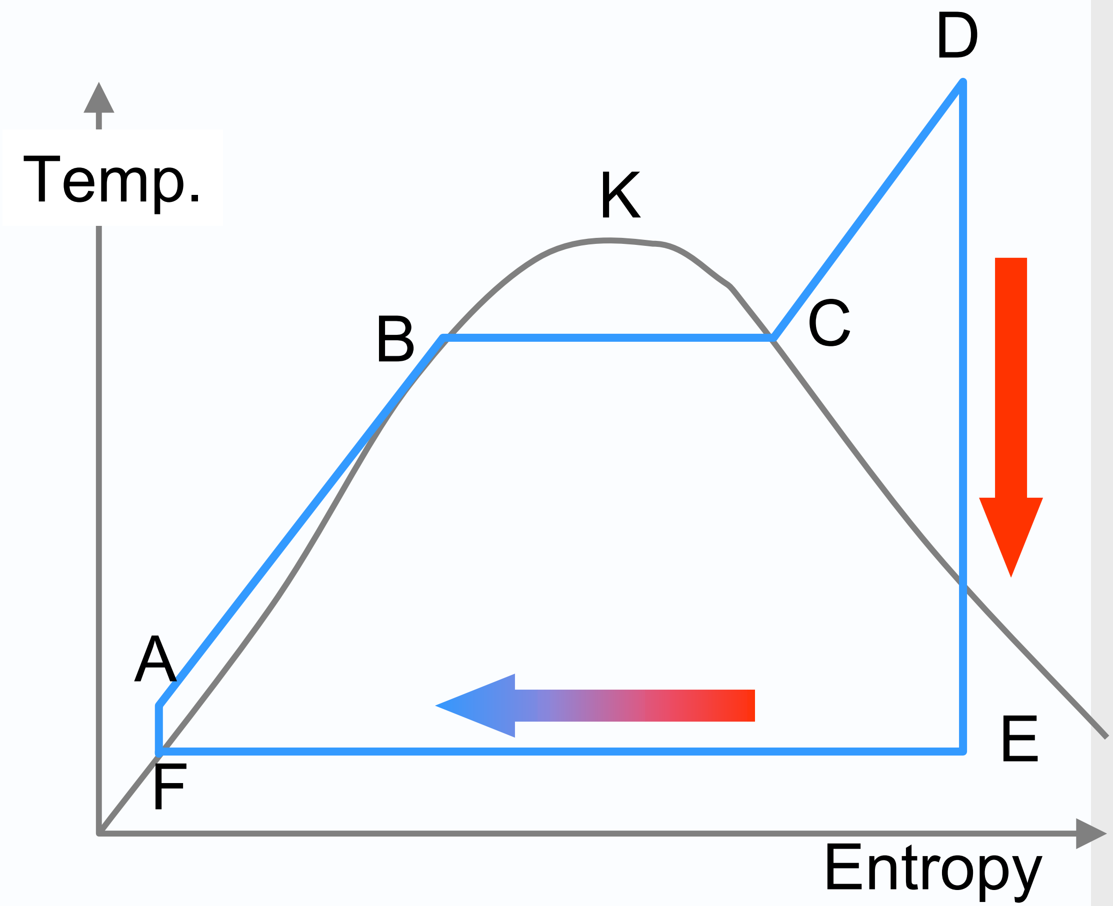
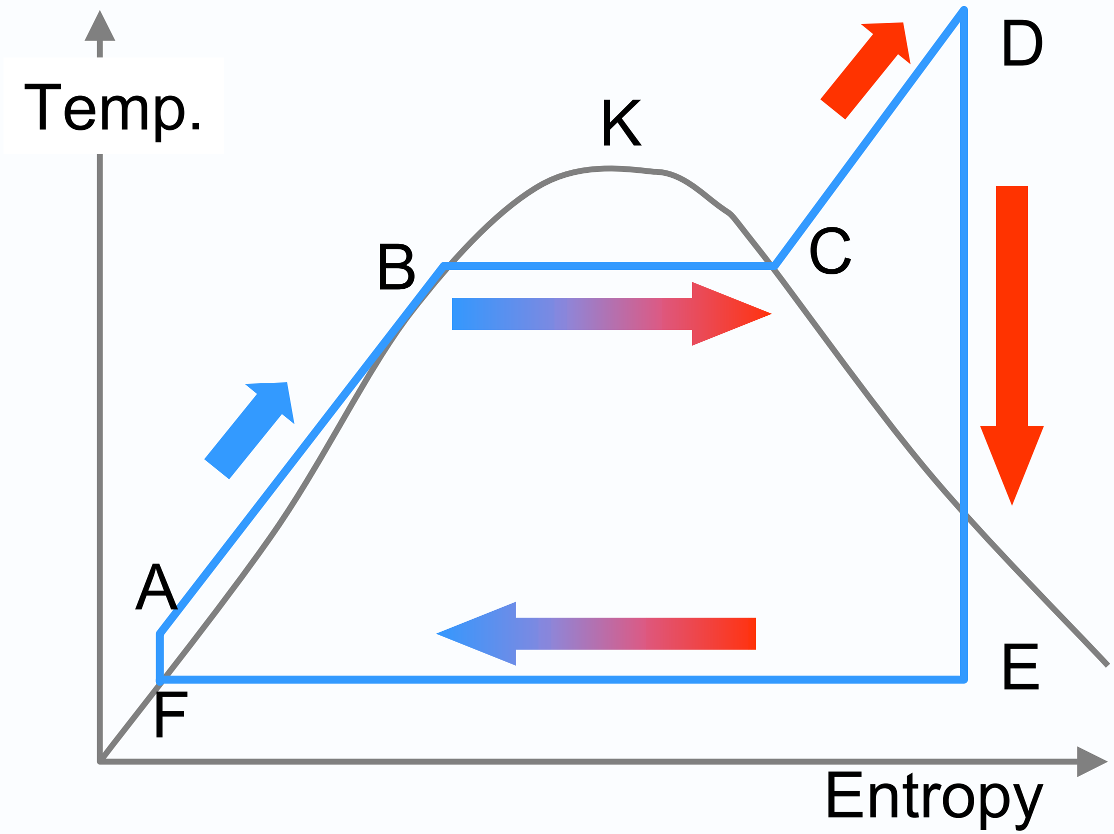
The Water-Steam Cycle outside the boiler



- D to E
  - expansion in the steam turbine
- E to F
  - steam is condensed and cooled in the condenser
- F
  - water available for a new cycle

Source : J. Goalvoueden in Les Techniques de l 'Ingénieur, B 124

Single Rankine Reheat Steam Cycle



Source : J. Goalvoueden in Les Techniques de l 'Ingénieur, B 124

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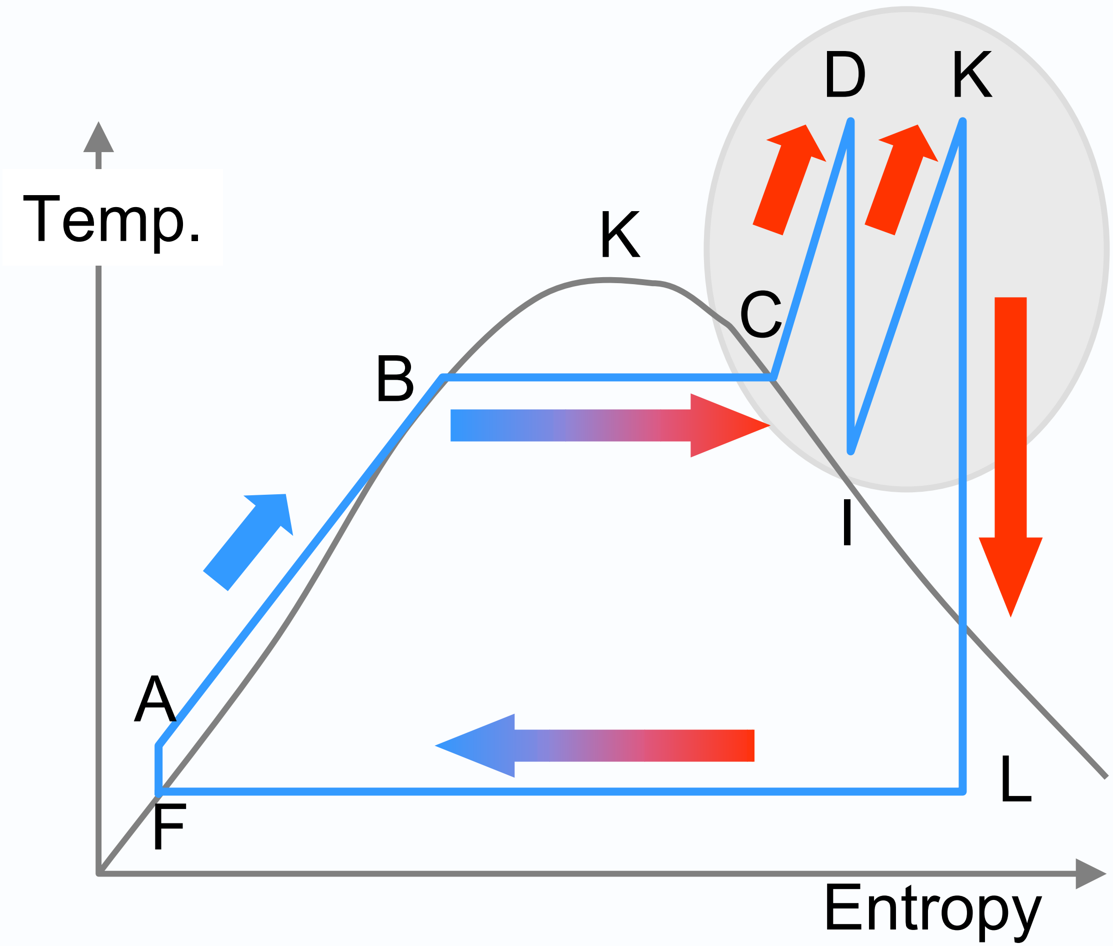
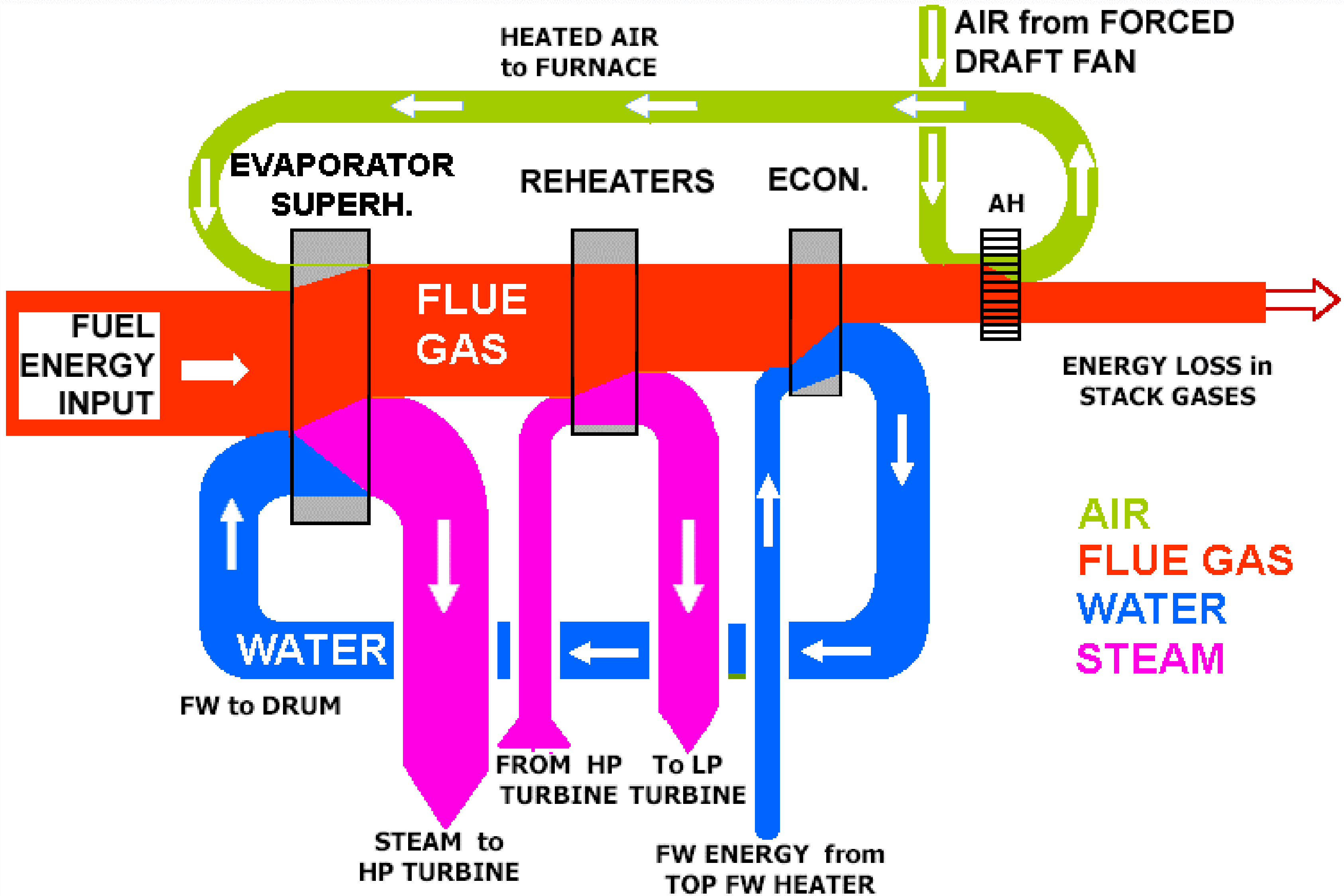
Double Reheat Steam Cycle



- D to I
  - expansion in the HP steam turbine
- I to K
  - steam returns to the boiler and is reheated
- K to L
  - expansion in the IP/LP steam turbine

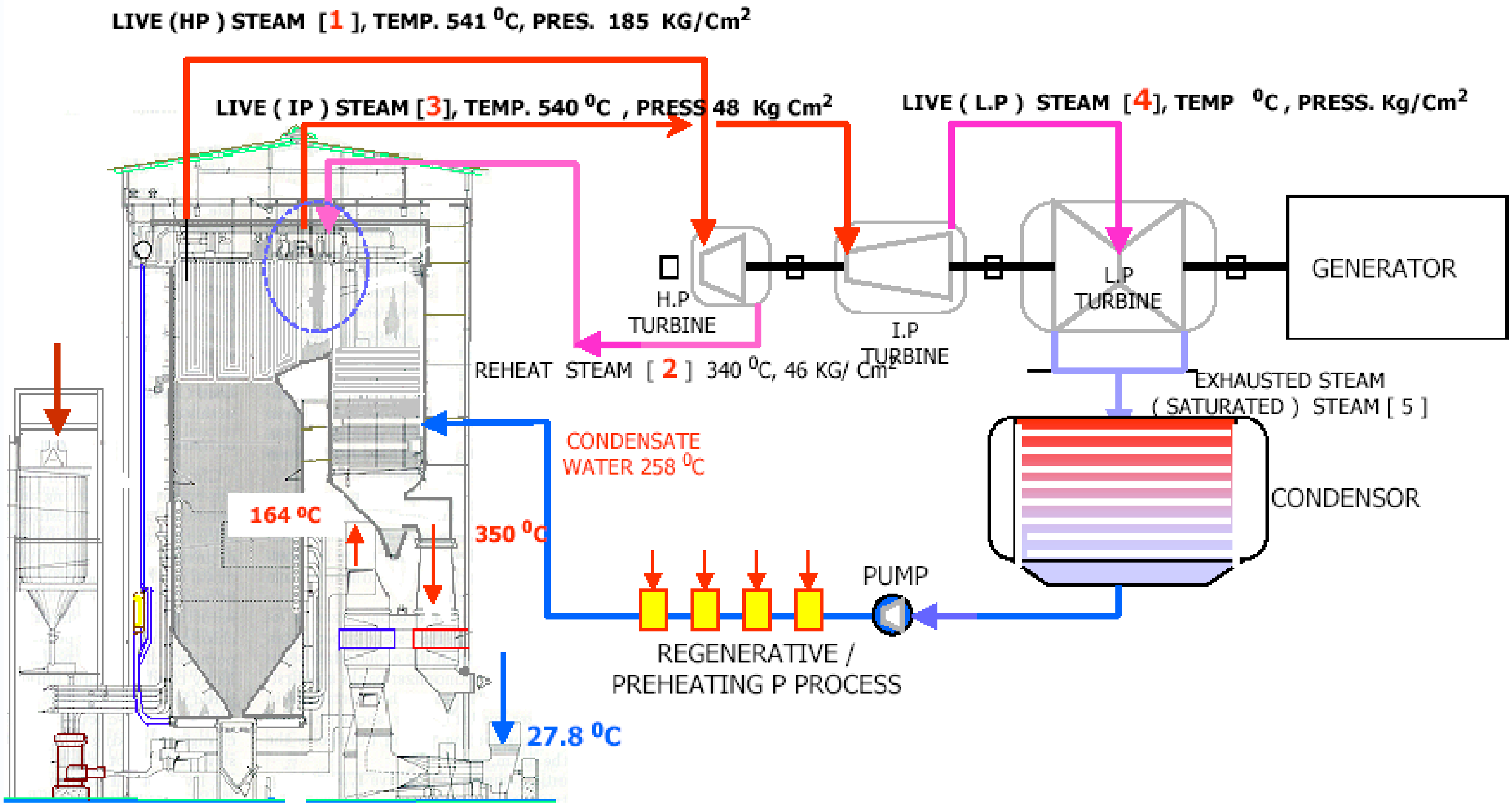
Source : J. Goalvoueden in Les Techniques de l 'Ingénieur, B 124

Flows and Heat Exchange in the Boiler



Source : Combustion, Fossil Power J.G. Singer 1991, ch 5 p 7 fig 2

The Complete Water-Steam Cycle



Source : ALSTOM Indonesia Boiler Seminar, April 2002

Summary

- History
- Thermodynamics for beginners
- Boiler design
- Utilily versus Industrial boilers
- Boiler Construction, Examples, and Troubles

- Boiler design
  - various boiler designs
  - type of operation
  - fuels, solid, liquid, gaseous
  - firing systems
  - steam water circulation

Based on :

• Intended use	industrial, power generation,
• construction	shop or field assembled
• firing system	grate, suspension, fluidized bed
• boiler arrangement	hanged or bottom supported
• water circulation	natural, controlled, forced
• fuel	solid, liquid, gas, waste heat

- Boiler design
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Utility plants and boilers : three types of operation

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- **Base load** : 100% capacity 24/7/365
  - highest capacities (up to 1000 MWe), high efficiency
  - no load-follow requirement
- **Peak load**
  - ultra-fast startup time, suitable for «golden hours»
  - competition with open cycle gas turbines
  - a few hundred hours per year
  - no high efficiency requirement
- **Intermediate load**
  - in between, high load-follow capability

- customized design versus type of operation -

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  - firing systems
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Note : this seminar is targeted to an area where use of coal is limited.
Consequently, the information provided for coal firing is purposedly limited.

Solid Fuels, Fossil

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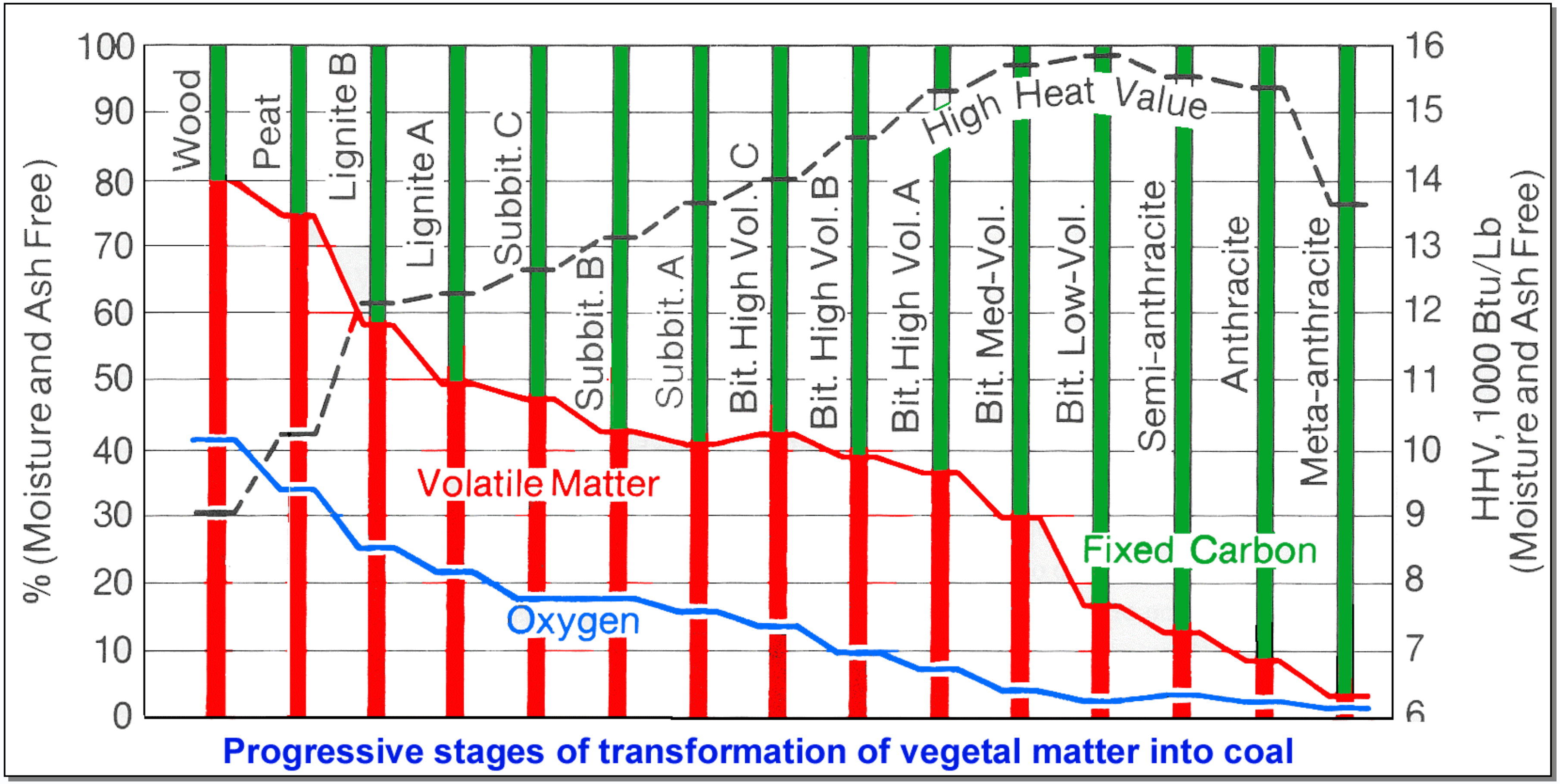
- Coal (from 15 to 30 MJ/Kg)



Source : Combustion, Fossil Power J.G. Singer 1991, ch 2

Solid Fuels, Non-Fossil

- Coke
  - fused solid residue from chemical processes involving coal or oil
- Petroleum coke (petcoke)
  - petrochem byproduct (32-36 MJ/Kg, 3-6% sulfur)
- Wood (20 MJ/Kg)
- Bark (mainly from paper mills)
- Food processing wastes
- Municipal and industrial refuses (7 to 15 MJ/Kg)

Source : Combustion, Fossil Power J.G. Singer 1991, ch 2

Liquid Fuels

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- Crude petroleum
  - high amount of volatile compounds
- Fuel oil

Fuel Oil Grade	FO n°1	FO n°2	FO n°4	FO n°5	FO n°6
Type	Distillate Kérosene	Distillate	Very Light Residual	Light Residual	Residual
Color	Light	Amber	Black	Black	Black
MJ/Kg	46,4	45,5	43,4	43,4	42,5
Sulfur content,%	0,1	0,4 - 0,7	0,4 - 1,5	2.0	**2.8**
Atomizing temp	Ambient	Ambient	-4°C min	50°C	93°C

- Oil fired boilers can be converted to crude firing -

Source : Combustion, Fossil Power J.G. Singer 1991, ch 2

Gaseous Fuels

- Natural gas
- Liquefied Petroleum gas (LPG)
- Refinery and oil gas,
- Gas from steel processing : coke oven and blast furnace gas

Gas	Propane	Butane	Natural Gas	LPG
	C_3H_8	C_4H_{10}	mix	mix
MJ/Kg	50	46	47	45

- Oil fired boilers can be converted to gas firing -

Source : Combustion, Fossil Power J.G. Singer 1991, ch 2

Fuels, Typical Problems

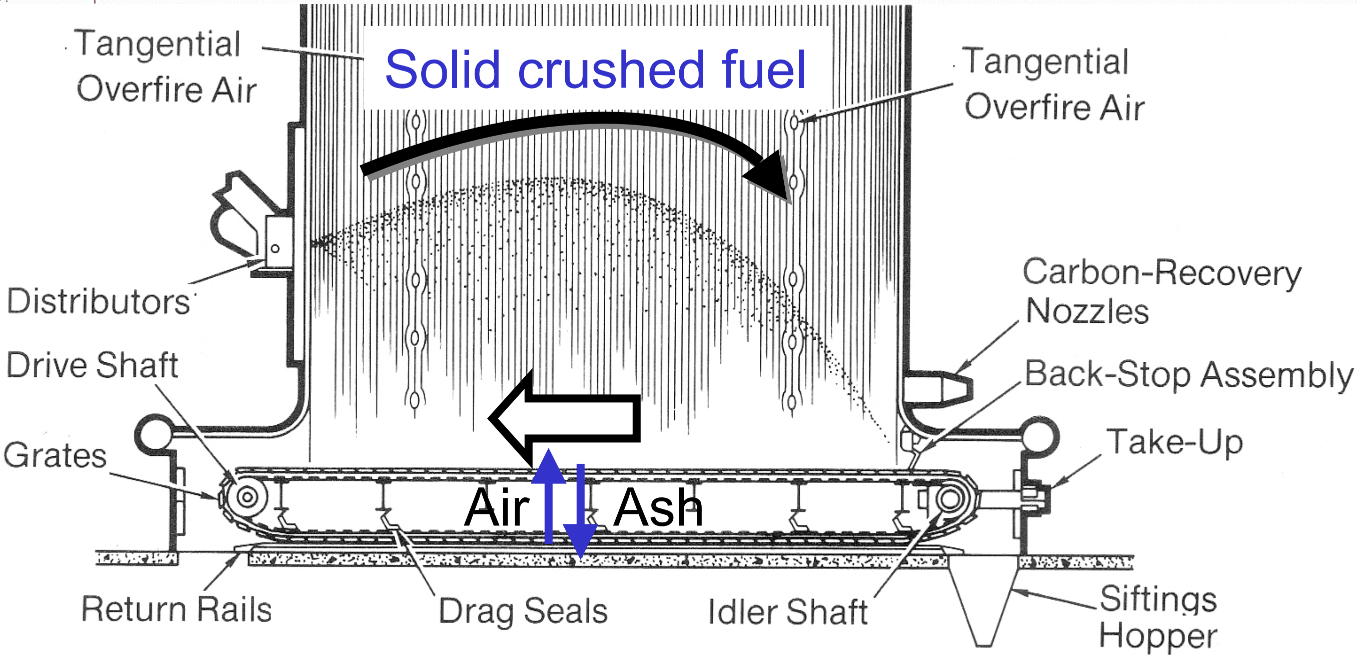
- Degradation of fuel quality with time
- Exhaustion of fuel resource with time, leading to fuel switching
- High quality fuel exported, low quality burned domestically
- Cost increase, leading to fuel switching
- NOx generation properties
- Sulfur content, inducing acid dew point corrosion
- Particulates content

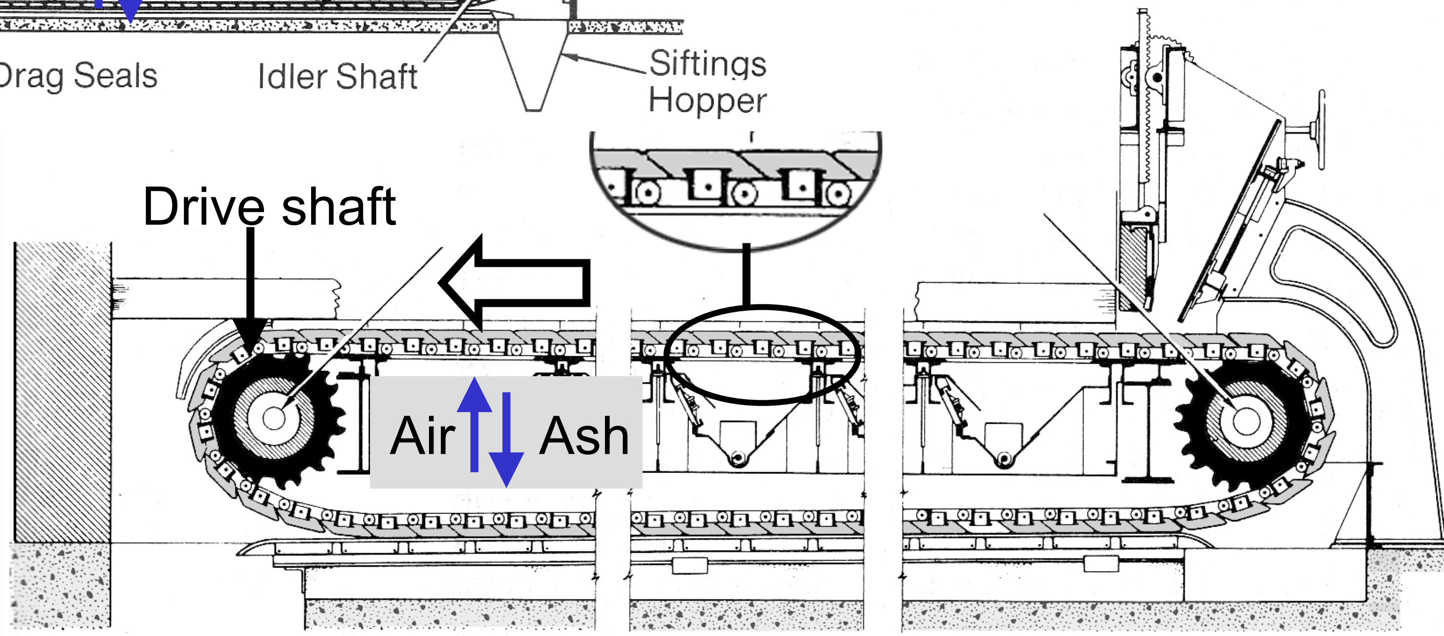
- Boiler design
  - various boiler designs
  - type of operation
  - fuels, solid, liquid, gaseous
  - firing systems
  - steam water circulation

Firing systems

- Firing on a travelling grate
  – suitable to un-pulverized solid fuels
- Suspended firing
  – suitable to pulverized coal, liquid and gaseous fuels
- Fluidized bed combustion
  – suitable to coarse pulverized solid low grade fuels

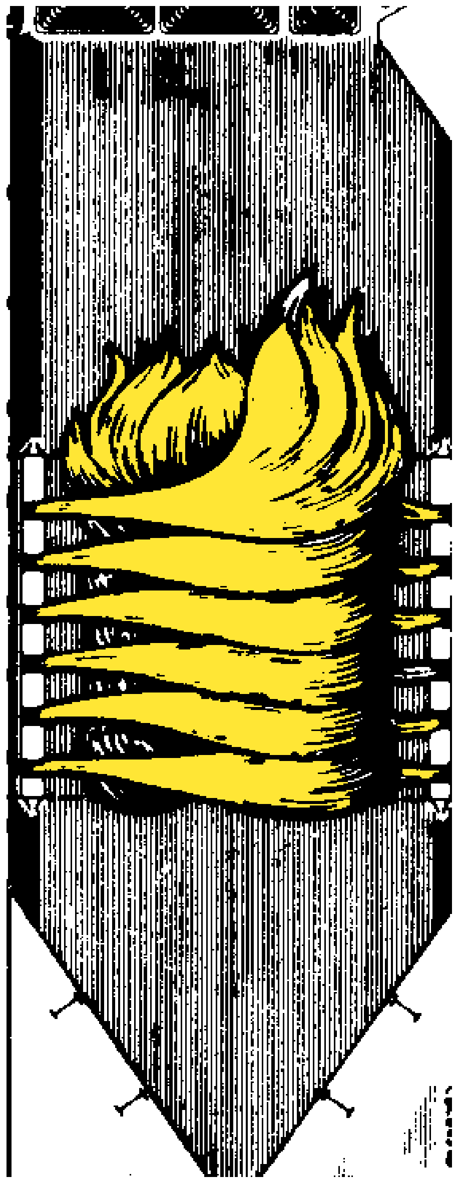
Firing solid fuels on a travelling grate





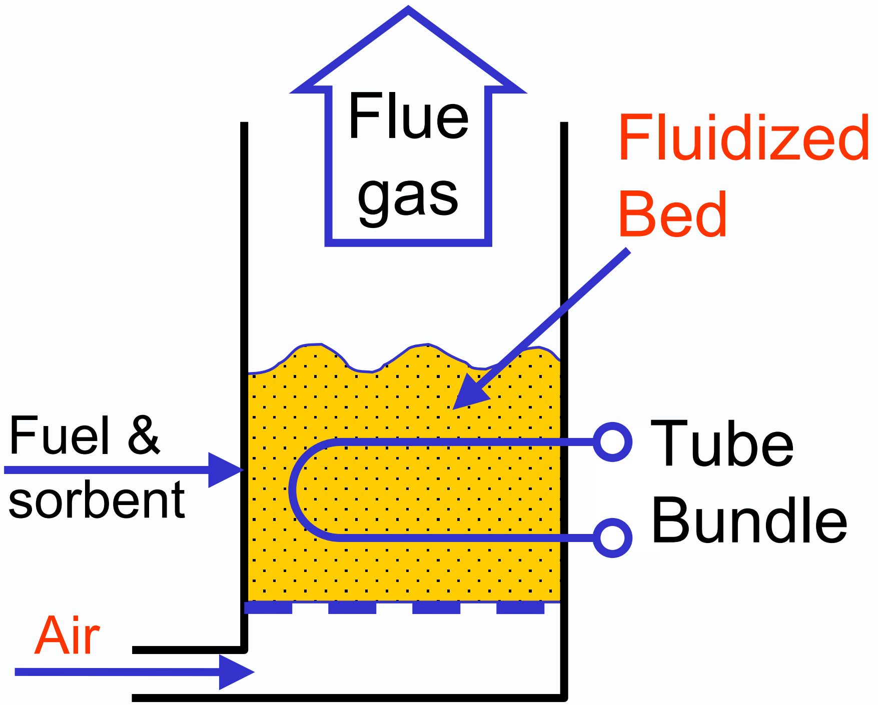
Suspension firing

Air +
pulverized
fuel



- Solid pulverized fuels
  - solid fuel ground to the fineness of face powder
- Liquid fuels
- Gases

Fluidized Bed Combustion, principle



- Ability to burn low-grade fuels
- Fuel flexibility
- Immune to ash properties
- NOx limited production
- In-situ SOx capture

Fluidized Bed Combustion, Types

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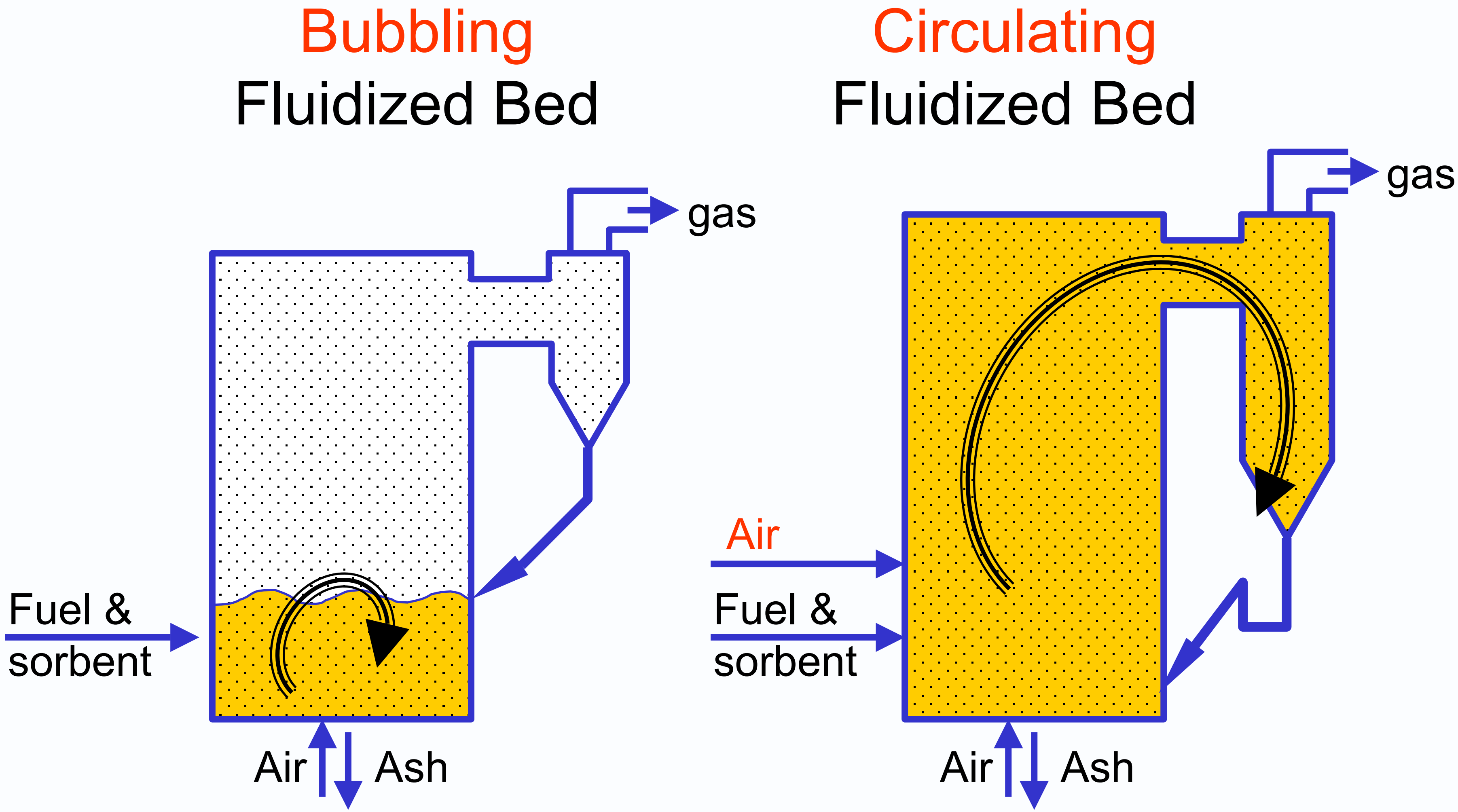

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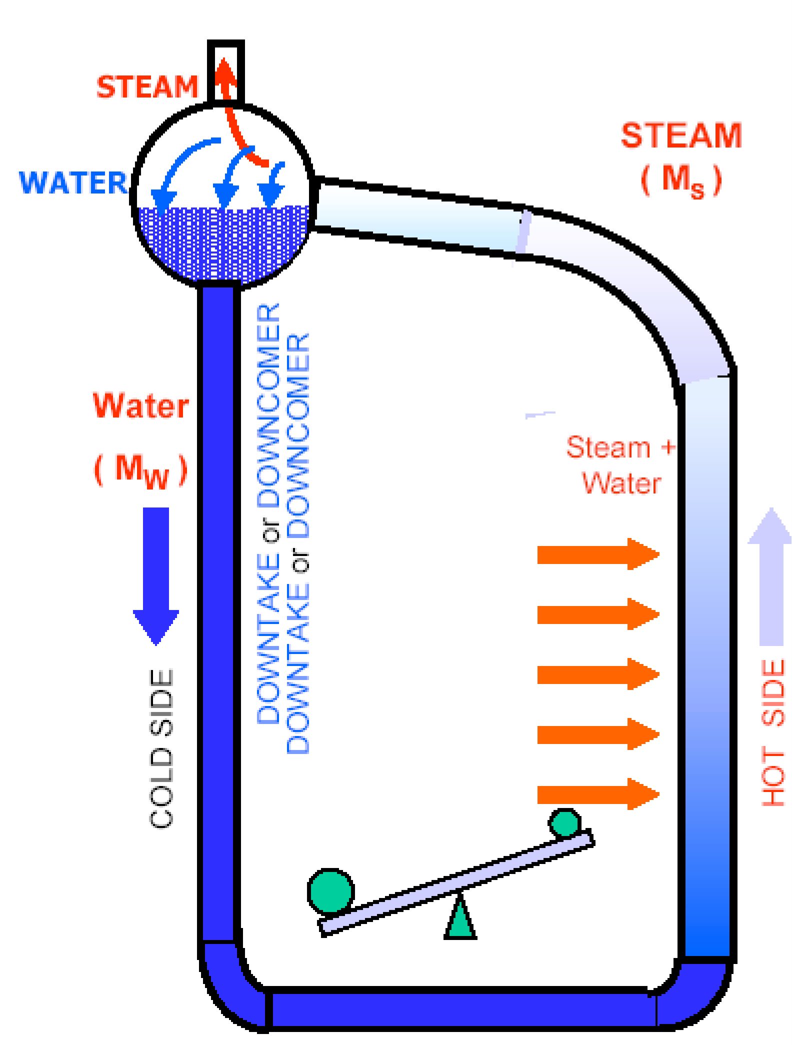
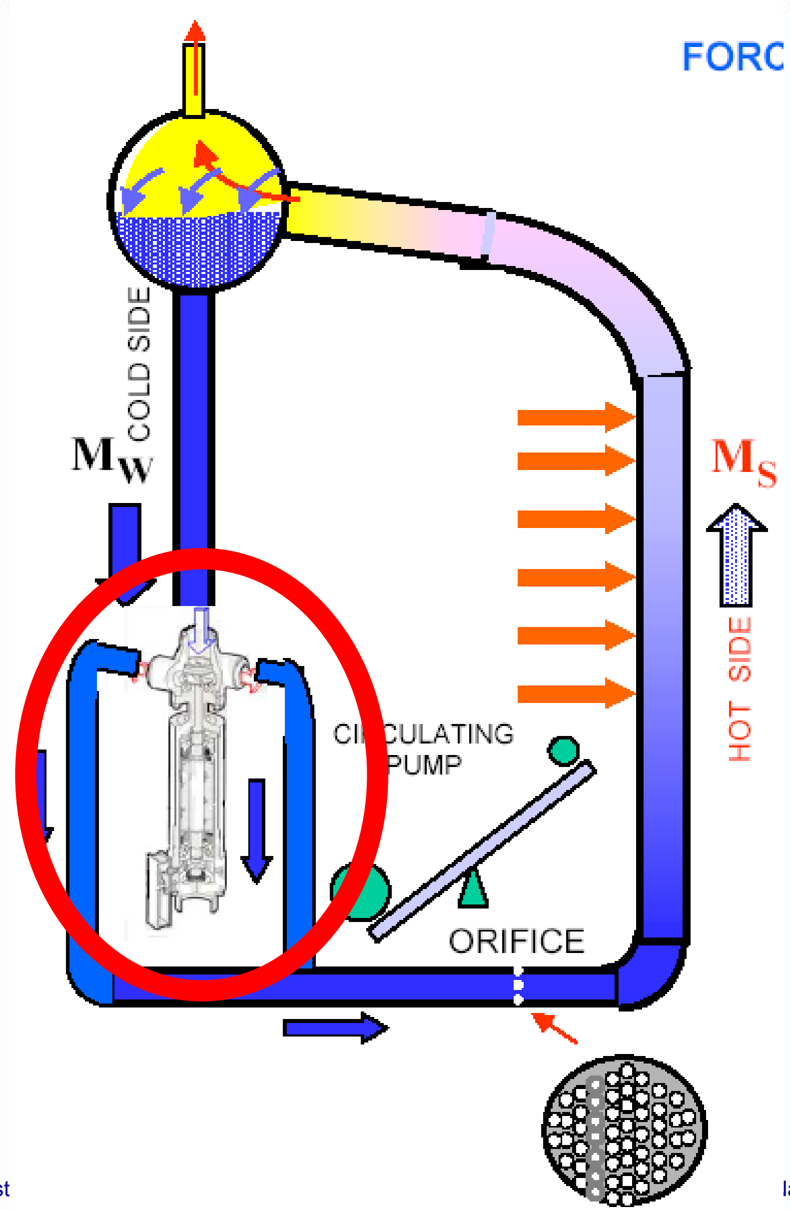
The Natural Circulation Boiler



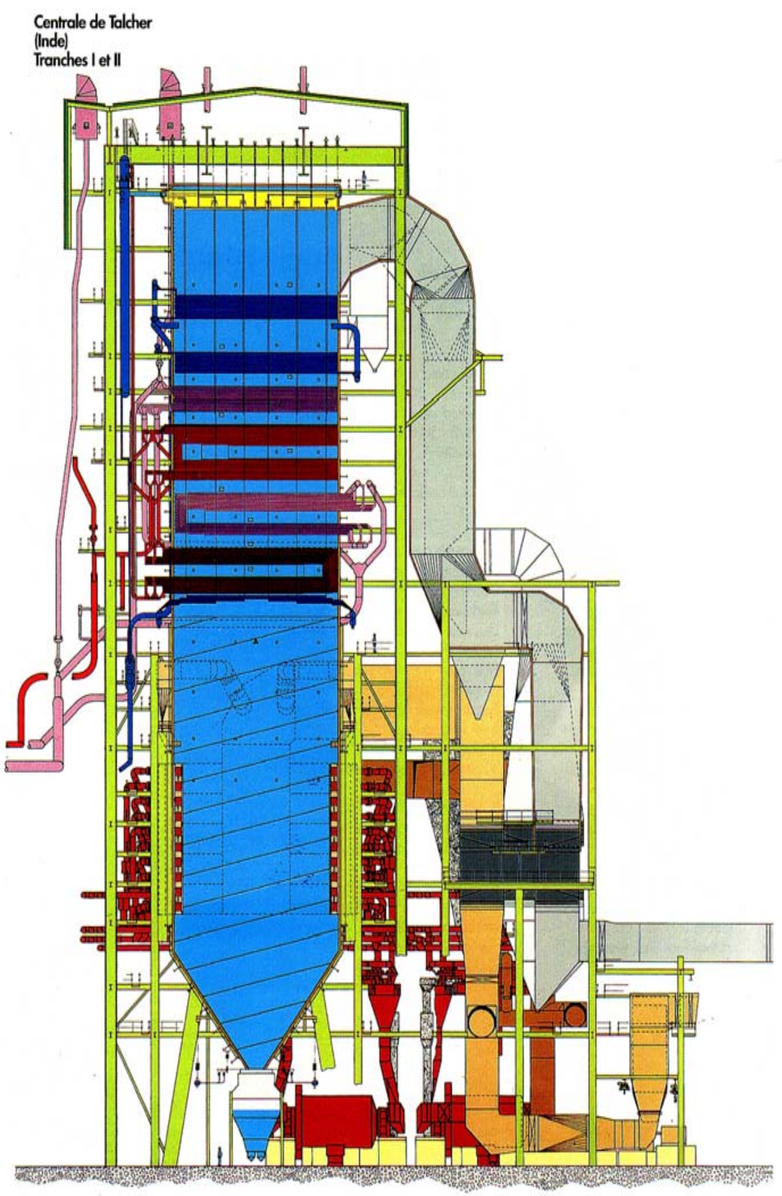
- No circulation pump
- circulation driven by density differences between water and steam/water mixture
- pressure increase detrimental to circulation : low pressure boilers only

Controlled Circulation boiler



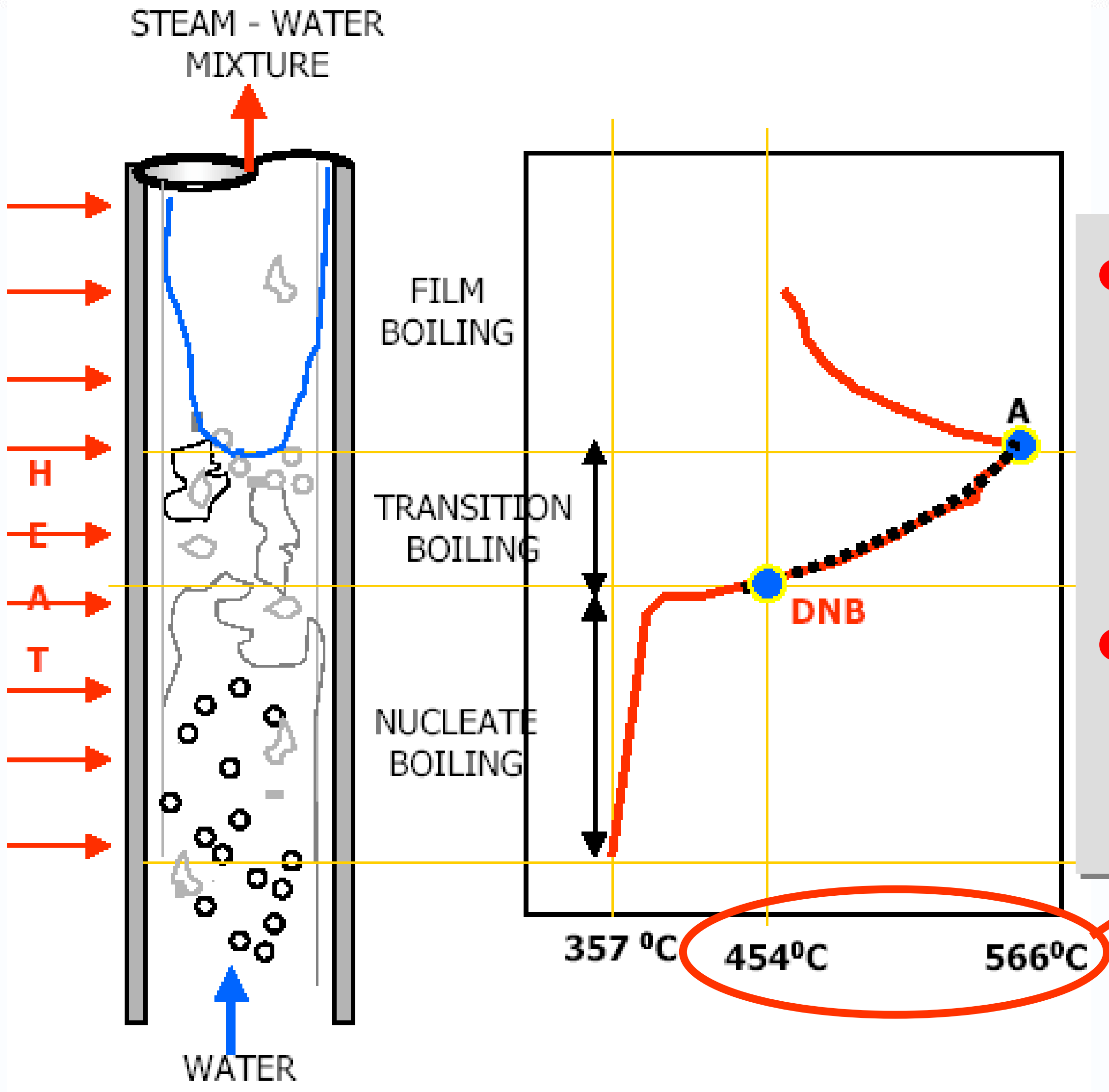
- circulation pump
- allow higher pressure levels and hence, capacities
- better load follow capability
- more complex
- auxiliary consumption
- drum thickness increase

Forced Circulation Boiler



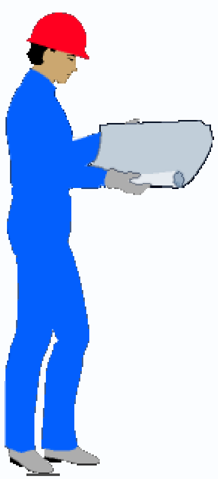
- No drum
- once-through circulation
- fast start-up/shutdown
- invented by Sulzer of Switzerland, now within ALSTOM
- the « tower » type boiler

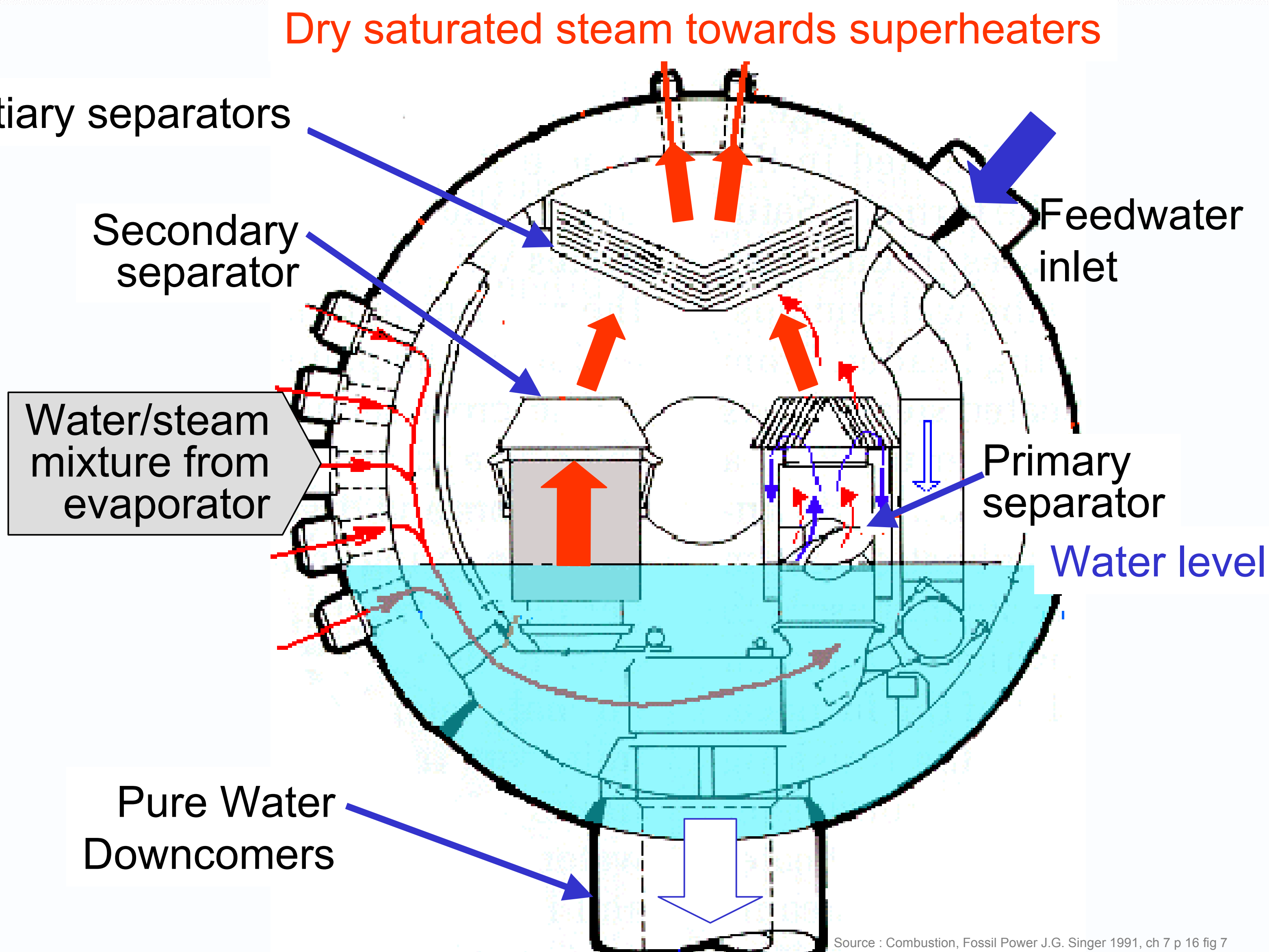
Evaporator Design



- Goal : avoid any departure from safe nucleate boiling (DNB)
- as tube integrity is therefore at risk

Steam - Water Separation : The Drum





Source : Combustion, Fossil Power J.G. Singer 1991, ch 7 p 16 fig 7

Boiler design basics
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Utility vs Industrial boilers

- Except size, no basic design difference between both : a boiler is quite always [(1)] a combination of a furnace where the combustion occurs, and, downstream, a series of heat exchangers where the combustion heat is transferred to the water and steam

- Utility boilers, whose final purpose is electricity generation, must provide high reliable service, and show good efficiency

1 - Except HRSGs

Utility vs Industrial boilers (+)

- Industrial boilers (whose final purpose is not electricity generation) must often show a great flexibility to meet quick load swings

- Both uses are mixed in combined heat-and-power stations such as desalination plants, pulp & paper, petrochemical, steel processing, food industries

1 - Except HRSGs

Shop vs site boiler construction

- Shop construction
  - integrated package with preassembled auxiliaries
  - shipping routes from shop to site must be carefully investigated
  - all construction by shop staff
  - option limited to small boiler
- Site construction
  - shop-assembled components easy to ship
  - significant amount of work by local staff
  - option required for large utility boilers
  - strong site construction supervision

Typical boiler specification

- Boiler
  - Information related to the water and steam generating equipment and unit designation
- Furnace
  - Dimensions / Total Volume
- Superheater and reheater design
  - mono/multistage, layout, pendant/panel/platen
- Air Heater
  - regenerative bi/tri sectors, cold end plate material
- Economizer
  - tube type, finned or plain,

Typical boiler specification (+)

- Fuel specification
- Combustion system
  - fuel preparation and handling, burners type
- Operating Conditions
  - Controll point, lowest load ensuring normal steam temp
  - Maximum Continuous Rating (MCR)
  - Guaranteed load, base for overall unit efficiency guarantee

Typical boiler specification (++)

- Boiler Capacity
  - steam flow rate at MCR
  - control load : steam temp achieved and controlled
- Boiler Efficiency
  - Efficiency of xx% means that xx% of the heat supplied by the fuel is transferred to the water / steam mixture, and 100 - xx% is lost
  - 100% efficiency is not achievable in a cost effective way

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Small / Medium size Boilers

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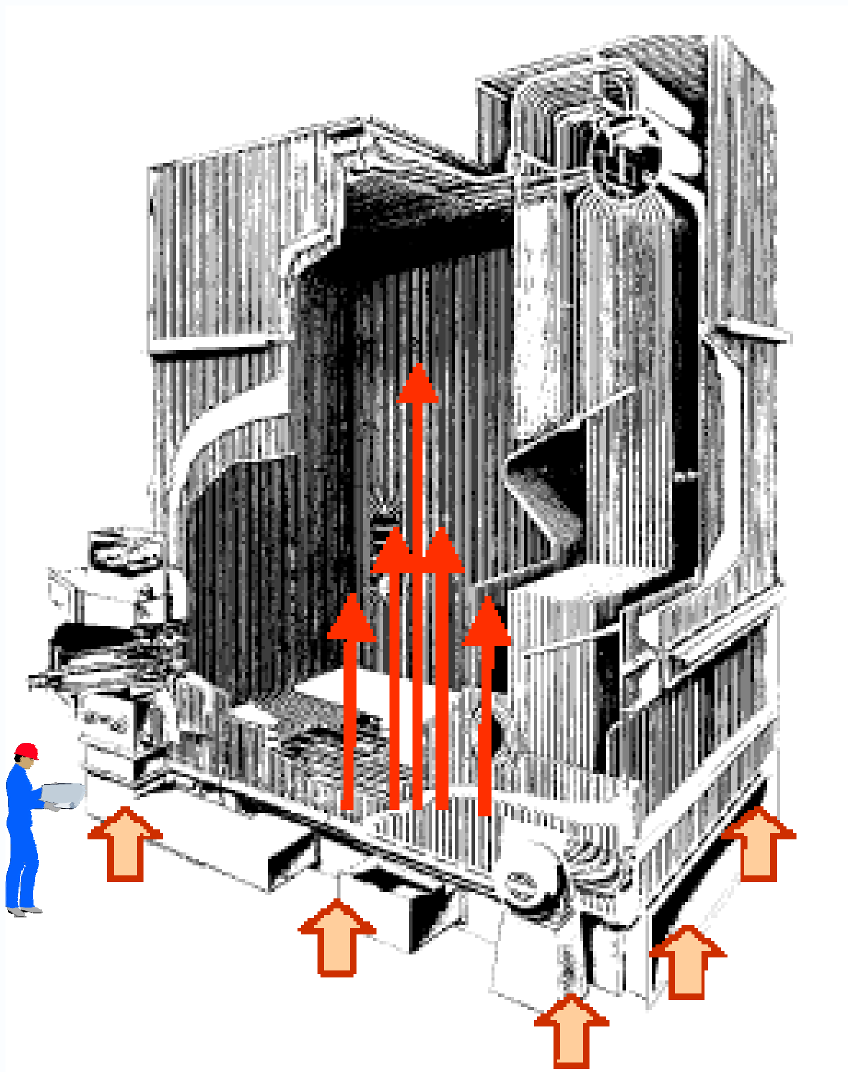
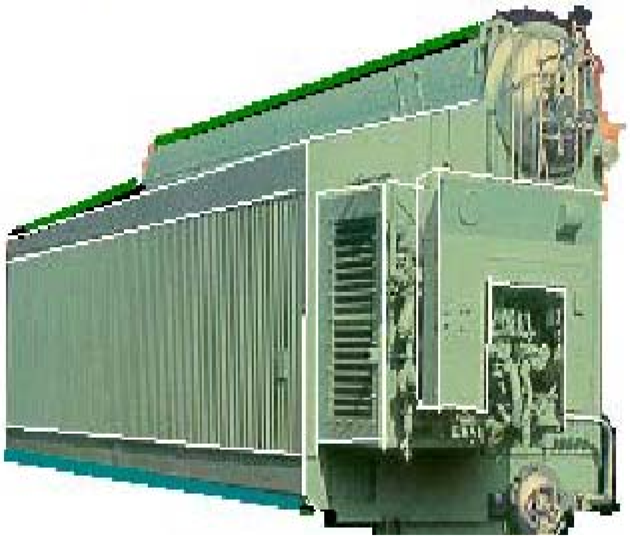
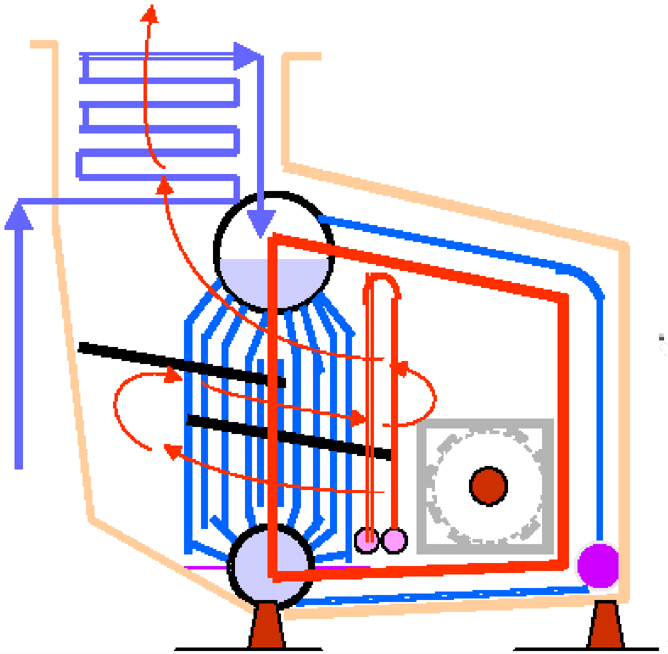


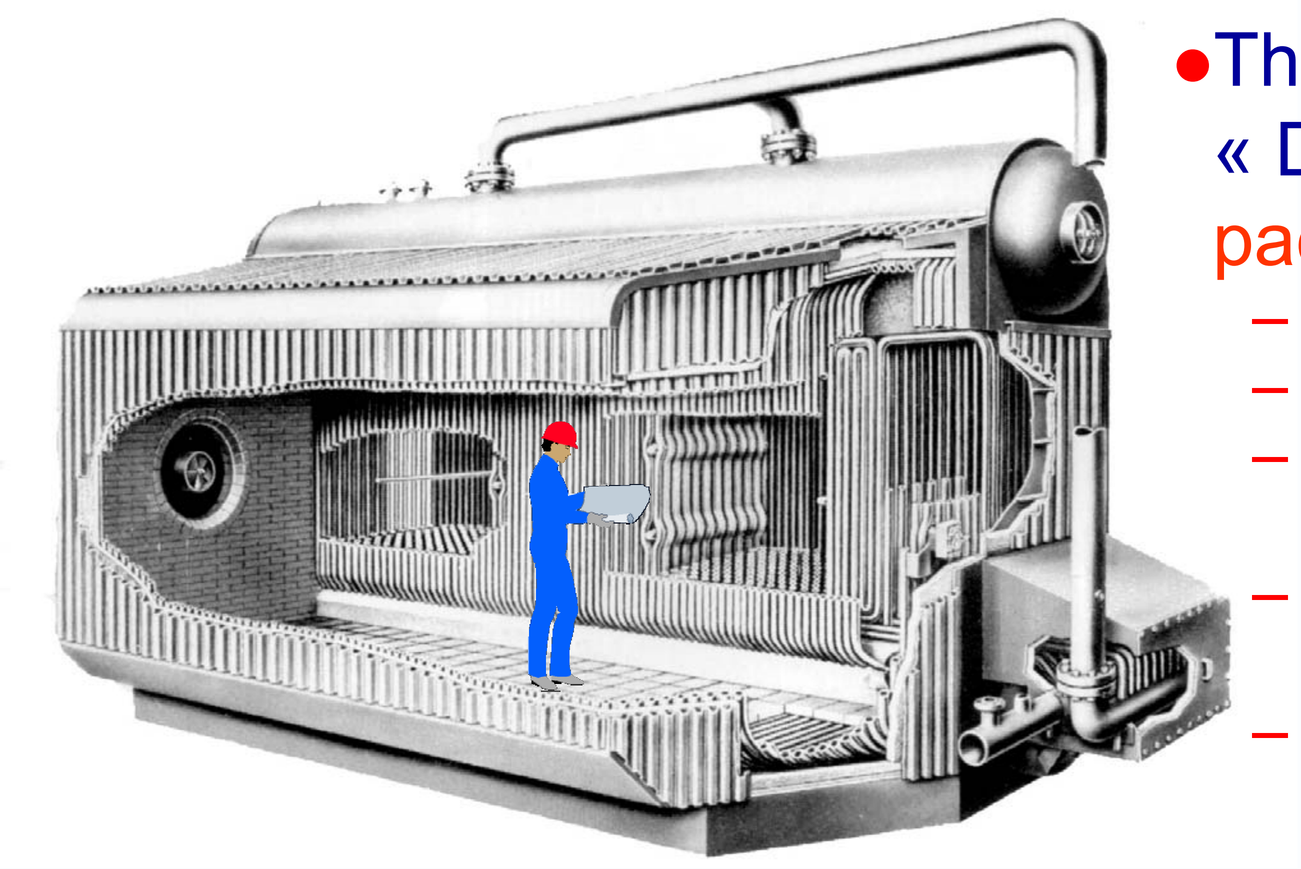
- Bottom supported
- Can be shop constructed (package boilers)
- All heat furnace and heat exchangers rest on ground
- thermal expansion lateral and upwards restrained
- sensitive to earthquakes

Small / Medium size Boilers
The ALSTOM« D » Package Boiler



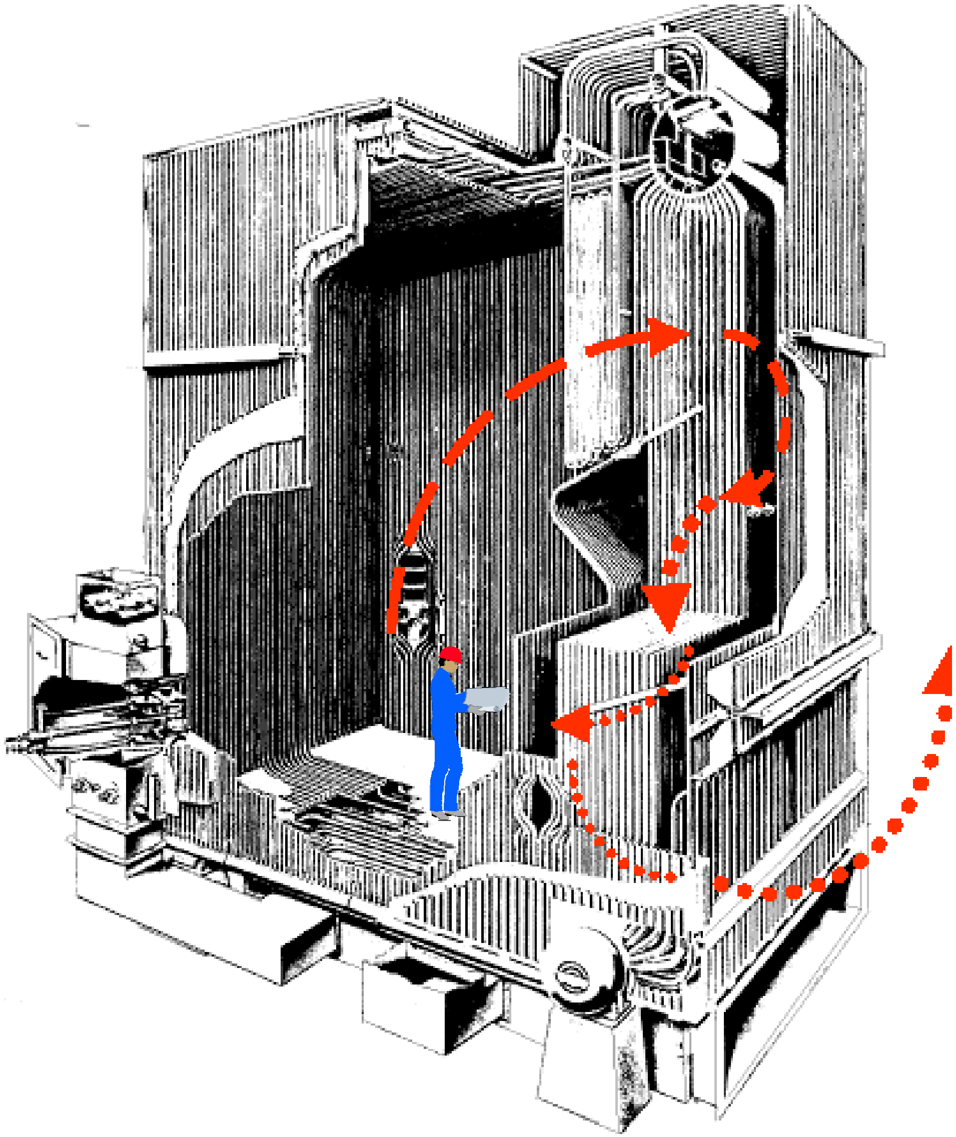
- compact
- small capacity
- 100% shop assembled
- shipped on train or barges
- fast erection





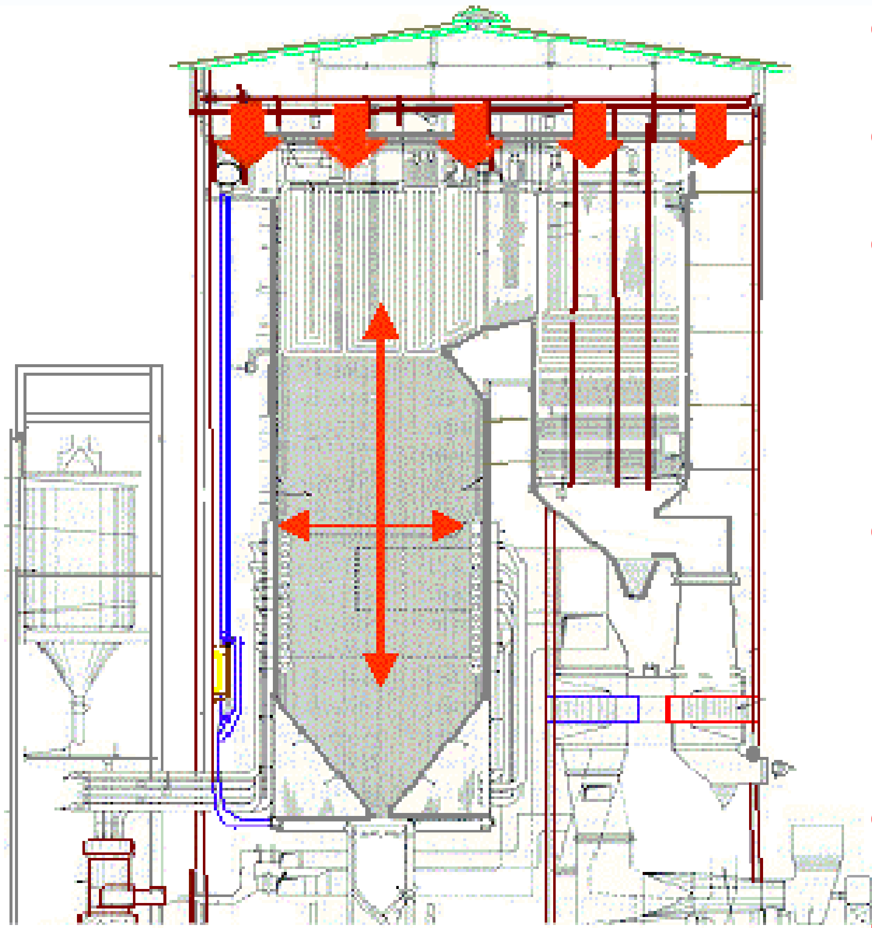
- The ALSTOM/CE « D » type VP package boiler
  - compact size
  - small capacity
  - 100% shop assembled
  - shipped on train or barges
  - fast erection

Small / Medium size Boilers



- The ALSTOM/CE « VU60 » D type package boiler
- up to 270 t/hr (approx 90 MWe power)

Large size Boilers



- Large Utility boilers
- Top supported/hanged
- All heat furnace and heat exchangers hanged from the top
- Allow easy thermal expansion both lateral and downwards
- resistant to earthquakes
- footprint minimized

Large size Boilers

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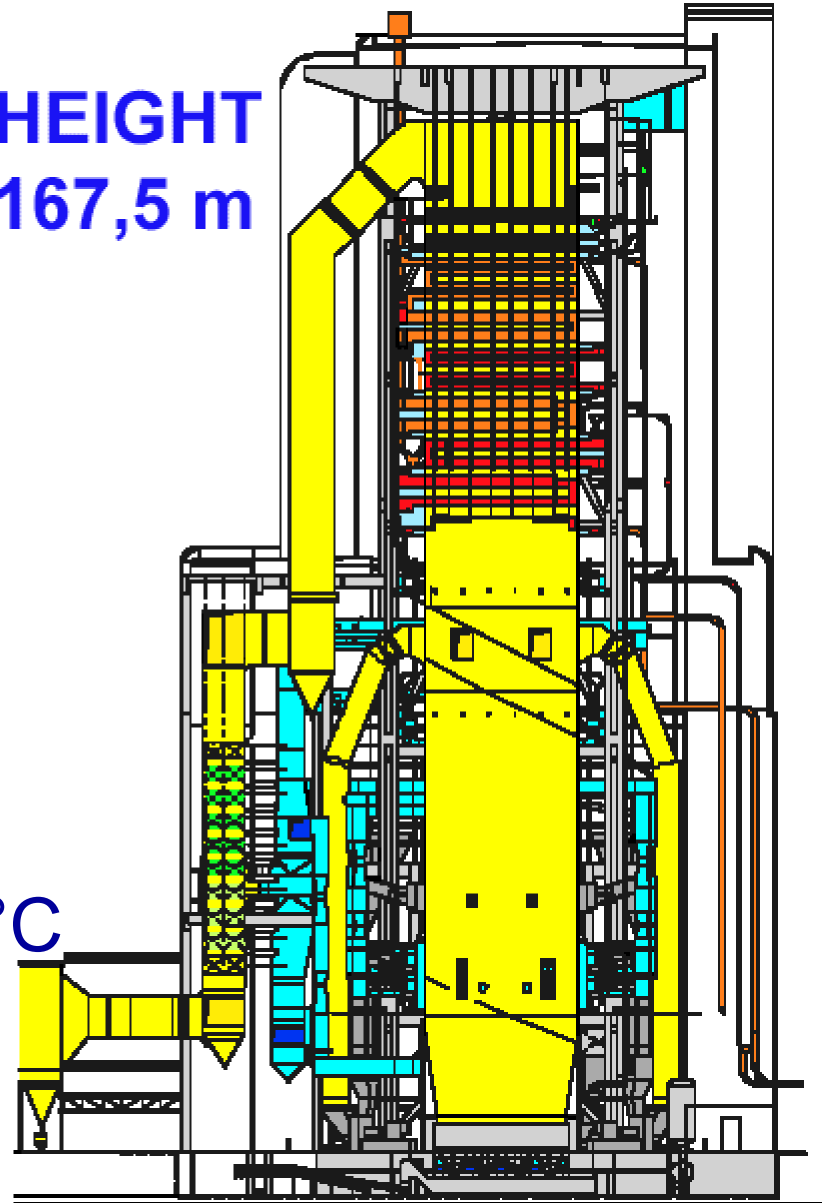
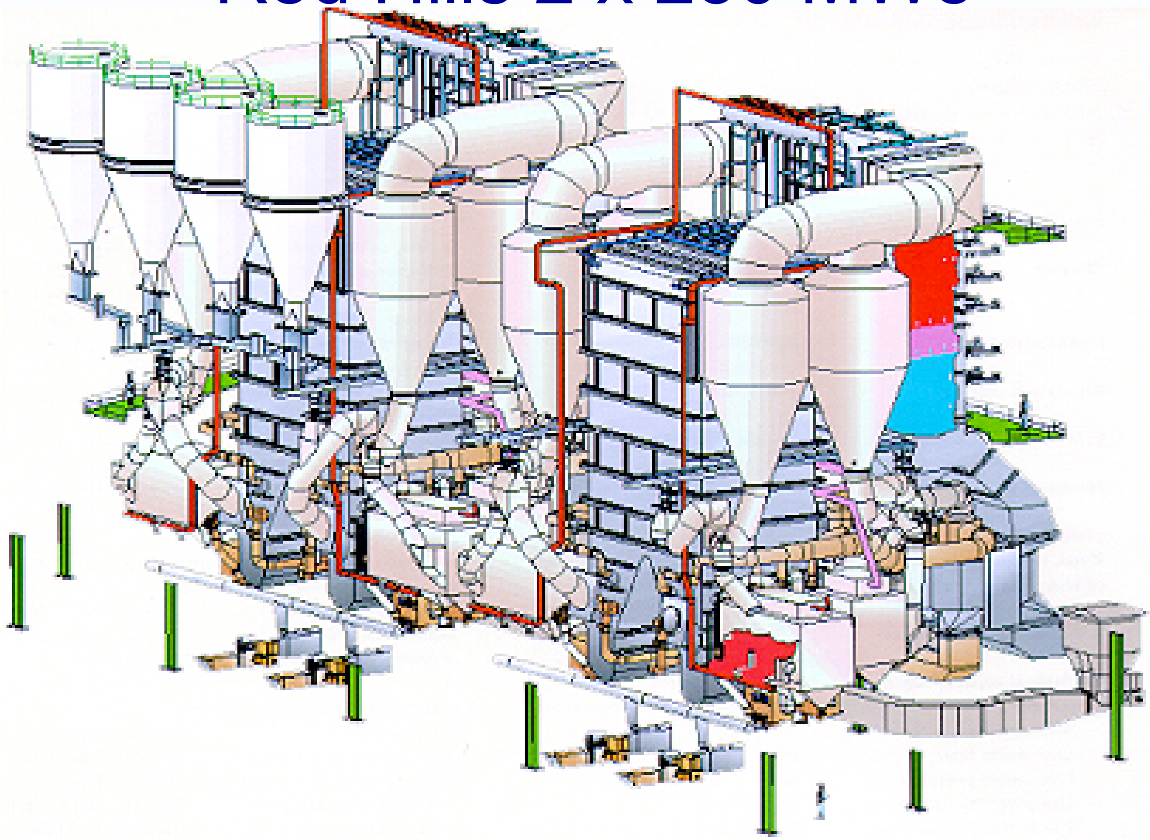
- Germany
- Niederaussem K
- 1012 MWe (gross)
- lignite
- once-through forced circulation supercritical
- operation: 2002
- Fuel: lignite
- Steam 274 bar, 580°C/600°C
- 94.4 % efficiency

HEIGHT
167,5 m



Large size Boilers

- USA
- Red Hills 2 x 250 MWe



- lignite
- Circulating Fluidized Bed
- operation: 2002
- Steam 184 bar, 541°C
- Bechtel

- Largest lignite-fired CFB in the world -

Large size Boilers

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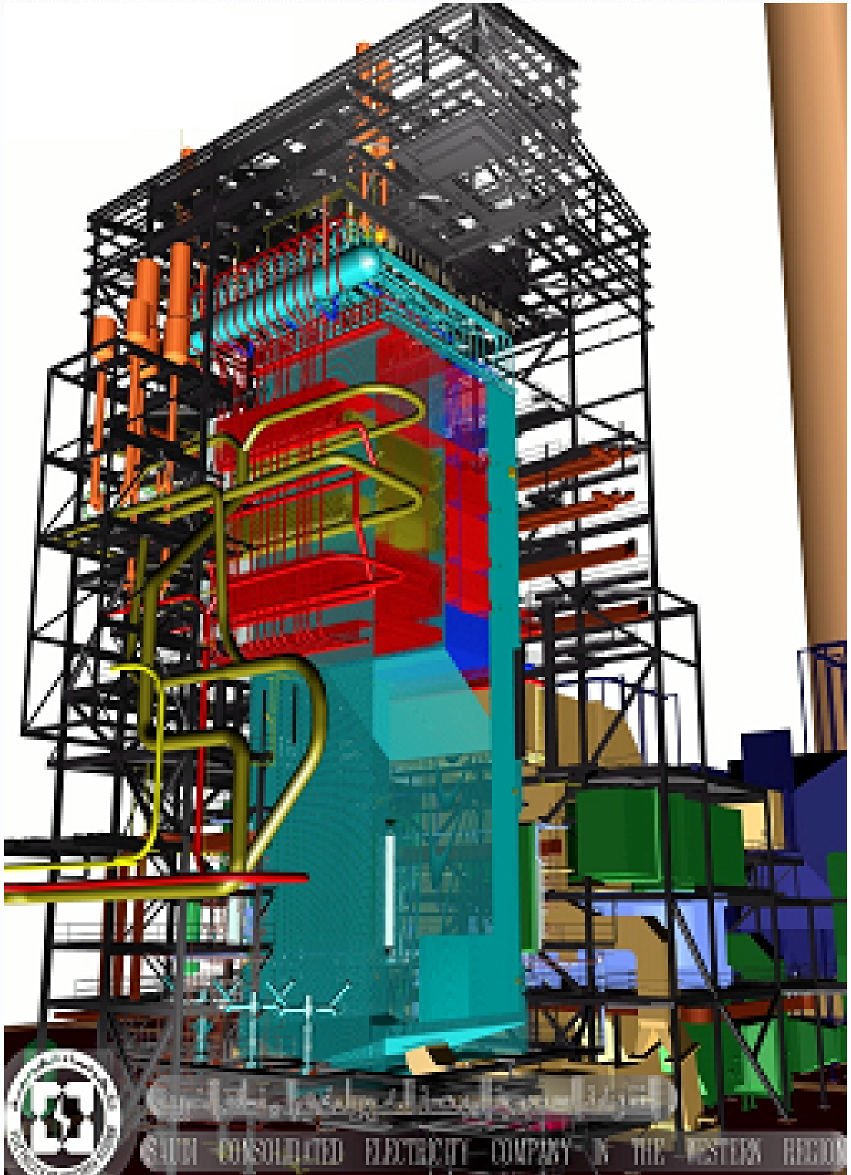
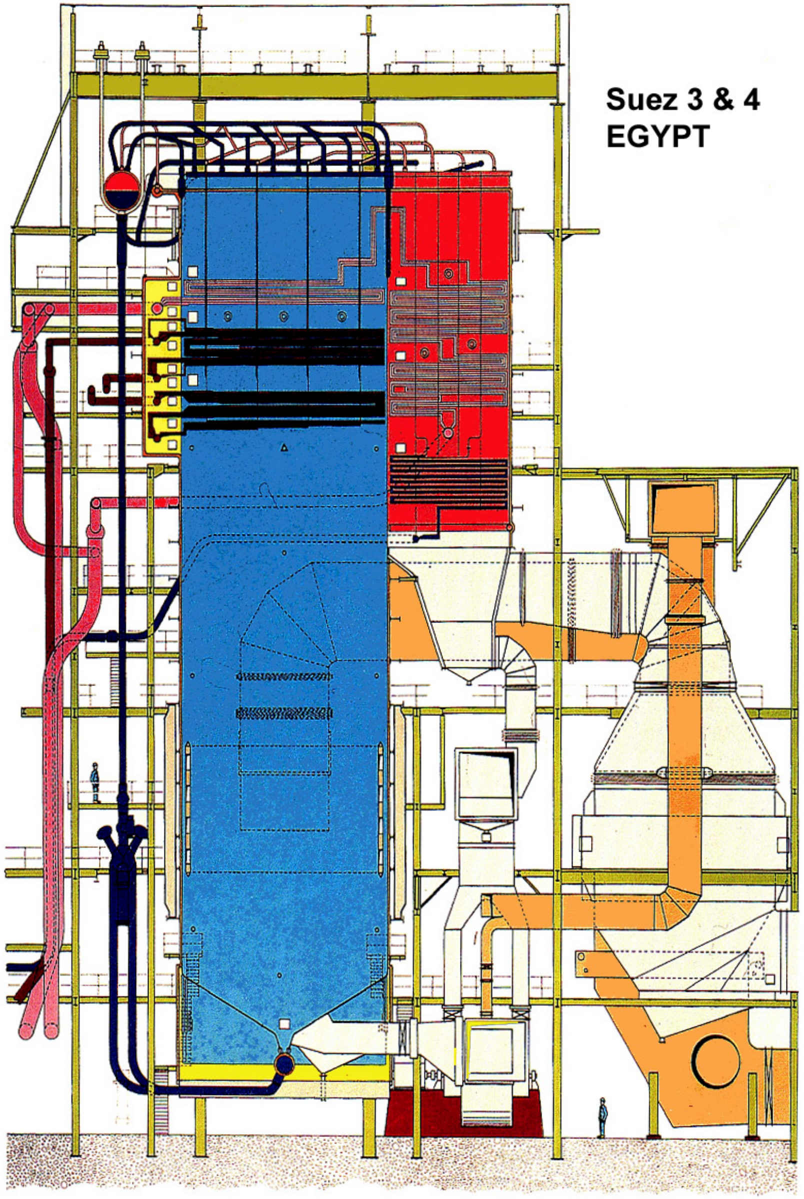


- Shoaiba, 3 x 350 MWe in Saudi Arabia
- Oil-fired
- 2 pass - subcritical Controlled® Circulation
- Operation: 2002
- Fuel: Oil & gas
- Steam 182 bar, 540°C/540°C

Large size Boilers



- Egypt
- Suez 3 & 4 (and Aboukir)
- 2 x 325 MWe
- Oil or gas-fired
- drum boiler, 2 coupled pass Controlled Circulation
- Operation: 1987
- Fuel: Oil & gas
- Steam 181 bar, 541°C/541°C

Large size Boilers

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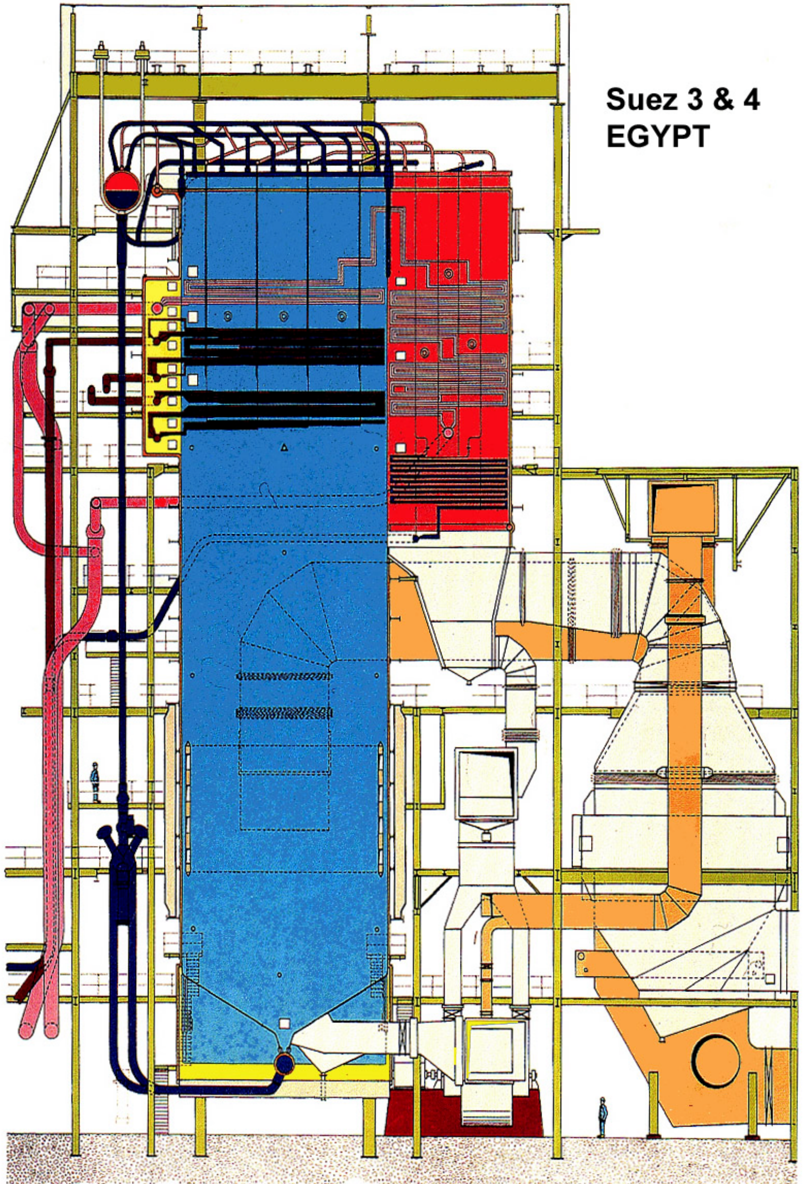
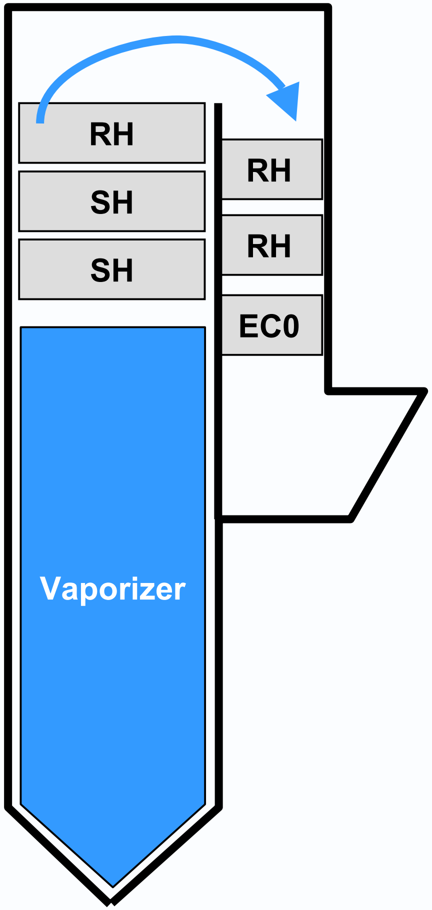
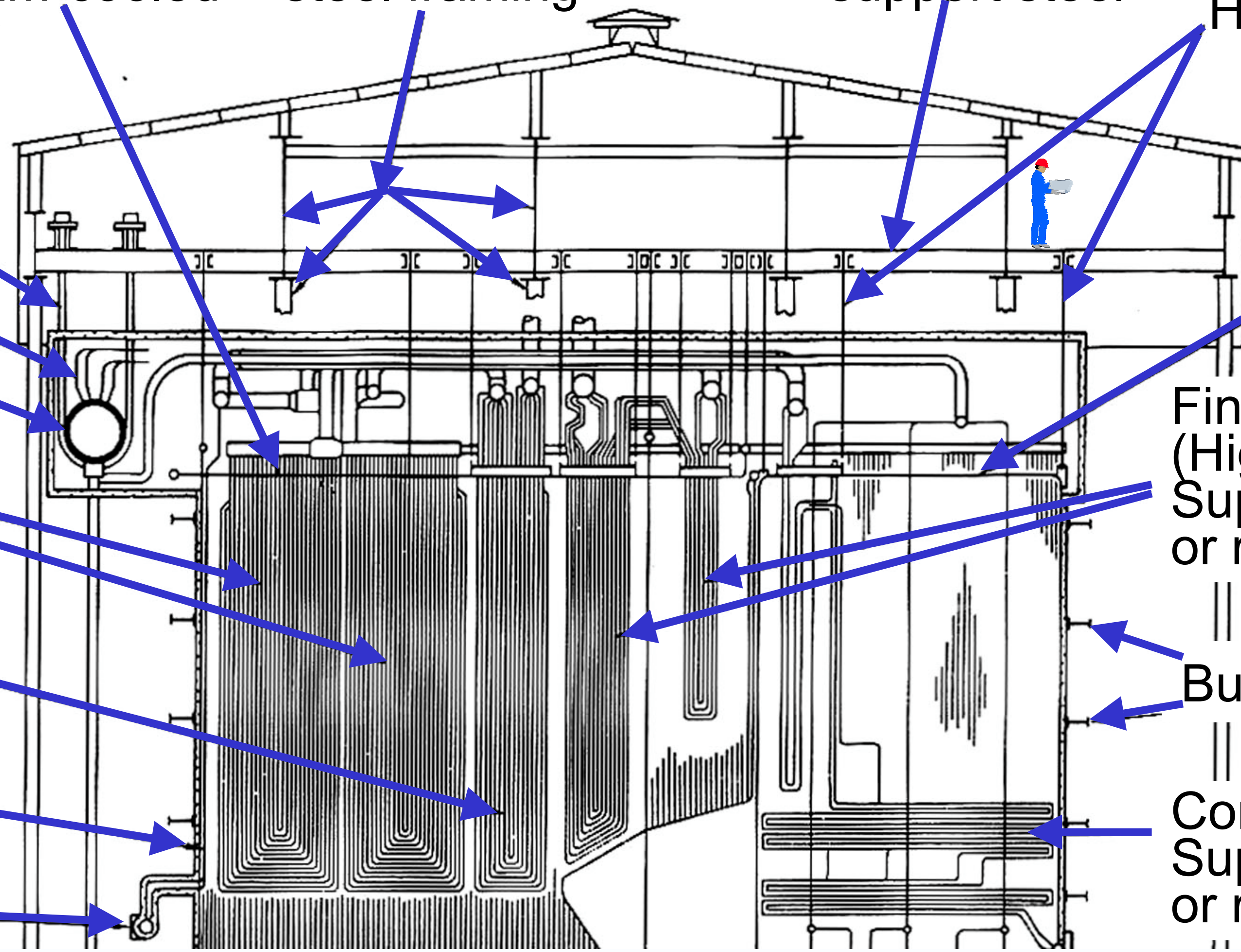
Heat Exchangers Arrangement



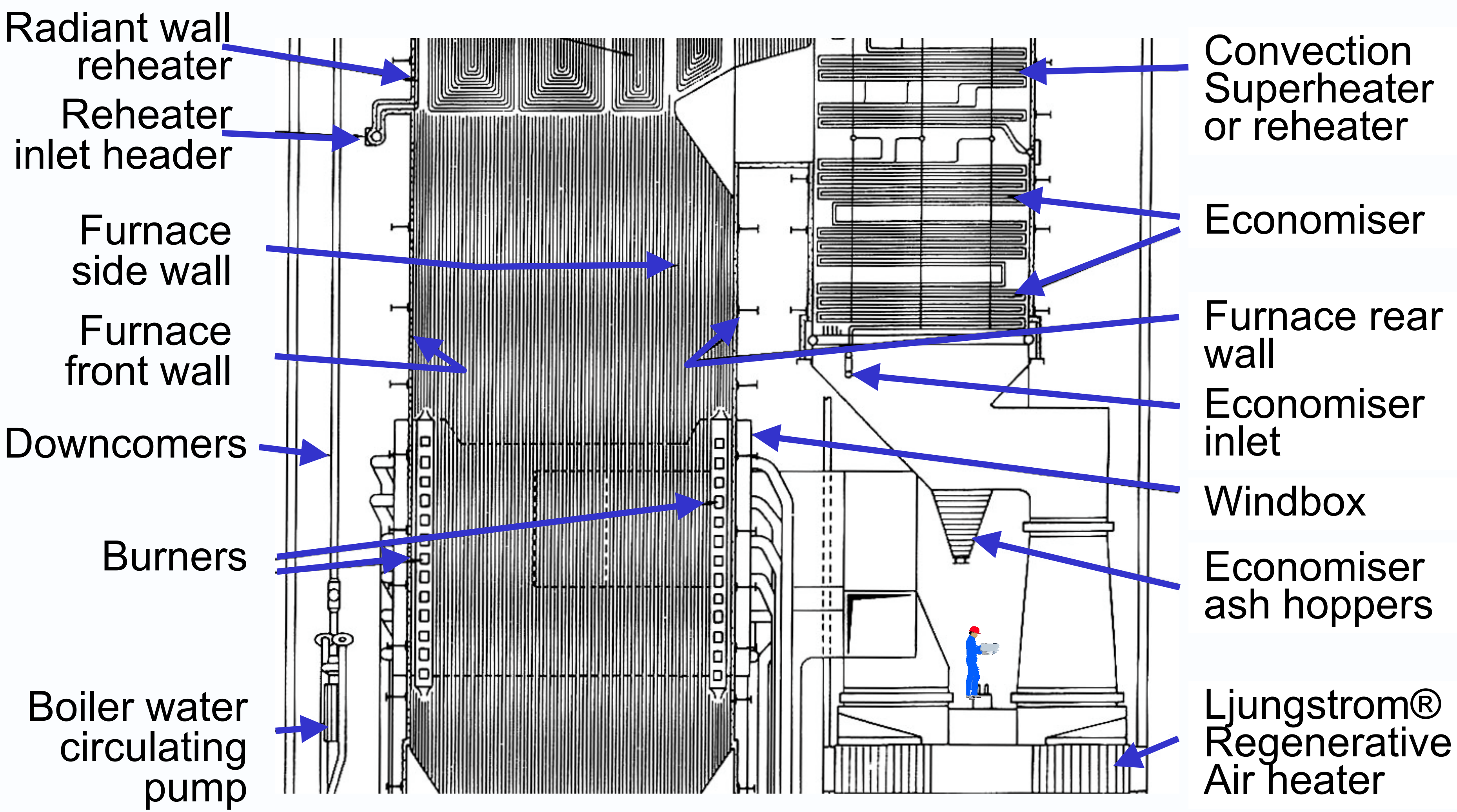


Large size boiler
Glossary, top



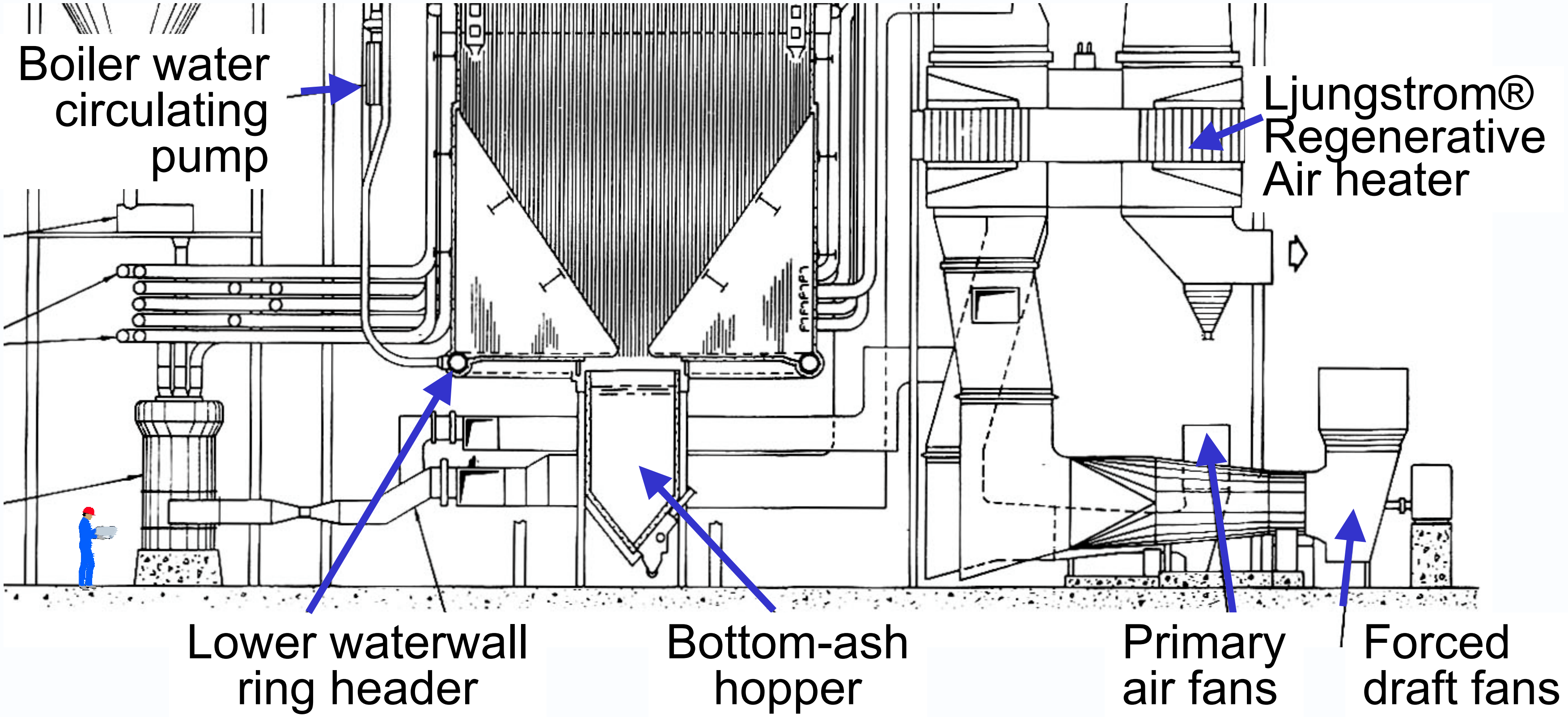
Source : Combustion, Fossil Power J.G. Singer 1991, ch 7 p 21 fig 11

Large size boiler
Glossary, middle



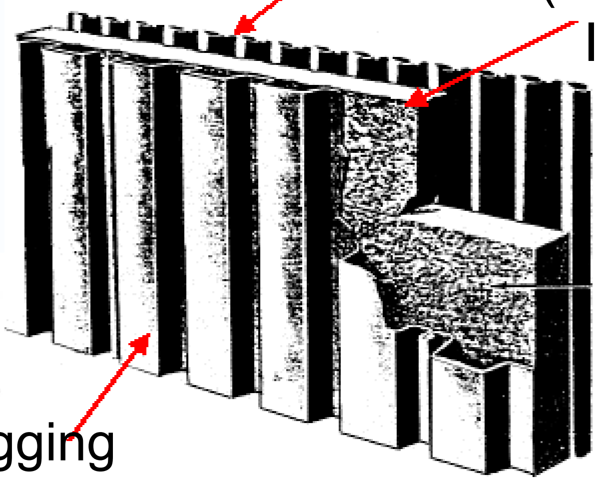
Source : Combustion, Fossil Power J.G. Singer 1991, ch 7 p 21 fig 11

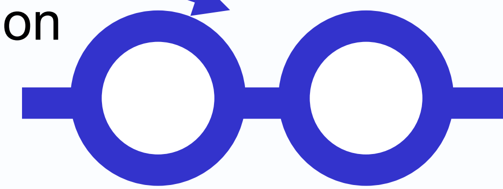
Large size boiler
Glossary, bottom

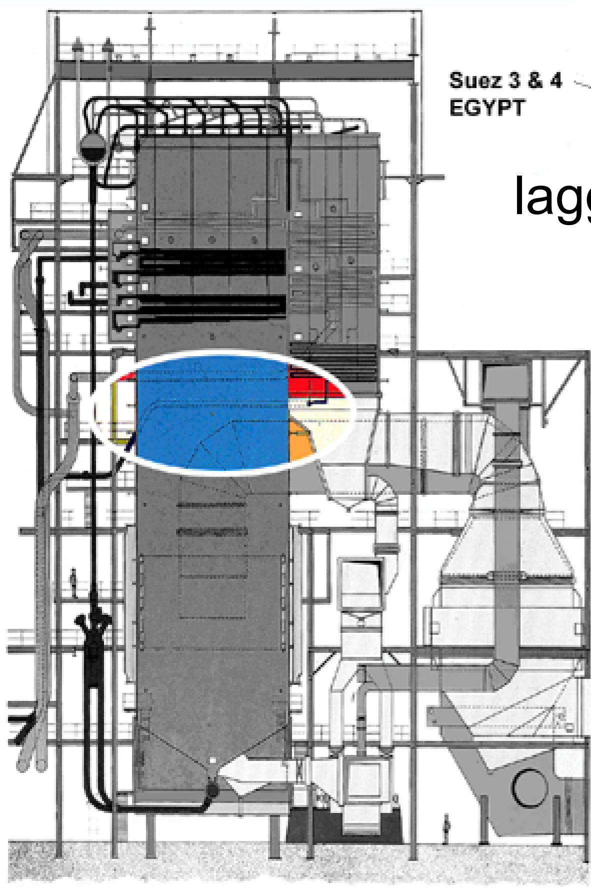


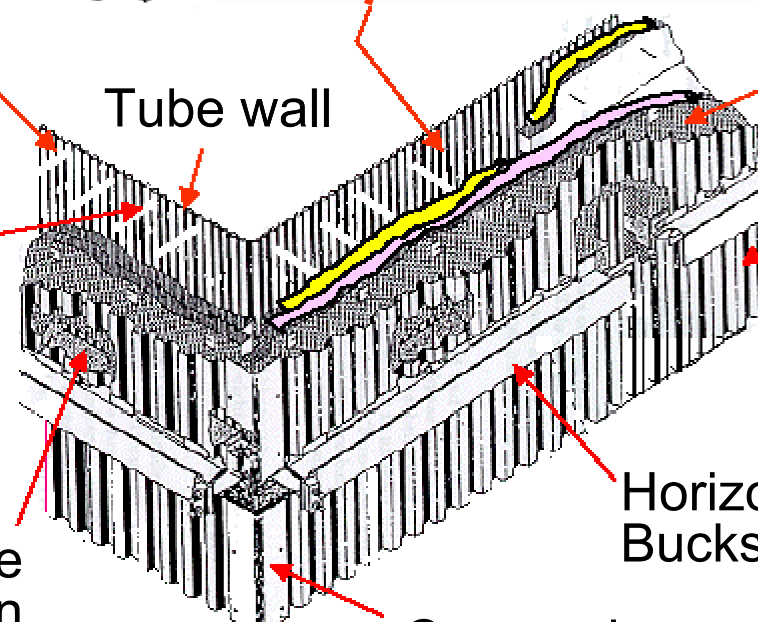
Source : Combustion, Fossil Power J.G. Singer 1991, ch 7 p 21 fig 11

Boiler Construction : furnace









Boiler Construction : Combustion Area

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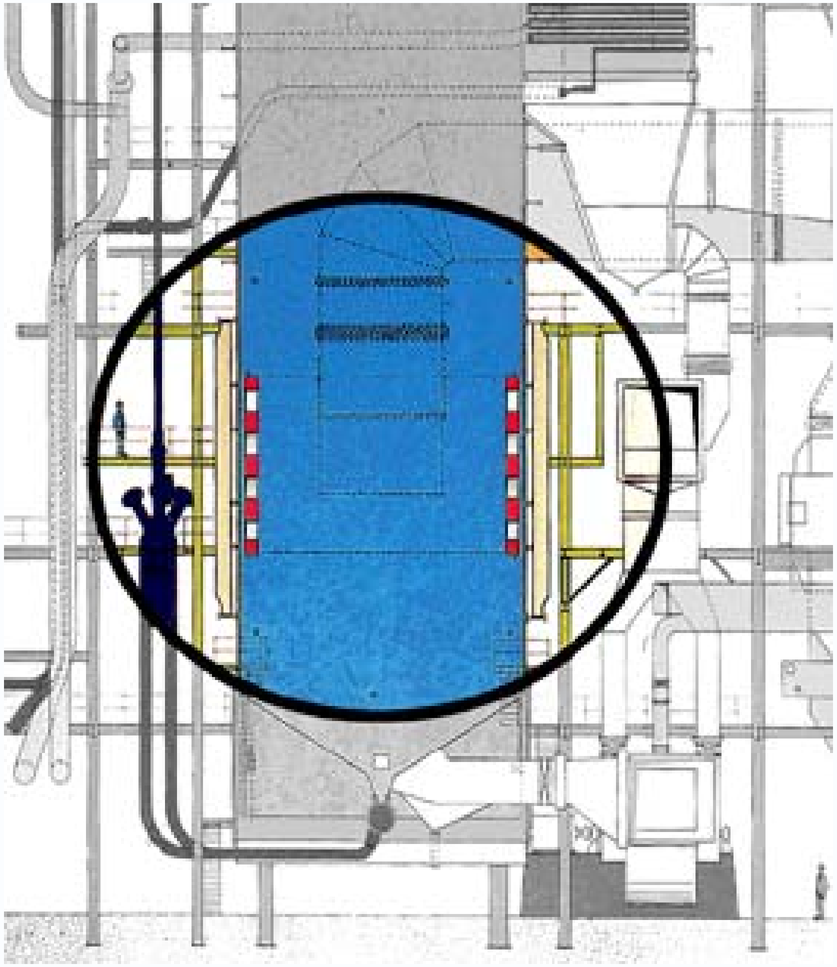
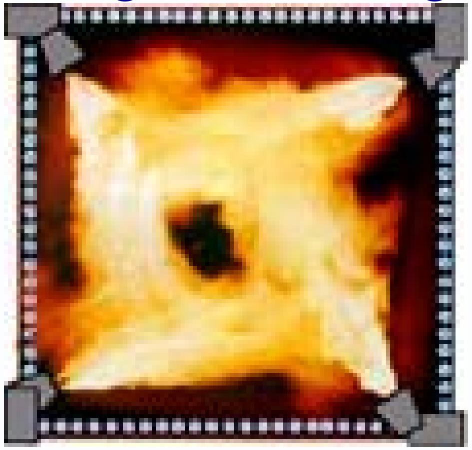
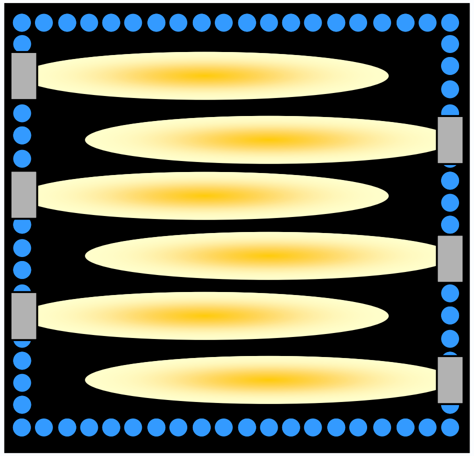


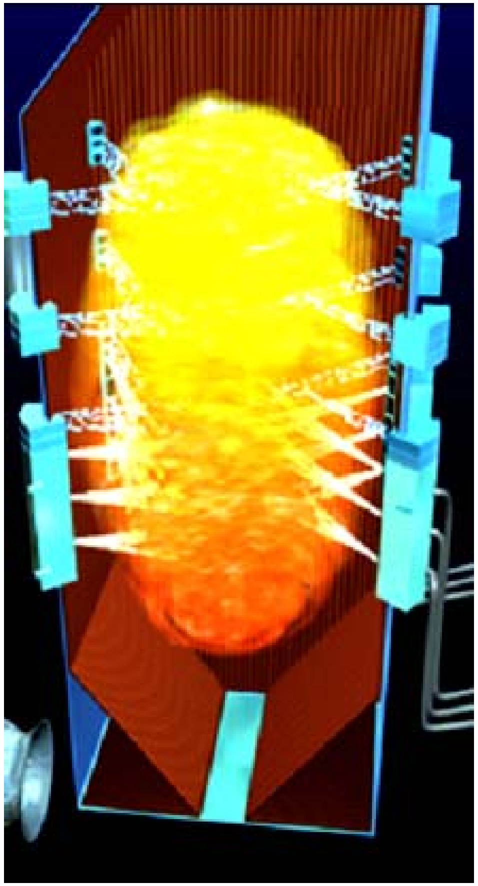
- Two firing types
  - tangential firing

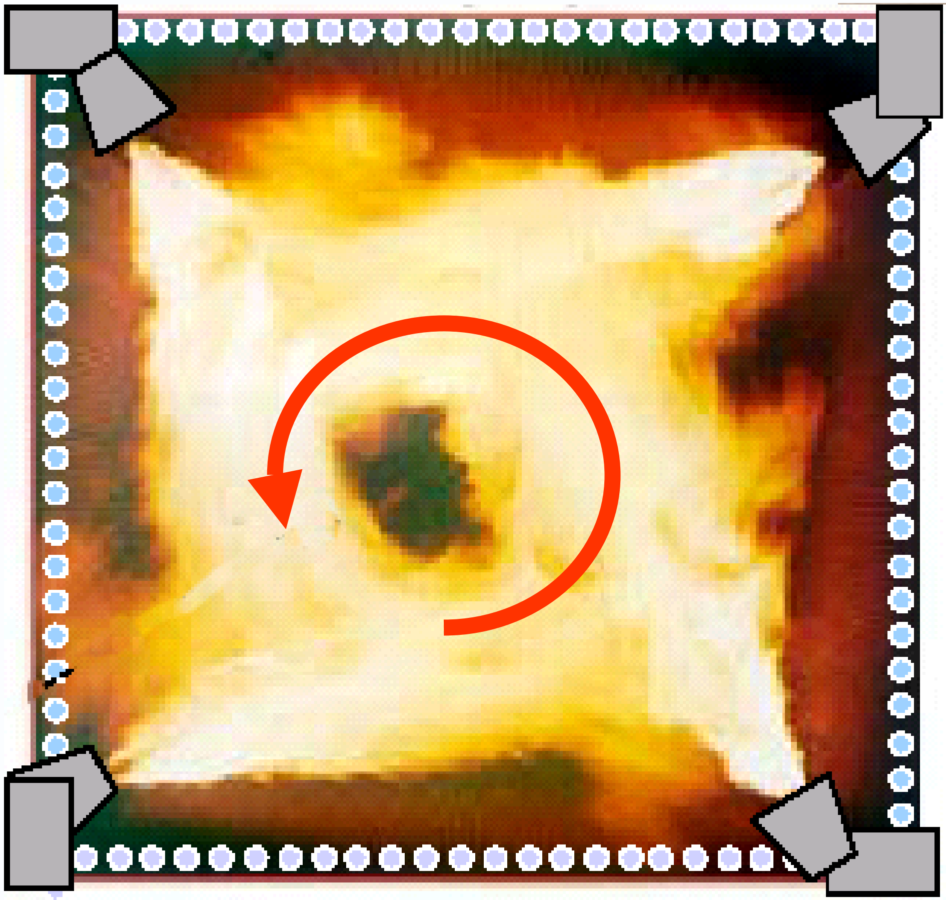


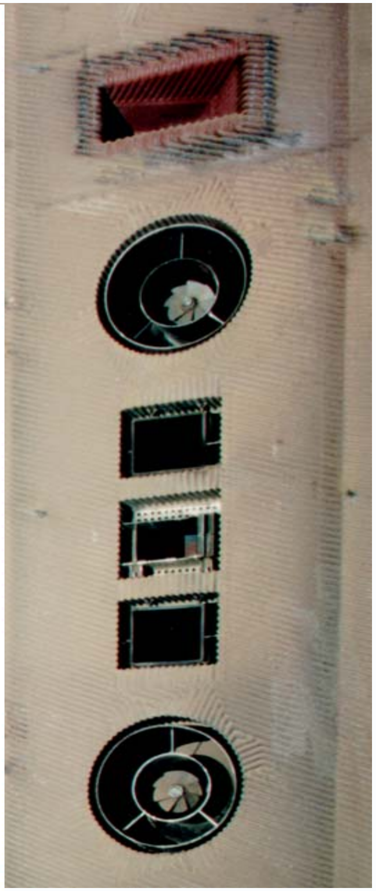
  - Front/wall firing



Tangential firing







Burners are located in the furnace angles
No individual flames but a rotating fireball

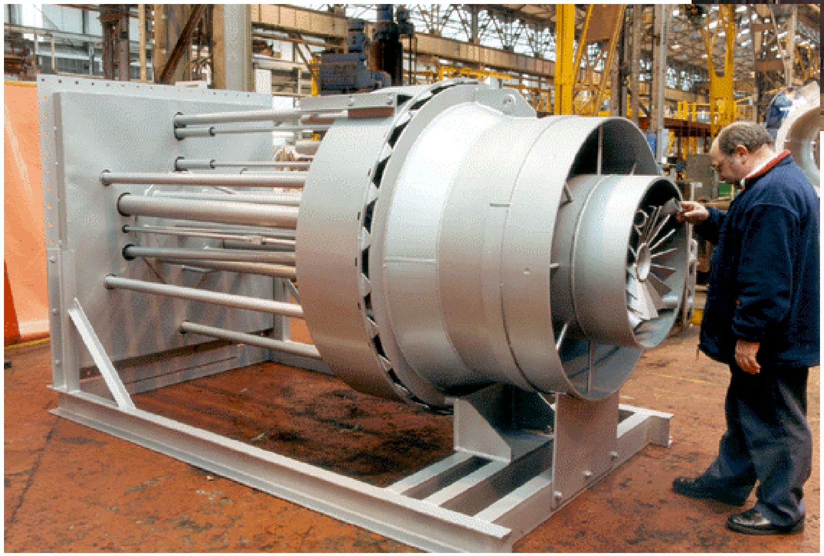
Boiler furnace : T / front firing

ALSTOM

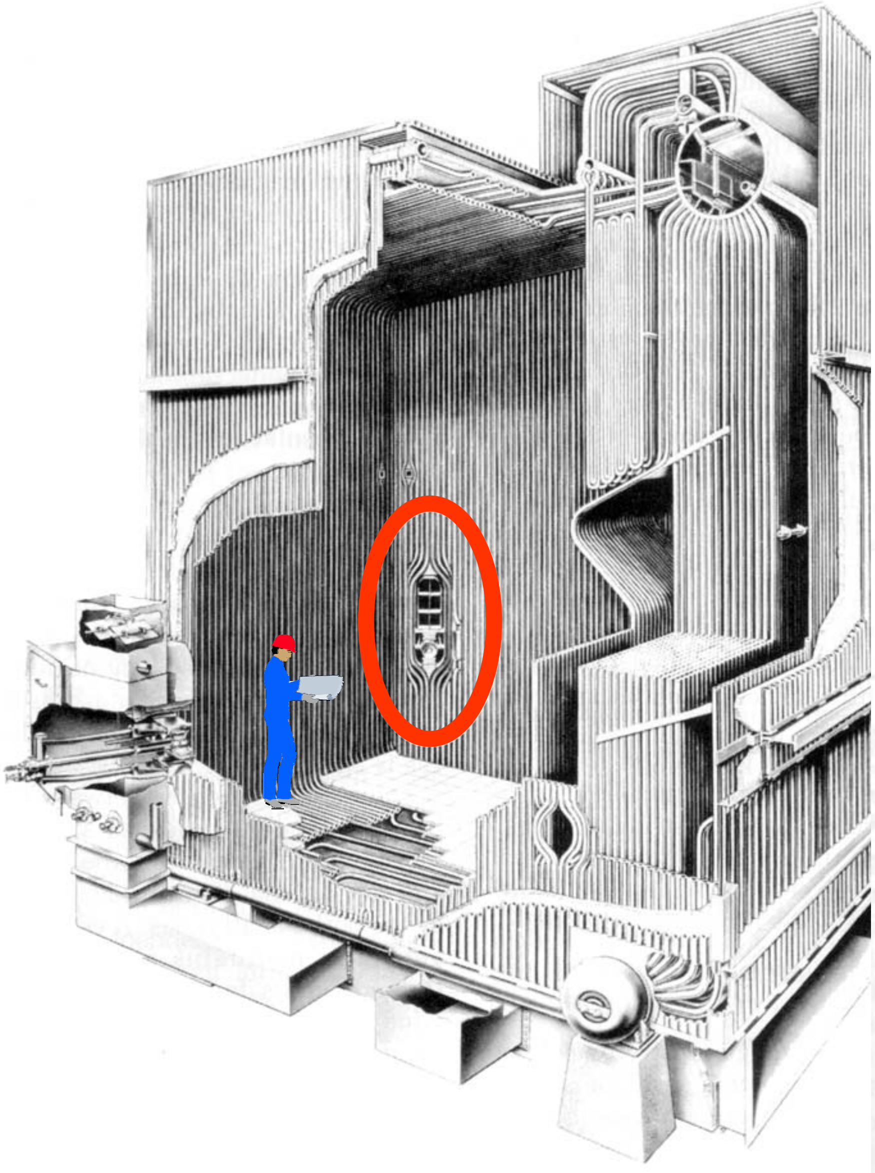
Front firing

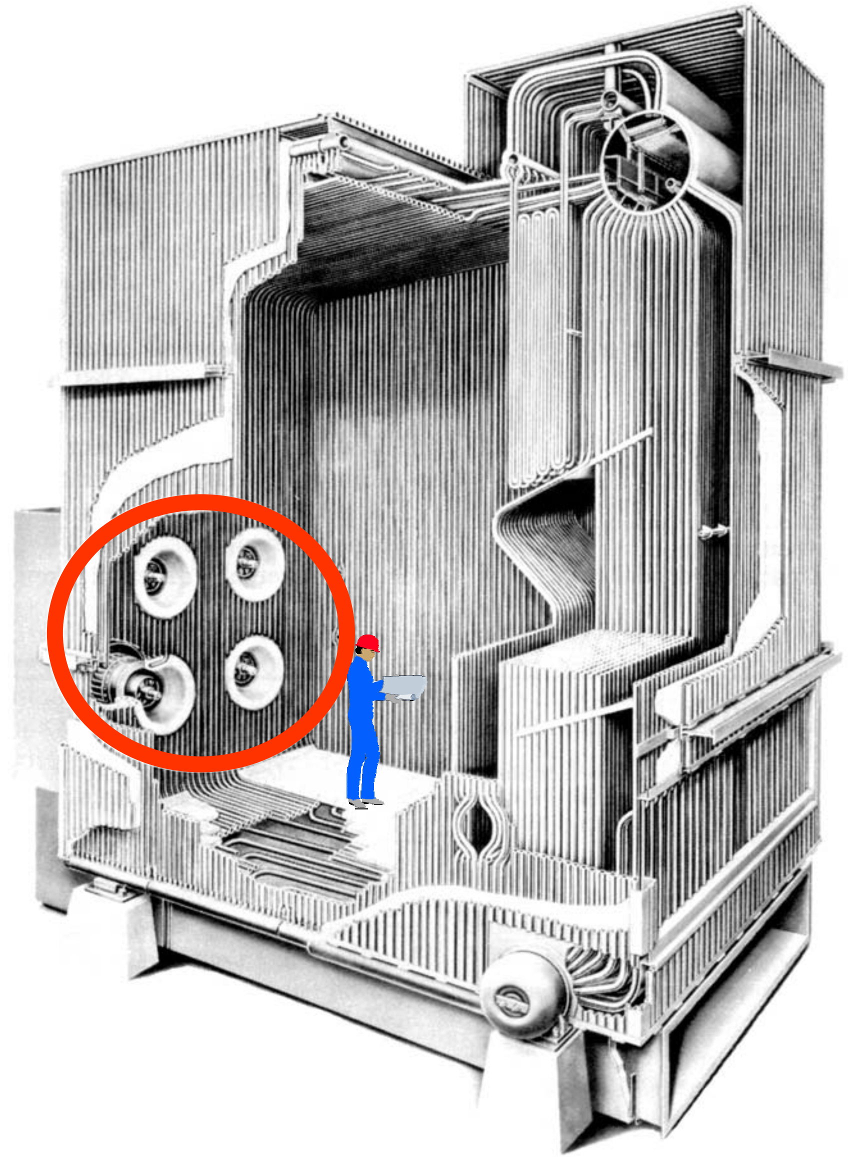
Burners are located on one furnace wall or two facing walls.

Flames stay individual



Tangential and wall fired VU 60 industrial boilers

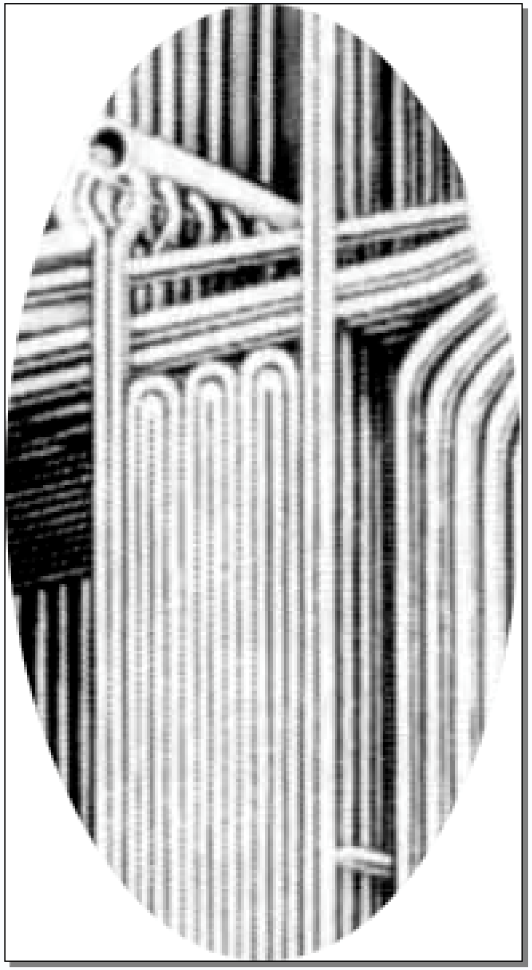




Combustion System Issues

- Incomplete/bad combustion : yellow flame, black smoke
- Lack of combustion air, insufficient excess air
- Flame too long (front firing)
- Flame too close from the wall (T firing)
- Flame instability at low loads
- Poor fuel oil pulverization
- Superheater / reheater burned on gas firing
- Emissions of NOx, SOx and particulates

Boiler Tube issues



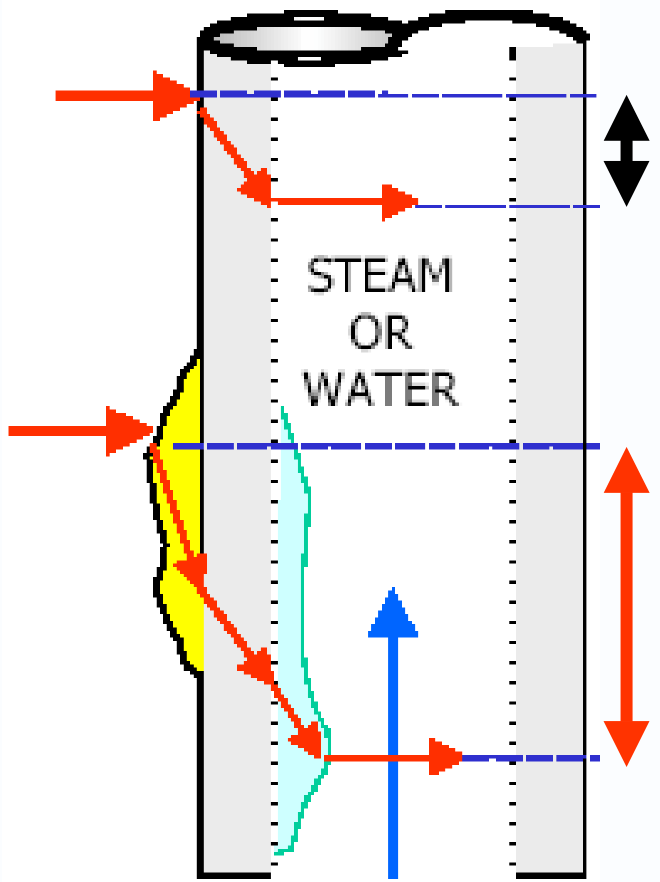
- Tube cleanliness
- Tube corrosion by combustion byproducts
- Tube overheating
- Tube pitting
- Hydrogen-induced tube embrittlement
- Tube ductile gouging

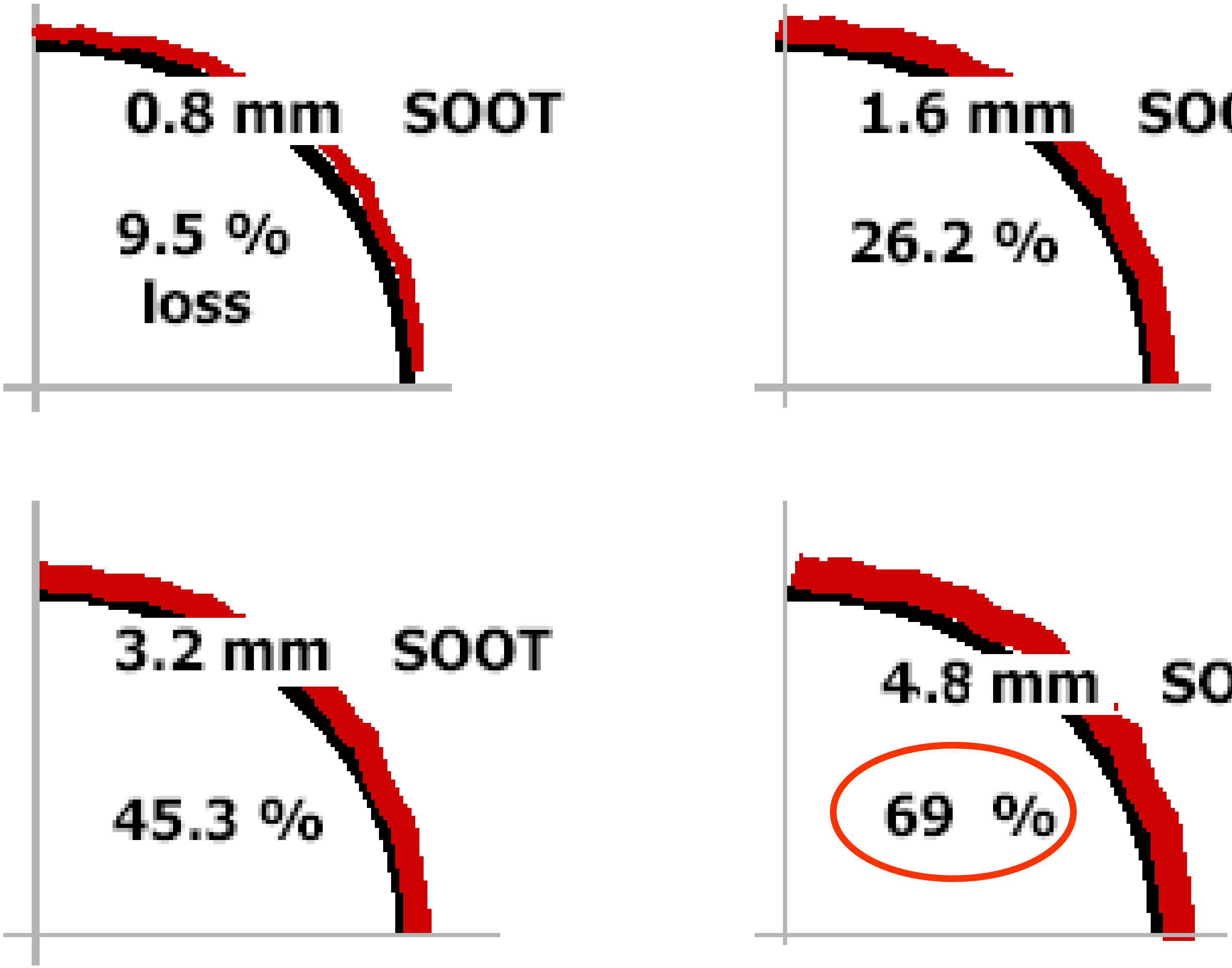
Energy Loss, clean tube

- Loss in the tube wall only

Energy Loss, fouled tube

- Loss in external deposits
- Loss in the tube wall
- Loss in internal deposits




0.8 mm SOOT
9.5 %
loss
1.6 mm SOOT
26.2 %
3.2 mm SOOT
45.3 %
4.8 mm SOOT
69 %

Heat Transfer and Tube Cleanliness

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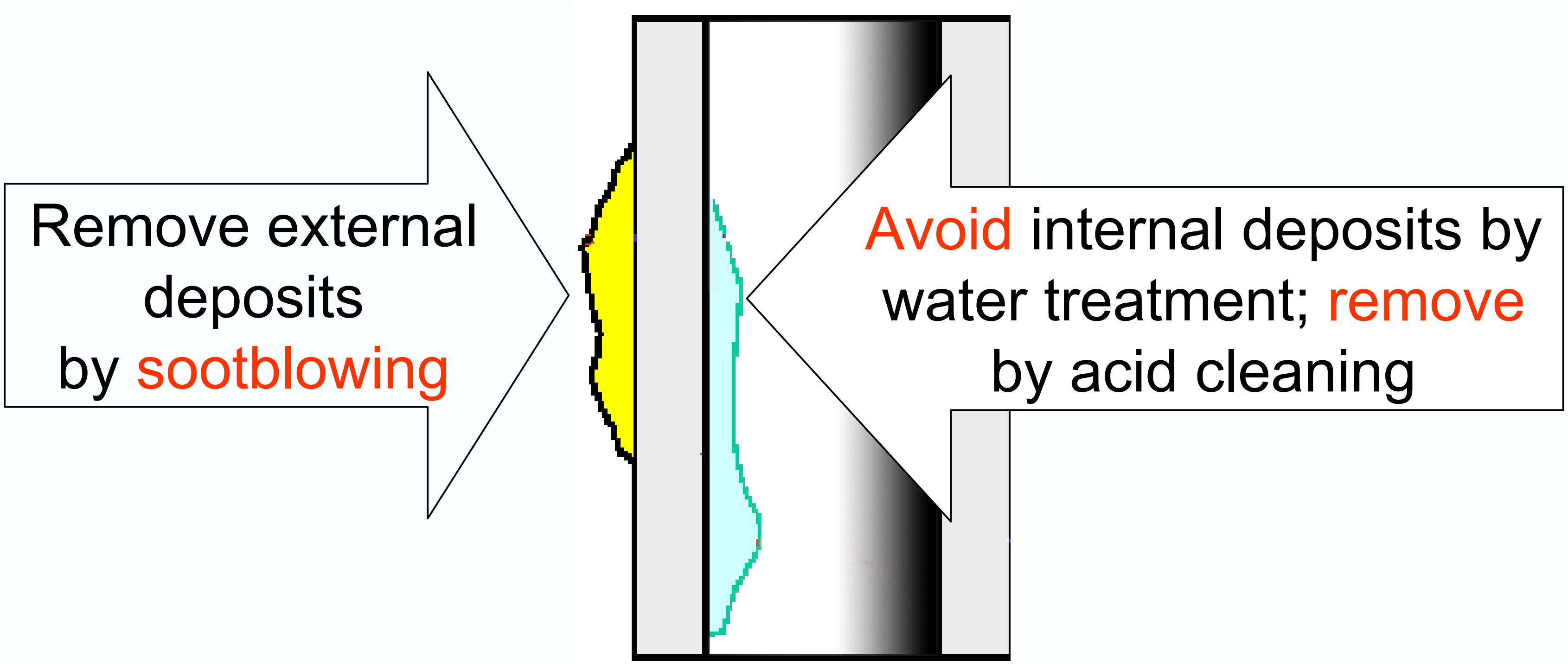
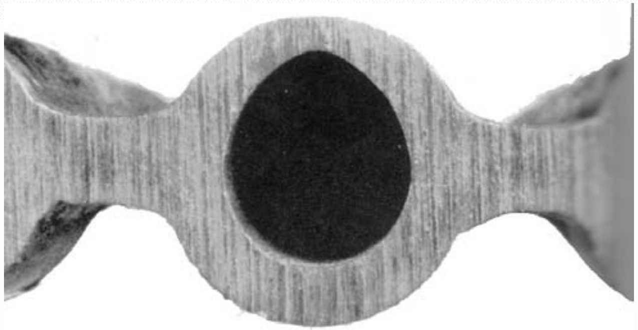


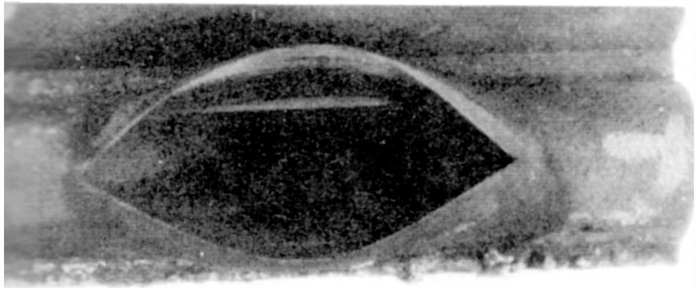
Corrosion of Heat Exchangers by Combustion Byproducts

ALSTOM

- High temperature corrosion in superheaters and reheaters
  - promoted by sodium and vanadium compounds
  - sensitive if metal temp. above 600°C
- Medium temp. Corrosion in evaporators
  - fixed through combustion system adjustment
- Low temp. Corrosion in cold areas
  - promoted by sulfur, which turns into sulfuric acid below dew point : keep temperature above 150°C

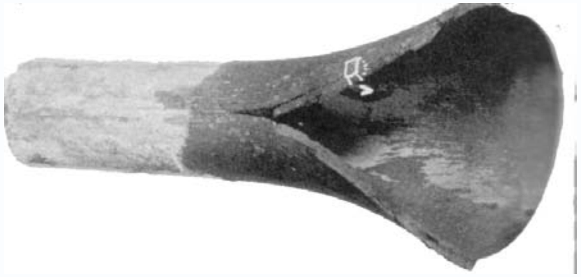


Cross section of a tube exposed to short time overheating
Cause : often DNB excursion



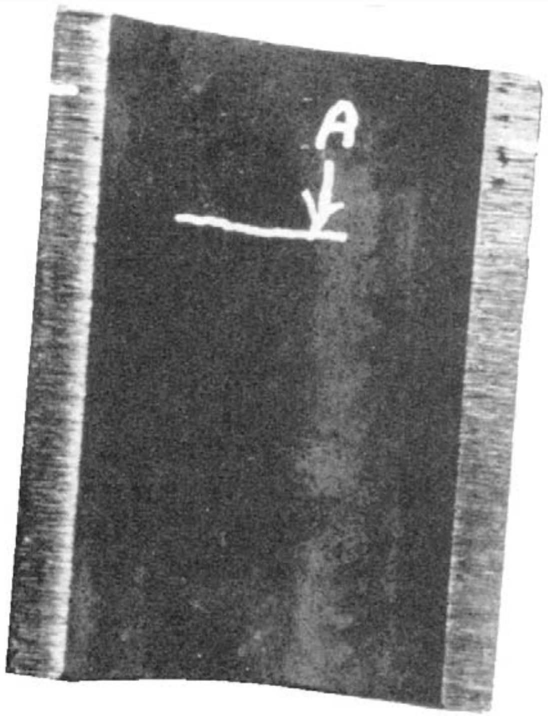
Short time overheating failure

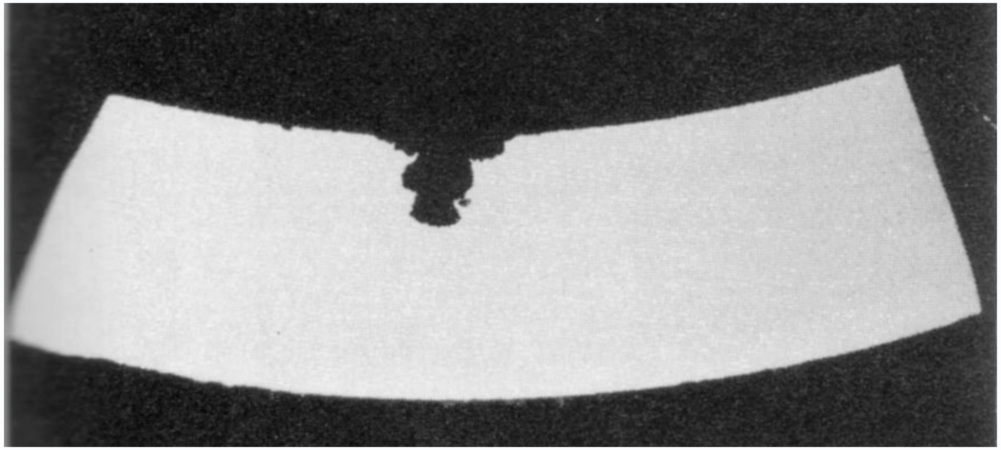
Long time overheating failure



Long time overheating failure

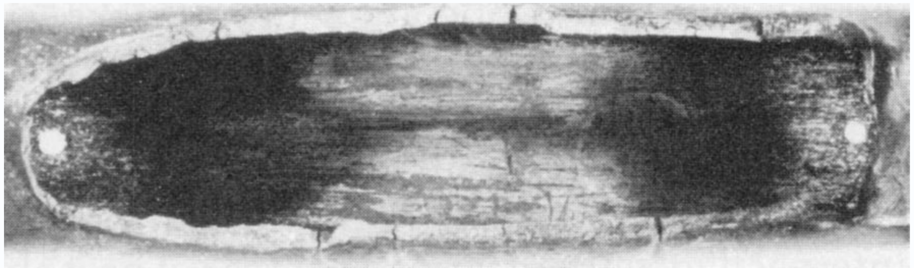
Electromechanical corrosion





Fix : appropriate water chemistry

Tube failures - Others



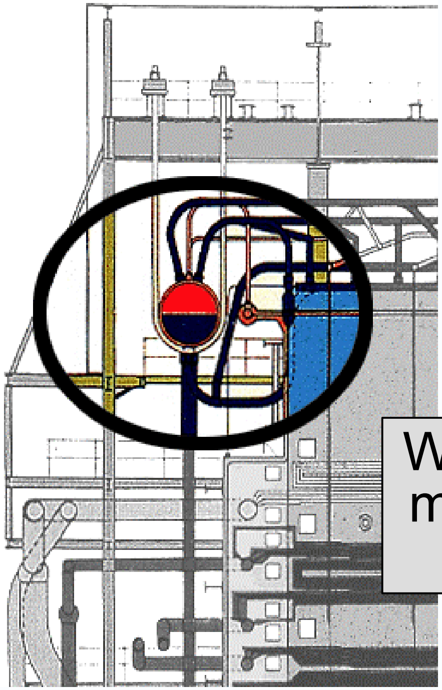
Hydrogen-induced tube burst : occurs beneath a relatively dense deposit

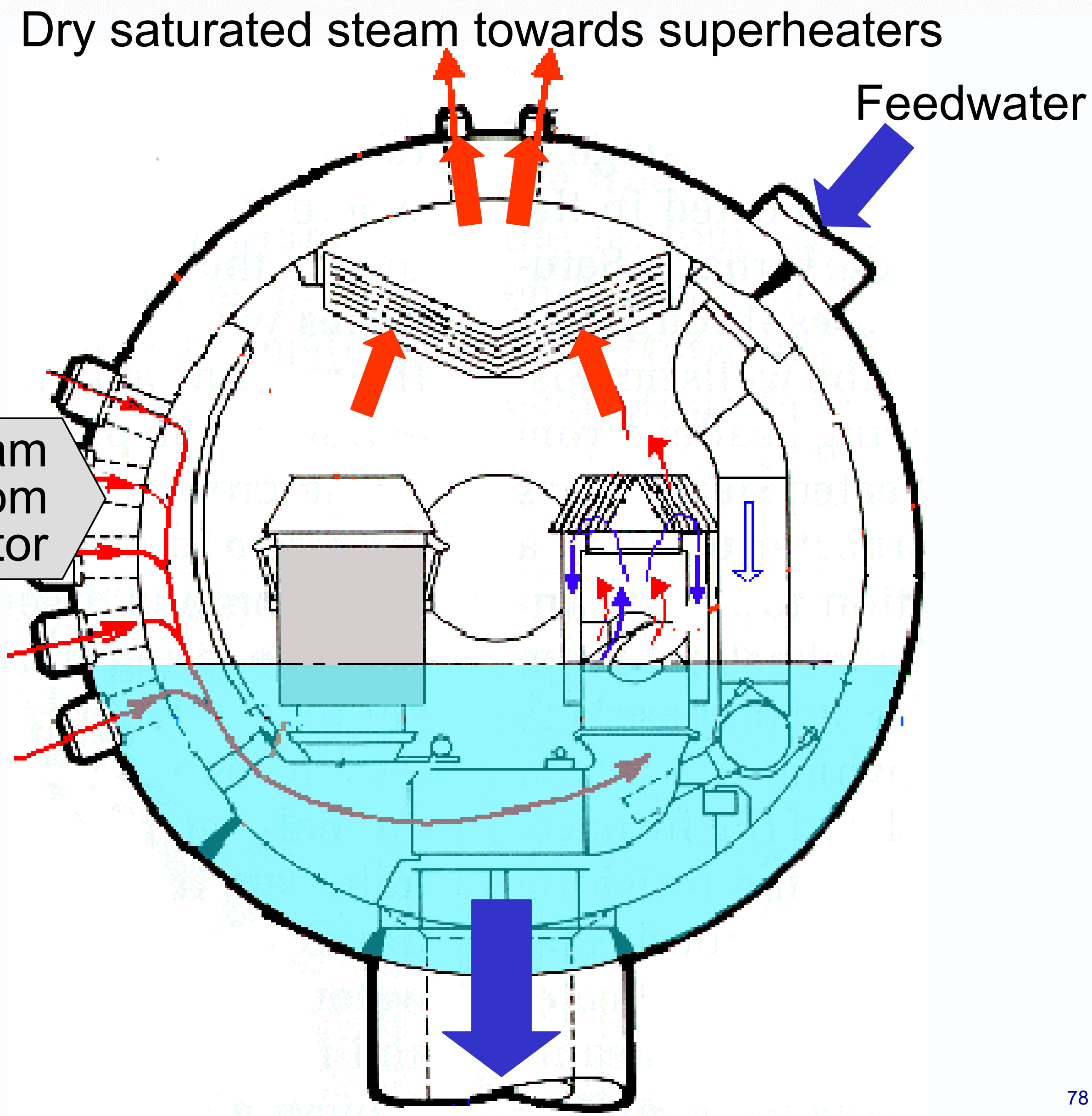
Fix : appropriate water chemistry

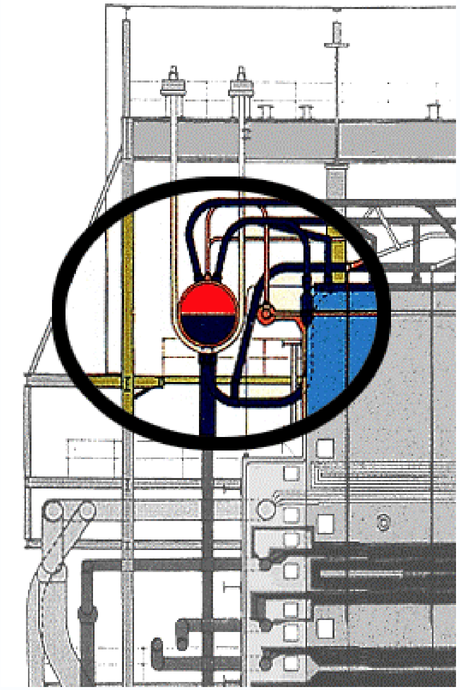
Ductile gouging :
irregular wastage of the tube meteal beneath a porous deposit

Fix : appropriate water chemistry

Boiler Construction : Drum

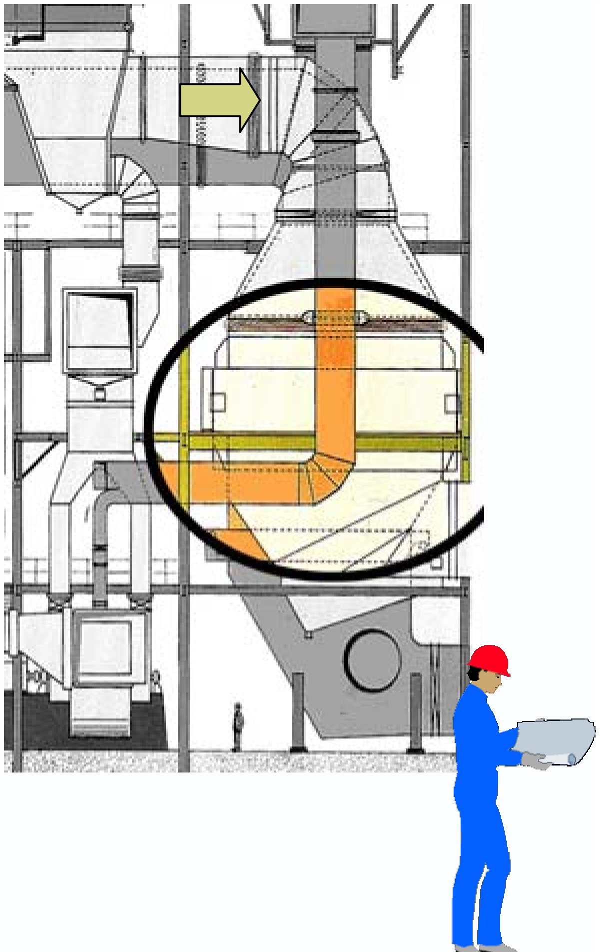


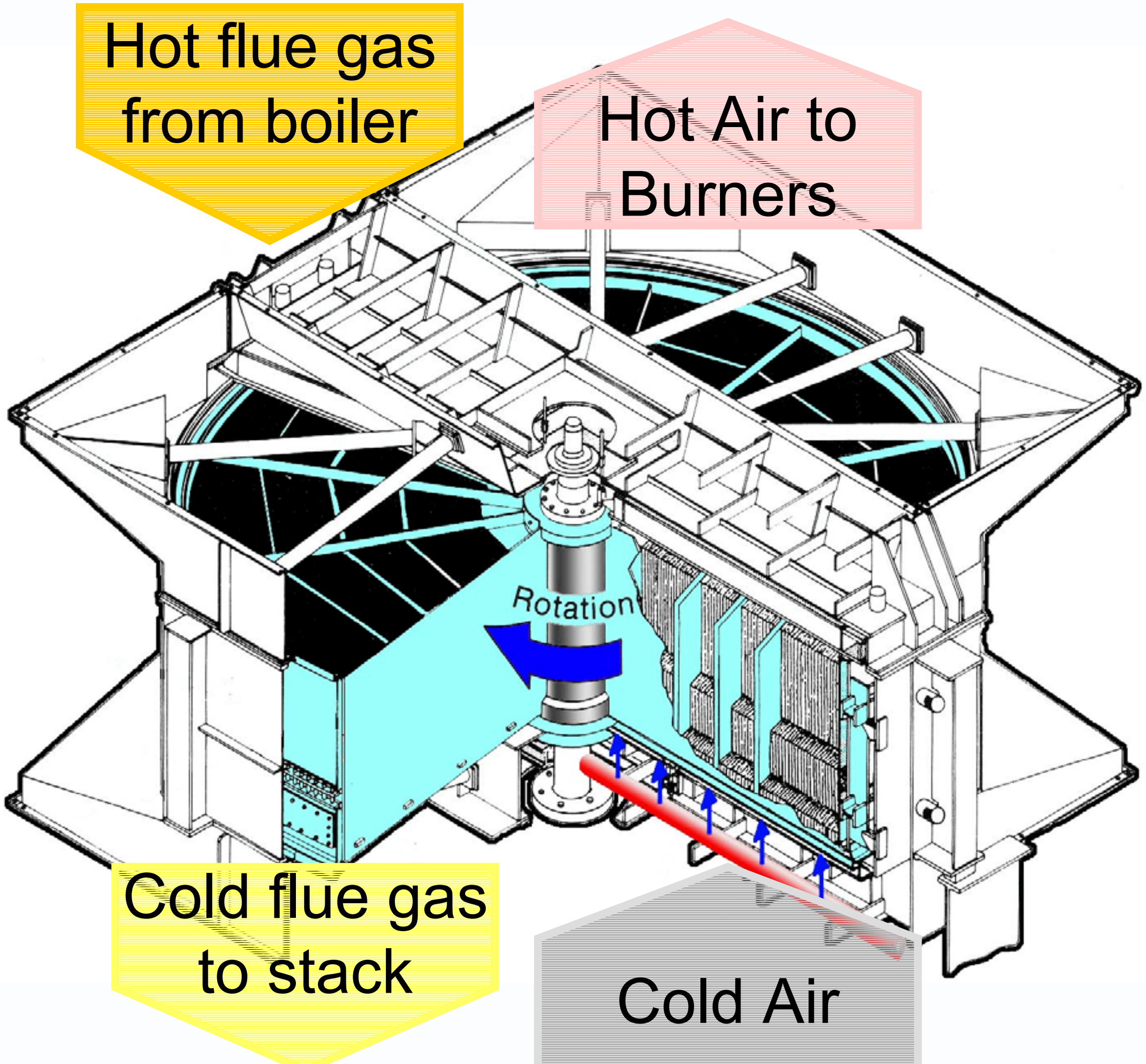




- Loss of level gauges
- water level controllers out of service
- corrosion
- moisture carry-over in the steam
- safety valves leaking
- leaks of roll-expanded evaporator tubes
- plugging of evaporator tubes

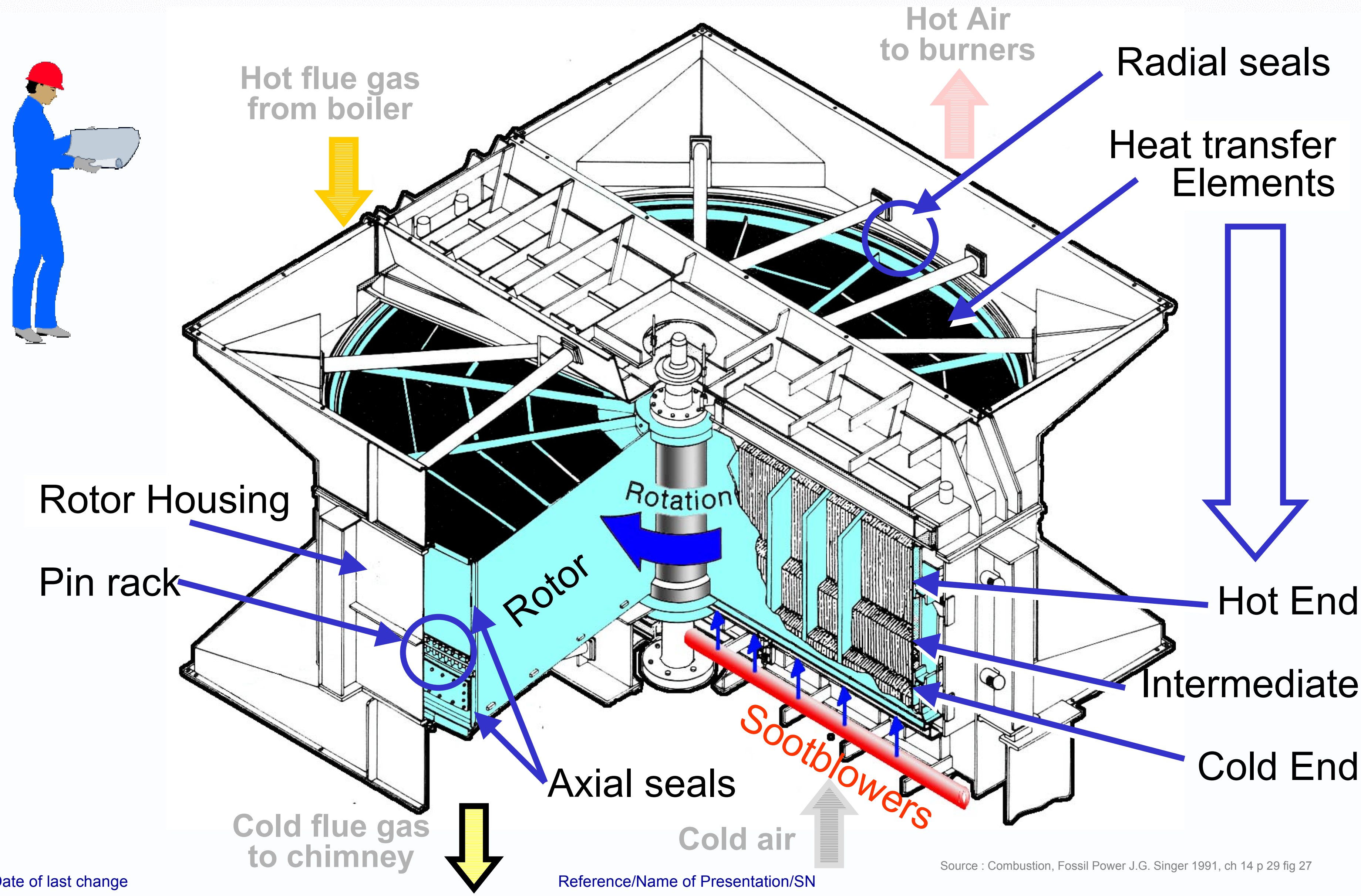
Boiler Auxiliary : Ljungstrom® Regenerative Air Heater





Ljungstrom® Regenerative Air Heater, Glossary

ALSTOM



Source : Combustion, Fossil Power J.G. Singer 1991, ch 14 p 29 fig 27

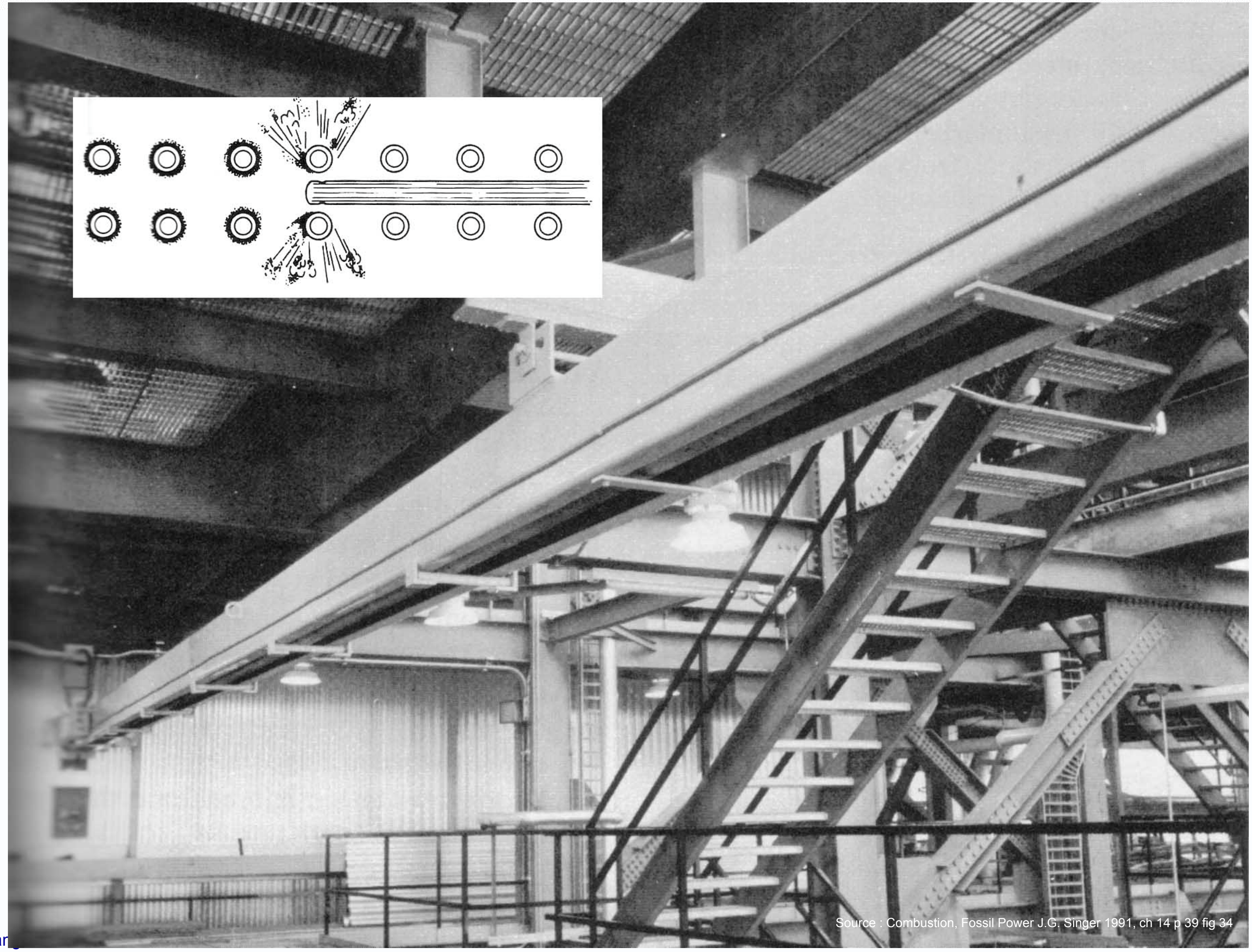
Ljungstrom® Regenerative Air Heater Issues

ALSTOM

- Leakages due to damaged axial or circumferential seals
- Cold end baskets damaged by acid corrosion,
- Poor sootblowing, triggering fires
- Standby pneumatic or DC motor not working or absent
- Broken / missing pins on the pin rack

- Heavy impact on boiler efficiency -

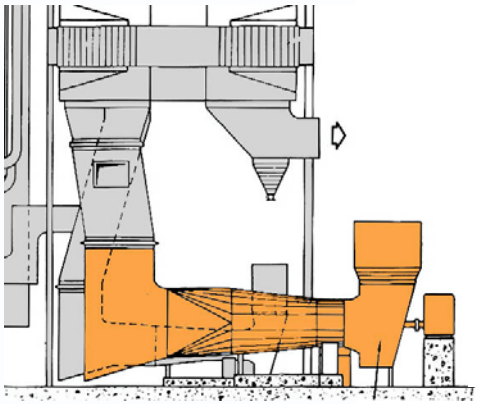
Boiler auxiliary : Sootblowers

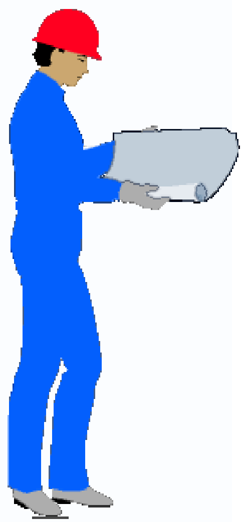


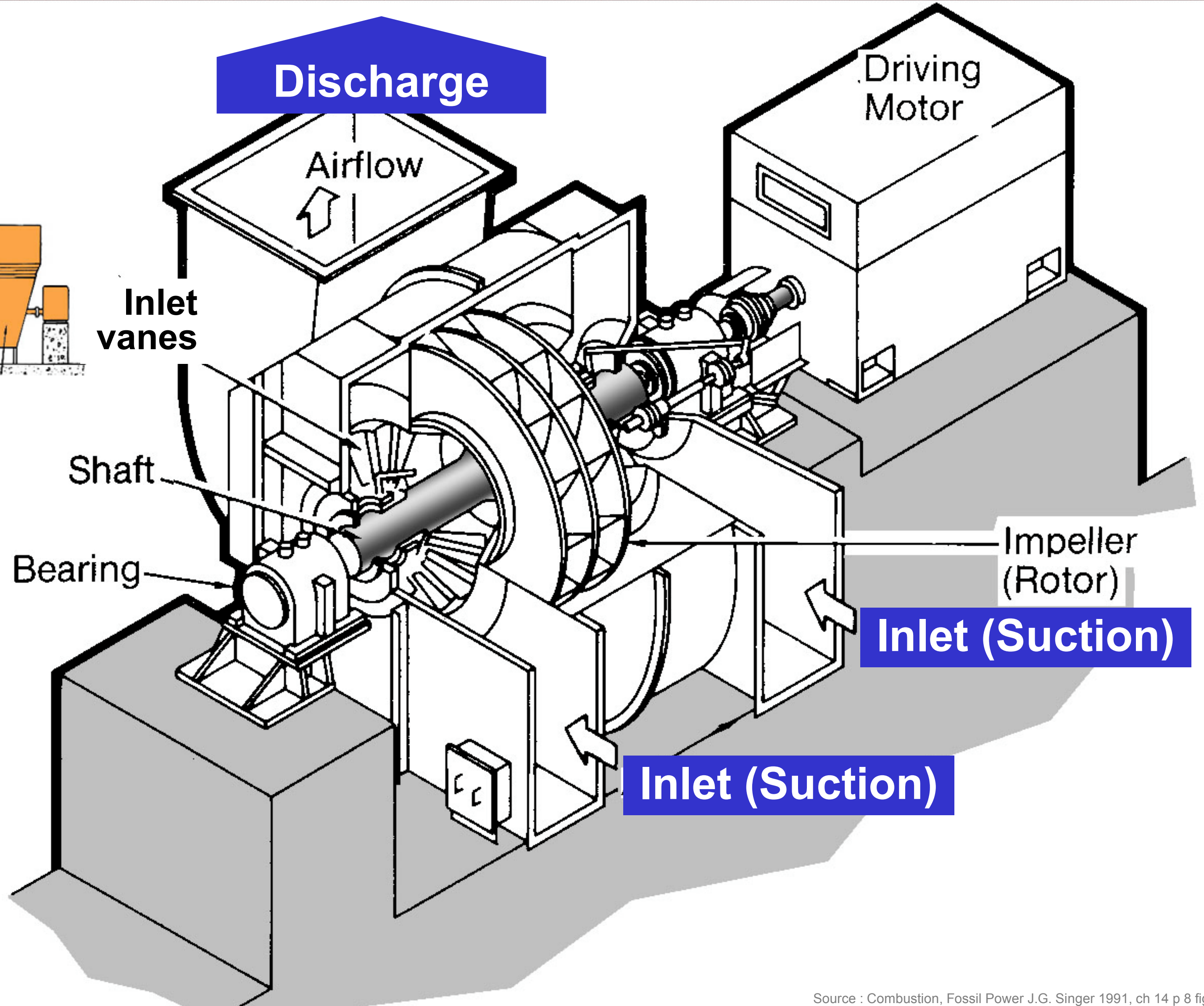
Sootblowers Issues

- Locked, unable to travel in the furnace
- Auxiliary steam not available
- Insufficient number of sootblowers
- Wear and tear of the steam nozzles
- etc.

Boiler Auxiliary : fans

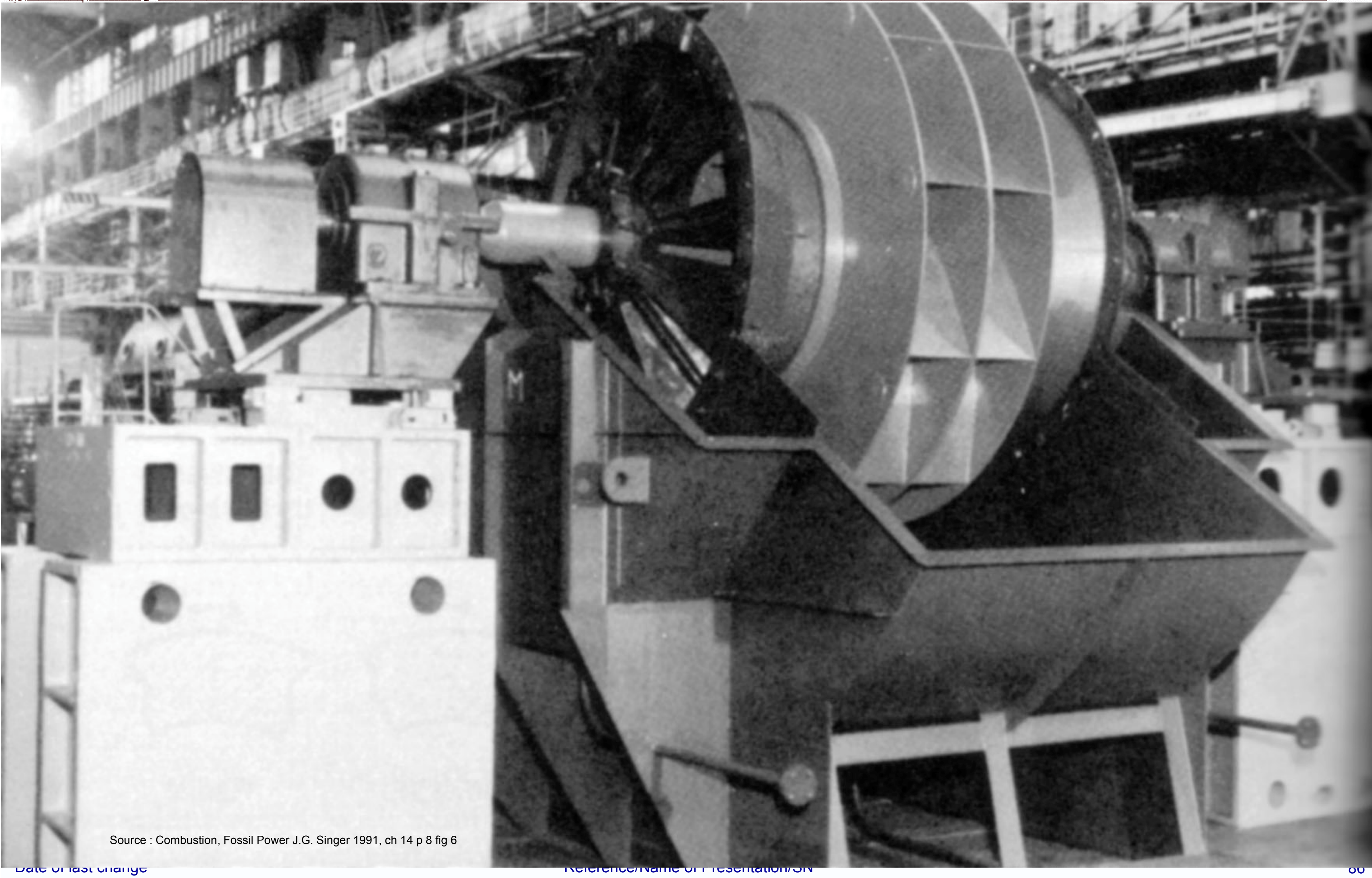






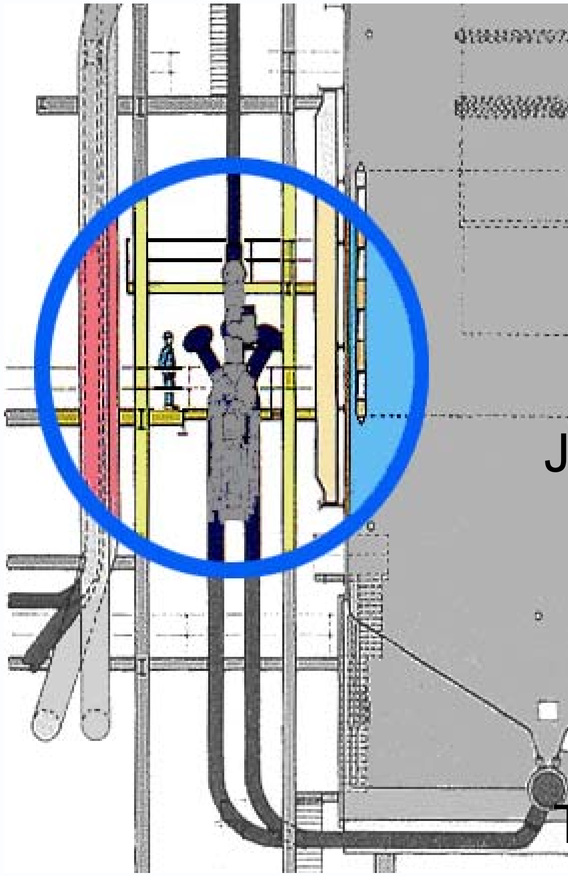
Source : Combustion, Fossil Power J.G. Singer 1991, ch 14 p 8 fig 5

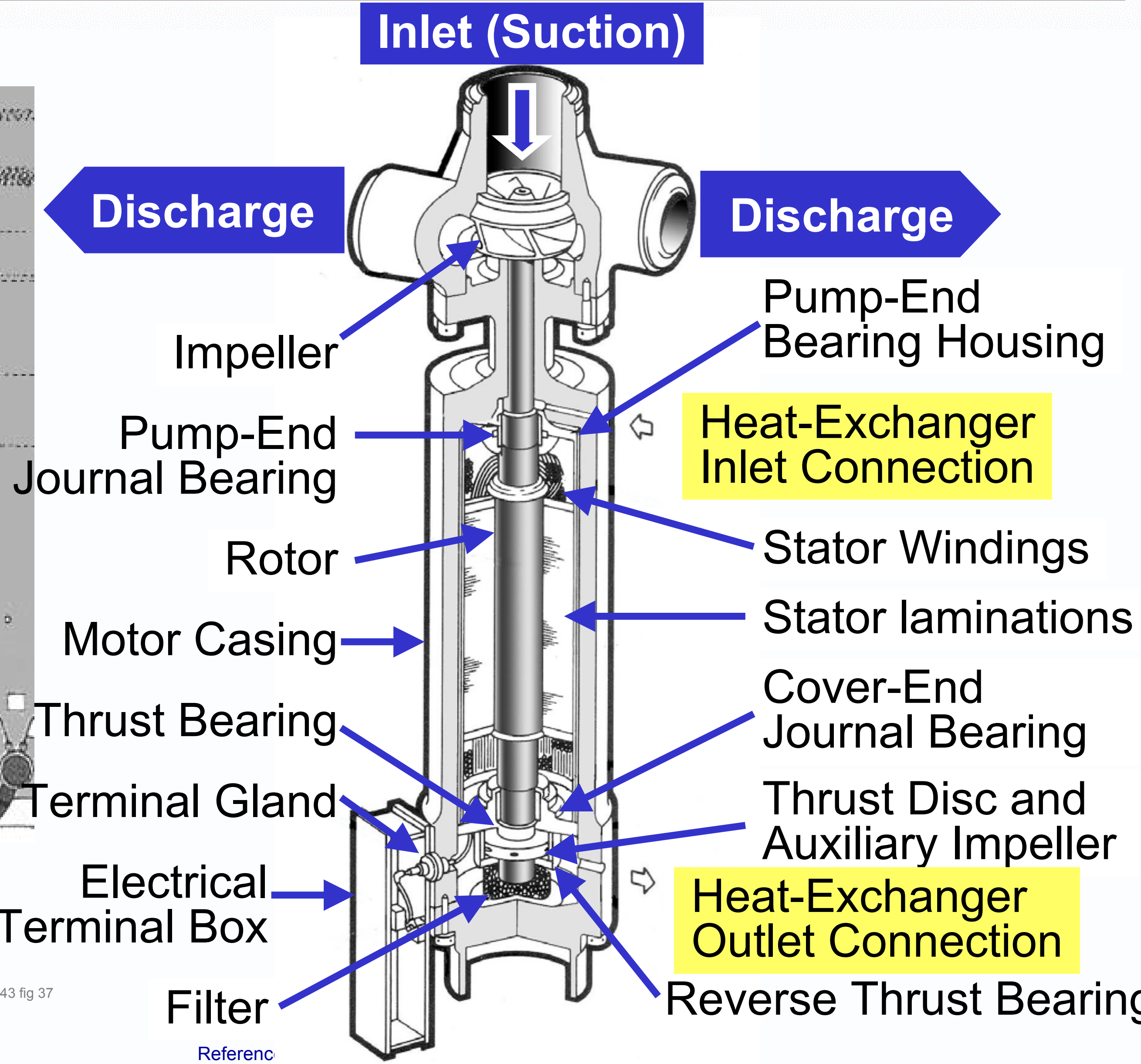
Boiler Auxiliary : fans



Source : Combustion, Fossil Power J.G. Singer 1991, ch 14 p 8 fig 6

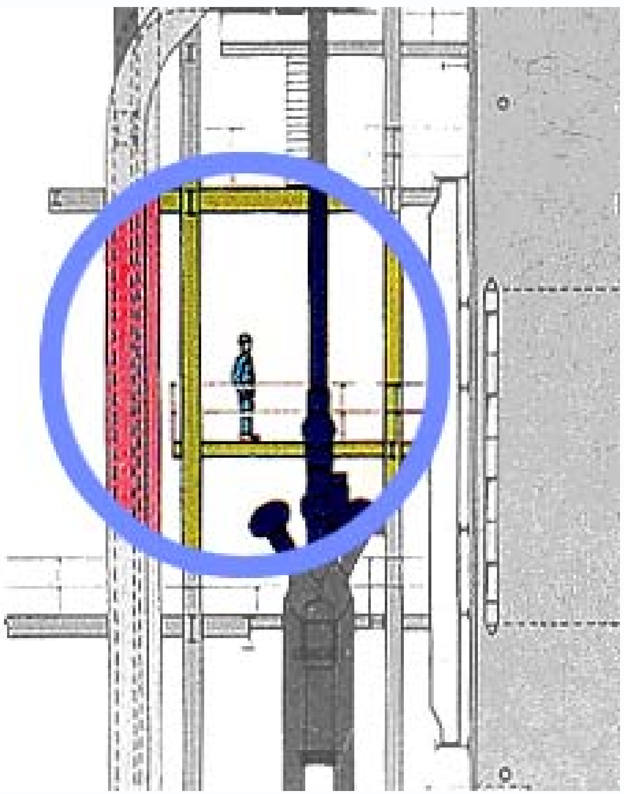
Boiler Auxiliary : Circulation Pump





Source : Combustion, Fossil Power J.G. Singer 1991, ch 14 p 43 fig 37

Boiler Operation Improvement : Training



Source : Combustion, Fossil Power
J.G. Singer 1991, ch 21 p 32

- Protection against pressure surges
  - safety relief valves on drum, reheaters and superheaters
- Lack of water in the drum
  - automatic trip if level comes too low to avoid operation of boiler without water
- Protection against explosions in furnaces
  - boilers on-off safeties : burner management system
  - flame scanners
- Environmental issues

Power Generation Glossary

ALSTOM

- **Capacity Factor**
  - energy generated by the unit during the reference period divided by the energy that could have been generated had the unit run at its full rating over the entire period
- **Net Plant Heat Rate [NPHR]**
  - the fuel-heat input required to generate one KWhr of energy delivered to the grid
- **Auxiliary Power Charges**
  - in-house power requirement of the installation (pumps, fans, motors, etc.)

Power Generation Glossary (+)

- **Gross Plant Heat Rate**
  - net plant heat rate plus the fuel-heat input needed to cover the auxiliary power charges
- **Replacement Power Cost**
  - the cost of purchasing the replacement energy if the concerned installation is not operating, due to a scheduled or forced outage
- **Black Start Capability**
  - in-house auxiliary generating station (diesel, generally) to cover the auxiliary power charges necessary to start the plant

Boiler Design Basics Introduced !

Thank you for your attention

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