Master of Science in *Energy Engineering*
Renewables for Environmental Sustainability

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School of Industrial and Information Engineering
Academic Year 2017-18

Lecture notes for:
Bioenergy and Waste-to-Energy Technologies

Production of electricity and heat: Direct Combustion Systems

Prof. Federico Viganò – Department of Energy

Lecture outline

- *Direct combustion of biomass – a historical view*
- *Disposal of waste – a historical view*
- *Direct combustion of waste – the historical perspective*
- *The waste fuel – the modern perspective*
- *The energy potential of waste*
- *Technologies*
- *Grate combustors*
- *Fluidized bed combustors*
- *Boilers*

Direct combustion of biomass
A historical view

- The discovery of fire (controlled fire) dates back to 790,000 years ago. It corresponds to the beginning of the energy use of biomass through direct combustion.
- The direct combustion of biomass has been for thousands of years the only artificial energy source for heating and cooking used by the humanity. This situation still happens in significant parts of underdeveloped and developing countries.
- The first direct combustion systems were simply bonfires – a technology that requires quite dry biomass to work.
- Sequential technologic improvements have led to more confined systems (fireplaces, stoves, furnaces, combustors), however the progress has been very slow and, still now, some direct combustions of biomass are carried out in very low technologic devices, even in advanced countries.
- During the industrial revolution (end of 1700, beginning of 1800) almost all the few large devices for the direct combustion of biomass (mainly for heating purposes) have been replaced by coal-fired devices.

India – traditional biomass for cooking & heating

Bonfires
A historical view

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The heat released by the combustion of quite dry biomass is so relevant that can easily generate a consistent convective regime. In this way, the flue gas are removed and the fresh air containing the oxygen needed to sustain the combustion is draught.

In good bonfires, the burning rate is usually determined (limited) by gas diffusion in the very near surroundings of the solid material (heterogeneous combustion), while the pressure drop of air-flue gas through the piles is usually largely compensated by the head generated by the density difference between the hot flue gas and the fresh air.

As a result, the available oxidant is always abundant with respect to the requirement, thus the combustion is characterized by a large excess of oxidant. This implies combustion temperature much lower than those achievable with lower oxidant excesses.

Fireplaces (1 of 2)
A historical view

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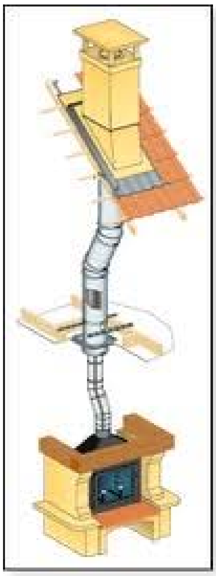
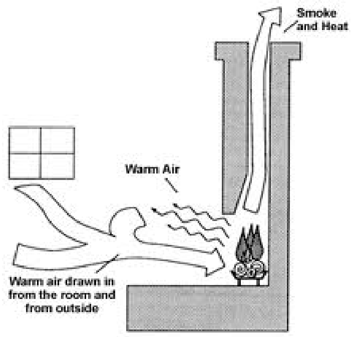


The only significant difference with respect to bonfires relies on the presence of a more or less tall stack.

The stack (when full of hot flue gas) generates a significant head that can drag the needed air also when the combustion temperature is not particularly high. For this reason, theoretically, fireplaces could be fed also with biomass of lower quality (= lower energy content typically due to higher moisture) than that required for a good bonfire.

Moreover, modern fireplaces are usually equipped with systems aimed at separating the fine ash produced during combustion from the fire zone, avoiding the creation of a bed of ash that could prevent the penetration of fresh air leading to incomplete combustion.

Fireplaces (2 of 2)
A historical view



Open Fireplace Operation

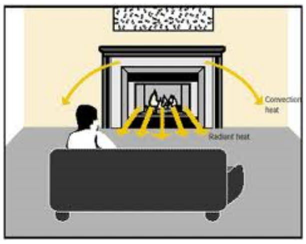
However, traditional fireplaces are quite inefficient ways of heating an ambient: the great head generated by the stack, although allowing a very stable and quick combustion, usually drags much more air than that strictly required, in certain cases, even more that the one that would be draught by a bonfire.

Thus, low temperatures are achieved and most of the heat release is lost through the stack.

Moreover, in traditional fireplaces such a great amount of air is draught from the ambient that is supposed to be heated up, putting it in depression with respect to the outside. This situation typically drags cold air from the outside to the inside, wasting a significant part of the heating effect.

To avoid this wasting, modern fireplaces have appropriate intake manifolds that bring the combustion air from the outside directly underneath the fire zone, but still some air is taken from the heated ambient.

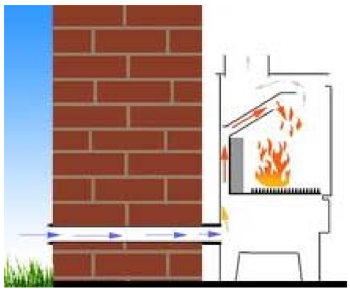
Stoves
A historical view



Traditional stoves differ from traditional fireplaces only in the way the released heat is transferred to the ambient.

While in fireplaces most of the heat transferred to the ambient follows the radiant way, in stoves it follows the convective way. (Felt temperature is somehow an average value between actual air temperature and the temperature of the surfaces that delimit the occupied ambient).

While traditional stoves present an only partially delimited fire zone, modern stoves are based on a sealed combustion chamber. These modern devices allow regulating the uptake of air, achieving very high combustion temperature and limiting consistently the stack loss.



Industrial direct combustion of biomass
A historical view

Industrial direct combustion of biomass began only in the second half of 20th century.

Industrial technology has been derived from combustion technologies for waste …

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Disposal of waste
A historical view

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Waste disposal in Middle-Age Europe

(Source: J. Vehlow, Institute for Technical Chemistry, Karlsruhe, Germany)

Disposal of waste
A historical view

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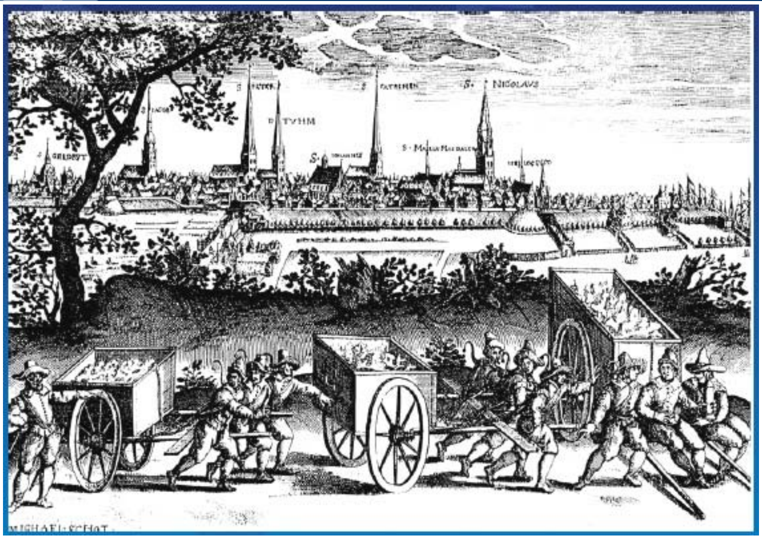

Prisoners collect the wastes of the city of Hamburg (Germany, 1609)

(Source: J. Vehlow, Institute for Technical Chemistry, Karlsruhe, Germany)

Disposal of waste: the open dump
A historical view

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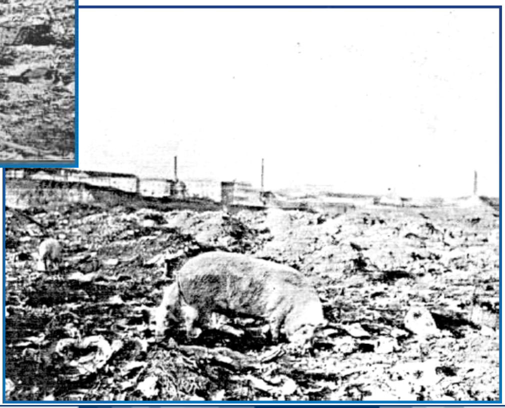

Landfill (open dump) (Wien, 1910)

(Source: J. Vehlow, Institute for Technical Chemistry, Karlsruhe, Germany)

Disposal of waste: first incineration plants
A historical view

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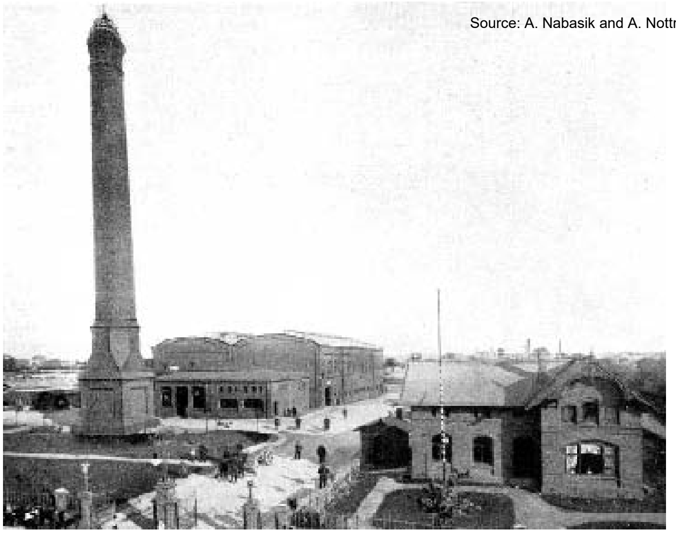
Source: A. Nabasik and A. Nottrodt

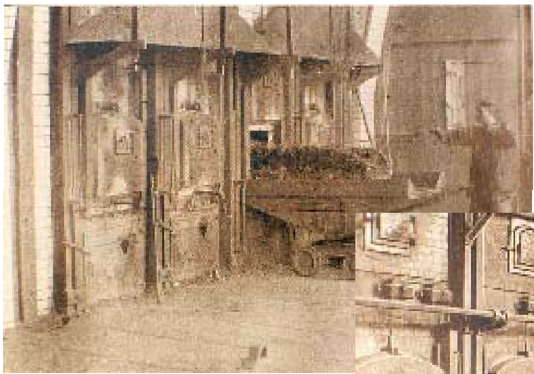


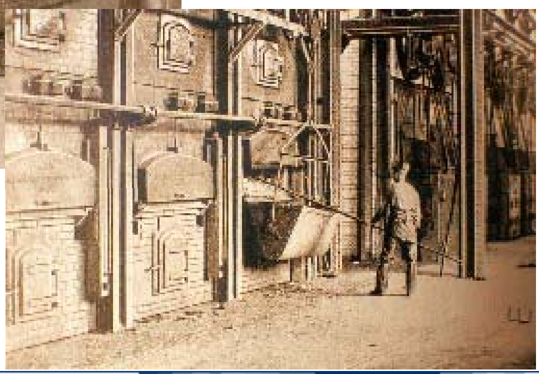
1896 – Hamburg (D) – Incineration plant

Disposal of waste: first incineration plants
A historical view

Source: E. Fleck, Martin GmbH, Recent developments in WtE grate combustion: Technology and Implementation. WTERT 2006 meeting, Columbia University, New York City, NY, October 19-20, 2006.

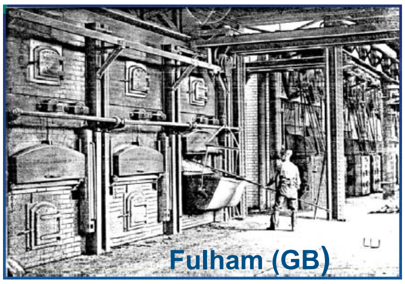
Disposal of waste: first incineration plants
A historical view





Source: E. Fleck, Martin GmbH, Recent developments in WtE grate combustion: Technology and Implementation. WTERT 2006 meeting, Columbia University, New York City, NY, October 19-20, 2006.

Incineration plants of the year 1910 circa
(Source: J. Vehlow, Institute for Technical Chemistry, Karlsruhe, Germany)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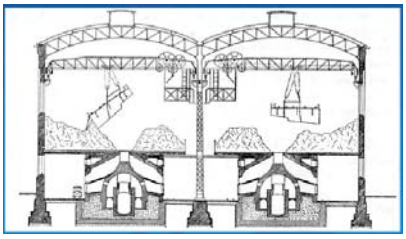
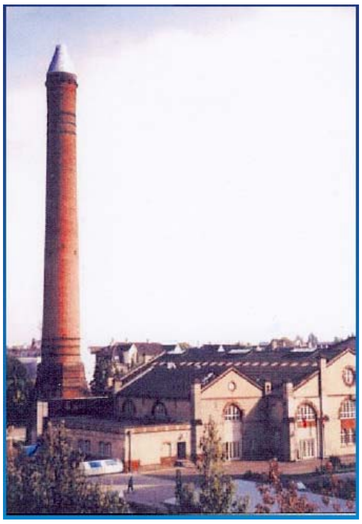

Hamburg (D)

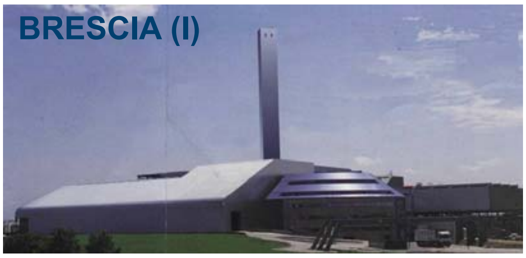

Frederiksberg (DK)

Disposal of waste: waste incinerators of ’60s
A historical view

Disposal of waste: modern incinerators
A historical view

PARIS (F)

WIEN (O)



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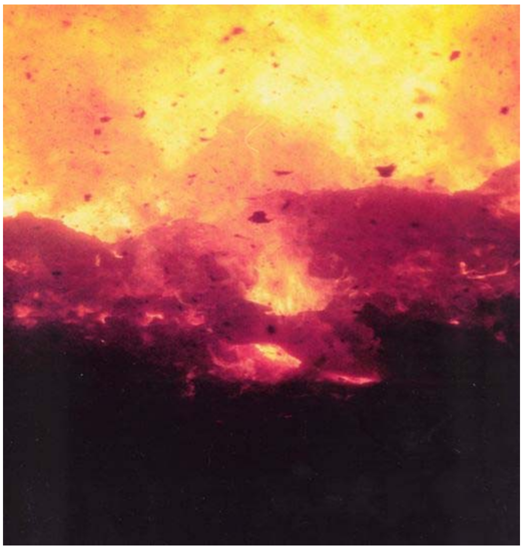
Direct combustion of waste: the historical perspective (1 of 2)

The **incineration** or thermal destruction warrants:

1. Hygienization.
2. Consistent volume reduction (about 90%).
3. Consistent mass reduction (about 80%).

These three reasons, mainly no. 1, have historically push the introduction of thermal destruction for waste.



Direct combustion of waste: the historical perspective (2 of 2)

- The incineration of waste was firstly introduced at the end of the 19th century as a way to solve the significant sanitary problems of the large urban areas.
- The technology was adapted from that of coal-fired furnaces, which, at that time, was considered sufficiently safe (confined fire, circa sealed combustion chamber) and reliable for this purpose.
- At that time, the characteristics of waste were not suitable for a self-sustaining combustion, thus an auxiliary fuel, typically coal, was required.
- The only aim of the first incinerators was to dispose of the waste. No energy recovery was performed.
- The properties of wastes have progressively improved, so that the amount of coal needed to allow the combustion has become less and less, until auxiliary fuel has become required only at startup, as in modern Waste-to-Energy (WtE) plants.

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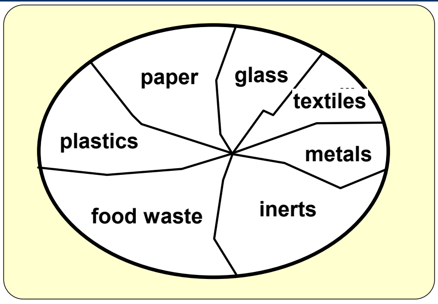
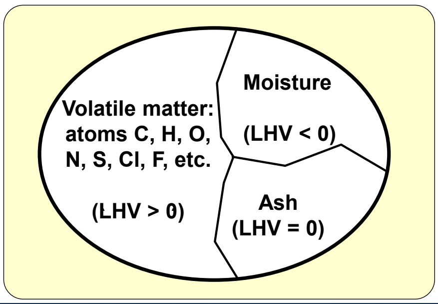
The waste fuel: composition

Composition based on waste fractions:

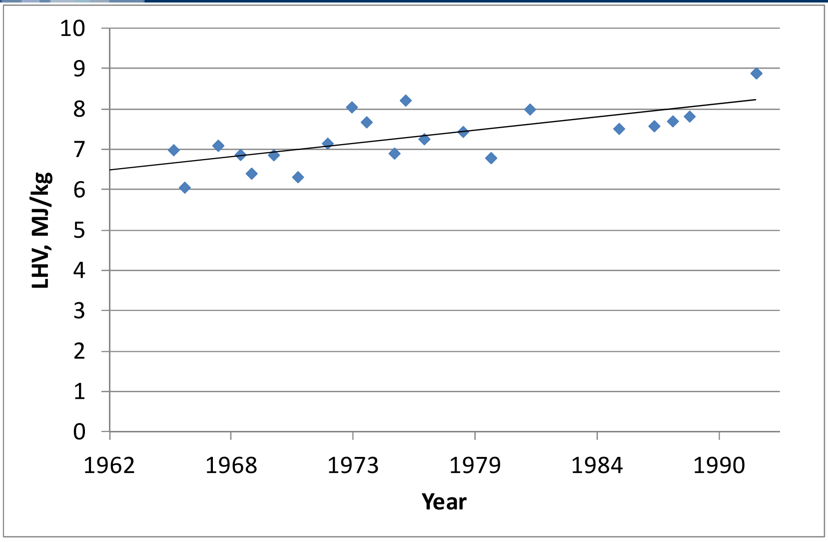


From the energy point of view, waste can be considered as a solid fuel, even if of low quality …

Elemental (ultimate) composition:

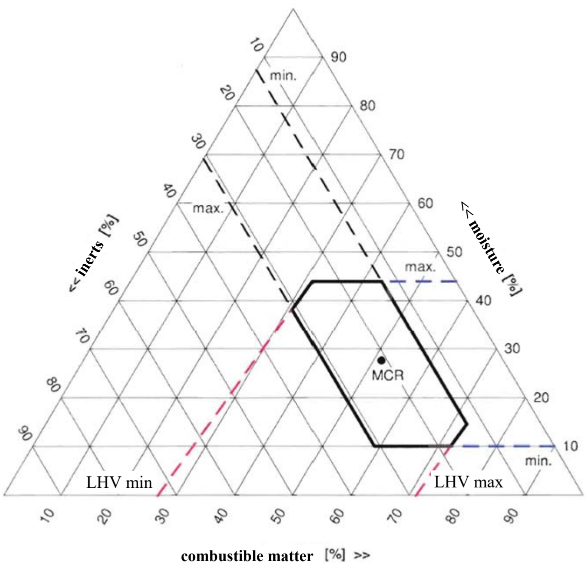


The waste fuel: historical evolution of the heat content



<u>Data for the city of Milan (I)</u> – Source: AMSA - Milano

The waste fuel: Tanner's diagram



<u>The waste fuel:</u>
When waste properties respect certain criteria, the waste can be used in a self-sustaining combustion, producing heat and, by means of a thermodynamic cycle, power (electricity), exactly as it happens for fossil fuels.
Modern incinerators (WtE plants) are peculiar power plants fed with the particular fuel "waste".

The waste fuel: critical aspects

1) Low LHV, thus achieving the same thermal power of a fossil fuel-fired plant requires:
   – larger flowrates → larger auxiliaries consumption
   – larger plant size → greater investment costs
2) Relevant content of elements that can originate toxic and corrosive compounds (Cl, F, Br, metals, etc…):
   – environmental impact concerns
   – achievable performances appreciably lower than those achieved by fossil fuel-fired plants
3) Almost incontrollable composition and physical properties of waste → max flexibility of treatment plants is required
4) Plant sizes much smaller than those of fossil fuel-fired plants → lower performances and higher costs

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The energy potential of waste

- In industrialized countries the production of Municipal Solid Waste (MWS) is about 1-2.5 kg per inhabitant per day, i.e. 400-900 kg/inh/y
- A reasonable level of Source Separation (SS) is of the order of 35% (Italian average), thus the amount of Unsorted Residual Waste (URW) left downstream of Separate Collection (SC) is about 250-600 kg/inh/y, with a LHV = 10 MJ/kg_{URW}
- The energy that can be released by this URW is equivalent to 70-150 kg of oil per inhabitant per year
- In industrialized countries the overall consumption of primary energy is about 3-6 toe/inh/y
- CONCLUSION: URW alone is enough to satisfy 2-3% of the overall primary energy consumption. Considering only fixed plants, this percentage rises to 3-5%. Adding also special wastes, it is possible to reach even 10%

The energy potential of waste: the case of Italy (1 of 3)

- In Italy, nowadays, about 10 million tons of URW (or RDF) are disposed of in landfills every year.
- Assuming (realistically) LHV = 10 MJ/kg_{URW} and an average net electric efficiency of incinerators of 25%, it could be possible to generate about 7 TWh of electricity, over 2% of Italian electric consumption of 2013 (330 TWh).
- This would require plants for an overall installed electric capacity of 900 MW (working 7800 equivalent hours per year).
- I.e. about 18 plants of size similar to those of the plants of Brescia and Milan. Meanly two in every Region, practically 3-4 for large Regions and 1 for small Regions.
- Actually in Italy, in 2013, there were 44 working incinerators … but …

The energy potential of waste: the case of Italy (2 of 3)

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- Gross electricity production from WtE plant of MSW in Italy in 2013: about 4.1 TWh, i.e. a little bit more than 35% of what could be produced (4.1 + 7 = 11.1 TWh).
- In addition, in 2013, WtE plant of MSW produced also ~1.5 TWh of thermal energy.

- **Why Italy produces only 35% circa of what could be produced?**

- There is a scarcity of plants.
- Most of the existing plants are obsolete and designed with the purpose of disposing waste (incinerators) rather than recovering energy (WtE plants).
- Most of such plants are quite small … (explained later)

The energy potential of waste: the case of Italy (3 of 3)

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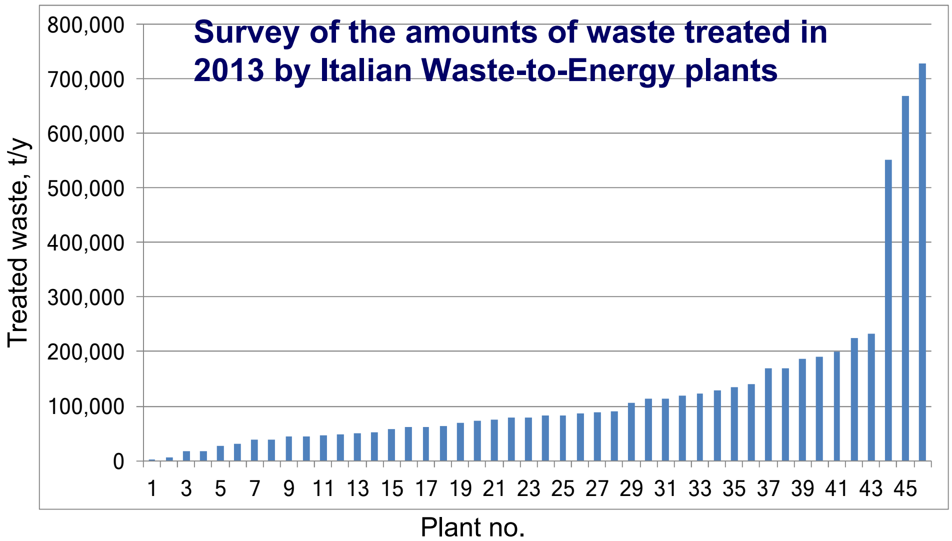

Source: ISPRA, Rapporto Rifiuti Urbani 2014

The crucial question:
Waste: PROBLEM or RESOURCE?

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How carrying out energy recovery from waste?

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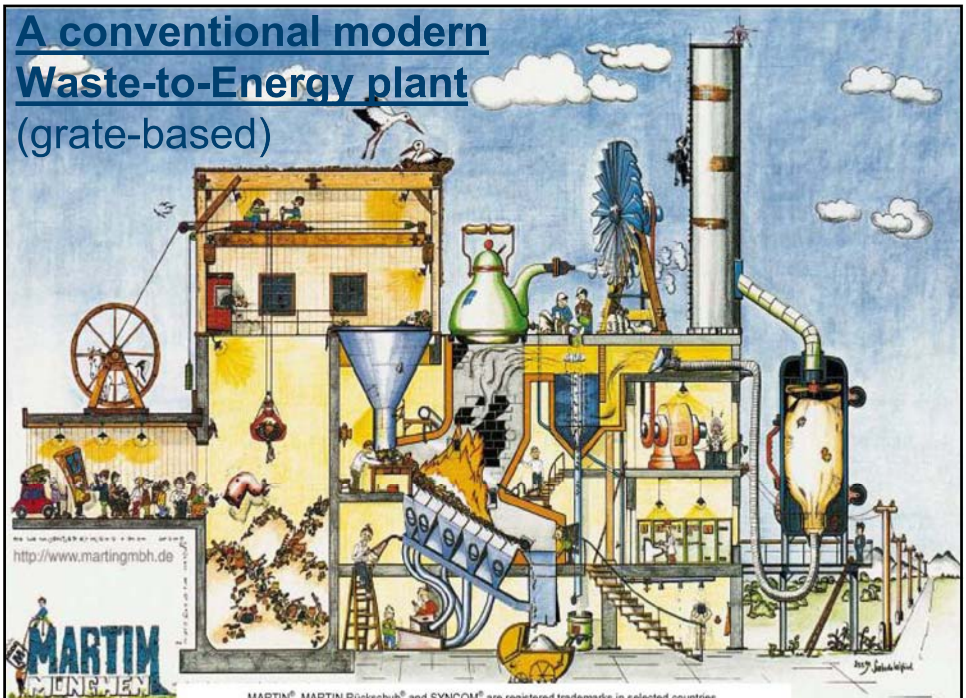
Technological proposals are very numerous:

1. Direct combustion of URW (traditional incineration).
2. Production of RDF (Refuse Derived Fuel, or SRF – Secondary Recovered Fuel) to be used in dedicated plants, cement kilns, coal-fired power plants.
3. Waste gasification or pyrolysis for the production of power through externally- or internally-fired power cycles, hydrogen, synthetic liquid fuels or chemicals.
4. Plasma gasification for the same purposes listed at the previous point.
5. “Molecular dissociation” (???).
6. Other further exotic technologies …

In reality only options no. 1 and 2 are widely commercialized and have proven good reliability.

F. Viganò 35

A conventional modern Waste-to-Energy plant
(grate-based)



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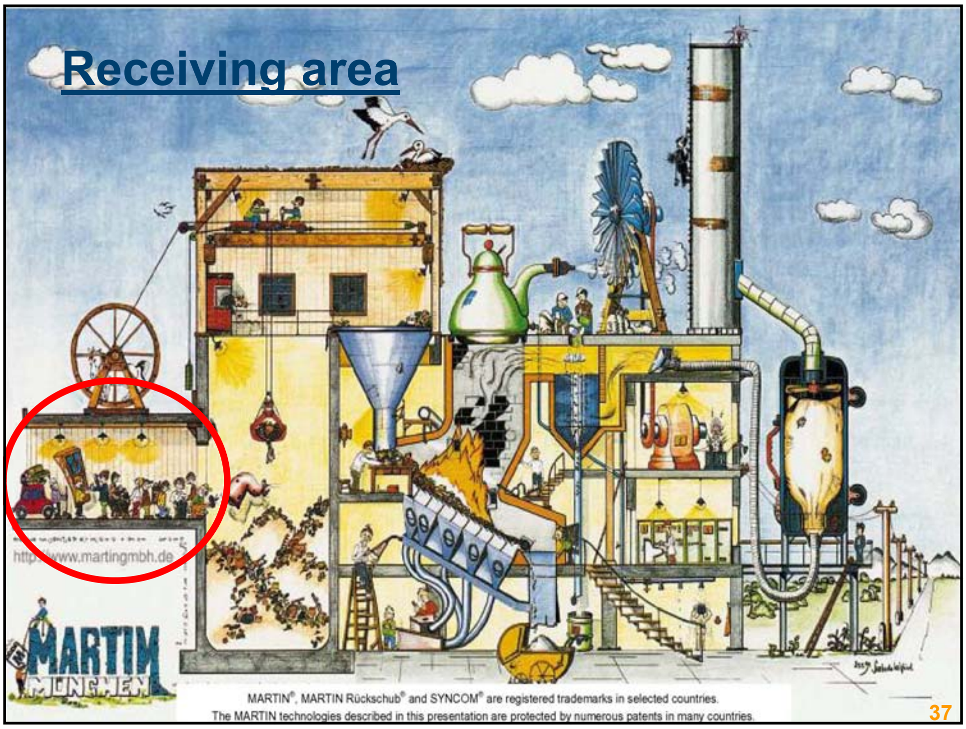
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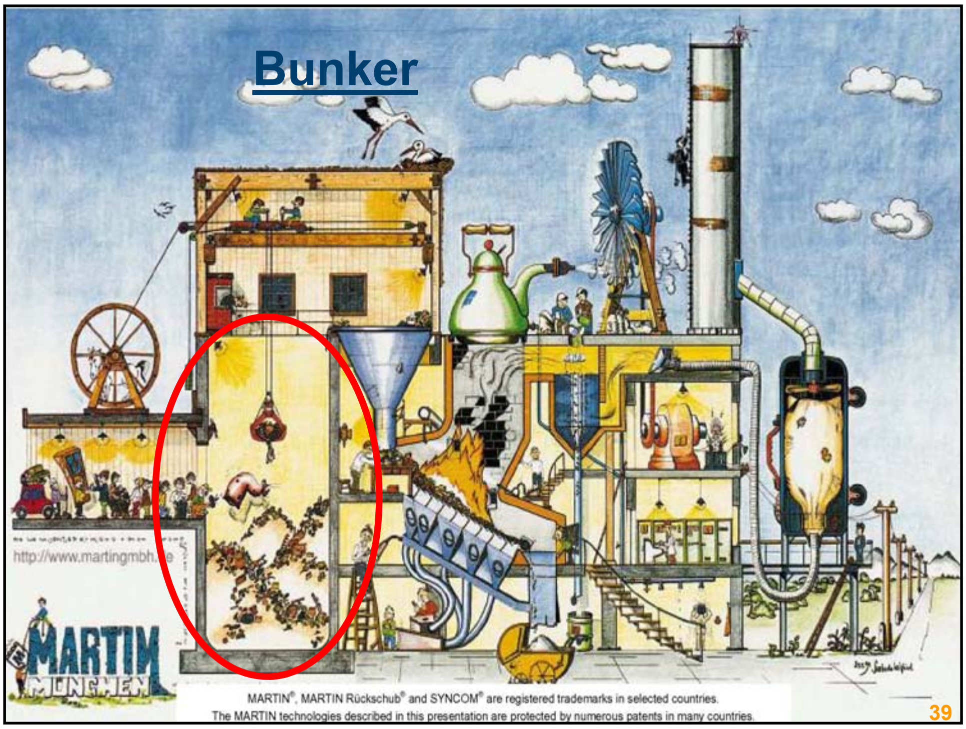
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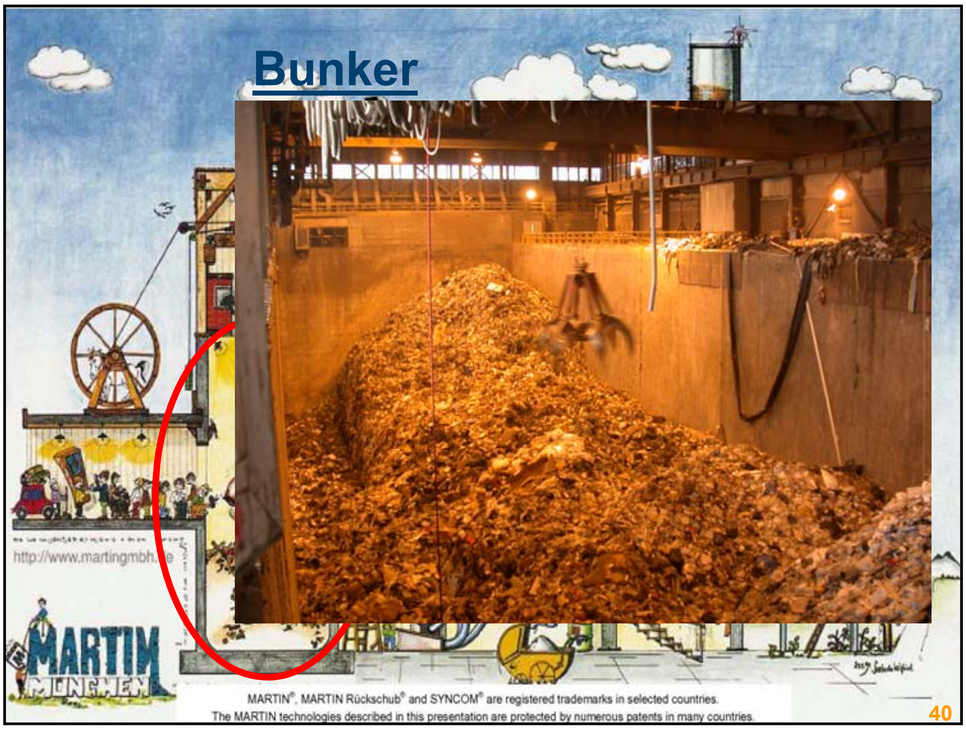
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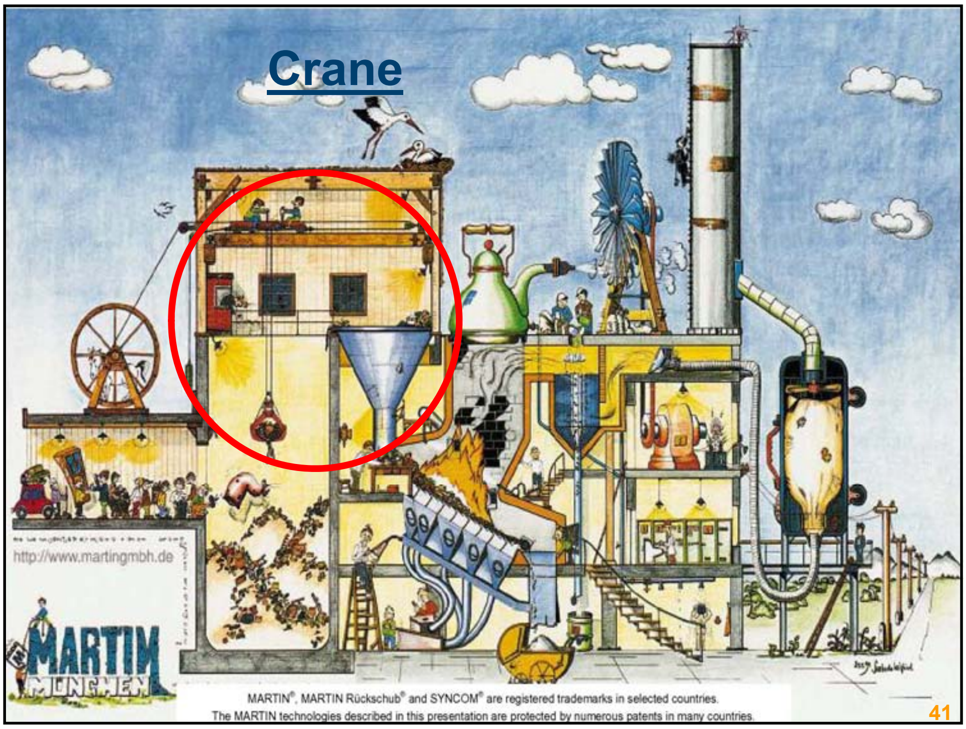
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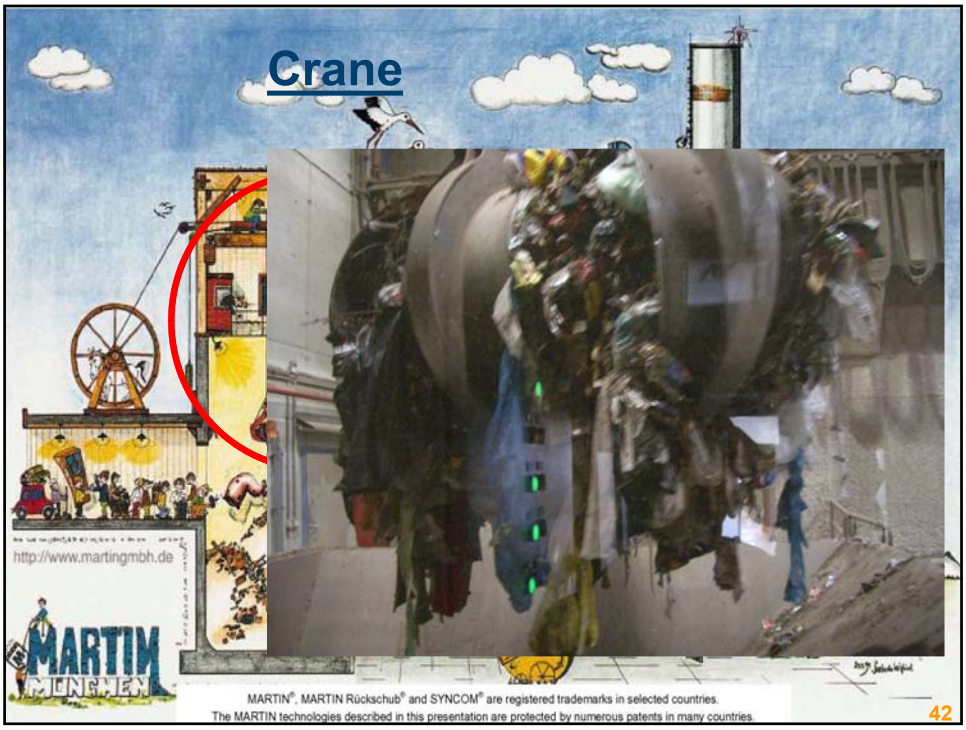
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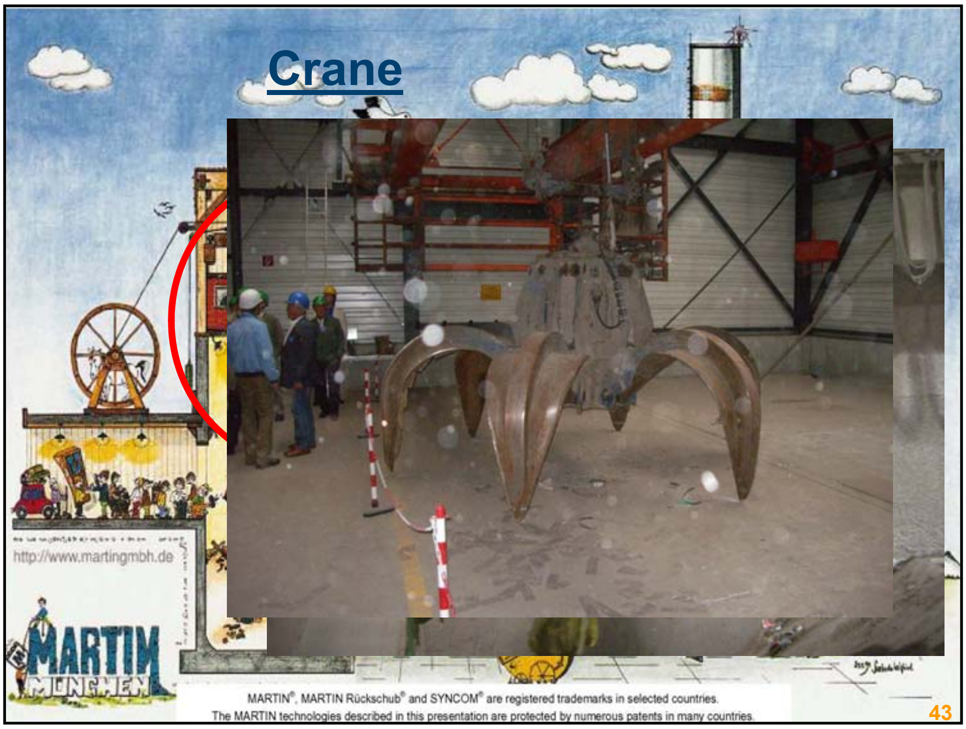
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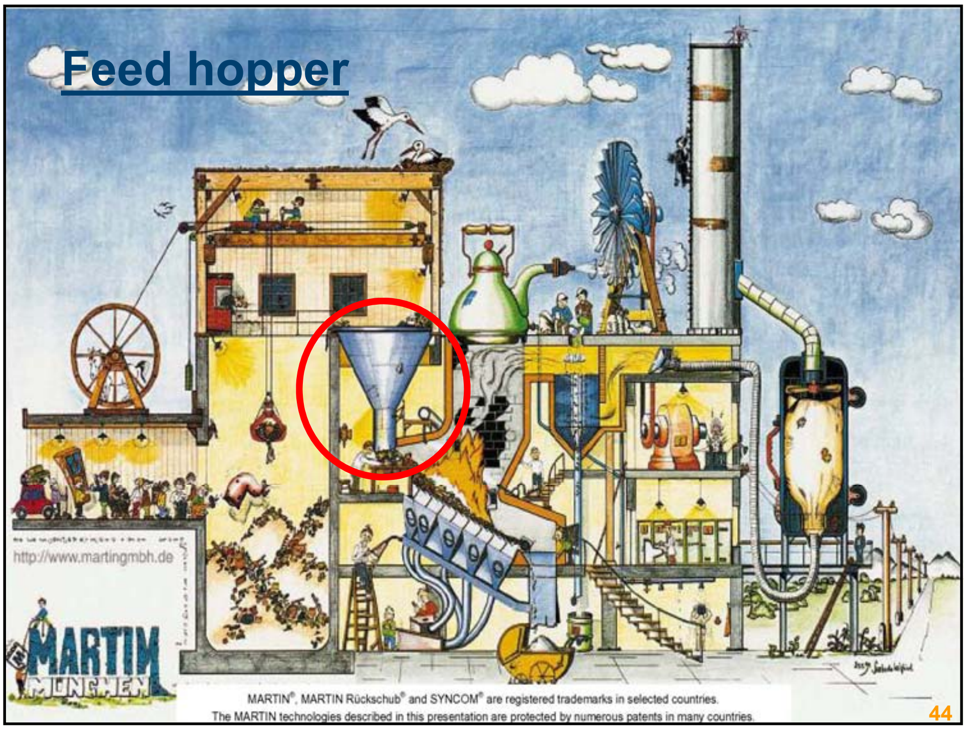
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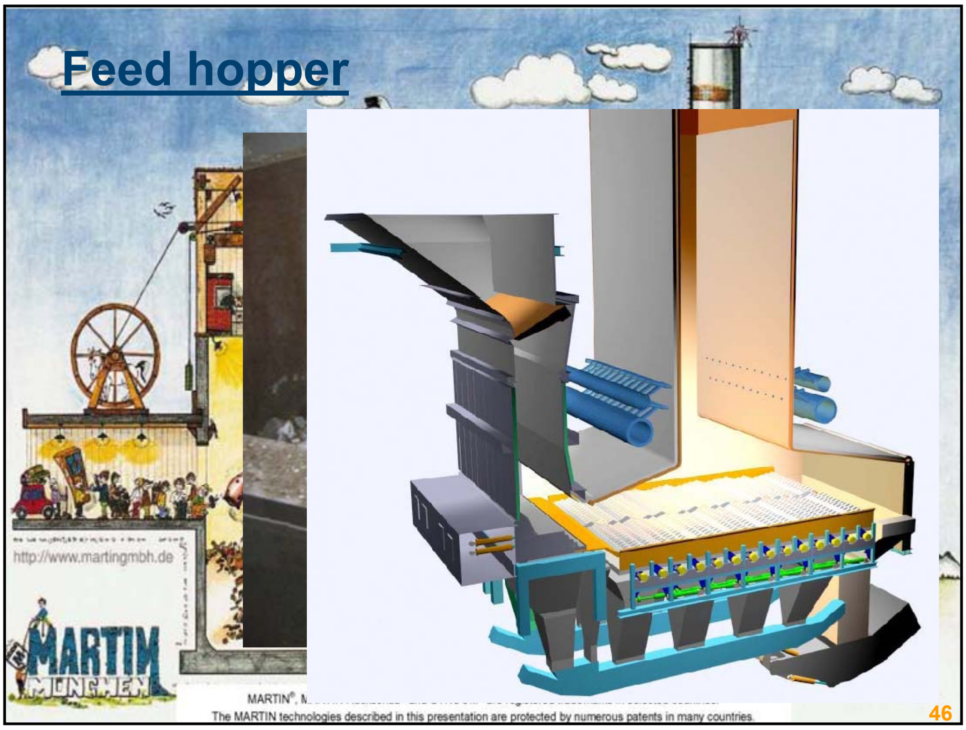

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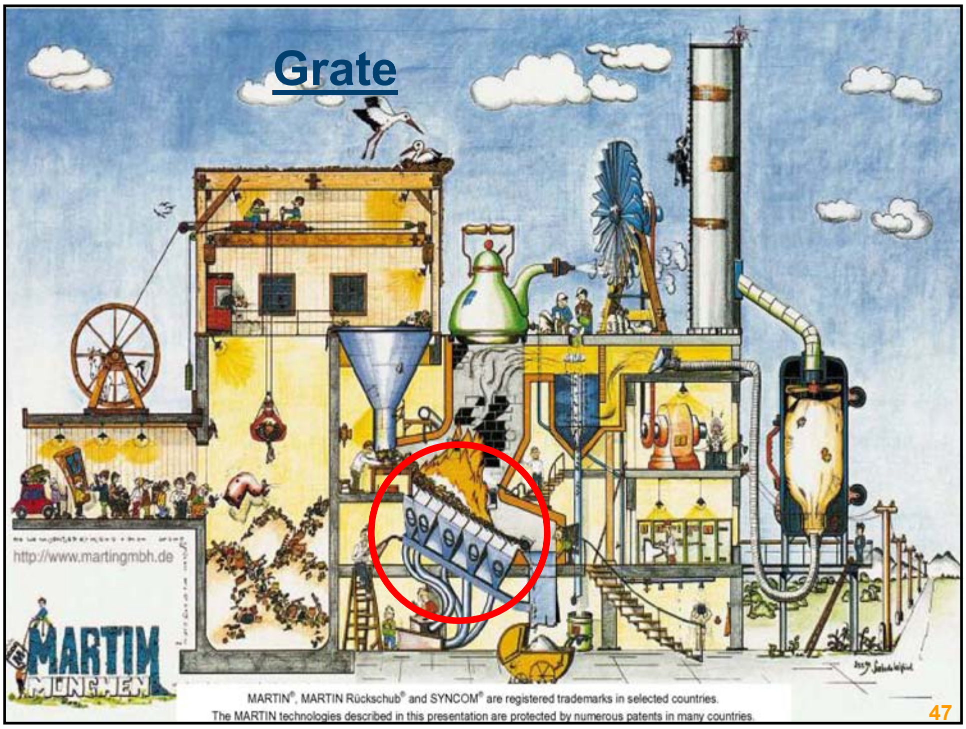
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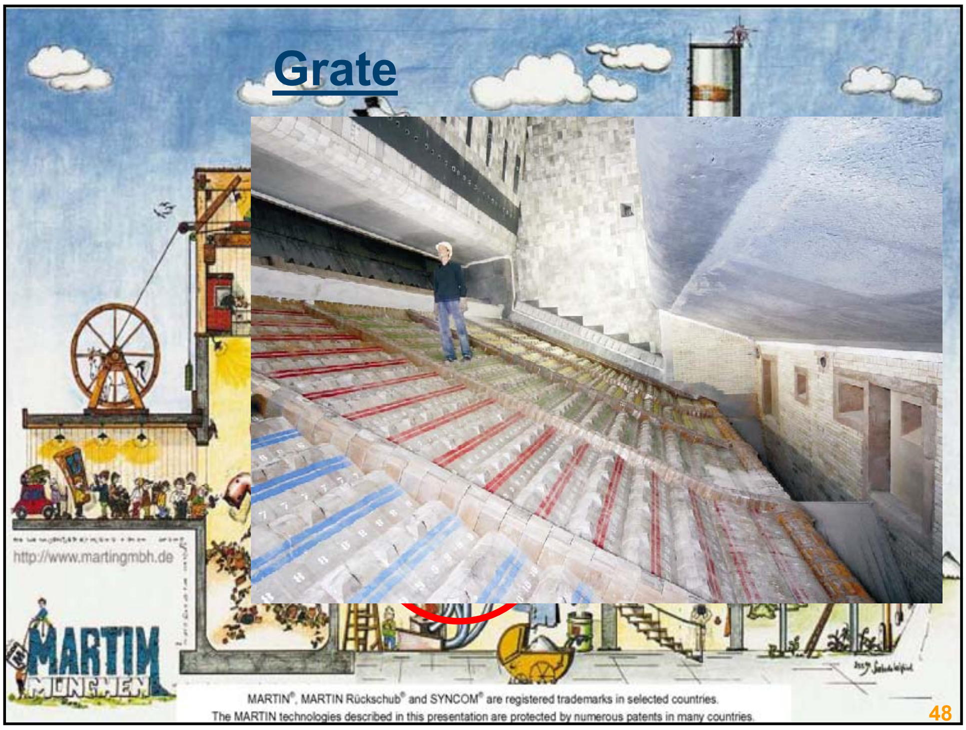
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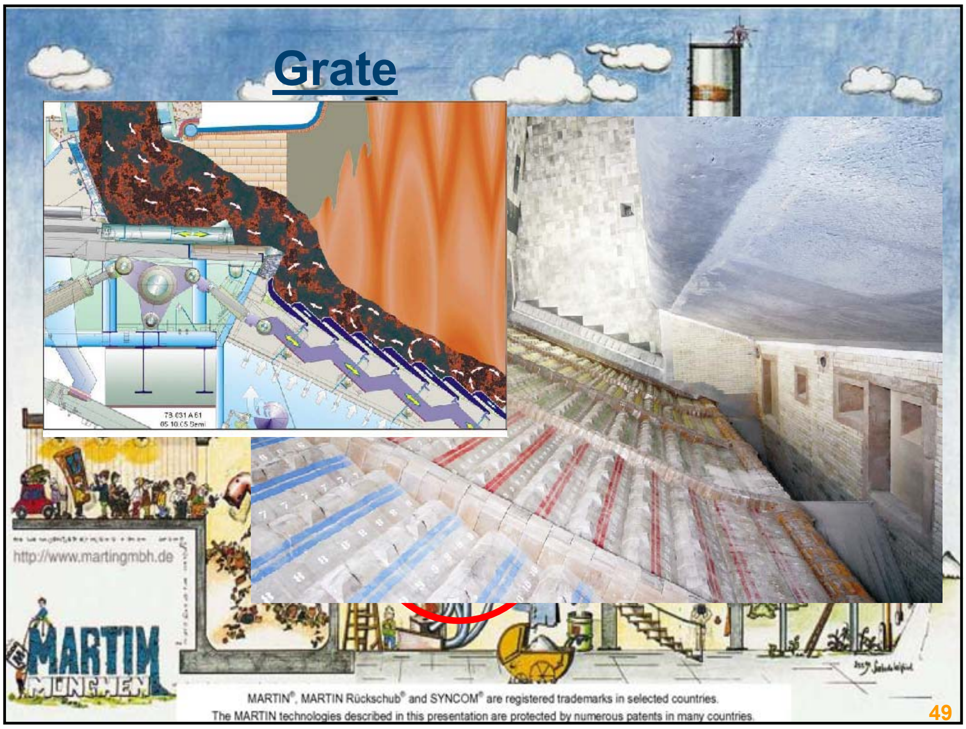
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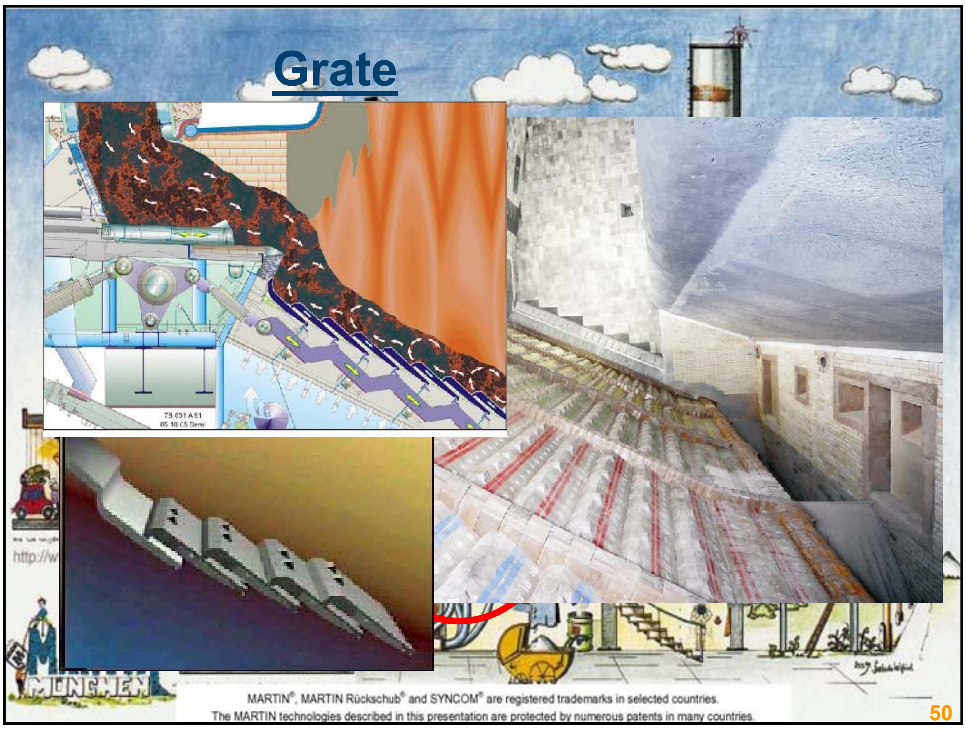
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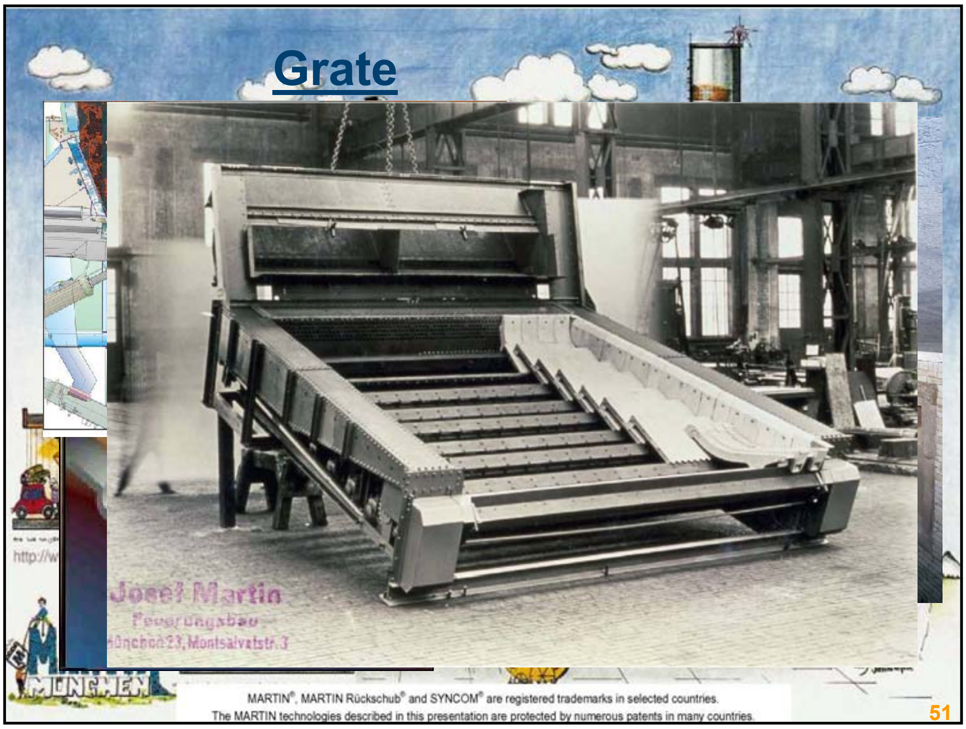
Grate
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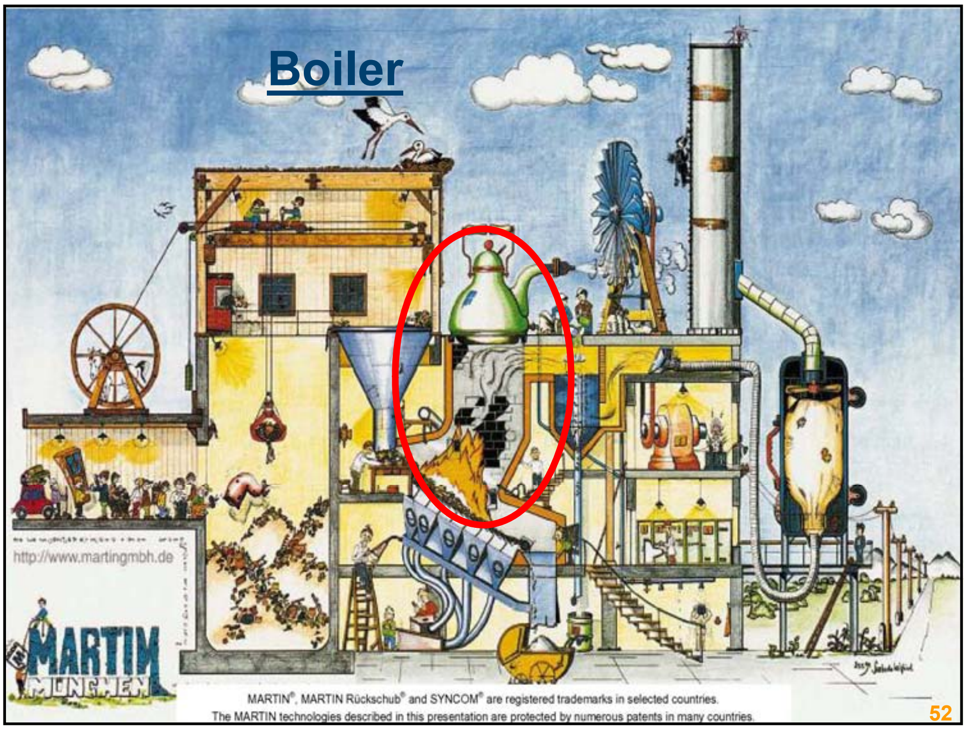
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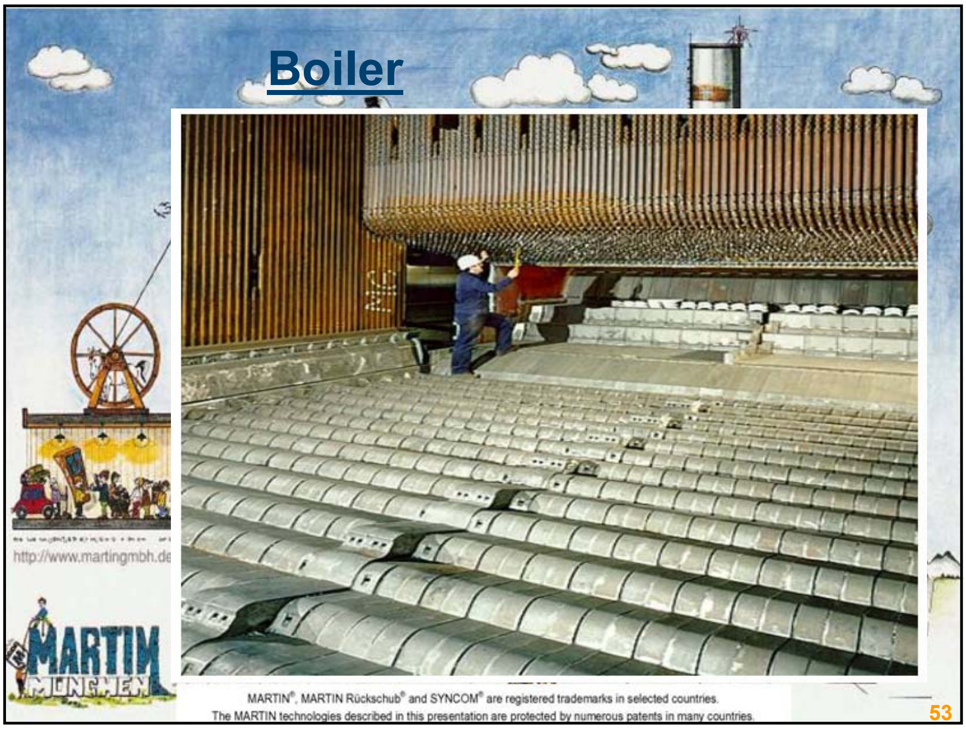
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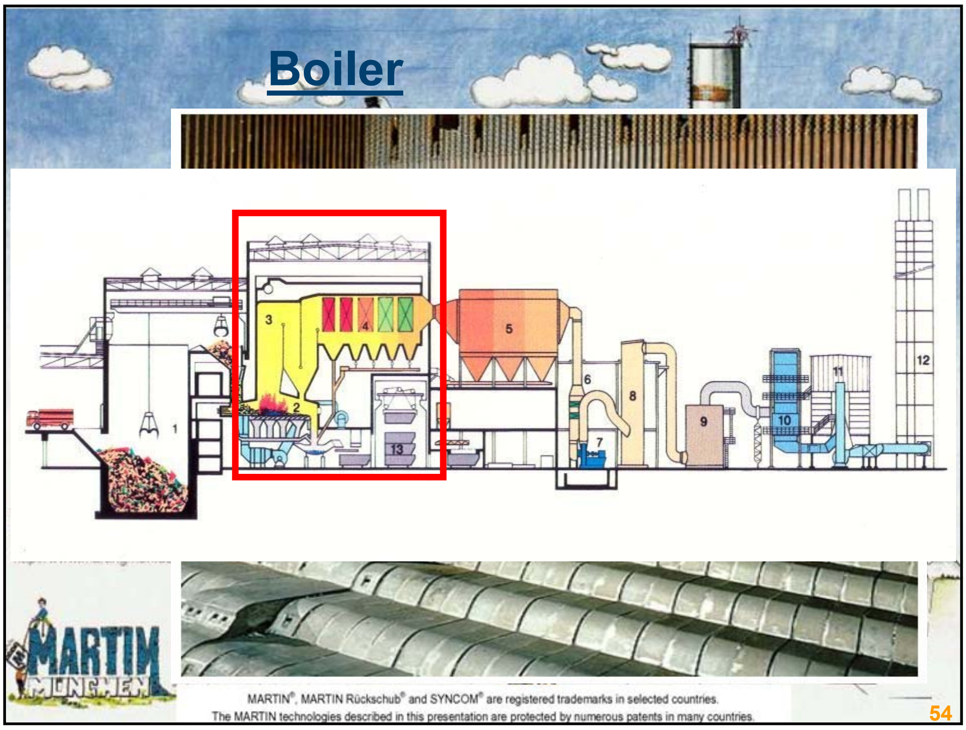
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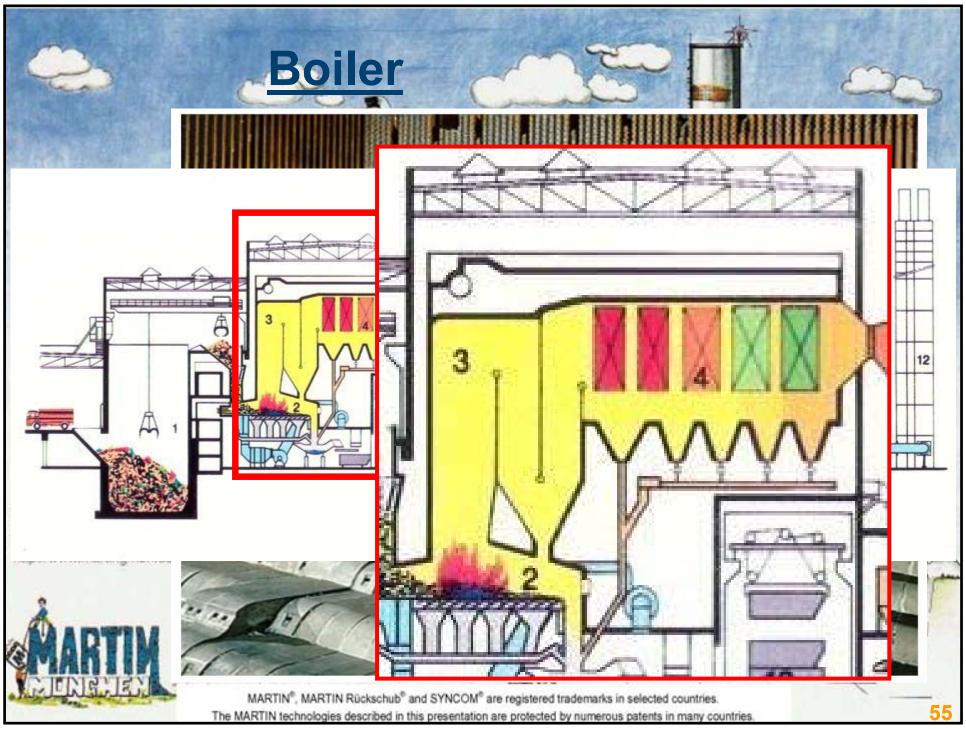
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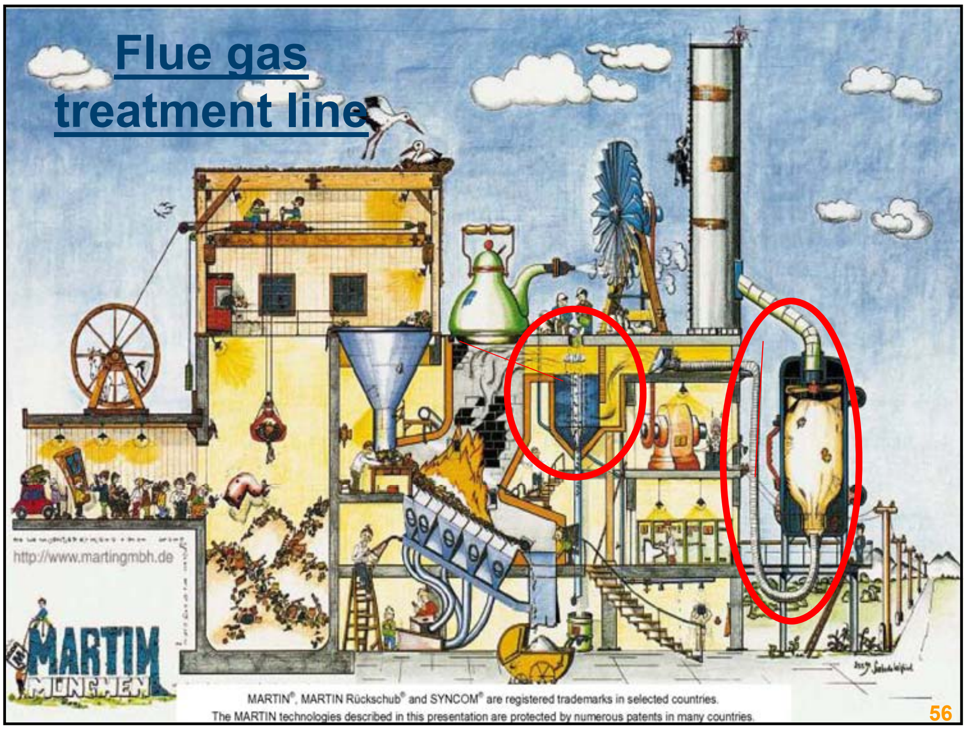
Flue gas
treatment line
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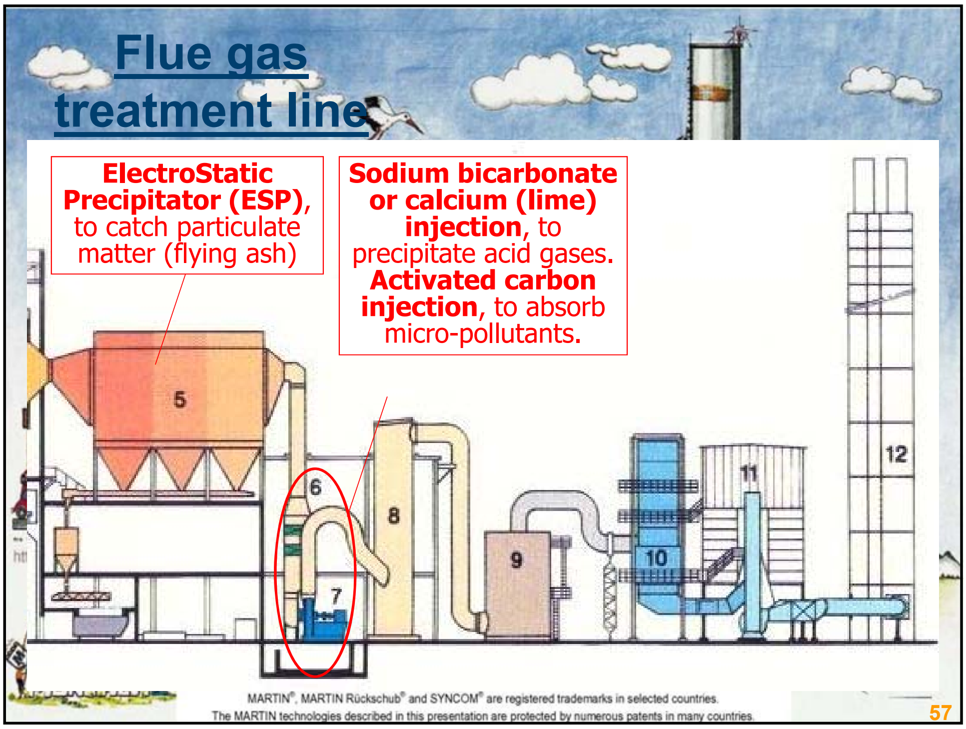
Flue gas treatment line
ElectroStatic Precipitator (ESP), to catch particulate matter (flying ash)
Sodium bicarbonate or calcium (lime) injection, to precipitate acid gases. Activated carbon injection, to absorb micro-pollutants.
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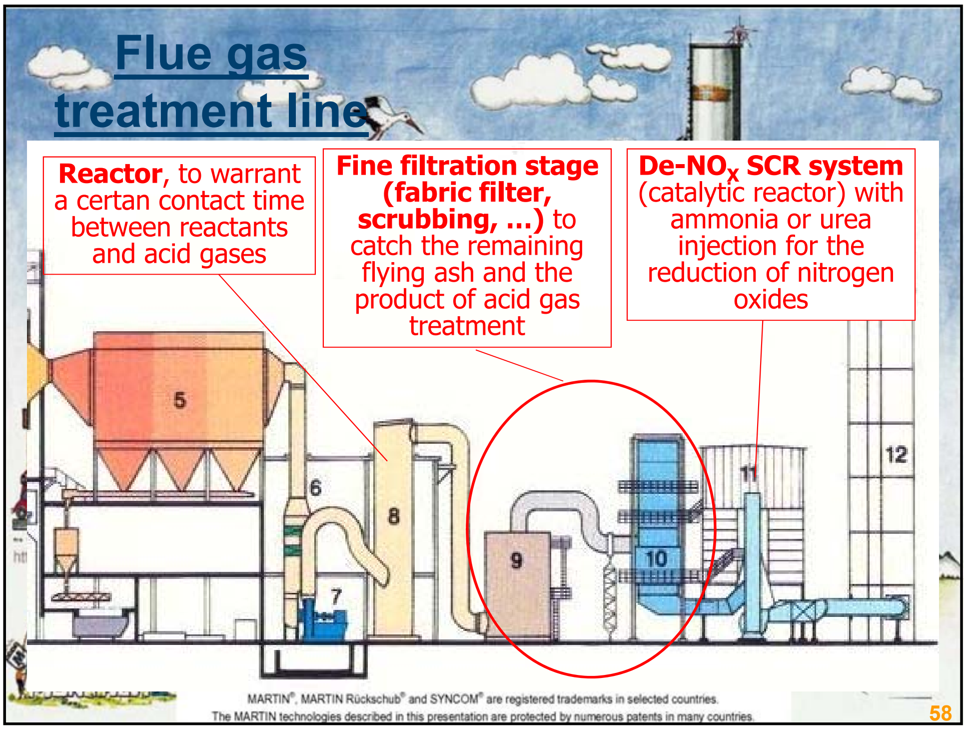
Flue gas treatment line
Reactor, to warrant a certan contact time between reactants and acid gases
Fine filtration stage (fabric filter, scrubbing, ...) to catch the remaining flying ash and the product of acid gas treatment
De-NO_X SCR system (catalytic reactor) with ammonia or urea injection for the reduction of nitrogen oxides
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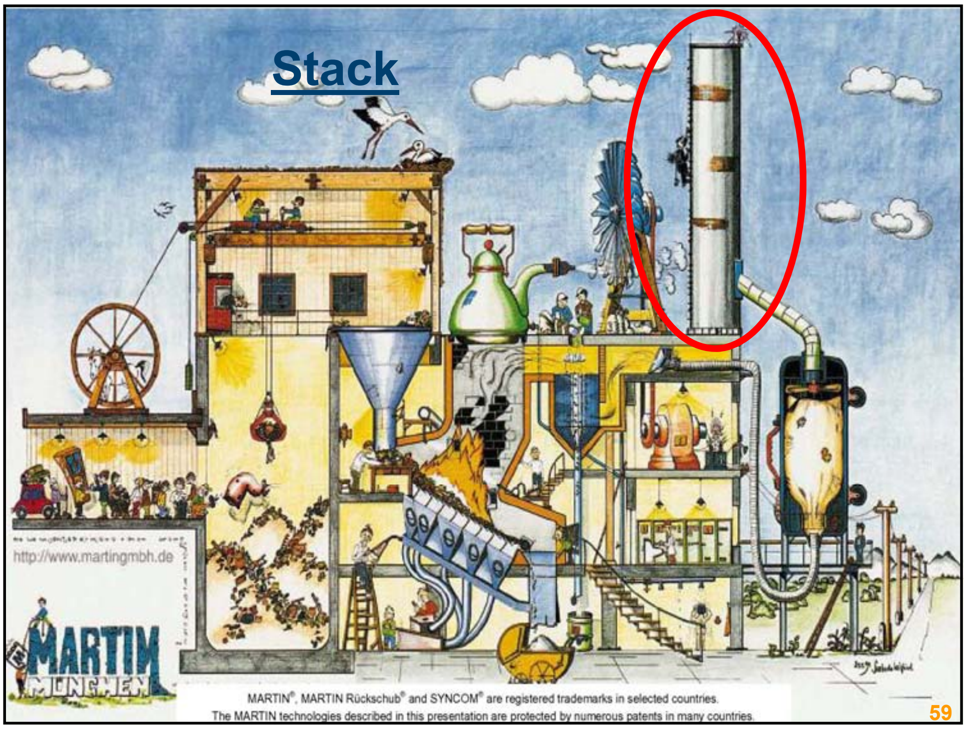
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Lecture outline

Grate combustors: basics

- Grate combustors are based on a mechanical component – the grate – which mechanically support the fuel during combustion.
- A variety of grate types exists:
  - fix vs. moving grate (direct vs. reverse acting grate);
  - sloping vs. horizontal grate;
  - uncooled vs. cooled grate (air-cooled vs. water- / oil-cooled);
  - etc.
- Besides supporting the fuel, the grate, or something acting on it, must make the fuel move from the feeding section toward the ash discharge section.
- Currently, for waste incineration, the most widespread grate technologies are based on cooled moving grate, sloping or horizontal.
- For the direct combustion of biomass a larger variety of grates is used, mainly in small scale application. However, at large scale, the same grate types used for waste cover most of the applications.

Grate combustors …

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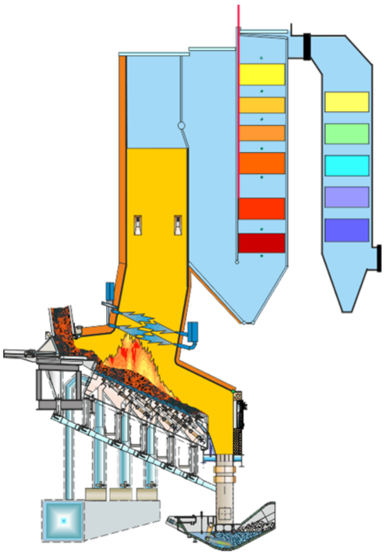
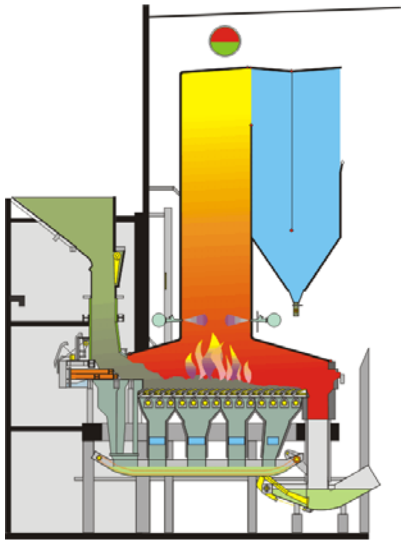


Sloping, reverse-acting grate



Horizontal travelling grate

Sloping, air-cooled, reverse-acting grate

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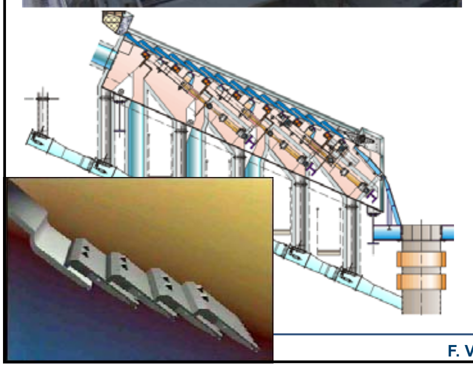
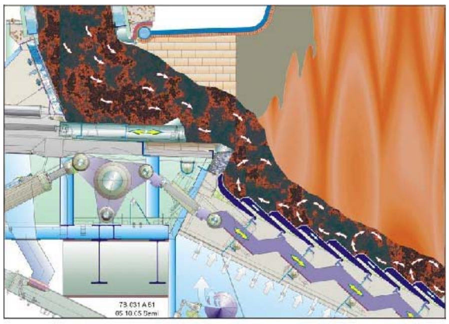




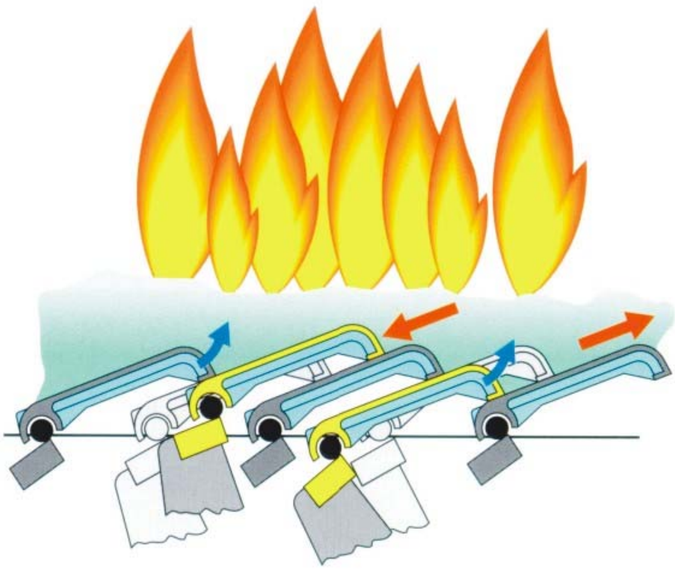
Horizontal, water-cooled, direct-acting grate

More elements are joint together by means of a girder to form a bar.

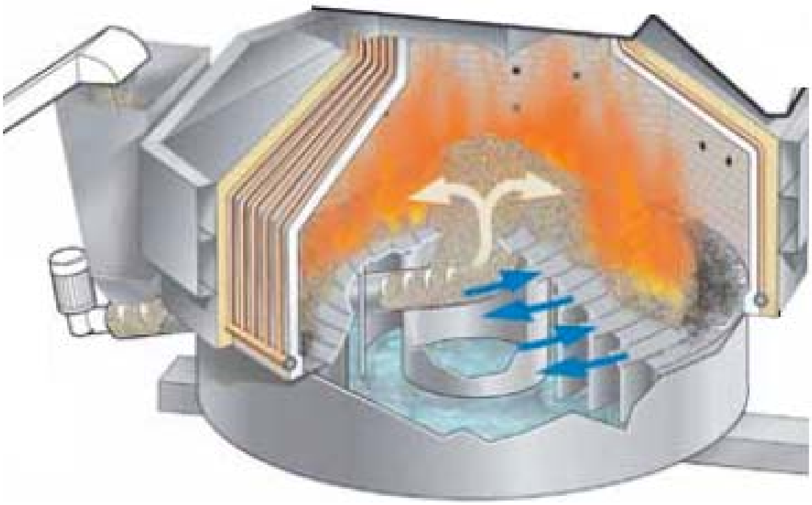
There are stationary and moving bars.

Every bar element has an internal circuit for water cooling. For moving elements, the internal circuit is connected to the external circuit through flexible pipes.

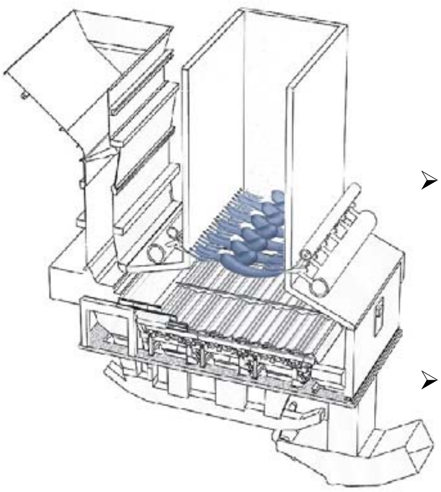
Horizontal, water-cooled, direct-acting grate
Bar movement, air path



Rotary grate for biomass-fired plants



Grate combustors: combustion



- Since a solid fuel is involved (heterogeneous combustion), the flame is always diffusive, thus fuel and oxidant reach the flame region from the opposite sides and they meet only at stoichiometric ratio in the flame.
- To limit the production of nitrogen oxides, the amount of oxidant supplied to the fuel bed (primary air) is a little bit less than that stoichiometric, so that a reductive zone is created immediately above the fuel bed.
- Combustion is completed in gas phase above the bed, where a certain amount of secondary air is supplied through injectors located in the walls of the combustor chamber.

Grate combustors: the travel of fuel on the grate (1 of 2)

- Since these combustion devices are studied for somehow "difficult" fuels, it is usually possible to distinguish at least three portions of the grate:
  - the first part, starting from the feeding side, where the fuel is dried, at least in superficial layers, and eventually begins burning;
  - the second and central part, where most of the combustion happens;
  - the third and last part, where combustion is finished.
- In certain cases it is possible to identify further portions where specific operations happen.
- Almost all the modern grates are divided into sections, which try to match the above mentioned portions.
- In every section it is usually possible to control the combustion air supply, in order to optimize the different operations carried out in every specific section.
- Some modern grates allow also to control in different manners the action of the moving elements of the grate in the various sectors.

Grate combustors: the travel of fuel on the grate (2 of 2)

- Sloping grates present slopes of 8-28°.
- Sloping, reverse-acting grate has the advantage of continuously tipping over the fuel bed. This is particularly useful with low quality (= low LHV) fuels, containing much moisture, which - in this way - are quickly dried and promptly burn.
- Other sloping grates (direct-acting) can present a step in the middle of the grate to favor at least one tip over of the fuel bed.
- Residence time on the grate depend on the reactivity of the fuel. Promptly burning materials, e.g paper, plastics, etc., burn as they reach the bed surface or even before. Bulky organic materials, typically with high moisture content, can last on the grate even one hour or more.
- An obsolete Italian law prescribed a residence time of – at least – two hours for sanitary wastes.
- The ideal travel of a elemental bed portion should last about one hour, however, when the ash content of the fuel is not particularly high, the ash left after combustion can be kept on the last part of the grate even several hours, with the aim of thermal insulating the grate.

Grate combustors: cooling

- Since grate elements support a bed of burning material, they are exposed at high thermal stress.
- In moving grates, grate elements must be preserved from excessive deformation and high temperature erosion / corrosion. For this reason they are always directly or indirectly cooled.
- All modern, large-size grates for the combustion of biomass and / or waste are designed with a cooling system.
- The most simple - but quite effective - cooling system consist of the use of the primary combustion air: it is supplied underneath the grate, passes through the grate elements cooling them and reaches the fuel bed where it is used as oxidant for the combustion.
- Moreover, the grate should never be directly exposed to the radiation coming from flames, but it should always be covered by a layer of combustion ash. This layer acts as thermal insulation, keeping within an acceptable limit the superficial temperature reached by the grate elements.
- In certain situations air cooling is not enough to warrant a sufficient lifetime to the grate. In these cases water / oil cooling is used.

Grate combustors: water / oil cooling

- The combustion of fuels with high LHV may required more intense cooling for the grate elements than that achievable with air cooling.
- Typically, LHV higher than 15 MJ/kg can be only difficultly managed by an air-cooled grate.
- Almost all modern grate combustors use pre-heated primary air and the preheating temperature can reach also 150°C and more. With a so hot coolant, the air cooling of the grate, especially when treating high LHV fuels, becomes very challenging.
- In those situations, in which air cooling is not anymore effective, other cooling systems are required. A possibility is represented by water / oil cooling. A liquid stream has a greater thermal capacity and heat exchange effectiveness than pre-heated primary air.
- Usually, the solution of one or more closed circuits filled with pressurized liquid is adopted. This liquid can then be cooled with ambient air, other cooling media, or with condensate from the steam cycle.
- Also mixed systems, with portion of the grate air-cooled and others water- / oil-cooled, are available.

Grate combustors: elements lifetime

- Typical lifetime of grate elements ranges from 2-3 up to 5-6 years.
- Usually, to warrant such a lifetime worn elements must be moved – during periodical maintenance interventions – to less stressed areas.
- Low melting point materials, like aluminum alloys, are very harmful to grate integrity and lifetime. In fact, they can melt on the elements enhancing erosion / corrosion, as well as occluding air passages and welding together different elements.
- Small pieces of hard metals are harmful too, because they can damage the joining surfaces of the elements.
- The inert content of the fuel (i.e. fuel ash) is essential for protecting mainly the last part of the grate from direct flame radiation, however it is the main source of erosion for the grate elements (inert materials are usually very abrasive).
- Fine combustion ash that falls through the grate elements is typically collected by appropriate pneumatic conveyors and properly managed.

Grate combustors: sizing criteria

- The area of grate is proportional to the amount of waste treated.
- There is a maximum thermal load that must be respected and a maximum mass load. Both these limits depend on the particular technology adopted.
- A traditional limit value for the thermal load is about 400 kW of thermal power (on LHV basis) per square meter of grate, but the most advanced technologies can reach values as high as 1000 kW / m^2.
- In modern grates, the limit on mass load is in the order of 300-400 kg/s/m^2.
- Grate producers typically offer grate trains characterized by a certain length (which is correlated to the characteristic velocity of the fuel on each grate type). The required grate area is obtained by changing the width of grate train within a certain range and, possibility, using more trains placed side by side.
- Multiple trains configurations (also 4-5) allow regulating the fuel velocity in each single train, optimizing the distribution of fuel on the grate.

Grate combustors: combustion chamber

- Combustion chambers can be designed in co-current, counter-current or neutral geometry.
- At one side, counter-current chamber favor the drying of the fuel before its combustion, so they are particularly suitable for very low quality fuels, with very high moisture content.
- At the other side, co-current combustion chambers are particularly suitable for dry fuels that promptly burn, since the produced flue gas rises the chamber by going through the hottest part and, thus, ensuring a very complete combustion.
- The neutral geometry is somehow a compromise between the two extreme solutions and it is widely adopted in the most modern plants.
- The typical design of a combustion chamber respect the rule of the three "T" (= temperature, turbulence, and time), which suggests to keep the flue gases well mixed (high turbulence) for a certain time at a high temperature in order to warrant a good combustion.
- Turbulence is increased by strong injection of secondary air, possibly recirculated flue gases and, in certain cases, even tertiary air.

Grate combustors: sizing of the combustion chamber (1 of 2)

- The volume of the combustion chamber can be determined by several factors.
- For low quality fuels, like waste (but also biomass falls in the same situation), the primary requirement that must be respected regards the residence time of flue gas at high temperature.
- A common sizing criteria, imposed by a number of laws in several countries, requires that the gaseous combustion products remain at not less than 850°C for a time not shorter than 2 s.
- This requirement is aimed at assuring the complete destruction of organic-clorated compounds (dioxins, furans), which are – in this way – thermally decomposed.
- With very low quality fuels, this requirement can be respected only using adiabatic combustion chambers, instead for fuels like biomass or waste from industrialized countries a moderate heat extraction is allowed.
- In the presence of adiabatic combustion chamber it is common to speak about furnaces, otherwise about combustors.

Grate combustors: sizing of the combustion chamber (2 of 2)

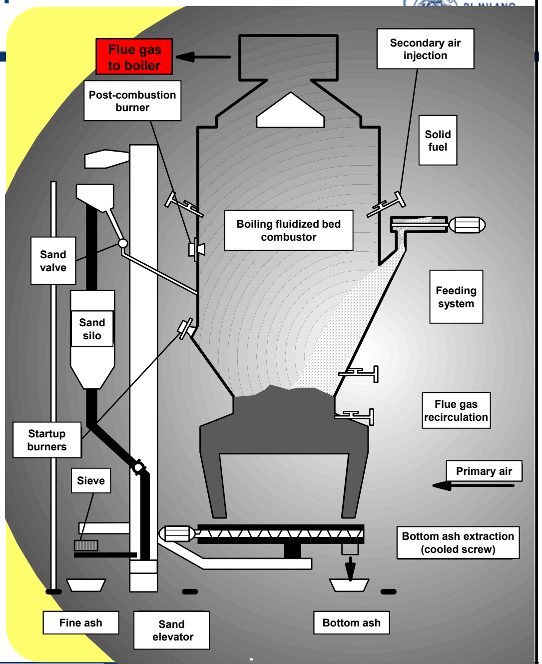
- When heat extraction is allowed in the combustion chamber (combustors), the combustor is integrated with the boiler.
- To limit the heat extraction from the combustion chamber, the cooled walls (typically evaporating walls of the boiler) are covered with refractory material, at least in the lower part of the chamber, near the flame region.
- The volume of combustion gas generated depends on the nature of the fuel (typical values: 0,45-0,55 m_n^3/MJ_{LHV} dry at 11% O_2).
- In large size, well-controlled combustors, very low oxidant excess can be adopted. Modern plants reach concentration of free O_2 at the exit of the combustion chamber of 5-6%$_{VD}$.
- Smaller devices, which suffers more unfavorable ratios Surface / Volume, to ensure complete combustion must adopt higher oxidant excess.
- A historical value of the free O_2 concentration at the stack of BtE and WtE plants is 11%$_{VD}$. Such a value is adopted to normalize flue gas flowrates and pollutant concentrations by several regulations.

Lecture outline

- *Direct combustion of biomass – a historical view*
- *Disposal of waste – a historical view*
- *Direct combustion of waste – the historical perspective*
- *The waste fuel – the modern perspective*
- *The energy potential of waste*
- *Technologies*
- *Grate combustors*
- *Fluidized bed combustors*
- *Boilers*

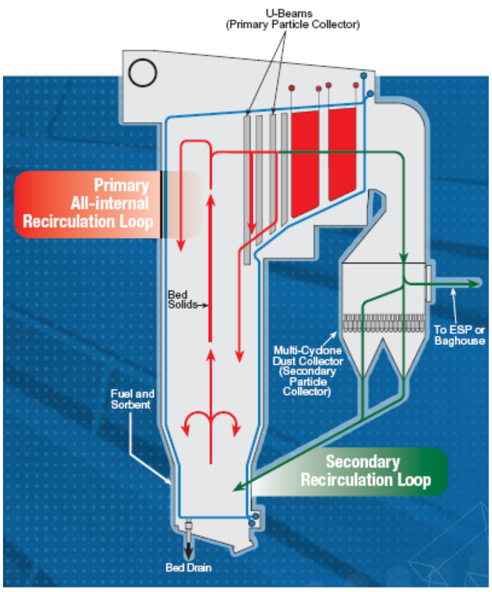
Fluidized bed combustor: Basics (1 of 3)

- A fluidized bed combustor is a tank partly filled with a mixture of fuel and sand (i.e. “the bed”).
- High velocity primary air injection from the bottom of the tank upward produce the “fluidization” of the bed.
- The bed becomes like a sort of fluid, suspended or transported by the air flow.
- When fluidization determines only an expansion of the bed, it is called “boiling fluidized bed”, otherwise, in the case of transportation of part of the bed beyond the top of the tank, it is called “circulating fluidized bed”.



Fluidized bed combustor: Basics (2 of 3)

- The temperature of the bed is regulated by acting on the heat extraction.
- Due to the high thermal inertia of the bed, it is possible to warrant good process stability against fuel property changes.
- Dimensional homogeneity of fuel is required, so this technology cannot be applied directly to URW, but rather to RDF produced starting from URW.
- The temperature of the bed must be controlled accurately to avoid sand sintering (T < 850-900°C).



Fluidized bed combustor: Basics (3 of 3)

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- No support is required to sustain the fuel during combustion: a number of issues about material resistance and corrosion are solved.
- Long residence time for the material within the reactor warrants complete oxidation of CO, HC, dioxins, furans, etc.
- Moderate working temperature helps limiting NO_X production.
- It is a technology that can be easily used also in small scale applications, because suffers much less the effect of the Surface / volume ration with respect to the grate technology.
- Since no grate is present, also high LHV fuels can be used. It is a technology used also for the combustion of coal.
- When used in WtE plants, some problems can occur due to the uncontrollable characteristics of waste ash (the inert part of the waste). Chemical species can be present that form eutectic mixtures with the sand of the bed, leading to sintering even if temperature remains under control.

Fluidized bed combustor: A WtE plant (Corteolona, Pv – Italy)

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Combustor diagram

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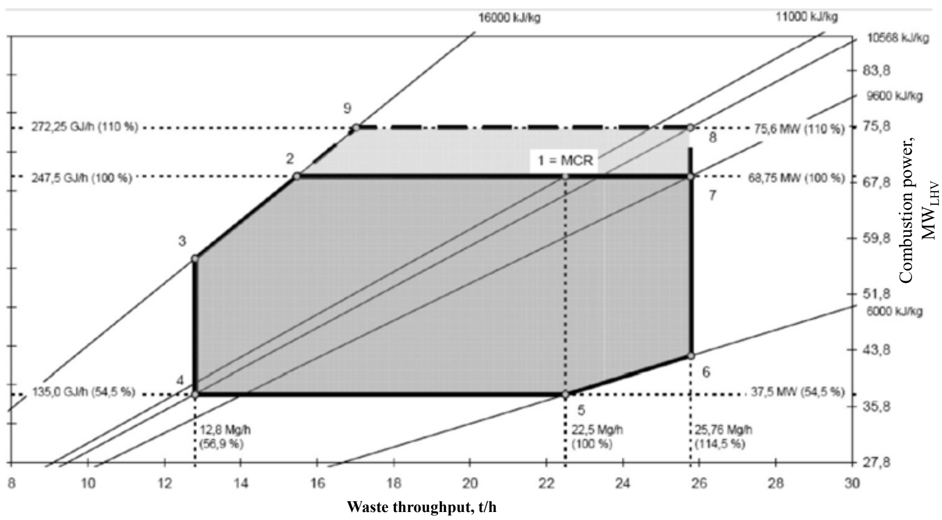

Lecture outline

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- *Grate combustors*
- *Fluidized bed combustors*
- *Boilers*

Boilers

- Boiler configuration for WtE plants is quite consolidated, although some particular designs can be found. A wider variety is available for biomass-fired plants.
- In WtE plants, boiler design is constrained by the corrosion problem.
- In both BtE and WtE plants, boiler design is less sophisticated than in coal-fired plants due to the much smaller scale of the former plants.
- In large plants the common solution is a water tube pressurized and superheated steam generator that typically feeds a Rankine steam cycle.
- In smaller plants (mainly BtE plants), smoke tube boiler can be used, as well as atmospheric diathermic oil instead of pressurized water / steam. In these cases, a small steam cycle can be present or, alternatively an Organic Rankine Cycle (ORC).

Large boilers (steam generators)

- Since in steam generators most of the heat transferred is used for evaporating water, almost all the walls that delimit the boiler volume are typically evaporator walls.
- They are made by a sequence of tubes welded together along the fins.
- For waste-fired boilers, the first sections of the boiler are empty radiant channels (often called boiler passes). The reason for this choice is to cool down the hot flue gas without exposing too much surface area to its action.
- In fact, waste flue gas commonly contains high concentrations of acid gases: HCl, HF, etc., which are very aggressive with iron.
- The radiant sections of a waste-fired boiler typically cools the flue gas down to about 650-600°C.
- At such a temperature, the flue gas can enter the convective section of the boiler, where several tube-banks are located to accomplish a number of tasks: superheating of the produced steam, further water evaporation (steam production), feedwater preheating (economization).

Scheme of a conventional large waste-fired boiler

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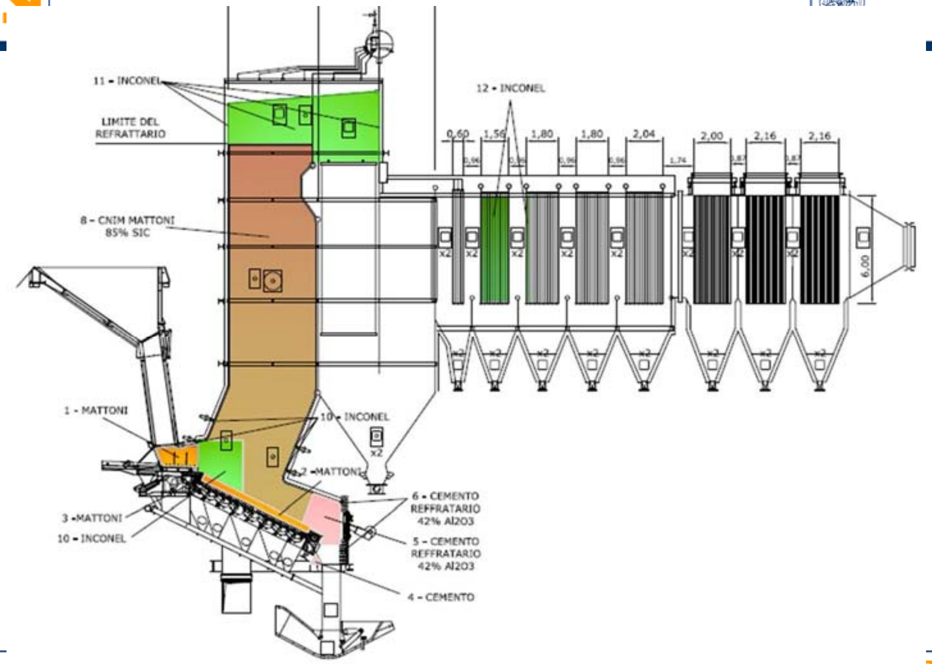

Corrosion risk in evaporators (waste-fired boilers)

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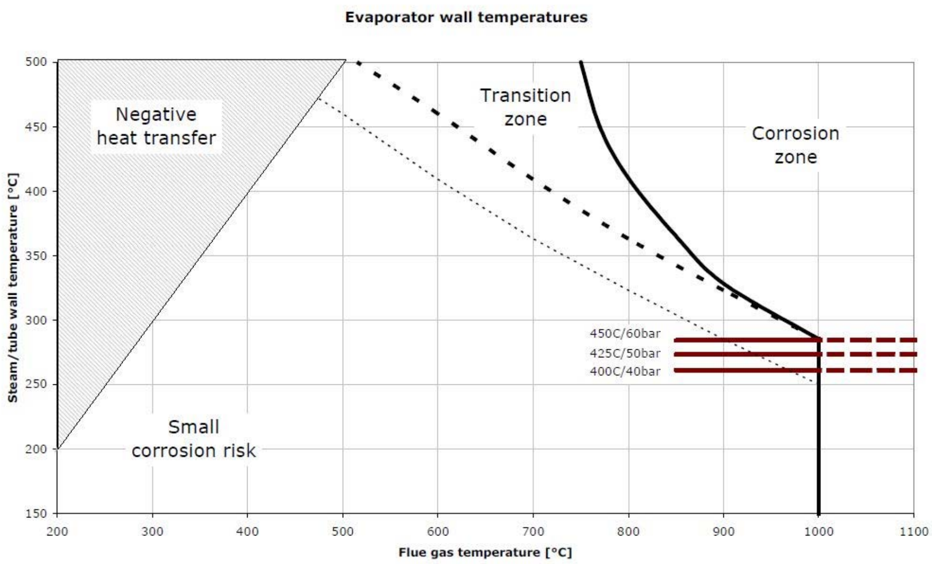
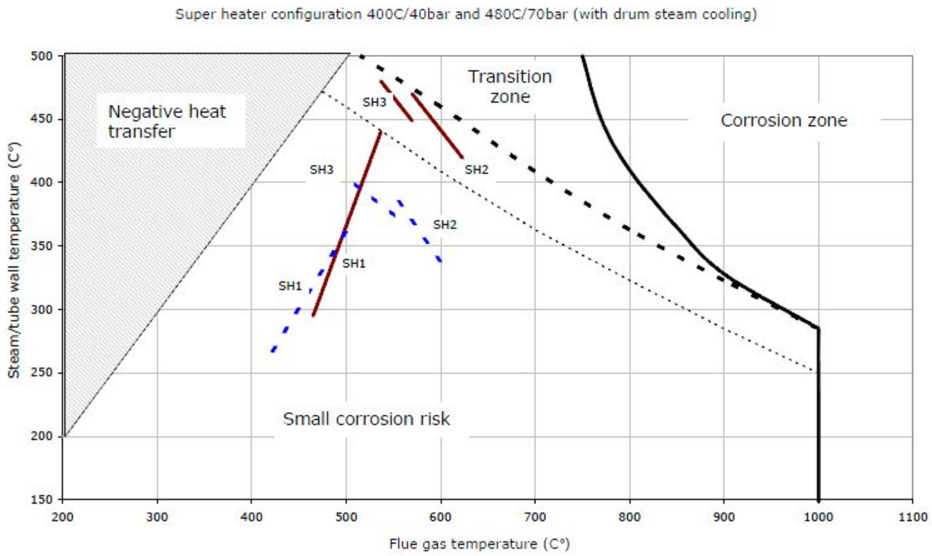


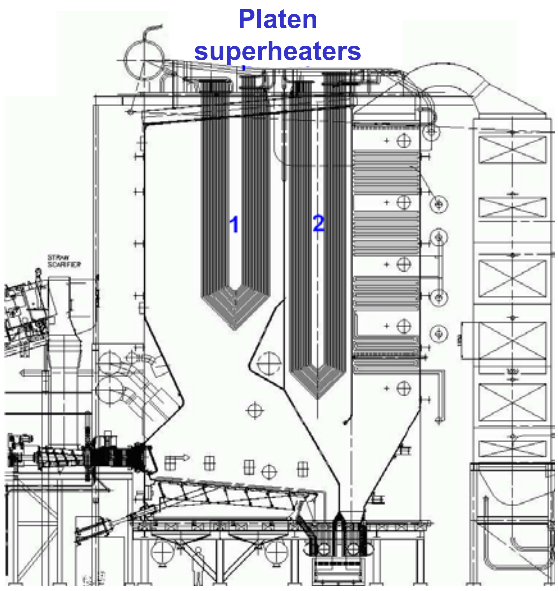
B. Kamuk, "Consequences by operating at extreme steam parameters". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

Corrosion risk in superheaters (waste-fired boilers)



B. Kamuk, "Consequences by operating at extreme steam parameters". 1st WTERT EU Meeting, Brno, Czech Republic, 12-14 October 2010.

Configuration of large biomass-fired boilers



Boiler fouling and damaging

Agglomeration	Fouling	Corrosion
		
High (additives/co-firing needed)	High (additives/co-firing needed)	High (additives/co-firing needed)