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WASTE INCINERATION SYSTEMS; CURRENT TECHNOLOGY AND FUTURE DEVELOPMENTS IN GERMANY

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ABSTRACT

Plants for thermal waste treatment may basically be subdivided into a section comprising the main thermal process and a section dedicated to additional process stages, such as flue gas purification, generation of electricity, etc.. Combined, these two sections represent the overall process. In the course of the past few years, technology, particularly for flue gas purification, was advanced and efforts and input were increased to such an extent, that today, practically all plants fulfil emission requirements, irrespective of the fact, whether the result obtained in the main thermal process is good or bad. However, it is this first section, which is essential in determining energy consumption, size of flue gas mass flows, etc. for the process as a whole. For this reason, development work currently focuses on the main thermal processes. This contribution, after a short characterization of various types of waste, will first describe elements of process engineering, followed by a portrayal of main influencing factors, and related devices. After that, an explanation is given, as to how systematic notation, classification, balancing and evaluation can be performed. This is followed by an overview over the current state of the art and future developments. Due to the multitude of such developments, we limit ourselves to those, which currently are under highly intensive discussion. Others can only be mentioned. In the realm of plant engineering, particularly for houshold waste and hazardous waste, the devices: "grate", "rotary kiln" and "combustion or gasification chamber" stand in the foreground. This applies to the state of the art as well as to future developments in "classic" and "new" processes.

It has become apparent, that the strong pressure brought about by so-called "new" processes - e.g. the „Schwelbrennverfahren nach Siemens KWU“, the „Konversionsverfahren nach NOELL“, the „Thermoselect-Verfahren“ etc. - triggered considerable development steps also for the "classic" processes whose technology is long established and well-proven. Thus, there are no indications for a take-over of "classic" processes by "new" ones at this time. Which process will prevail is not an issue right now. Depending on the conditions of compatibility which must be taken into account for each individual application, there are possibilities for implementing any of these processes. It makes good sense not to exclude any process, as it is important to prove efficiency with the aid of expected operational results of plants working on an industrial scale. Only then will valid comparisons of processes become possible.

KEY WORDS

thermal waste treatment, household waste, hazardous waste, combustion, gasification, pyrolysis, waste incineration, gas purification, residue post-treatment.

CONTENTS

1 INTRODUCTION

The increase in industrialization, particulary over the last decades, has resulted in a dramatic increase in the quantity of waste produced. Even if an increase in the development of low-refuse production technologies could reverse this trend in the future, the treatment of waste will gain importance as a branch of environmental protection in the sense of both recycling and waste disposal. Figure 1 exemplifies several inherent basic engineering processes. Mechanical processes already enable a part of building rubble to be recycled. Wastes such as paper, for example, still require chemical-physical processes to succeed the mechanical steps before they can be utilised. For harmless native organic wastes, biological treatment using aerobic or anaerobic processes can be taken into consideration, etc. On the whole, it can be assumed that there is no one process suitable for the disposal of all types of waste. In order to preserve the resources available, it is necessary to develop a concept for the treatment of each type of waste. For this purpose, the basic processes illustrated in fig. 1 are interconnected in a suitable way whereby care should be taken that no excessive energy or effort is exerted in the individual steps. For wastes with a very low portion of biologically decomposible materials, for example, one should consider whether a separation followed by a biological treatment of these components is worthwhile compared with the possibility of the entire waste undergoing thermal treatment, in particular as the latter is unavoidable. Conversely, for a high portion of easily separable inert substances or native organic materials, it is in many cases not expedient for all fractions to undergo thermal treatment (e.g. combustion) etc.; a pre-separation would be advantageous. As a rule, however, regardless of which combination of process steps is selected, a remainder (residual waste) is left for which the only means of disposal is thermal treatment. The extent of this residual waste should (with justifiable effort) be kept as low as possible.

All types of treatment plants are required to fulfil the emission limits, listed in figure 2, concerning the release or depositing of pollutants into the air, water and soil. Special reference should be made here to the loss on ignition and the TOC of the solid residues which escape from the treatment plants as in the future, only those residues may be deposited if the values of 5%, 3% or 1% of the loss on ignition or TOC-value are not exceeded. At present, biological methods of treatment often result in values higher than those stipulated. However, it is frequently emphasised that a biological decomposition of the organic materials allows residues with higher values for the loss on ignition and TOC to be deposited without risk to the environment. It will be seen whether future legislation will take this into account. As a result of the present emission values for loss on ignition and TOC, thermal treatment plants are preferred.

Incineration has since the beginning of this century become an established method for waste disposal [5]. As will be discussed in the following, a thermal treatment is understood to include not only incineration but also a variety of possible processes which are themselves subdivided into numerous steps. Waste incineration systems is given as a collective term for thermal treatment. The main aim is disposal, i.e. the destruction of pollutants, mineralization, etc., i.e. the conversion of the substances to allow their distribution in the environment. The second aim is the utilisation of energy and finally the third aim a material utilisation.

Wastes which are treated thermally (residual wastes) originate largely from:

- household waste and similar wastes from industry,
- hazardous waste,
- sewage sludge.

The majority of thermal treatment plants can be classified according to these types of waste.

Over the last 10 years, the flue gas purifying plants have been much improved with considerable technical effort (so-called secondary measures). The current emphasis lies increasingly in the field of primary measures, i.e. in the development and optimisation of the process control for the main thermal process in order:

- to reduce the volume of exhaust gas and thus to scale down the flue gas purifying plants and also
- to improve the energy utilisation and
- to lead to an improved recycling of valuable and raw materials.

This report will describe the state of the art and future developments of thermal treatment plants in Germany and will also include criteria to evaluate the processes.

2 WASTE CHARACTERISATION AND QUANTITY RATIOS

The individual steps taken in a thermal process are firstly dependent on the quantity and the composition of the wastes. In general, they can be classified by:

- a high inert component (ash, water, CO_2, N_2, etc.),
- high pollutant content (S, Cl, F, PCB, PCDD/F etc.),
- a low volatile content (solids),
- a heterogeneous composition,
- varying consistency (coarse, pasty, powdered, liquid or gaseous wastes and compounds of coarse, powdered, pasty and liquid wastes).

In the following, the groups of waste:

- household refuse (predominantly coarse),
- hazardous waste (coarse, pasty, liquid and corresponding compounds) and
- sewage sludge,

which are important in connection with a thermal treatment, will be considered in greater detail.

2.1 HOUSEHOLD REFUSE

The Federal Republic of Germany currently produces ca. 27 million t/annum of household refuse and similar wastes form (figure 3). Most of this waste is landfilled and only a small amount undergoes thermal treatment or is composted. Figure 4 exemplifies the composition of household refuse for one district. The calorific value lies (normally) in the range of $h_u = 6$ MJ/kg to 11 MJ/kg. In accordance with the calorific values for the individual fractions, it is possible to assume a mean calorific value (overall calorific value) for the composition in fig. 4 of ca. $h_u = 8.5$ MJ/kg [56]. Figure 4 also shows that the mean calorific value is influenced in particular by fractions possessing a calorific value which deviates considerably above (e.g. plastics) or below (e.g. inert material) the mean value. The compostable component, however, has no direct influence as its calorific value lies in the range of the overall value. The composition of the waste allows initial statements to be made, e.g. on the combustion properties. Thus, the influence of the air ratio λ on the expected temperatures is given for the aforementioned composition (fig.4) in figure 5. It is expedient to keep the air excess as low as possible in order to attain sufficiently high temperatures (taking losses into account) and also to reduce the volume of exhaust gas and thus to ease the succeeding aggregates. In the present case, due to the relatively low stoichiometric amount of air (here $l_{min} \approx 2.8$ kg air/kg waste), the influence of an air preheating to increase the reaction temperature is slight. The possibilities for process control will be dealt with in greater detail at a later stage.

2.2 HAZARDOUS WASTE

The German regulations concerning hazardous waste have not as yet been standardised. In the narrow sense, the term hazardous waste is understood to cover those wastes which constitute a considerable risk to health, air or water, are explosive or inflammable or which contain agents of infectious diseases. In addition, wastes excluded from the obligatory public refuse disposal system and which require compulsory registration are also classified as hazardous waste.

The determination of wastes requiring special monitoring using a waste index (in German „Abfallschlüssel“) and their transportation are stipulated by appropriate regulations and laws. The disposal of waste products is laid down in the "Technical guide on the storage, chemical/physical, biological treatment, combustion and depositing of wastes requiring special monitoring" [8].

Industrial plants and hospitals produce ca. 16 million t/a of these specially monitored waste products. Figure 6.1 illustrates that over half of these materials are delegated to public treatment plants and ca. 13 mass% undergo a private thermal treatment by the producing industry.

In the realm of public plants the amount of hazardous waste is 1 million t/a whereby ca. 88 mass% are landfilled, ca. 7 mass% undergo thermal treatment and ca. 5 mass% are treated directly.

If the hazardous wastes are homogeneous (e.g. gases), a thermal treatment is possibly "simpler" than the treatment of household refuse as it is possible to develop a specific stationary process (e.g. combustion chamber with gas firing). Hazardous waste products are comprised frequently of compounds of coarse, pasty and liquid substances which consequently impose exacting requirements on the mechanical and process engineering due to the heterogeneous consistency (possibly including barrels), the high pollutant contents and the complexity of the pollutants. Figure 6.2 depicts the composition of hazardous wastes originating from various branches of industry. It should be emphasised that hazardous wastes from different industries can deviate strongly from the compositions and calorific values given here. Thus, chemical wastes frequently show calorific values ranging from h_u = 18 MJ/kg to h_u = 25 MJ/kg. Although, as a rule, the high calorific value of these wastes enables sufficiently high temperatures to be reached (exceeding 1200°C), the example given in fig. 6.2 (h_u = 11.5 MJ/kg) requires the consideration of appropriate process engineering measures (e.g. additional fuel, oxygen enrichment, lowering of the air ratio) in order to attain such temperatures. Examples will be given to illustrate how these measures are to be evaluated in particular with regard to efficiency and exhaust gas mass flows.

2.3 SEWAGE SLUDGE

Currently in Germany ca. 60 million t/a of municipal sewage sludge with a solid percentage of ca. 5 mass% accumulates for disposal. Figure 7 is a pie chart illustrating to what percent the methods of disposal: "landfill", "agriculture", "compost" and "thermal treatment" are used. It can be assumed that against the background of the TA-Siedlungsabfall (fig. 2) the amount of sewage sludge currently landfilled will decrease in the future. Furthermore, reservations have been expressed against the use of sludges in agriculture due to possible soil contamination. Consequently, the only possible means of disposal for contaminated sludges is at present a thermal treatment. Figure 7 exemplifies an elemental and a trace analysis of a solid substance. From the point of view of combustion, the relatively high organically combined nitrogen is of central importance and should be taken into account by the process control. In addition, the calorific value is of significance for the temperatures to be attained and is influenced in particular by the drainage intensity (water content) of the sludge. For an assumed water content of w = 30 mass%, the composition given in fig. 7 is used to calculate a adiabatic combustion temperature of 1150°C where the air ratio $\lambda = 1.5$. A water content of w = 50 mass% results in a temperature of 850°C. Sludges with a high water content require the application of appropriate process engineering measures, such as heat recovery from the ash (e.g. in story furnaces).

2.4 OTHER WASTES

In addition to the wastes mentioned above, there are numerous more or less complicated materials, such as

- building rubble,
- old cars or
- electrical scrap,

which cannot be dealt with within the scope of this report. Means of disposal still need to be developed for some of these waste materials, although at least for certain fractions, a thermal treatment will be possible in the future.

3 THERMAL PROCESSES

The minimum aim of the various thermal processes, which frequently form the final stage in an overall concept, is the disposal (i.e. pollutant destruction, mineralization): a material transformation to allow an environmentally friendly disposal or release into air or water. In addition, an energy or, if possible, a material use should be viewed as further aims.

For a systematic representation it is effective to firstly establish an inner system boundary for the so-called "main thermal process". In a second step, the system boundary is enlarged to comprise the "overall process", i.e. inclusive of flue gas purification, utilisation of the generated gas.

3.1 MAIN THERMAL PROCESS

The field of the thermal treatment of waste belongs to the special field of high temperature process technology, whereby materials are treated thermally in so-called industrial furnaces, e.g. with the aid of combustion or the gasification of fossil fuels [14, 15]. Examples include the burning of cement in rotary kilns, the sintering of ore on blown through, moving belts etc. These types of apparatuses with appropriate process engineering elements are employed for the thermal treatment of wastes.

3.1.1 PROCESS ENGINEERING ELEMENTS AND MAIN ACTING VARIABLES

A discussion on the possibilities of process control must be preceded by a consideration of the main acting variables (figure 8). Not only the respective level but also the distribution of the main variables along the reaction path should be taken into account. As a rule, the input material (waste, residual waste) is specified and is described as a function of time with regard to consistency, composition and quantity. The oxygen supply allows a differentiation between thermolysis (pyrolysis), gasification and combustion. Thermolysis requires no oxygen supply.

The addition of heat causes drying, gasification and pyrolysis. For gasification, the oxygen is supplied such that understoichiometrical conditions are set. The oxygen added during combustion results in stoichiometrical or overstoichiometrical conditions.

The process control (adjustment of the level and distribution) of the variables along the reaction path can be influenced by numerous means as or when required. The oxygen concentration, for example, can be varied by air or fuel staging, flue gas recirculation, the supply of oxygen or inert gas, the state of the load, etc. Similar measures can also be considered to regulate the temperature along the reaction path, to limit the pollutants (e.g. NO_x) and influence the burn-out [16, 21 to 26, 29, 32]. Further possibilities to influence the process control include the separation into different reactor types, measures for a direct heat exchange (e.g. addition of gases, water spray) or an indirect heat exchange (e.g. radiation furnace, heat exchanger). Depending on the objective and type of input material (waste), it is possible to combine numerous measures, whereby the different tasks are executed one after the other in a series connection of reactors. In some plants (in particular in those of older construction), these various optimisation tasks have a limited success as the requirements (including legal) at the time of construction were correspondingly low. Consequently, an important aspect for plants to be developed further in the future is the series connection of elements whereby each element enables the fulfilment of a partial objective.

The scope of this survey allows for two examples of process control (for more details, see [7,17,18,27,28,35]):

> Figure 9 is a schematic diagram of a multistage combustion reactor for gaseous, liquid and powdered fuels (wastes). To avoid quench effects on the cold walls, a refractory lining should be selected for the actual reaction chamber; combustion and heat transfer should remain separate. A continuously stirred reactor (CSR) for mixing of reactants should be succeeded by a plug flow reactor (PFR) for burn-out optimisation [31]. Flue gas recirculation can be considered to regulate the temperature and oxygen concentrations. Finally, the task of pollutant minimisation could necessitate an air and fuel staging. Figure 9 and these keywords suffice to realise that the engineering is relatively complicated with correspondingly complex apparatus.
>
> Figure 10 depicts a separate process control for coarse and pasty wastes with gasification in the initial unit and subsequent multistage afterburning. In the first unit, a graduated supply of the reaction gas along the reaction path dries and degasses the solid which is subsequently gasified due to the on the whole understoichiometrical ratios. Non-lumpy materials can bypass the first unit and directly enter the afterburning (unit 2) in which, as the name suggests, the gases and dusts from the first unit also undergo afterburning. The 2nd unit can be depicted as an independent plant (fig. 9), i.e. the elements of a liquid fuel, gas or dust firing also occur in a plant for coarse and pasty wastes and/or in plants for compounds of coarse, pasty and liquid wastes.

In principle, this type of process control allows a separate optimisation with regard to burnout, primary measures for emission reduction for the coarse and pasty wastes in the 1st unit as well as for the gas and fly dust in the afterburning unit. Further combinations are of course possible, depending on the aims of the thermal treatment of waste. Figures 9 and 10 exemplify an arrangement of typical elements for process control.

3.1.2 APPARATUS

In the realisation of a process of thermal treatment, the input materials define on the one hand the possible apparatus which on the other hand determine at least partly the possible level of the main acting variables as well as the possibilities for their control along the apparatus (reaction path). Thus, for the thermal treatment of coarse wastes, for example, a grate is frequently required if a staged process control should be realised along the reaction path; for compounds of liquid and solid materials, it is usually necessary to fall back on a rotary kiln etc. Accordingly, the apparatus can be classified with regard to the set requirements, the main acting variables and their level and control along the reaction path. There are three main types:

• **combustion chamber**	(e.g. for gaseous, liquid and powdered materials; often employed in afterburning and gasification systems;. figure 11),
• **grate**	(e.g. for the solid conversion of household refuse in the 1st unit; figure 12),
• **rotary kiln**	(e.g. for the conversion of hazardous wastes in the 1st unit; figure 13).

Other types of apparatus are:

• **fluidized bed reactor**	(e.g. for the conversion of sewage sludge or other similarly prepared powdered to coarse residues with suitably small particle-size distribution in the 1st unit),
• **story furnace**	(e.g. for the conversion of sewage sludge and coarse materials in the 1st unit with the possibility of heat recovery from the ash),
• **continuous heating furnace**	(e.g. for the solid conversion in the 1st unit for processes with extremely long residence times,
• **blast furnace,**	
• **etc..**	

At this point, it should be emphasised that a careful distinction is to be made between the terms "process" and "apparatus". An apparatus can be employed in very different processes. A rotary kiln, for example, is employed not only for "hazardous waste incineration" but also in lines of development with pyrolysis processes [30]. Likewise for the "grate". Frequently used terms, such as "rotary kiln process" or "grate process" convey little about the actual process and can be even misleading.

3.1.3 SYSTEMATIC REPRESENTATION

The main thermal processes can be roughly divided into two thermal units as is depicted in figure 14. The first unit is for the treatment of coarse, pasty wastes and/or compounds of coarse, pasty and liquid wastes by thermolysis, gasification or combustion with the aim of

- producing an inert residue (ash or slag) with a correspondingly high burn-out (low values for ignition loss and TOC) and/or
- a material separation of solid solutions and/or
- a material or raw material recovery.

The second unit serves to convert by combustion or gasification

- the gas emitted after the 1st unit (flue gas, pyrolytic gas, gasification gas) and the associated fly dusts and
- the pyrolytic coke produced in the 1st unit after an intermediate treatment, depending on the objective.

If the 2nd unit is a combustion process (processes A,B,C in fig. 14), the combustion gases are used to produce, as a rule, either process steam or electrical energy by means of a boiler and a turbine. If the 2nd unit runs as a gasification (processes D, E in fig. 14), it is intended to produce a process gas (synthetic gas) which, however, with the addition of a subsequently added combustion (e.g. motoric) can also be employed to generate electrical energy.

With regard to the comparability of the processes, it is necessary to firstly define the identical objectives. Succeeding this, as many partial steps are to be combined until the objectives are fulfilled, i.e.

- until the same aim, i.e. the generation of electricity or process steam, for example, has been fulfilled and
- until each of the emerging material flows (remaining residue) meets the same requirements (elutriation of the residues, pollutant concentrations in the exhaust gas) and
- until each of the emerging material flows can be released directly into the environment or be directly utilised.

It is expedient, as mentioned above, to initially establish the system boundary only for the main thermal process (segmental balance). Subsequently, using the same objectives and the same requirements on the emerging materials, the system boundary is to be enlarged to cover the overall process. For the case of generation of electrical energy, the scope of the balance for the overall process should include:

- in classical combustion processes
    - ♦ the flue gas purifying plant,
    - ♦ the turbine and
    - ♦ the generator

and

- in a process with synthetic gas production
    - ♦ the additional combustion with a gas engine,
    - ♦ the purification of the accompanying exhaust gas of the engine,
    - ♦ the generator, etc..

The process concept A (fig. 14) is exemplified in figure 15 as a block flow diagram illustrating the system boundaries for the main thermal process and the overall process for a standard incineration of waste. The block flow diagram depicts within the system boundaries the more important components and their coupling, whereby the additionally required flows (auxiliary materials, electrical energy) and also existing flows (effective energy, heat loss, exhaust gas, residues) should be included.

Depending on the consistency of the waste, the first unit can comprise, for example, a grate system or a rotary kiln. As a rule, grate systems are currently in use for the incineration of household refuse and rotary kilns for hazardous waste. In most cases, air and occasionally additional oxygen are supplied as reaction gas for the incineration process. At present, the waste products are not as yet pre-treated with regard to the homogenisation of the combustion conditions, which is why a high air excess is frequently necessary to attain a low ignition loss at the end of the first unit of the process. As a rule, the residues are extracted from the grate system in the form of ash or in a sintered state and from the rotary kiln in a molten state. If, for reasons of comparability, a post treatment of the ash or suspended dust requires additional treatment units, these should also be integrated into the balance of the main thermal process. Using this method of examination, it is possible for processes which provide for a so-called integrated residual treatment (producing slag) to be evaluated on the same basis as processes in which a supplementary post treatment of the residues is necessary. In the process concept A (fig. 14), steam is initially produced which can be employed as an energy supply or, as mentioned above, acquires a use as process steam. A further discussion on the process concepts is given in section 6.

3.2 PRE-TREATMENT AND POST-TREATMENT

3.2.1 PRE-TREATMENT

To improve the course of the process of a thermal treatment [42, 43], it is often recommendable, if the effort is justifiable, to pre-treat the waste materials by

- crushing,
- separating,
- homogenisation,
- pollutant removal,
- beneficiation (by drying, briquetting, etc.).

As a rule, basic mechanical and physical methods of operation are employed (fig. 1). The extent of the pre-treatment unit depends in the first place on the waste products to be treated and the apparatus used in the main thermal process. The application of a fluidized bed reactor, for example, requires for the homogenisation and particle-size distribution, a considerably greater effort than that for a rotary kiln. The addition of an appropriate crushing unit before the grate of a standard incineration plant for household refuse could lower the air ratio considerably and an improved burn-out could be achieved. Plants without pre-treatment can be compared with plants with pre-treatment if a pre-treatment unit is hypothetically added. The effects of such a supplementary installation on the operation of the plant can then be investigated. In this way, one avoids undue comparison of newer lines of development with old-fashioned plants in which the stricter requirements of the present day cannot be fulfilled over a period of transition.

3.2.2 POST-TREATMENT OF RESIDUES FROM THE MAIN THERMAL PROCESS

In the thermal treatment of wastes and the ensuing purification of the flue gases, residues always remain in the form of slag, ash, or dust. The quantity, consistency and composition of the residues (e.g. slag discharge from the rotary kiln, ash, or sintered ash from the grate) are mainly dependent on the composition of the waste, the process control and the applied plant technology. In principle, the treatment of the residues can either be integrated into the main thermal process (see chapter 6) or, if required, be incorporated as an additional treatment into the system boundary of the main thermal process. Depending on the requirements made on the remaining residues, there are a variety of post-treatment processes, such as

- beneficiation (e.g. separation of metal from ash),
- solidifying (e.g. addition of a binding agent for the deposit of suspended dust),
- melting (e.g. melting of ash and suspended dust in order to convert these into a leached, utilizable residue),
- washing (e.g. the removal of easily soluble salts and heavy metals).

For a detailed description of the separate processes, please refer to the relevant literature. As was described above, a comparability of the plants is achieved by the series connection of as many segmental steps as necessary to fulfil the identical objectives.

3.2.3 GAS PURIFICATION

Gas purification belongs to the so-called secondary measures. It comprises the tasks:

- separation, reduction, destruction of pollutants from the process or exhaust gas (e.g. HF, HCl, SO_2, heavy metals, NO_x, PCCD/F) [40, 41, 48, 49, 58, 73].

A variety of different processes are available to achieve this aim. These themselves are implemented using different engineering elements. The scope of this report allows a description of only a few of the more common processes:

1. **filtering:** removal of particles using a cloth filter or dry/wet electrostatic precipitator;

2. **drying:** removal of the process and flue gas constituents SO_2, HF, HCl, heavy metals etc. by the injection of dry additives, such as activated coke hydrate or calcium hydroxide, fly dust, fixed bed reactors or moving bed reactors;

3. **quasi-drying:** removal of process and flue gas constituents SO_2, HF, HCl, heavy metals etc. by the injection of wash solutions (water and additive) which vaporise in the flue gas flow;

4. **wetting:** removal of process and flue gas constituents SO_2. HF, HCl, heavy metals etc. by washing (water and additive);

5. **SCR process:** reduction of nitrogen oxide using ammonia and a catalyst in a temperature range of 170°C - 350°C;

6. **SNCR process:** reduction of nitrogen by the addition of ammonia in a temperature range of 850°C - 1000°C;

7. **activated coke filter.**

The cleaning concepts are numerous. Appropriate concepts for a hazardous waste incinerator, a waste incinerator and a gas purifying unit are illustrated in figure 16.

It should be emphasised that the exhaust gas or gas cleaning processes frequently require that the plants are free of waste water as it is prohibited to allow waste water to flow into lakes, rivers and canals (fig. 2). It is currently under discussion whether this requirement is sensible from an energy and ecological point of view if an appropriate waste water purification process is available.

It is also worth pointing out that flue gas purifying plants are able to keep the emission limits listed in fig. 2, irrespective of a negative or favourable result in the main thermal process. Thus, it is understandable that now developments are concentrated on improving of the main thermal process. Endeavours are being made

- to reduce the energy expenditure,
- to lower the exhaust gas mass flow,
    - which would result in smaller flue gas plants and
    - an accompanying reduced energy expenditure,
    - smaller quantities of additives and
    - reduced pollutant transports etc.

For a long time, the main emphasis of development was attached to the reduction of pollutant emissions. In the future, more attention has to be given to energy expenditure (efficiency) and to the extent of exhaust gas and residual waste flows. As will be explained in the following section, it is necessary to firstly clarify how and what can be balanced and how an evaluation can be made.

4 BALANCING AND EVALUATION OF THE THERMAL TREATMENT PROCESS

As explained above, an evaluation and the comparability of processes necessitate uniform system boundaries, the same requirements on residual and exhaust gases and identical objectives with regard to the significance of the plant (e.g. generation of electrical energy or process steam). A lack of identical requirements renders a comparison useless.

4.1 MASS BALANCE

The term balance comprises firstly the comparison of the "sum of the entering and emerging flows" for a prespecified system under balance for identical units. It is expedient to itemise possible sources as supply (entering) and negative sources as removal (emerging) in the system boundary. The sum of the entering flows is thus equal to the sum of the emerging flows. It is recommended further to firstly draw up balances for the so-called "main thermal process" and then for the "overall process". Figure 17 exemplifies, based on fig. 15, a mass balance of the overall thermal process for a combustion-post-combustion process of household waste. To allow a clear representation, the individual mass flows should be numbered and each mass flow should possess the same number as the inherent energy flow. For formal reasons, "empty flows" also arise. Flow No. 8, for example, in the mass balance depicted in fig. 17 is an "empty flow" because in figure 18, No. 8 represents an electrical flow (energy flow not combined to mass flow). This formulation appears to be necessary as the term "empty flow" is adopted for example in a cumulative primary energy or material analysis. Thus, in the drawing up of a cumulative carbon dioxide balance, for example, i.e. a balance taking the primary energy conversion into consideration, it is necessary that the aforementioned "empty flow" No. 8 in fig. 17 is occupied by the quantities of CO_2 which arise in a power station for the generation of electricity, etc. [51]. Furthermore, such a formulation yields a clear representation from which all mass, material and energy balances can be processed using identical flow diagrams. In the drawing up of mass balances it is useful to differentiate between:

- input materials,
- additional fuels (natural gas, fuel oil, etc.),
- admixed materials (oxygen, air, water, limestone etc.),
- residues (slags, metals etc.).(To simplify, fig. 16 is not classified in detail.)

On the whole, a balance must depict which mass flows arise in addition to the input material (waste), how the material flows divide during the process and which material flows emerge from the system under balance.

4.2 MATERIAL BALANCES

Material balances differ from mass balances in that the masses of the materials involved are not considered in total, rather as individual materials, groups of materials or elements. Furthermore, it is the task of a material balance to determine how the quantities of a material contaminating the waste (e.g. a heavy metal) are distributed among:

- the residues (ash, slag etc.) from the first unit,
- the residues (ash, slag, etc.) from the second unit,
- the residues from flue gas purification,
- the exhaust gases leaving the stack, etc..

If the materials accumulate at certain points in the process, an appropriate discharge at these points should be attempted [57].

4.3 ENERGY BALANCES

Figure 18 depicts the energy balance inherent to fig. 15 and 17. Following the mass balance, an identical approach applies to this case also. A distinction should be made between energy flows which

- are coupled to the mass (enthalpy), such as
    - the calorific value of the waste, the calorific value of the supplementary fuel (natural gas, fuel oil, etc.),
    - sensible enthalpy of the flow (preheated air etc.)

and which

- are not coupled to the mass (process variables), such as
    - electrical current,
    - heat flow (heat flow due to energy loss, converted useful heat),
    - supplementary energy (external heating etc.).

In this way it becomes clear how much effort is required for the overall thermal treatment, how the energy flows are distributed within the process, how much useful thermal energy (here steam) can be decoupled from the process and which losses ensue.

The required primary energies are determined by drawing up a separate balance according to the same form (not illustrated here). The primary energies required for the ratios depicted in fig. 18 are summarised as the primary energy flow for the main thermal process (MTP) and that for the overall system (OS).

4.4 EFFICIENCY

Applying the relevant balances depicted in the figures, it is now possible to form criteria in the form of efficiencies to evaluate the individual systems under balance described above. In general, the term efficiency η is understood to be the ratio of success to effort [53, 54].

Depending on what is regarded as „success“ and „effort“, highly diverging efficiencies ensue for the given systems under balance (fig. 19).

Considering the system under balance of the main thermal process (MTP), the useful thermal energy flow $H_{th,use,MTP}$, decoupled from the exhaust gas flow and in the form of high-pressure steam, can be evaluated as "success". The "effort" is, in this case, the energy flow supplied with the residue H_W and the additional energy flows E_{MTP} required to operate the plant. The ratio success to effort yields the thermal efficiency for the main thermal process $\eta_{th,MTP}$ (fig. 19). Enlarging this analysis to cover the overall process gives the thermal efficiency for the overall system $\eta_{th,OS}$.

Next the additional energy supplied to operate the plant, the energy flow of losses for the conversion of primary energy (e.g. flow of losses for the generation of electricity in the power station) are also added to the "effort". The total of the primary energy flows H_{pr} required for plant operation are evaluated as effort:

- primary energy for electricity ($H_{pr}=E_{el}(1/\eta_{K,el})$),
- primary energy for oxygen production,
- primary energy to produce other auxiliary materials, etc..

In this way one obtains from the ratio success to effort the so-called primary efficiency for the main thermal process $\eta_{pr,MTP}$ and for the overall process $\eta_{pr,OS}$ (fig. 19).

If the useful thermal energy flow (e.g. high-pressure steam) is employed for the generation of electricity, the thermal efficiencies η_{th} and the primary efficiencies η_{pr}. thus yield, allowing for conversion losses, the respective electrical efficiencies $\eta_{el,th}$ or $\eta_{el,pr}$.

4.5 EFFORT FACTOR

The primary energy required for a thermal treatment could be preserved if there were no waste to be treated. Consequently, the net energy flow $H_{net,OS}$ of the overall process is given by deducting the required primary energy flow $H_{pr,OS}$ from the useful thermal energy flow

$H_{th,use,OS}$ (fig. 19). If the net energy flow $H_{net,OS}$ attained in this way is positive, then the effort factor a_{oS} is obtained by forming a ratio of this useful energy flow to the energy flow supplied with the waste H_W ($a_{OS} > 0$, fig. 19). In the case of a high primary energy requirement, the difference formed for the net energy flow $H_{net,OS}$ can assume a negative value, i.e., the waste is not able to run the process on its own enthalpy. In this case in the denominator of the effort factor the absolute value of the negative net energy flow has to be considered in addition to the energy flow from the waste ($a_{OS} < 0$, fig. 19). Then the lowest value cannot be lower than $a_{min} = -1$. The effort factor is generally only required for the overall process. In the case of a positive effort factor one obtains for the overall system with the efficiency of electrical power generation a corresponding electrical effort factor a_{el}, which is finally the determinative factor. The efficiencies and effort factors described in this report illustrate that depending on the interpretation and aims, quite different magnitudes are applied to evaluate a thermal treatment process. Consequently, it is not surprising that "efficiencies" for one and the same process are frequently cited between a few and 80 percent.

5 PRESENT STATE OF THE ART OF THERMAL TREATMENT PROCESSES

5.1 HOUSEHOLD WASTE AND SIMILAR WASTES FROM INDUSTRY

5.1.1 GENERAL ASPECTS

Very early, grate firing plants were used for thermal treatment of household waste. Reports for the use of "grates" for the "removal of sweepings" first appeared in the literature of the beginning of this century [5]. However, the grate was primarily used for the generation of steam and electricity with coal (lumpy charging material). With the development of pulverised coal firing, grate technology was pushed into the background. Later, during the 60ies, the grate became generally accepted for thermal treatment of household waste. Out of the experiences in the first decades of this century in the coal combustion [36, 37, 52, 62 to 66], as well as later discoveries in the field of combustion technology, reaction kinetics and developments in chemical analysis, the "grate" developed continuously.

51 thermal refuse treatment plants are now in use in Germany (figure 20). 49 of them are equipped with grate technology in the first unit, and two with rotary kiln technology. All of them have post-combustion in the second unit, so that these plants as a whole can be classified as waste incineration plants according to process A in fig. 14. No plants exist in the New Federal States right now, because in the former GDR, household waste was solely deposited in landfills. The grate has become widely accepted in the field of thermal treatment of household waste, as with this device, process conditions along the reaction path (grate path) are well controllable, which is highly advantageous, considering that the composition of waste and thus its reaction behaviour changes continuously [34, 39, 59]. Approximately 30% (8

mio. t/a) of household waste and similar wastes from industry are thermally treated at present. In addition to the comparatively lumpy household waste, dewatered sewage sludge (pasty) can be fed to the grate [61].

Often, several lines exist in one location. Waste throughput is adjusted to requirements of the area served and ranges from 2 to 23 t waste/h per installed line. Total capacities per site range from 15000 t/a to 500000t/a.

5.1.2 DESCRIPTION OF THE PROCESS TECHNOLOGY

By way of example, figure 21 shows a profile of a thermal treatment plant as it is generally used today. fig. 15 represents a block flow chart, the fig. 17, 18, 20 and 23 depicts an example of mass and energy balance. Essential components of the main thermal process as shown in fig. 21 are, apart from waste hopper with breaker for bulky materials, charging plant and charging bunker, grate, post-combustion chamber, heat exchanger (boiler plant) and ash hopper. Extending the scope of balancing to the overall thermal process, spray absorbers, cloth filters, suction draught ventilators, scrubbers, devices for monitoring analyses and chimney are to be mentioned for flue gas purification. The two parts "grate" and "post-combustion" represent the core of thermal treatment.

The conversion of solid matter on the grate can be influenced along its path by various measures, which, as already mentioned, has many advantages, considering the continuously changing composition of the waste and its reaction behaviour. This allows appropriate adjustments and regulations also in the course of operation runs.

The following should be mentioned particularly:

- changing distribution of primary air (4 zones in fig. 21),
- changing grate element speed (conveying speed) for the purpose of changing residence time and residence time behaviour (e.g. 0.5 h to 2 h) of the bed,.
- supplementary control of bed height via feeding speed,.
- feeding additives to the bed (lime products for the treatment of noxious matters, to influence ash characteristics, etc.)

Drying, degassing, gasification, and burn-out processes as well as characteristics of ashes can be influenced by these measures [19]. However, it has to be noted that, as a rule, primary air also has the task to cool the grate elements. In order to protect them from overheating, such a large primary air volume flow is often required, that for the grate alone, an excess air coefficient of $\lambda = 1.4$ results. This means, that maximum ash temperatures of 850°C to 950°C can be achieved, and consequently, that residual matter cannot be drawn off as slag (liquid). With regard to eluate behaviour, it is shown [20] that 950°C can be sufficient. However, it has to be explicitly stressed, that an additional melt-down unit has to be installed downstream, if fused mass (slag) is to be obtained.

With regard to project design, process control can be further influenced by:

- the type of grate (travelling, drum, advancing and reciprocating grate, etc.) (in fig. 21, reciprocating grate) and by
- conducting the gas flow immediately above the grate (parallel flow, countercurrent and main stream conductance; in fig. 21, countercurrent conductance); (for a more detailed characterisation of the device, see fig. 12).

The grate is followed by the post-combustion unit. At its entrance, secondary air is blown in, in order to intensify mixing of the products for post-combustion (for jet mixer unit, see fig. 9). This is followed by a zone more or less intended as burn-out section (plug-flow unit, fig. 9). The high primary air flow required for the grate, as mentioned above, necessitates additional fuel (plus tertiary air), provided that a temperature of about 1200°C is to be reached in the post-combustion chamber. Residence times range from one up to several seconds. In a number of plants, measures as explained in fig. 9 are applied to a growing extent, including recycling of flue gases (also as replacement for secondary air), staging in order to reduce NO_x (for a more detailed characterisation of post-combustion and/or combustion chamber equipment, see fig. 11).

5.1.3 PROCESS MATERIALS AND RESIDUAL MATTERS

Operation of a plant for thermal waste treatment requires a number of process materials, such as combustion air, oxygen, nitrogen, water, hydrochloric acid, caustic soda lye, liquid ammonia, limestone, etc. The number and amount of process materials largely depends on plant engineering, particularly on the design of the flue gas purification plant. The material flows required are shown for one example in a simplified mass balance (fig. 17). In the 1st unit of the main thermal process, a grate is used, the 2nd unit comprises a post-combustion chamber.

Residual matters from a plant for thermal refuse treatment can be allocated to the following four components of the plant:

1. Ash and boiler slag from grate, post-combustion chamber and boiler

   The majority of ashes (1.8 mio. t/a) from grate plants in Germany are presently used as building materials. The remainder (0.8 mio. t/a) is deposited on landfills above ground [38]. It is being discussed, whether ashes should be subjected to post-treatment in a smelting process. The meltdown process has the goal to convert mineral substances into extraction-safe granulates, to tie up heavy metals and chlorides or to reclaim them as valuable substances, after upgrading.

2. Filter dust from dust precipitator

   Filter dust (0.21 mio. t/a) mainly contains heavy metals, soluble salts and organic, noxious matters as e.g. dioxins and furanes. The dust is either directly deposited above or underground, or it is neutralised with additives such as cement and then deposited or subjected to post-treatment in a smelting process

3. Reaction salts (e.g. NaCl, $CaCl_2$), hydrochloric acid, gypsum, water, sludges, additives from flue gas purification

   The type of residual matters exiting from flue gas purification plants (0.11 mio. t/a) mainly depends on the purification process applied and the additives used. As a rule, only gypsum from wet flue gas purification can be won as immediately useable product. Other residual matters currently are deposited above ground, due to lacking exploitation facilities.

4. Exhaust steam residues from evaporation plants

   When an evaporation plant exists, sludges, beside process waters, are disposed of by thermal process (see below). As a rule, exhaust steam residues are deposited in underground cavities.

5.1.4 RESULTS AND EVALUATION

The primary goal of thermal treatment of household waste is, first of all, disposal, i.e. to decompose organic substances introduced by the refuse as far as possible, to obtain a well-calculated decrease for selected noxious matters, to achieve inertness of the residual matters and to relieve pressure on landfill space. The goal of energetic utilisation of waste by steam generation and conversion into electric energy is only secondary. Location of the plant permitting, a district heating network is often operated in addition. Material utilisation, e.g. use of steam as process steam in industrial operations, is rare.

In summary, the following findings have been made with the overall thermal process in household waste treatment plants equipped with grates:

- safe, well-perfected technology, tested over many years, broad experience gained in the operation of approx. 50 plants;
- no limitations of flexibility with regard to throughput, composition of waste and calorific value for typical household waste and similar wastes from industry;
- plants work at an availability rate of more than 7500 hours per year and are very flexible in their operation;
- there is still considerable development potential in process control for grate technology (see chapter 6);
- legal requirements according to fig. 2;
- post-treatment of residual matter is not integrated into the process, when post-treatment is necessary, additional processes have to be installed (e.g. melt-down process).

As the majority of plant complexes in the meantime fulfil legal requirements (emissions) as shown in fig. 2, mass and energy balances are to a growing extent being relied on for evaluation and assessment purposes. Of particular interest in this context are mass flows of process materials and residual matters, flue gas mass flows and connected loads of noxious matters, as well as efficiency and effort factors.

Only individual examples are suitable for evaluation. For this reason, a typical example is briefly explained in the following chapter. Our examination focused on an combustion - post-combustion process (fig. 15, process A in fig. 14), with the grate in the first unit of the main thermal process. The operational goal is power generation. Simplified mass and energy balances are shown in fig. 17 and 18. Values relate to a refuse mass flow of 1000 kg/h (calorific value of h_u = 10.6 MJ/kg). In figure 22, the respective mass balance, relating exclusively to the main thermal process, is, by way of example, broken down in more detail. In addition to that, flue gas mass flows created during transformation of primary energy for the generation of electricity in the power plant are also taken into account. These flows are diverted around the process elements and, as shown, hypothetically united with the emerging flue gas mass flow. Also in figure 23, the energy balance for the example considered is broken down in more detail in the form of a flow chart solely showing the main thermal process. Here too, primary energy flows for power generation are taken into account as well, with the respective primary energy loss flows (assumed as $\eta_{P,el}$= 0.33 here), being diverted around the individual process elements as in the mass flow chart, and being combined as loss flows at the end of the process.

Similar flow charts result, in analogy to fig. 22 and 23, for the process as a whole, which however, are not shown here. With the aid of the energy balance (fig. 18), the efficiency and effort factors shown in a generalised manner in fig. 19, can be concretely defined for individual examples. For the main thermal process [55] considered here, and taking primary energies into account, a primary efficiency factor of $\eta_{pr,OS}$ = 69% results. When primary energy is deducted from the useful thermal energy flow of the overall process, an effort factor of a_{OS} = 65% results. Assuming utilisation of the steam for power generation, this results in an electrical effort factor of approx. a_{el} = 21 % for the process as a whole. When a melt-down unit run with fossil fuel is added, to convert the ash to slag; the electrical effort factor decreases to a_{el} = 17% and to a_{el} = 13% if electrical energy is used.

5.2 HAZARDOUS WASTE

5.2.1 GENERAL ASPECTS

Hazardous wastes often occur as mixtures of solid, pasty and liquid substances, also including barrels containing partly unknown waste (e.g. waste from hospitals). For such mixtures, the "grate" is unsuitable (e.g. because of the liquid portion). For this reason, the "rotary kiln" (fig. 13) is preferred for hazardous wastes. This technology originates from the industrial furnace sector, where it is used for thermal treatment of materials for industry (e.g. cement). At present, 29 plants for thermal treatment of hazardous waste are in operation in Germany. Plant site locations (fig. 20) are mainly distributed across larger industrial areas and the plants are partly equipped with several lines. Typical capacities per plant line are 10000 to 35000 t/a.

5.2.2 DESCRIPTION OF THE PROCESS TECHNOLOGY

Figure 24 shows, by way of example, a plant for the treatment of hazardous waste. Here too, fig. 15 shows the related block flow chart. The 1st unit of the main thermal process, however, has to be imagined as a rotary kiln (tilted cylinder with refractory lining). Principal components of the main thermal process, apart from waste hopper, charging system and barrel lift, mainly are rotary kiln, post-combustion chamber and heat exchanger (boiler plant). The flue gas purification plant downstream comprises the components electrostatic precipitator, multistage flue gas scrubber, suction draught ventilator and chimney [33, 39, 70, 71, 72].

In summary:

- Practically any waste consistency (including containers) can be fed, which is the top priority for the case at hand.
- Rotary kilns for hazardous waste are designed with diameters between 1 m and 5 m and lengths between 8 and 12 m, in exceptional cases up to 20 m.
- Because of very fast evaporation and degassing reactions of combustibles immediately after charging due to waste heterogeneity sufficient oxygen has to be readily available, i.e. air ratios of about $\lambda = 1.8$ to 2.0 are required. If the contents of the charged barrels is known beforehand, than additional oxygen can be injected in short intervals. This additional well defined oxygen supply allows lowering of the air ratio.
- Oxygen distribution along the reaction path is hardly controllable in contrary to the grate process.
- The residence time of solids (e.g. 0.5 h to 1. h) can by varied by continuous speed adjustment (typical speed values are 0.05 to 2 rev./min.) and the degree of filling of the kiln (e.g. typically, 20 % of the cross section of a kiln are covered with waste) via waste mass flows. Typical waste mass flows range from 0.3 to 20 t/h.
- The rotary kiln may be constructed as parallel flow or as countercurrent device. For hazardous waste, which usually has a high calorific value, parallel flow operation prevails. Countercurrent operation is applied for waste with low calorific value (hu < 8 MJ/kg) (heating up of waste in countercurrent).
- Temperatures within the rotary kiln (particularly burn-out) range from 900°C to 1200°C (partly also higher). In case of low calorific values, additional fuel has to be added through support burners, if necessary. In any case, care is taken that, depending on their composition, residual matters can be drawn off in a molten state. Generation of the smelting phase is thus integrated into the process.

The rotary kiln with slag outlet is followed by the post-combustion chamber. Here, legal requirements for the incineration of hazardous waste, such as

- balance temperature of 1200°C (statutory) and
- prescribed residence time of 2 s minimum

are fulfilled.

Further the remarks for post-combustion listed in the previous chapter 5.1 apply here.

5.2.3 PROCESS MATERIALS AND RESIDUAL MATTERS

The types of process materials used in a plant with a rotary kiln differ only insignificantly from those applied in a plant with a grate. Contrary to a grate process, inert substances leave the rotary kiln in a molten state. Slag is cooled down in a wet outlet process and then either deposited in a landfill or used as building material. Mass flows of process materials and residual matters, however, vary widely depending on waste composition.

5.2.4 EXPERIENCES AND EVALUATION

Here too, the primary goal is disposal. In many cases, energetic utilisation is not possible, due to increased expenditure (see below).

In summary:

- safe, well-perfected technology, tested over many years, broad experience gained in the operation of approx. 30 plants;
- very high flexibility with regard to the range of wastes, throughputs and calorific values;
- availability rates of plants amount to more than 7500 hours per year;
- development potential primarily with respect to automatic control of operation and logistics for charging waste of rapidly changing consistency, application of oxygen enrichment, decrease of excess air by pre-treatment of waste (if possible), etc.;
- legal requirements according to fig. 2;
- post-treatment of residual matter (smelting) is integrated into the process.

In the same manner as in the chapter on thermal treatment of household waste, compilation of mass and energy balances, as well as calculation of efficiency and effort factors is, by way of example, shown for the treatment of hazardous waste in a rotary kiln. The basis is a waste mass flow of 1000 kg/h as a mixture of solid, pasty and liquid shares with a calorific value for the mixture of h_u = 10.2 MJ/kg (fig. 6.2). A mass flow chart for the main thermal process of an combustion - post-combustion process with natural gas as additional fuel, is shown in figure 25 ; figure 26 contains a energy flow chart [53]. This example is not valid for the plant shown in fig. 24. The energy balance of the overall process (not explained in detail here) results in a primary efficiency factor of $\eta_{pr,OS}$ = 46%, the effort factor amounts to a_{OS} = -33%. This only represents thermal disposal of the waste. The energy input only by the waste is not sufficient to run the process in this case. This is mainly caused by the required high excesses of air and the additional fuels, which are often necessary in order to obtain a minimum balance temperature of 1200°C in post-combustion. Improvements can be achieved by oxygen enrichment of the combustion air, by pre-treatment of the waste (if possible) in order to achieve a decrease of the high stoichiometry factor, etc. (see e.g. [53]).

5.3 SEWAGE SLUDGE

Thermal disposal of sewage sludge will only be mentioned briefly, reference is made to the relevant literature [13, 74 to 77, 113, 115].

As explained in the introduction already (chapter 2.3), thermal treatment of sewage sludges will grow considerably on account of current regulations laid down in the "TA Siedlungsabfall"[***]. Presently however, only 10-12% are covered, with the following distinctions.

> Combined incineration (co-incineration) with household waste [e.g. 77] as described in chapter 5.1. exists. Because of odours emitted during transportation to the thermal treatment plant, the sludge is first subjected to anaerobic sterilisation. Mechanical dewatering suffices before charging the grate with sludge together with household waste. It is also possible, to "throw" the sludge via a separate charging roller onto the refuse lying on the grate (incineration stock bed). A share of up to 20% of sewage sludge is possible without any considerable effect on reaction conditions on the grate as described above.
>
> Isolated incineration (mono-incineration) of sewage sludge.
>
> For mono-incineration of sewage sludge, dewatering to dry substance contents of at least 30% are required, which can still be obtained mechanically. Digested sludge (ripe sludge) allows self-fluxing incineration only from dry substance contents of approx. 50% onwards. This percentage range can be achieved in part with thermal drying. However, digestion for reasons of odour avoidance is not necessary, when the sewage sludge can be transported to the thermal treatment plant by pipeline.
>
> Incineration can be performed in a fluidized bed reactor as 1st unit of the main thermal process, with temperatures to be reached, or maintained (amongst other reasons in order to avoid softening of ashes) ranging at 800 to 950°C. Post-combustion as the 2nd unit follows directly in the freeboard above the fluidized bed. It is thus coupled directly to the fluidized bed, so that the entire conversion of matter practically occurs in one single reactor.
>
> Mono-incineration of sewage sludge is also performed in story furnaces as first unit of the main thermal process. In this process, combustion air and flue gases

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[***] Technical Instruction Pertaining to Civilization Refuse

are conducted in countercurrent to the sewage sludge, which progresses downwards from one deck to the next. The hot ashes in the lower decks can be used for pre-heating combustion air (heat recovery from the stock). The heat recovery of the story furnace is thus similar to that of the tunnel furnace (e.g. in the brick manufacturing industry). Post-combustion is often designed as separate post-combustion chamber, to which previous statements (e.g. fig. 9) apply. Ashes from domestic sewage sludge are similar to the ones from household waste plants.

Finally, incineration can also be performed through pulverised stock firing (e.g. use in power plants), requiring thermal pre-drying to 90% dry substance contents (fully dried) and enhancement for the transportation of the pulverised matter similar to that applied in pulverised coal burners. Full drying is performed with efficient energy utilisation by heat recovery plants etc.. Incineration in power plants does not incur technical problems, however, it encounters difficulties with being accepted in the course of approval procedures.

6 FUTURE DEVELOPMENTS

Currently, a large number of thermal processes is under development. However, not only "new" processes, also advancement and development potential of existing processes should be taken into consideration. New as well as existing processes can be allocated to the categories shown in the diagram in fig. 14. This chapter 6 is divided in accordance with the abbreviations A to E allocated to the individual processes outlined there. Only those developments discussions are currently focused on can be represented here.

6.1 INCINERATION-POST-COMBUSTION-PROCESS (A)

As explained in chapter 5, classic processes of thermal treatment are to be allocated to this category. As the steps of advancement outlined below do not represent basic changes in the process flow charts, reference is made to fig. 15, 17, 18, 22, 23.

6.1.1 ADVANCEMENT OF THE CLASSIC PROCESS (HOUSEHOLD WASTE)

(Application of grate and post-combustion chamber)

a) Grate with cooling by primary air

- Apart from varying primary air distribution, experiments with different grades of oxygen enrichment in various zones of the grate are being conducted in industrial plants [34]. This allows additional improvement of burn-out (ash of landfill category I) and reduction of the flue gas flow. Furthermore, the gas flow streaming through the bed is reduced, which leads to a diminution of flue dust volumes and of the diameter of flue dust particles (improvement of dust burn-out in the post-combustion chamber). With a view to the function of primary air as grate cooling agent (avoidance of over-heating) however, these options for oxygen enrichment can only be applied to a very moderate extent (e.g. O_2-enrichment up to 30%).

- Mixing conditions at the entrance of the post-combustion chamber are optimised by blowing in not only secondary air, but also flue gas, which is drawn off upstream of the flue gas purification plant. Thus, the post-combustion chamber is separated from the grate and at its entrance, a CSR zone and following PFR zone (see fig. 9) is created, facilitating further improvement of the burn-out of gas and dust.
- By the last-mentioned measure, i.e. replacement of secondary air by recirculating flue gas, the flue gas flow of the plant as a whole, and thus also the load of noxious matter, is reduced.
- Depending on requirements, also the other options for influencing processes within the post-combustion chamber as shown in fig. 9 (cascading, NO_x-reduction, etc.) are applied to a growing extent.
- In pilot plants, where post-combustion chambers can be operated completely separate from the grate, i.e. not only fluidically but also geometrically (e.g. by means of a pipeline) [27, 101], further improved options for optimisation become apparent. This is due to the fact that with respect to the task at hand (e.g. combustion of additional fluid waste with air cascading, blending in gases emanating from the grate, etc.), no attention has to be paid to possible influences on the process taking place at the grate, as this may be the case with post-combustion chambers, the body of which stands in immediate connection with the zone above the grate. Higher consideration should be given to this point of view when planning new plants in future.

b) Water-cooled grate

- Water cooling of a grate requires a far greater input of design than cases, where cooling is only achieved by primary air.
- However, this has the advantage that, contrary to grates cooled solely by primary air, distribution of primary air can now be modified without having to pay any attention to design (cooling) [92]. The measures and their accompanying advantages as mentioned under item 6.1.1.a) can thus take a far more definite effect. Excess air coefficient, flue gas and flue dust flows can be further reduced, temperature can be increased to such an extent (e.g. 1000°C), that ashed are sintered or smelted, which may satisfy e.g. elutability [20] requirements.
- Furthermore, water cooling has the advantage [92]
  - that wear and tear caused by thermal influences decreases and that no thermal overloadoccurs, even in case of high calorific values.

    - that fall-through through the grate is reduced (lower expansion permits narrower gaps between grate elements).
- Concerning post-combustion, statements concerning item 6.1.1.a) apply.

Finally, development efforts aiming at improved regulation with the aid of infrared cameras are to be mentioned. These cameras monitor the grate bed and discover by measuring temperature fields where the main reaction zone is situated. This zone can, by re-distribution of primary air, be moved towards the entrance or the exit area of the grate in a controlled manner and according to requirements [85, 89, 94].

Also, work is performed on simplified mathematic models of the solid matter conversion on the grate [78, 79, 82, 86, 91, 93] which are to support on-line process control with regard to the expected dynamic behaviour of operational interventions.

In addition to the points named here there is a series of developments to further improve the standard proecss for thermal treatment of household waste [80 to 84, 87, 88, 90].

If residual matter is to be drawn off liquid in the form of slag, it has to be clearly stressed, that in such a case, in spite of the advancements mentioned above, it is still necessary to smelt the residual matter originating from the grate (e.g. 300 kg/t domestic refuse) in a downstream process, which has to be included into the balancing scope of the main thermal process. As previously mentioned in chapter 5.1, the electrical effort decreases by adding a melt-down plant run by fossil fuel from a_{el}=21% (a_{el}=18%; h_u=10 MJ/kg [94]) to a_{el}=17% (a_{el}=15% [94]) For an electrically powered melt-down plant the factor decreases to a_{el}=13 % (a_{el}=12% [94]).

6.1.2 ADVANCEMENT OF THE CLASSIC PROCESS (HAZARDOUS WASTE)

(Application of rotary kiln and post-combustion chamber)

- Efforts are taken, to "smooth" the highly varying, instationary operational conditions within the rotary kiln by more elaborate logistics in waste feeding (compilation of "waste menus") and by upgrading waste (where possible), in order to lower e.g. the input of additional fuel quantities (primary energy) [117, 118].
- The input of additional fuel (primary energy) can be further reduced by enriching combustion air with oxygen, with other process conditions remaining constant [53]. Savings in additional fuel by far exceed the required primary energy for oxygen generation.
- If one succeeded in achieving operating conditions within the rotary kiln with only very low fluctuations, thus permitting a reduction of the excess air coefficient, then this measure in turn would, considering the input of primary energy, be more effective than oxygen enrichment [53].
- The measures mentioned above deserve particular attention against a background of sinking calorific values of hazardous waste and a rise in the

share of solid waste in future, whereas the temperature level (1200°C) will have to be maintained.

6.2 THERMOLYSIS POST-COMBUSTION PROCESS (B)

6.2.1 „SCHWELBRENNVERFAHREN NACH SIEMENS-KWU"

(Application of rotary kiln and separate post-combustion chamber)

In the „Schwelbrennverfahren nach Siemens-KWU" [95 to 98], the process-technological elements of thermolysis and combustion are arranged in series (figure 27 and 28). Overall goals are separation of valuable substances after the thermolysis unit, draw-off of molten slag from the post-combustion chamber (integrated slag draw-off), generation of process steam, heating steam or electric energy and a considerable reduction of the flue gas flow as compared to the classic procedure, to a value equivalent to combustion at an excess air coefficient of $\lambda \approx 1.3$. Residual refuse, unsorted domestic, industrial and bulky waste as well as sewage sludge as admixture to the wastes mentioned above are thermally treated. The low-temperature combustion process was preceded by a relatively long development phase. In 1988, Siemens erected a demonstration plant for a throughput of 0.2 t/h household waste at Ulm. Currently, a plant for a throughput of 1 t/h household waste is being tested in Japan. At Fürth (Germany), a plant with a capacity of 100000 t/a is being built (2 lines), which is to process a mixture of household waste, industrial and trade waste together with sewage sludge (calorific value 8.4 MJ/kg). In summary, the features of the process (figure 27) can be described as follows:

- Pre-treatment of waste to "fine refuse" by shredder.
- Thermolysis (so-called "pyrolytic conversion") of fine refuse in an indirectly heated rotary kiln at approx. 450° and residence times of approx. 1 h.
- Treatment of residual matter leaving the rotary kiln by separation into metals, pyrolysis coke and inert matter with the aid of magnetic separation, screening, grinding, etc.. Valuable substances can thus be extracted (reclamation of valuable substances).
- Propelling pyrolysis gas and conveying pyrolysis coke, as well as remaining fractions containing carbon, etc. into the post-combustion chamber, which is operated completely separate (by means of pipelines etc.) from the rotary kiln and can thus be optimised.
- Post-combustion chamber: the fuels pyrolysis coke and pyrolysis gas are incinerated with air. As feeding of pyrolysis coke can be adjusted to fluctuations in pyrolysis gas, combustion at an excess air ratio of about $\lambda = 1.3$ and, in combination with the calorific values, a balance temperature of about 1300°C is possible, thus permitting liquid draw-off of residual matter (slag). Combustion itself can, if required, be performed in several stages (see fig. 9). In correspondence to the low excess air ratio, lower flue gas mass flows result.

- Heat is drawn off through a steam boiler.
- Flue gas purification plant, consisting of electrostatic filter, fibrous filter, dual-stage dust scrubber, De-NO_X-Plant (SCR), flux reactor, fibrous filter.
- Utilisation of steam for process steam, district heating, generation of electric power.

The following applications have been reported for residual matters leaving the plant:

- ferrous metals and non-ferrous metals are fed into a metallurgical process;
- stones, glass, ceramic particles (≥ 5 mm) can be used for landscaping or road construction purposes,
- the granulate from the smelting process can be used as additive in the building industry;
- residual matter (salts, adsorbents, etc.) from waste-water-free, flue gas purification are deposited in landfills;

When the process is utilised for power generation, the electric effort factor for the entire plant is reported to be $a_{el} = 16\%$ [96] for a given heating value h_u=10 MJ/kg.

6.2.2 „DUOTHERM VERFAHREN“

(Application of grate, rotary kiln and post-combustion chamber)

Figure 29 shows a block flow chart. In a thermal pre-treatment unit, solid waste is subjected to a pyrolytic process on a grate. Heat is introduced directly through highly under-stoichiometric combustion of the generated pyrolysis gases by feeding in oxygen above the grate bed. As a whole, this process may hence also be called gasification. Process gas, flue dust and pyrolytic residues are than fed into a rotary kiln serving as 1st combustion unit (excess air coefficient $\lambda > 1$), from which residual matter is to be drawn off as liquid. Flue gases and flue dust are then subjected to post-combustion in a combustion chamber (2nd combustion unit). Thus, the "grate", "rotary kiln" and "combustion chamber" are arranged in series in three units in this so-called "Duotherm Verfahren" by "Von Roll" [99]. This serial arrangement of pyrolysis (solid matter on grate) and combustion allow this process to be categorised under "B" (fig. 14). However, one could also consider the two combustion units as "classic process" and thereby categorise them under "process A" (section 6.1.), with pyrolysis on the grate classified as some kind of auxiliary, initial thermal enrichment process. This process is in the planning stage.

6.2.3 „THERMOCYCLING VERFAHREN“

(Application of rotary kiln (thermolysis), rotary kiln

(combustion) and post-combustion chamber)

The process [100] is to be mentioned here, because it provides for part of the waste materials (hazardous waste) thermolysis (indirectly heated pyrolysis cylinder serving as rotary kiln) as pre-treatment, followed by a 1st combustion unit with rotary kiln and a 2nd combustion unit in a post-combustion chamber. The aspect stressed as essential in this process is, that for combustion, no air, but only oxygen is provided, with the oxygen being mixed with recirculated flue gas (flue gas recirculation). By doing so, the nitrogen load of combustion air is, as compared to customary plants, replaced by $CO_2$and H_2O ("SYNAIR", i.e. synthetic air) and the flue gas mass flow through the chimney is reduced accordingly (reduction of load with noxious matter, while fulfilling emission values as shown in fig. 2). The process is in the planning stage.

6.3 GASIFICATION POST-COMBUSTION PROCESS (C)

6.3.1 ADVANCEMENT OF THE CLASSIC PROCESS FOR HOUSEHOLD WASTE

(Application of grate and separate post-combustion chamber)

In a gasification process (e.g. stoichiometric coefficient $\lambda \approx 0.4$), just as in a combustion process, almost complete conversion of solid matter can be achieved, with a correspondingly small loss at red heat (e.g. by 1%) in the residual materials [101]; hence, pyrolysis coke is avoided. Enrichment of residues from gasification and withdrawal of valuable substances is possible as well.

Essential for achieving this goal and for optimising the process is, that the main influencing variables (fig. 8) along the reaction path are controllable. Thus, the "grate" appears to be suitable. Gasification gas and flue dust are subjected to post-combustion in a post-combustion chamber. Figure 30 shows a block flow chart. The process is intended for household waste and various combinations of devices are presently under development or have already reached the test phase [92]. Characteristics can be outlined as follows.

- A grate appears to be advantageous for obtaining the goal of an optimum degree of conversion (avoidance of pyrolysis coke) in so far, as - this was already mentioned several times - main influencing variables (fig. 8) along the reaction path are very well controllable.
- When gasification of "normal domestic refuse" (section 2) on the grate with primary air distributed along its length is performed in such a way, that a primary air coefficient of about $\lambda = 0.3 - 0.5$ is obtained, bed temperatures of about 850°C to 900°C result. In this case, water cooling is not required.
- A water cooled grate [92] has the additional advantages indicated in section 6.1.1.b (primary air flow and distribution can be varied irrespective of cooling problems). With high as well as low calorific values, control of the primary air coefficient according to requirements is possible, increasing flexibility with regard to utilisation of different types of refuse.
- Residual matters at the exit of the grate can be separated into metals and inert substances, following enrichment (withdrawal of valuable substances).

- Taking a primary air coefficient of $\lambda \approx 0.4$ to 0.5 as a basis, gasification gas is obtained, which has a sufficiently high calorific value for performing independent, gradual combustion (secondary and tertiary air), if required with flue gas recirculation (reduction of CO_2, C_xH_y, NO_x, etc.) in a post-combustion chamber [17, 101]. The latter should be completely separated from the grate (connection via short pipeline with refractory lining, or similar), in order to be able to optimise gasification and combustion independently of each other. As the gasification gas itself comes with temperatures of approx. 600°C to 700°C, temperatures of about 1300°C or more can be reached in the post-combustion chamber, permitting liquid draw-off of inert substances (integrated slag generation). The separate post-combustion chamber has the additional advantage of facilitating take-in of other gaseous, liquid and dusty residues (see block flow chart 30, diagram according to fig. 10, as well as layout diagram of a pilot plant according to figure 31).
- Furthermore, with a primary air coefficient of $\lambda \approx 0.4$ to 0.5, total air coefficients (including secondary and, if required, tertiary air) of about $\lambda_{ges} \approx 1.2$ can be achieved [101], signifying a considerable reduction of flue gas flows as compared to those mentioned in chapter 5.1, and thus also a reduction of noxious matter loads.
- The low primary air coefficient also leads to considerable reduction of the flow rate through the bed and thus considerably reducing flue dust [101].
- As these developments represent an advancement of the combination grate and (separate) post-combustion chamber, the gasification-post-gasification process may, in the case at hand, also be classified as advancement of "classic household waste incineration" as described in section 5.1..

6.3.2 „PLASMOX VERFAHREN“

(Application of rotary feed table and separate post-combustion chamber)

The so-called „Plasmox Verfahren“ represents a process for particularly toxic wastes requiring special treatment, contaminated soil, etc. [102, 103]. The first unit of the main thermal process consists of a refractory lined, parabolic, rotary feed table, which is charged with the waste. The rotary plate revolves under a fixed plasma torch, which, apart from the waste, effects considerable additional input of electric energy. Oxygen supply can be controlled independently. In this manner, very high balance temperatures of about 1800°C and more can be achieved. As operation in batches is also possible, residence times for the liquid phase generating from the inert substances (slag) can be prolonged "indefinitely". Due to the high input of electric energy, this process is, as already mentioned, applied for particularly toxic substances.

Flue gases are mixed again and incinerated in a separate post-combustion chamber. This is followed by steam boiler and flue gas purification.

6.4 THERMOLYSIS - POST-GASIFICATION PROCESS (D)

6.4.1 „KONVERSIONSVERFAHREN NACH NOELL“

(Application of rotary kiln with separate "combustion chamber"

as a high-pressure high-temperature gasification reactor)

The „Konversionsverfahren nach NOELL“ (figure 32 and 33) is to be explained here by way of example [104 to 106]. Goals of the process are separation of valuable substances after thermolysis (pyrolytic rotary kiln), generation of synthetic gas in a flux gasification plant, high pressure (35 bar), high temperature (1400°C), and draw-off of molten slag from the flux gasification reactor.

The two elements thermolysis and flux gasification have been developed independently of each other. In 1984, test operation on industrial scale of the "Pyrolyse-Anlage-Salzgitter" (pyrolysis plant Salzgitter) started. The centre piece of the plant was an indirectly heated rotary kiln with a diameter of 2.8 m and a length of 28 m. The plant was designed for a refuse throughput of 6 t/h. A four year trial period provided layout data for various types of refuse (used tires, plastic materials, sewage sludge, shredder waste, etc.) as well as findings with regard to plant engineering. In the same year, test operation on industrial scale of a 130 MW-flux gasification plant for the generation of city gas was initiated at the "Gaskombinat Schwarze Pumpe" (gas combine black pump) in the former GDR. Development efforts focused on pressure gasification of soft coal (30 t/h), used oil, tar and tar-oil sludge. In 1993, both processes were combined in the concept of the „Konversionsverfahren nach NOELL“, which arranges thermolysis and flux gasification in series. It is planned to utilise the gas generated in the gasification process as synthetic gas in the chemical industry, or to burn it in a power generator process, or in a motoric incineration process for the generation of electric power (refer e.g. to figure 32). Currently, a pilot project (as a test plant for the time being) on a 1:1 scale is planned at Northeim, which is to be operated as an industrial plant later. It is designed for a total waste volume of 100000 t/a (14.3 t/h). The refuse designated for thermal treatment shall consist of 84% household waste and 16% sewage sludge (combined calorific value of $h_u \approx 9$ MJ/kg as layout value). As general categorisation, one can state that the 1st unit of the main thermal process (thermolysis in a rotary kiln) does in principle pursue the same goal as the „Schwelbrennverfahren nach Siemens-KWU“. In the 2nd unit however, the „Konversionsverfahren nach NOELL“ pursues gasification at high pressures and with oxygen, in order to generate a synthetic gas, which is to open up new paths into chemical industry as well as generation of electric energy.

In summary, the following characterisation can be given:

- pre-treatment by shredding and drying;
- thermolysis (so-called pyrolytic conversion) in an indirectly heated rotary kiln at 550°C;

- separation of residues from the rotary kiln by magnetic separation, screening, grinding etc. into metals, inert substances, pyrolysis coke and extraction of valuable substances (reclamation of valuable substances);
- cooling and storing of pyrolysis gas;
- propelling of pyrolysis gas with pressure of 35 bar and transportation of pyrolysis coke and remaining fractions containing carbon, etc. into the gasification unit (flux reactor).
- complete separation of thermolysis (pyrolysis) and flux gasification, so that both processes can be operated and optimised independently.
- flux gasifier: charging materials (pyrolysis gas and pyrolysis coke) can be fed separately (but also simultaneously) and with high regularity. Gasification is performed with oxygen at high pressures (35 bar) and high temperatures (1350-1500°C), permitting liquid draw-off of residual matter in the form of slag. Due to gasification with oxygen, only small mass flows of gasification gas are generated as compared to gasification with air.
- purification of synthetic or gasification gas: small mass flows of gasification gas lead to a small gas purification plant (for layout refer to fig. 33). In balancing, these should be included in the main thermal process (see fig. 32).

At Northeim, gasification gas is to be used in a gas and steam turbine process for the generation of electric energy. First, the gas is burned with air in a gas turbine and expanded, following that, waste heat of the flue gas created is utilized in a downstream steam-power-process. In fig. 32, motor combustion (with air) is outlined. It should be noted that in utilisation of synthetic gas for power generation, the combustion process (with air) involved should be conducted in such a way, that downstream measures for purification of the flue gases created by combustion of synthetic gas are minimised.

As reported [106] the residual matter from thermal treatment can be handled as follows:

- metal residues can be used in metallurgical processes;
- granulates from smelting can be used in road construction, etc.;
- the waste water (condensate of exhaust vapours) can be fed into a sewage treatment plant;
- sulphur can be recoverd in the gas purification process;
- other residual materials, such as salts and sulphides of heavy metals can be used as filling materials in mining.

Efficiency and effort factors (for definitions refer to fig. 19 are of course dependent on the utilisation of synthetic gas. When it is intended to generate electric power, an electricity effort factor of $a_{el} \approx 7.3\%$ (for a heating value $h_u = 11.1$ MJ/kg) can be calculated from the data given in [106]. More details will emerge from operational experience of a plant for household waste to be erected at Northeim.

It should be mentioned at this point that trials to gasify sewage sludges in a separate, independent flux reactor have shown promise as a measure for treatment of sewage sludge.

6.4.2 „THERMOSELECT VERFAHREN“

(Application of degassing channel with gasification reactor)

The „Thermoselect Verfahren“ too, utilises the two basic units, thermolysis and gasification, in the main thermal process (figure 34 and 25) [108 to 110]. The aim of this process is generation of synthetic gas for utilisation in the chemical industry or for the generation of electric power, and drawing off of molten residual matter from the high-temperature gasification reactor (temperature 1200 °C, ambient pressure level).

In 1989 basic experiments were started to investigate carbonisation behaviour of household waste. Following this in 1991 a pilot plant in Fondotoce (Italy) was set-up and in 1992 experimental operation started. Several trial phases of thermal treatment of household waste with throughputs of up to approx. 3 t/h (calorific value 12-13 MJ/kg) with utilisation of synthetic gases in a 1.2 MW gas engine have already produced results. [108]. Currently, several locations in Germany are being discussed as sites for „Thermoselect Verfahren“ plants with 2 lines of 10 t/h throughput each.

For general classification of the process one can state, that in the first unit of the main thermal process, thermolysis takes place in a stationary channel, heated externally with synthetic gas (degassing channel). The waste is pushed through the channel and simultaneously compacted. Materials from thermolysis immediately enter the second unit of the main thermal process, the high-temperature gasification reactor. Contrary to other processes, no intermediate treatment of materials prior to entering the second unit is performed here. For better process control, the first and second units are both practically one single unit.

In summary, the following characterisation can be given:

- waste compacting by press;
- thermolysis in a discontinuously charged channel (heated indirectly), thermolysis here essentially progresses up to degassing, which is the reason that the 1st unit of the main thermal process is called "degassing channel";
- immediate transit from degassing channel into the high temperature reactor;
- high temperature reactor: gasification of the materials flowing in from the degassing channel with the aid of oxygen and natural gas at ambient pressure level and temperatures of approx. 1200°C. On account of gasification with oxygen, small mass flows of synthetic gas are created, as compared to gasification with air.
- solid residues originating from the degassing channel fall directly into the melting pit of the gasification reactor. Here, secondary treatment of the liquid phase, e.g. with oxygen, can be performed,

- purification of synthetic or gasification gas: the comparatively small mass flows of synthetic gas result in a matching small gas purification plant (for layout see figure 35). For balancing, it should included in the main thermal process (see fig. 34).

When synthetic gas is utilised to generate electric power, it has to be noted once again, that combustion of the synthetic gas (with air) has to be conducted in such a manner, that flue gas purification of related flue gases (expansion of the balance limits to the entire process, see block flow chart 34) is minimised.

The following uses are quoted for the residues resulting from this process:

- mineral substances can be used as additives in the building industry;
- metal alloys are fed into a metallurgical process;
- mixed salts from the condensation plant and precipitates from process water treatment are deposited in landfills.

When synthetic gas is utilised for electric power generation, at the current state of planning for the process as a whole, electric effort factors for the process as a whole, a_{el}, based on a standard plant (2 to 10 t/h) and depending on the layout of the heat-power-configuration and of auxiliary facilities, ranging from a_{el}=4.7% to a_{el}= 8.5% (for a heating value of h_u = 10.4 MJ/kg) are given [108].

6.5 OTHER PROCESSES

Based on the processes applied frequently at present, which are realised by means of the apparatuses "grate", "rotary kiln" and "combustion chamber" (section 5), the "sections" 6.1. to 6.4. predominantly deal with those processes, where future advancements of these devices are in the offing. For completeness' sake, a multitude of other processes will be shortly referred to at this occasion.

For certain types of waste, which do not fall under those mentioned up to now, such as electronic scrape etc., specially tailored processes are required [111]. Modifications are also necessary, when certain types of waste can be channelled into production processes (such as combustion of used tires or used oil in cement factories, injection of plastic waste into the orifices of blast furnaces for pig iron production, etc.).

Furthermore, processes with fluidized bed and circulating fluidized bed technology, with story furnaces and shaft reactors are to be mentioned. For instance, one tries to convert residual waste of a consistency similar to granules in a gasification-post-gasification process (process E in fig. 14), applying a gasifier with circulating fluidized solids technology in the 1st unit and, in the 2nd unit, an additional gas cracker for carbohydrates of higher valences [112, 114]. Generally, the increasing scope of sewage sludge, synthetics and rubber treatment by pyrolysis should be called to attention. Furthermore, fixed bed reactors are to be mentioned, which are being utilised for trials to gasify household waste together with coal [116].

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	mechanical treatment	physical treatment	chemical treatment	biological treatment
low temperature examples	disassembling seperating crushing	dissolving drying	neutralization wet oxidation	anaerobic aerobic
high temperature examples	separation of dust from hot gas	drying degassing melting	combustion gasification pyrolysis	—

Figure 1: Basic units of treatment of waste materials (examples).

air:

toxids	TA Luft (Germany, 1986)		17. BImSchV (Germany, 1990)	
	24h	1/2h	24h	1/2h
	average		average	
total dust	30	60	10	30
organic	20	40	10	20
HCl	50	100	10	60
HF	2	4	1	4
SO_2	100	200	50	200
NO_2	500	1000	200	400
CO	100	80/200	50	100 *)
dust containing special substances			avarage for given sampling period	
class I Cd, Tl, Hg	0,2		Cd, Tl Hg	0,05 0,05
class II As, Co, Ni, Se, Te	1,0		Sb, As, Pb, Cr Co, Cu, Mn, Ni, V, Sn	total 0,5
class III Sb, Pb, Cr, cyanide, F, Cu, Mn, Pt, Pd, Rh, V, Sn	5,0		PCDD, PCDF (TEQ)	0,1ng/m^3

in [mg/m^3] at 11 vol% O_2 (dry at STP)

*) hourly avarage

water: Rahmen - Abwasser VwV, Anhang 47, 2.2.3, Germany, 1992 :
release prohibition on waste water from exhaust gas cleaning.

IEVB / tk13e / 23.02.95

landfill:

TA-Siedlungsabfall, Germany, 1994; Anhang B		disposal class I	disposal class II	unit
strength				
	vane shear strength	≥ 25	≥ 25	[kN / m^2]
	axial deformation	≤ 20	≤ 20	[%]
	uniaxial compressive strength	≥ 50	≥ 50	[kN / m^2]
organic portion of dry resedue of original substance				
	loss on ignition	≤ 3	≤ 5	[mass %]
	TOC	≤ 1	≤ 3	[mass %]
eluant criteria				
	pH	5,5 – 13,0	5,5 – 13,0	[-]
	conductivity	≤ 10000	≤ 50000	[μs/cm]
	TOC	≤ 20	≤ 100	[mg / l]
	phenole	≤ 0,2	≤ 50	[mg / l]
	arsenic	≤ 0,2	≤ 0,5	[mg / l]
	lead	≤ 0,2	≤ 1,0	[mg / l]
	cadmium	≤ 0,05	≤ 0,1	[mg / l]
	chromium - VI	≤ 0,05	≤ 0,1	[mg / l]
	copper	≤ 1,0	≤ 5,0	[mg / l]
	nickel	≤ 0,2	≤ 1,0	[mg / l]
	mercury	≤ 0,005	≤ 0,02	[mg / l]
	zink	≤ 2,0	≤ 5,0	[mg / l]
	florine	≤ 5,0	≤ 25	[mg / l]
	ammonium - N	≤ 4,0	≤ 200	[mg / l]
	cyanide, easily dispersed	≤ 0,1	≤ 0,5	[mg / l]
	AOX	≤ 0,3	≤ 1,5	[mg / l]
	water soluble (resedue on evaporation)	≤ 3,0	≤ 6,0	[mass %]

Figure 2: Emission limits for toxids into air, water and landfills [1, 2, 3, 4].

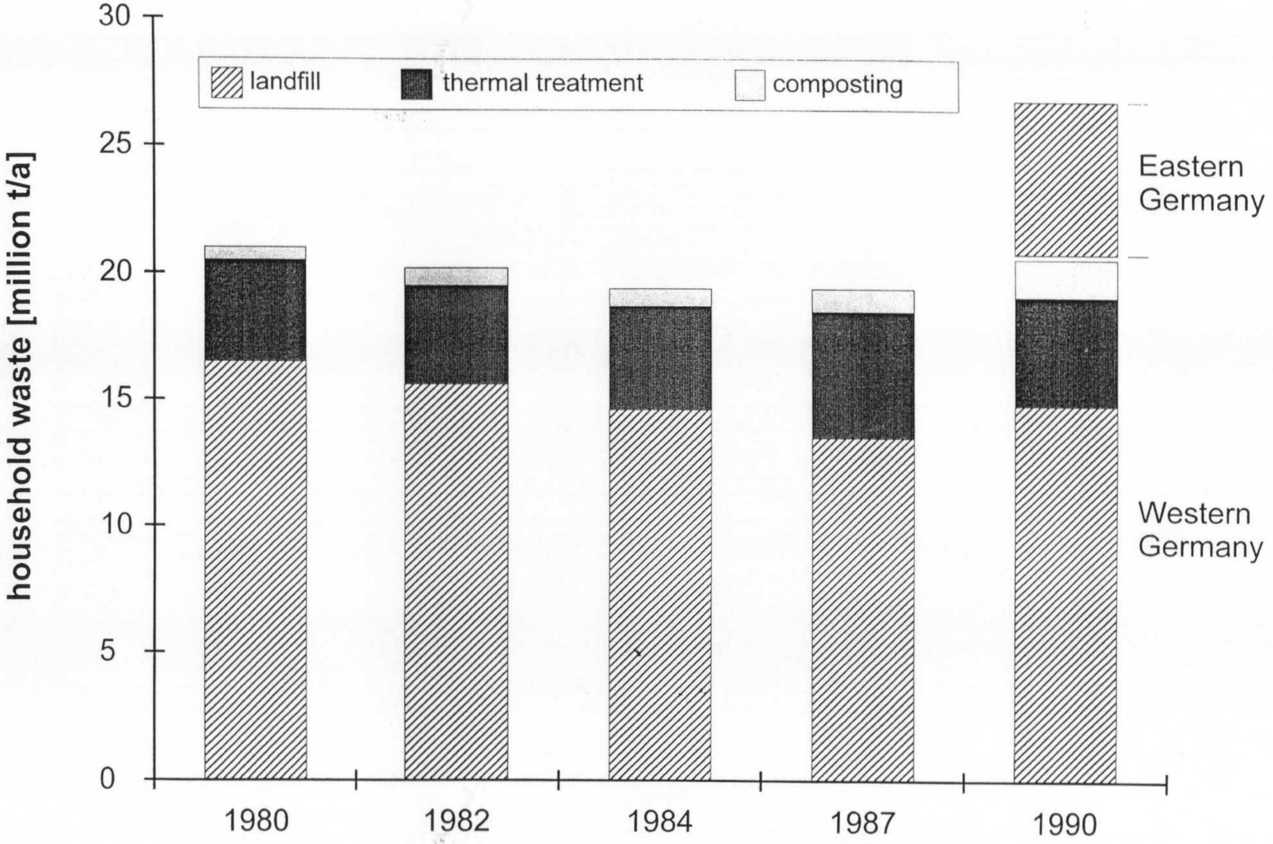


Figure 3: Overview of collected household wastes and disposal in Germany [6].

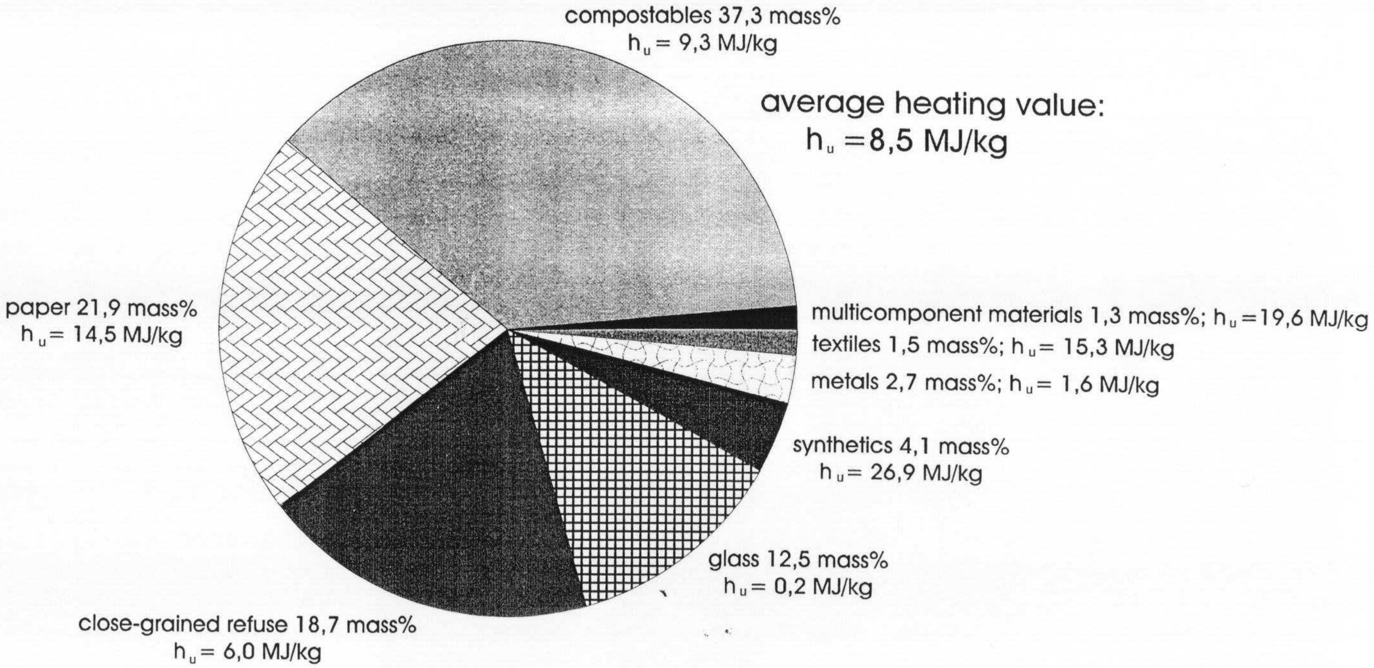


Figure 4: Household waste: composition and heating values (example).

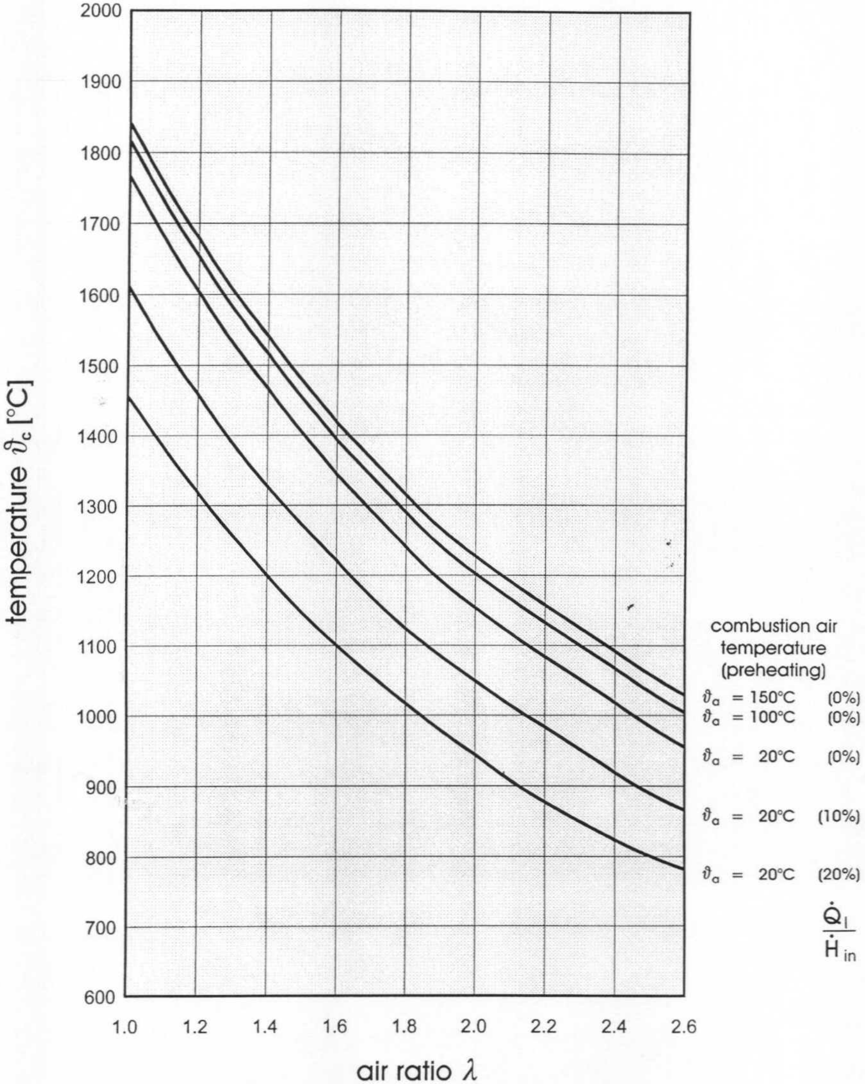


Figure 5: Combustion temperatures ϑ_c of household waste (fig. 4) versus air ratio λ for given combustion air temperature ϑ_a (preheating) and heat losses ($\dot{Q}_l / \dot{H}_{in}$) [7].

[compulsory registration expanded from 80 to 320 substances in 1990]
ca. 16 million t/a

disposal

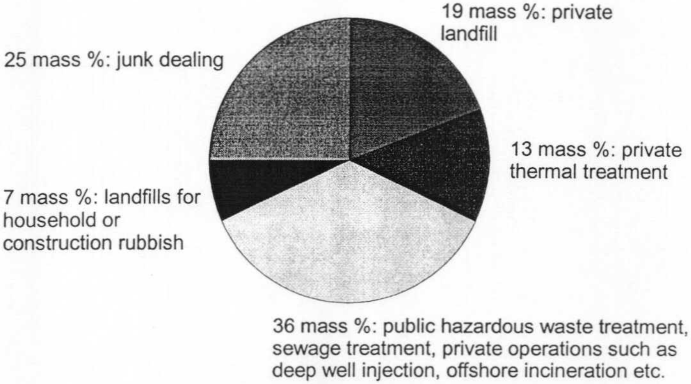


Figure 6.1: Waste from industries and hospitals for special monitoring [9, 10].

waste consistency	[mass%]
solid in sealed containers	60
pasty	20
liquid	20
sum	100

elemental analysis:

material	solid	pasty	liquid	mixed
carbon	23,7	22,8	44,7	27,7
hydrogen	2,5	3,4	6,0	3,4
oxygen	10,1	12,7	0,0	8,6
nitrogen	0,7	0,8	0,7	0,7
sulfur	0,2	0,8	0,2	0,3
chlorine	0,8	1,7	7,7	2,4
florine	0,3	0,3	0,3	0,3
water content	25,6	29,6	40,4	29,7
inerts	36,3	27,9	-	27,3
sum [mass %]	100,0	100,0	100,0	100,0
heat value h_u [kJ / kg]	8900	9200	21300	11500

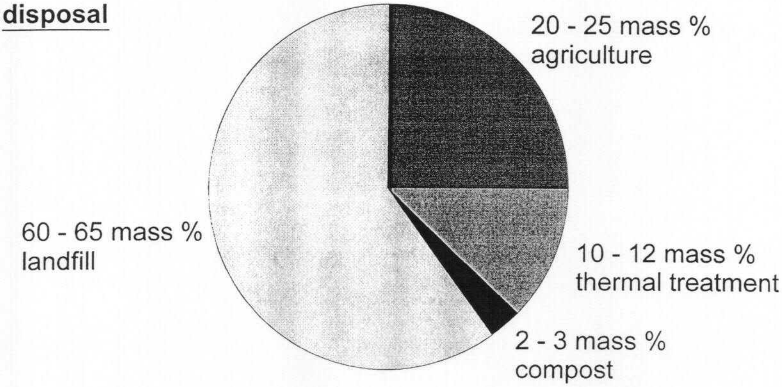
trace analysis:

mercury	25 mg/kg	arsenic	200 mg/kg
lead	1000 mg/kg	PCB	500 mg/kg
cadmium	20 mg/kg	PAK	500 mg/kg
copper	1000 mg/kg	ΣPCDD/PCDF(TEQ)	10000 ng/kg

Figure 6.2: Example composition of hazardous waste.

community sewage sludge as of 1990

ca. 60 million t/a with 5 mass % dry solids
(equals ca. 3 million t/a dry solids)



sample composition of dry solids

elemental analysis	
element	mass%
C	30,5
H	1,9
O	9,0
N	2,8
S	1,4
ash	54,4
sum	100,0
h_u [MJ/kg]	10,8

Σ AOX *)	192	[mg/kg]
Σ PCB *)	0,16	[mg/kg]
PCDD/F *)	38,6	[ng/kg] TE

trace analysis	
element	[mg/kg]
As	18
Cd	2
Cl	361
Co	15
Cr	309
F	91
Hg	3,1
Mn	467
Ni	819
Pb	127
Sb	7
Sn	26
Ti	< 2
V	31
Zn	1750

Figure 7: Community sewage sludge; overview of amounts [6], disposal [11] and composition [12, 13].

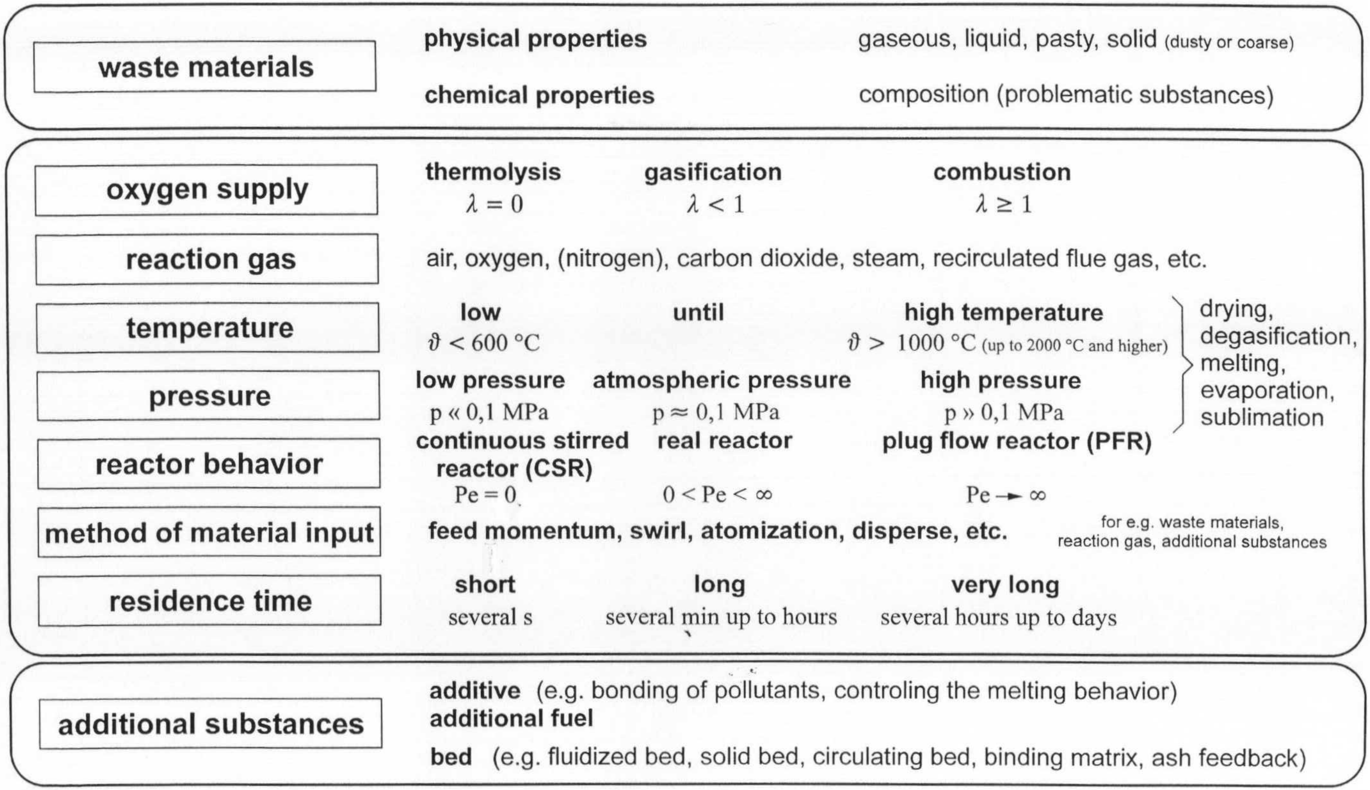


Figure 8: Main influencial parameters for thermal treatment [50].

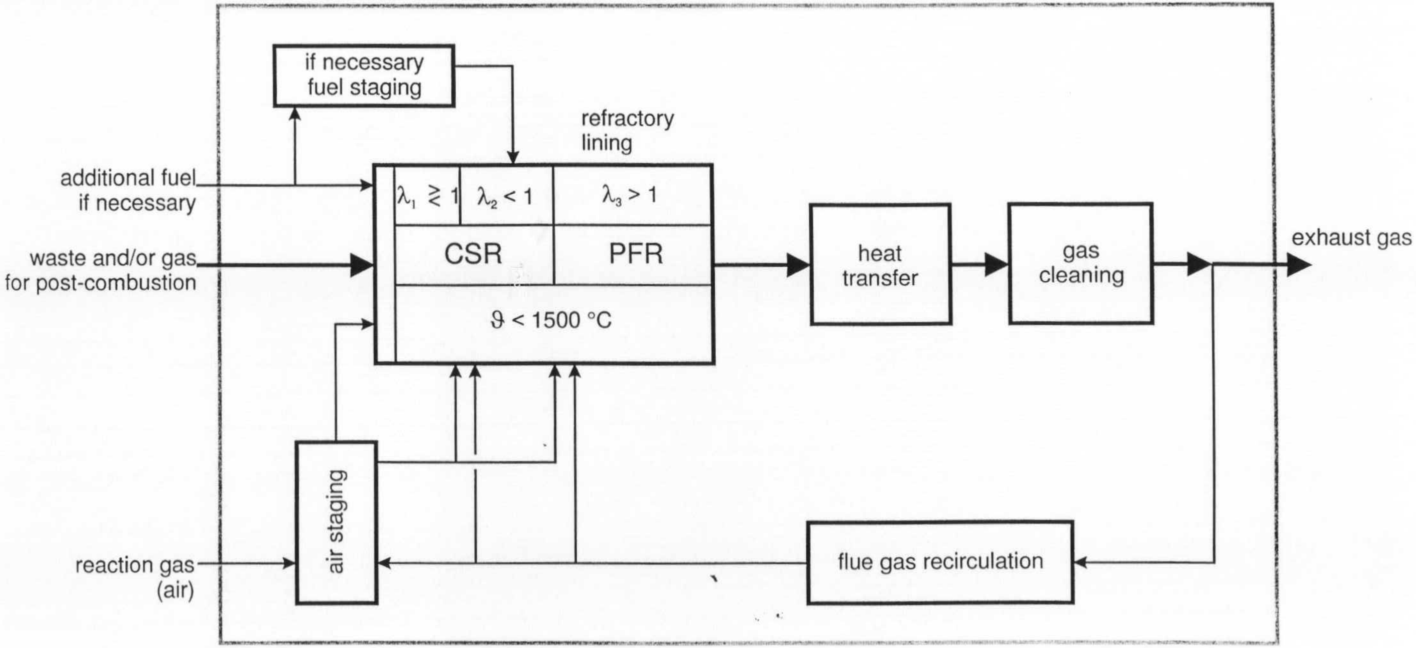
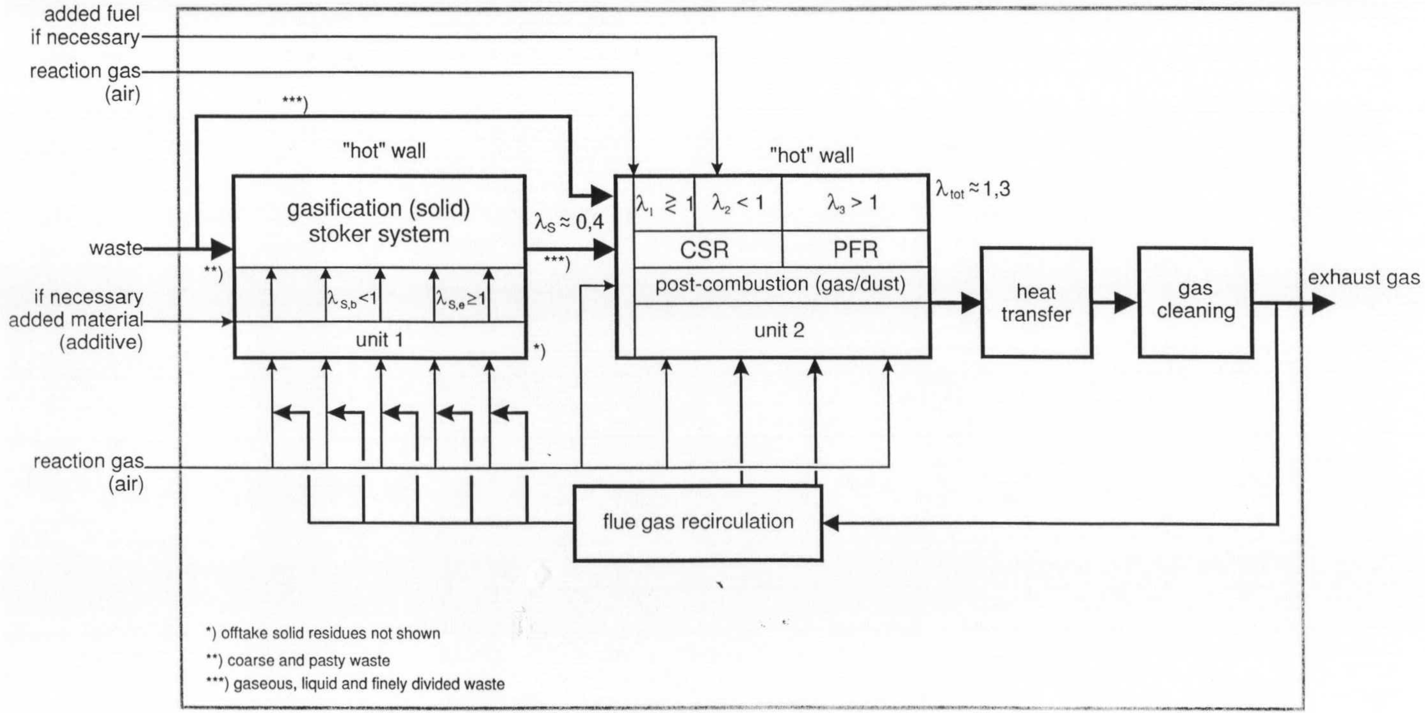


Figure 9: Block diagram of process operation of combustion of gaseous, liquid, or dusty wastes or respectively of post-combustion for coarse waste [18].



*) offtake solid residues not shown

**) coarse and pasty waste

***) gaseous, liquid and finely divided waste

Figure 10: Block flow diagram with independent units of thermal treatment for coarse waste (example) [7].

Apparatus	**Combustion Chamber**
Substance Treated	Gaseous, liquid, dusty.
Oxygen supply level	Understochiometric to overstochiometric variable to wide ranges from „combustion“ at reactor exit (overstochiometric) to „gasification reactor“ at process end (understochiometric).
control along reaction path	Easily obtainable through staging of oxidants and fuels along reaction path (fed over the stirred reactor).
Temperature level	Combustion temperatures ranging from 1000°C to 2000°C and higher.
control along reaction path	Together with the staging of oxidants and fuels along the reaction path and especially the recirculation of exhaust gas, injection of water, indirect temperature control with heat and cooling systems and more are possible.
Pressure	A small number of Pa underpressure result from technical conditions. Combustion at high pressures is uncommon. Pressurised gasification is more common.
Reactor Behaviour gas/dust	Flows for gas and dusts can be approximated as stirred reactors or as plug flows.
Residence Time level (average residence time)	Ranging in seconds (appropriately longer at high pressures), with feed conditions and reactor dimensions adjustable.
control along reaction path	Possible only with difficulty. Distribution of residence times variable via reactor behaviour.
Additives	Additives are needed especially for stirred reactors, the sorbing of toxins (e.g. sulphur and nitrogen dioxides), and the control of melting temperatures of the dusts and properties of the slag.
Application	Combustion of liquid residues. Post-combustion in the second unit of thermal treatment of gas and dusts. High temperature gasification of residues for the production of process gas (low and high temperatures). Special combustion processes (e.g generation of valuable HCl form chlorine and more).

Figure 11: Characterisation of combustion chambers [50].

Apparatus	**Stoker Systems**
Substances Treated	Lumpy or pasty when mixed with a solid or inert bed.
Oxygen Supply level	Usually overstochiometric (combustion), understochiometric (gasification) self sustaining post-combustion possible. in the absence of oxygen (pyrolysis) not customary.
control along reaction path	Easily adjustable in the separate zones (e.g. air/oxygen staging, fluegas recycling, etc.). The partial steps: drying, degasification, gasification, burnout of remaining solid can be influenced.
Temperature level	Bed surface temperature up to approx. 1000°C and higher, temperature of middle bed is lower.
control along reaction path	Sufficient possibilities through division into zones, as in the case of control of oxygen concentration (air preheating, fluegas recycling, water/steam cooling).
Pressure	Small number of Pa underpressure result due to technical reasons.
Reactor Behaviour solid	Depending on grate movement, the zones can be considered to as a CSR (e.g. reverse acting grate) or PFR (e.g. travelling grate). PFR characteristics are approached over the total reactor length.
gas	a) Oxidants are forced through the bed and are evenly distributed over bed surface: very good contact between gas and solids. b) Counter-current and co-current flows above the bed are possible. Gas treatment is necessary in process steps that follow (e.g. post-combustion).
Residence Time level (average residence time)	Ranging from minutes to hours. Adjustable by grate speed and massflow rate, and design dimensions: length and width.
control along reaction path	Good adaptation is possible through speed adjustments in the grate elements of the separate zones. Burnout at the end of the gate can be improved if necessary with control of the discharge roll.
Additional Substances	Additive for sorbing of pollutants into the solid and control of residue properties (ash, partially molten ash, slag). Inert beds e.g. binding matrix for low melting substances such as plastics.
Applications	For conversion of solids in the first unit of household waste combustion. Low temperature separation of metals from mixtures with understochiometric conditions.

Figure 12: Characterisation of stoker systems [50].

Apparatus	**Rotary Kiln**
Substance Treated	Liquid, pasty, lumpy, (including. packed, sealed containers etc.).
Oxygen supply level	inert atmosphere (pyrolgris); overstochiometric (combustion); understochiometric (gasification) not common.
control along reaction path	As a rule not possible. Some cases through special oxygen lances.
Temperature level	Low temperature (for example pyrolysis, indirect heating. 400°C for example) to high temperature (1000°C, 1200°C, 1500°C and higher) using appropriate refractory linings.
control along reaction path	Direct and indirect heat transfer using both co-current and counter-current flows; further possibilities limited.
Pressure	Small number of Pa underpressure result due to technical reasons.
Reactor Behaviour solid	Some sections are cross-sectionally considered to approximate a stirred reactor due to the stirring of solids. Plug flow characteristics are approached over the total reactor length.
gas	Reactor behaviour can be characterised by plug flow. Gas flows over solids and is separately post-combusted
Residence Time level (average residence time)	From minutes to hours, adjustable by variation of rotational frequency and filling levels, also by design dimensions leugth and diameter of rotary kiln.
control along reaction path	Hardly possible.
Additional Material	Additive to vary melt temperatures and properties of the slag as example.
Applications	The first unit of incineration of hazardous materials or for the thermolysis unit (pyrolysis) in the treating of household waste.

Figure 13: Characterisation of rotary kilns [50].

Symbol	unit 1	unit 2	processes and examples
A.	combustion ***)	combustion	combustion - post-combustion - process (e.g. figure 15) (e.g. standard waste incineration)
B.	thermolysis *)	combustion	thermolysis - post-combustion - process (e.g. figure 27) (e.g. Schwel-Brenn-Verfahren nach Siemens KWU)
C.	gasification **)	combustion	gasification - post-combustion - process (e.g. figure 30) (advanced standard waste incineration)
D.	thermolysis	gasification	thermolysis - post-gasification - process (e.g. figure 32) **(e.g. Konversionsverfahren nach NOELL, Thermoselect-Verfahren etc.)**
E.	gasification	gasification	gasification - post-gasification - process (e.g. [112]) (e.g. gasification and gas decomposition by LURGI)

*) here: includes the processes drying, degasification and pyrolysis
**) here: includes the processes drying, degasification and gasification
***) here: includes the processes drying, degasification, gasification and combustion

Figure 14: Systematic division of main thermal processes [53, 78].

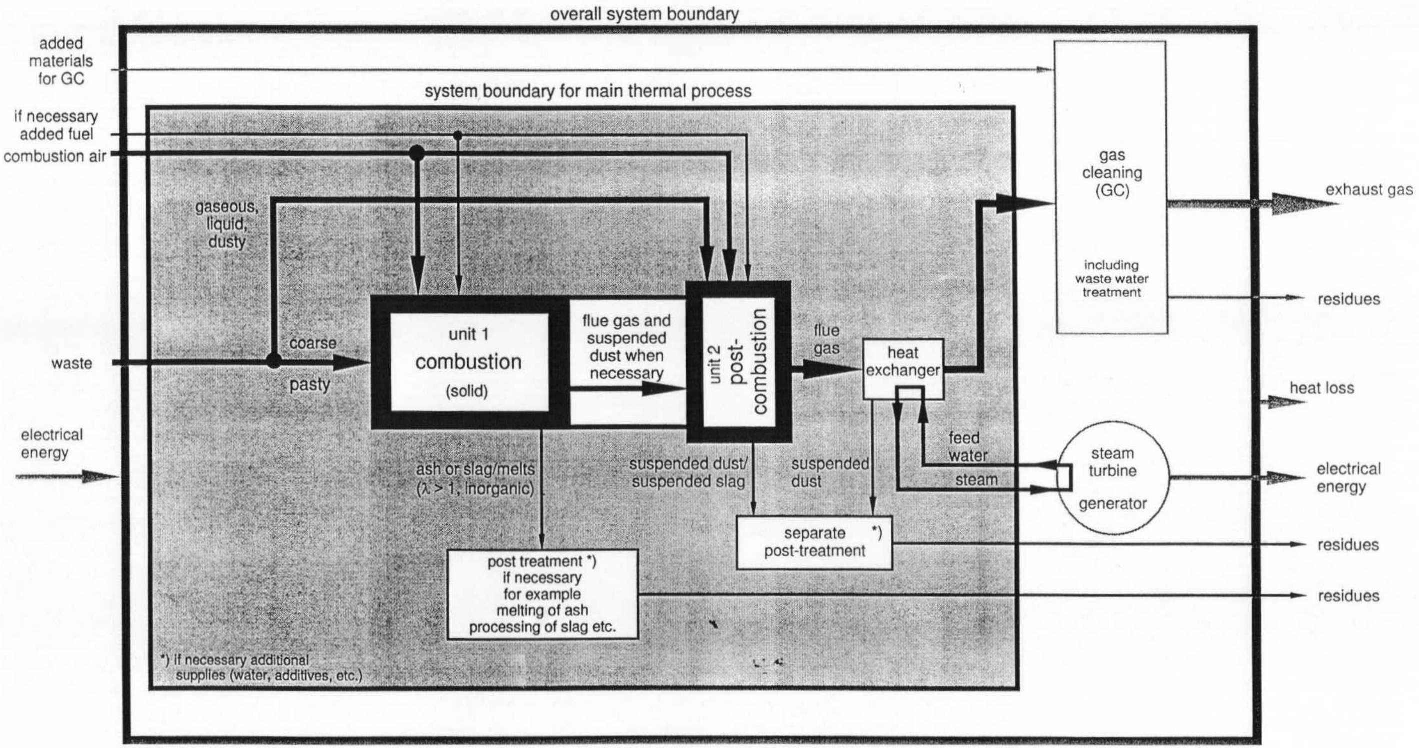
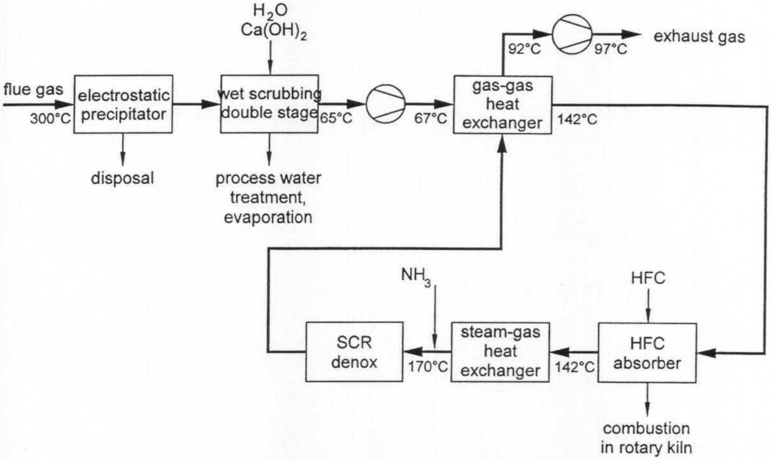
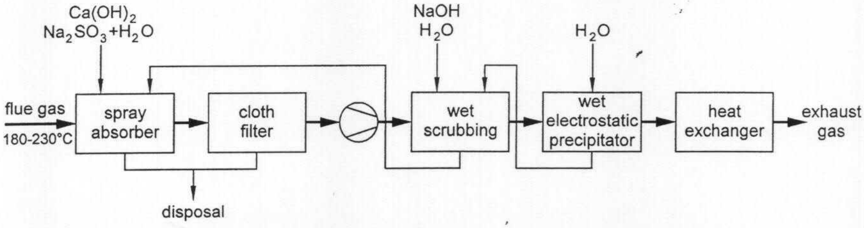


Figure 15: Block diagram for a combustion - post-combustion process;
example: standard incineration of waste [53] (see also fig. 17, 18, 22, 23).

example of gas cleaning for hazardous waste incineration [47]



example of gas cleaning for a household waste incineration [60]



example of process gas cleaning unit added onto for a gasification plant [108]

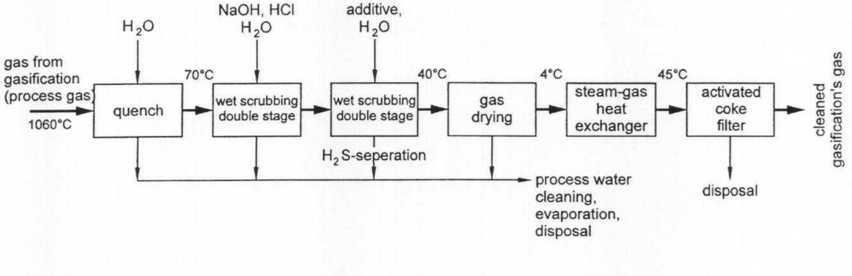


Figure 16: Examples for gas cleaning and process gas cleaning concepts.

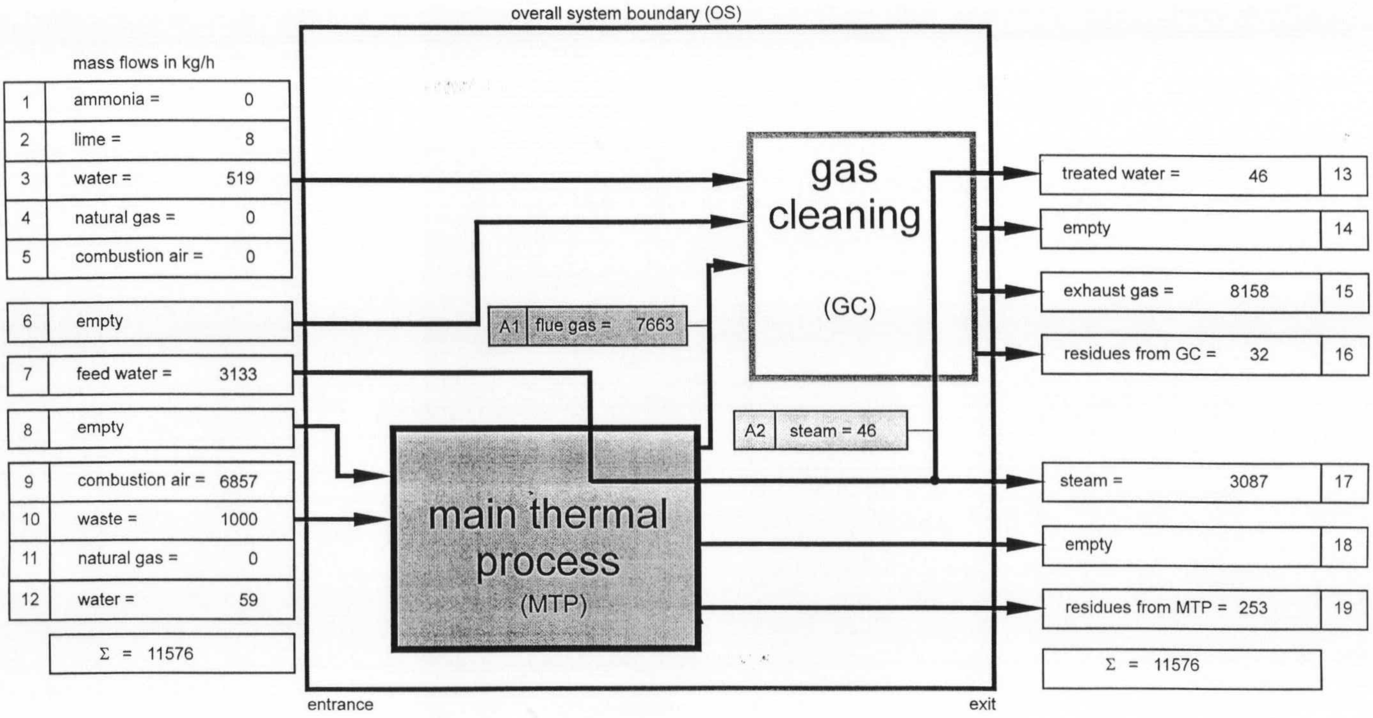


Figure 17: Simplified mass balance for a combustion - post-combustion process [55] (see also fig. 15, 18, 22, 23).

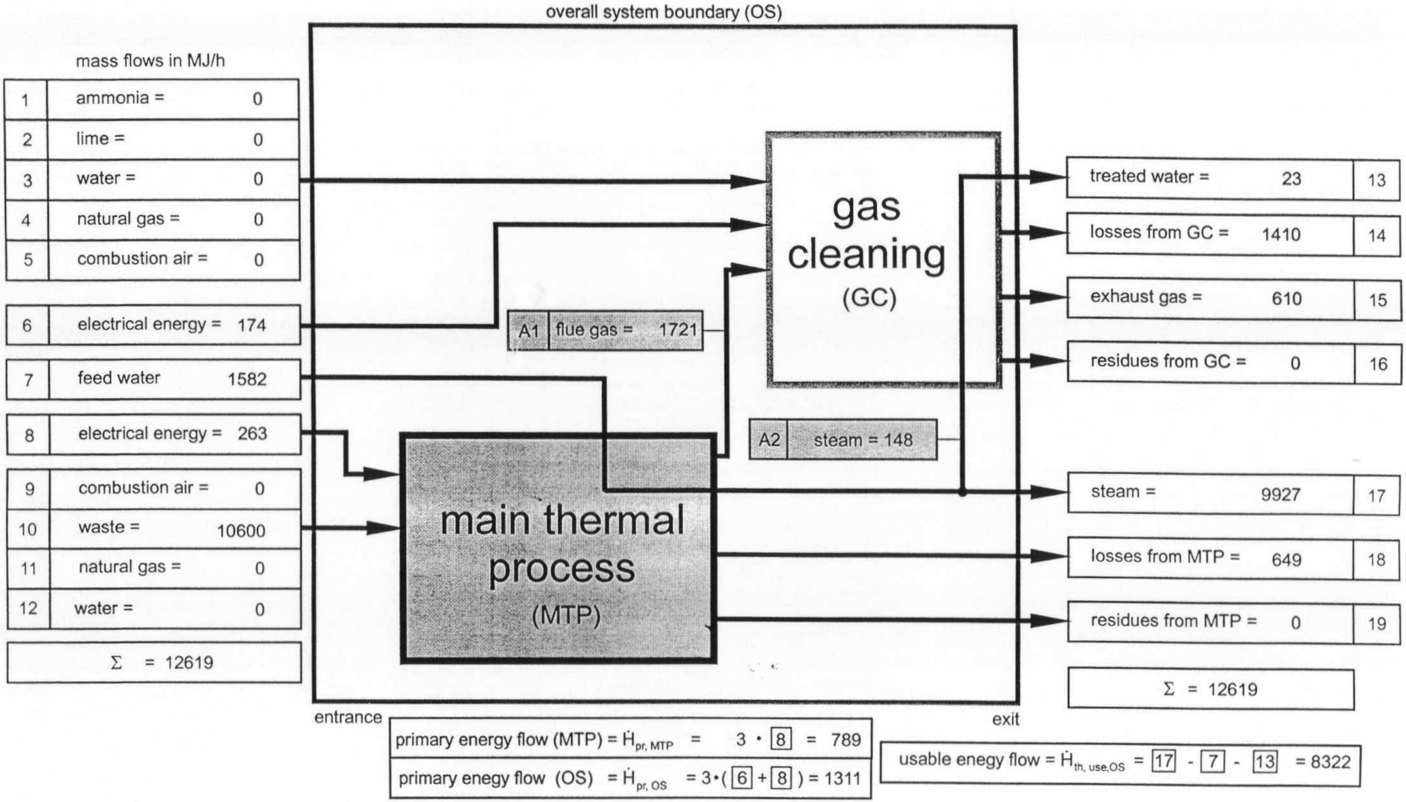
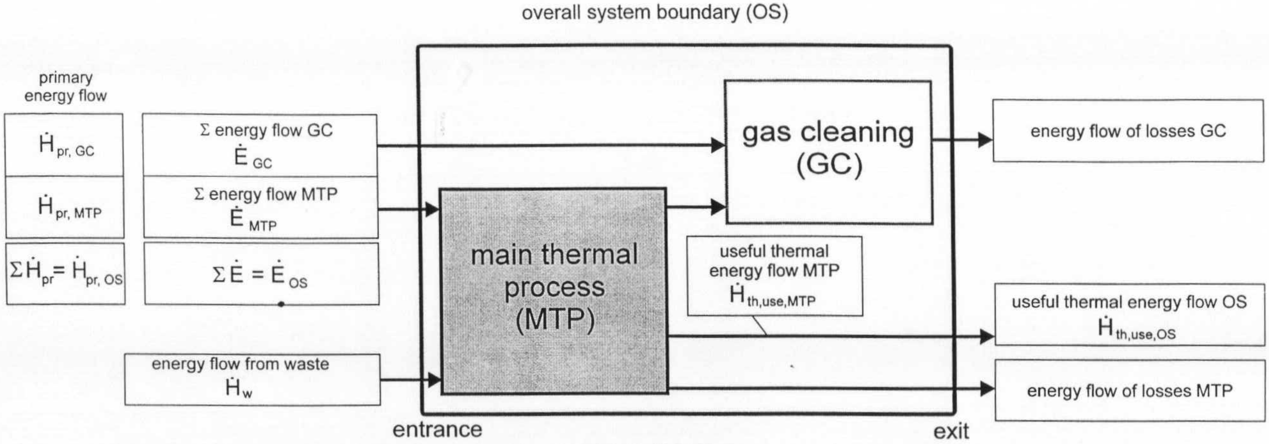


Figure 18: Simplified energy balance for a combustion - post-combustion process [55] (see also fig. 15, 17, 22, 23).



$$\eta_{th,MTP} = \frac{\dot{H}_{th,use,MTP}}{\dot{H}_{w} + \dot{E}_{MTP}}$$

$$\eta_{pr,\,MTP} = \frac{\dot{H}_{th,use,MTP}}{\dot{H}_{w} + \dot{H}_{pr,MTP}}$$

$$\eta_{th,OS} = \frac{\dot{H}_{th,use,OS}}{\dot{H}_{w} + \dot{E}_{OS}}$$

$$\eta_{pr,OS} = \frac{\dot{H}_{th,use,OS}}{\dot{H}_{w} + \dot{H}_{pr,OS}}$$

$$a_{OS} = \frac{\dot{H}_{th,use,OS} - \dot{H}_{pr,OS}}{\dot{H}_{w}} = \frac{\dot{H}_{net,\,OS}}{\dot{H}_{w}} \quad \text{for } \dot{H}_{net,\,OS} > 0, \text{ d.h. } a_{OS} > 0$$

$$a_{OS} = \frac{\dot{H}_{th,use,OS} - \dot{H}_{pr,OS}}{\dot{H}_{w} + \left|\dot{H}_{th,use,OS} - \dot{H}_{pr,OS}\right|} = \frac{\dot{H}_{net,\,OS}}{\dot{H}_{w} + \left|\dot{H}_{net,\,OS}\right|} \quad \text{for } \dot{H}_{net,\,OS} < 0, \text{ d.h. } a_{OS} < 0$$

Figure 19: Various possibilities for evaluation of thermal processes [53].

Figure 20: Thermal treatment plants for waste in Germany [6].

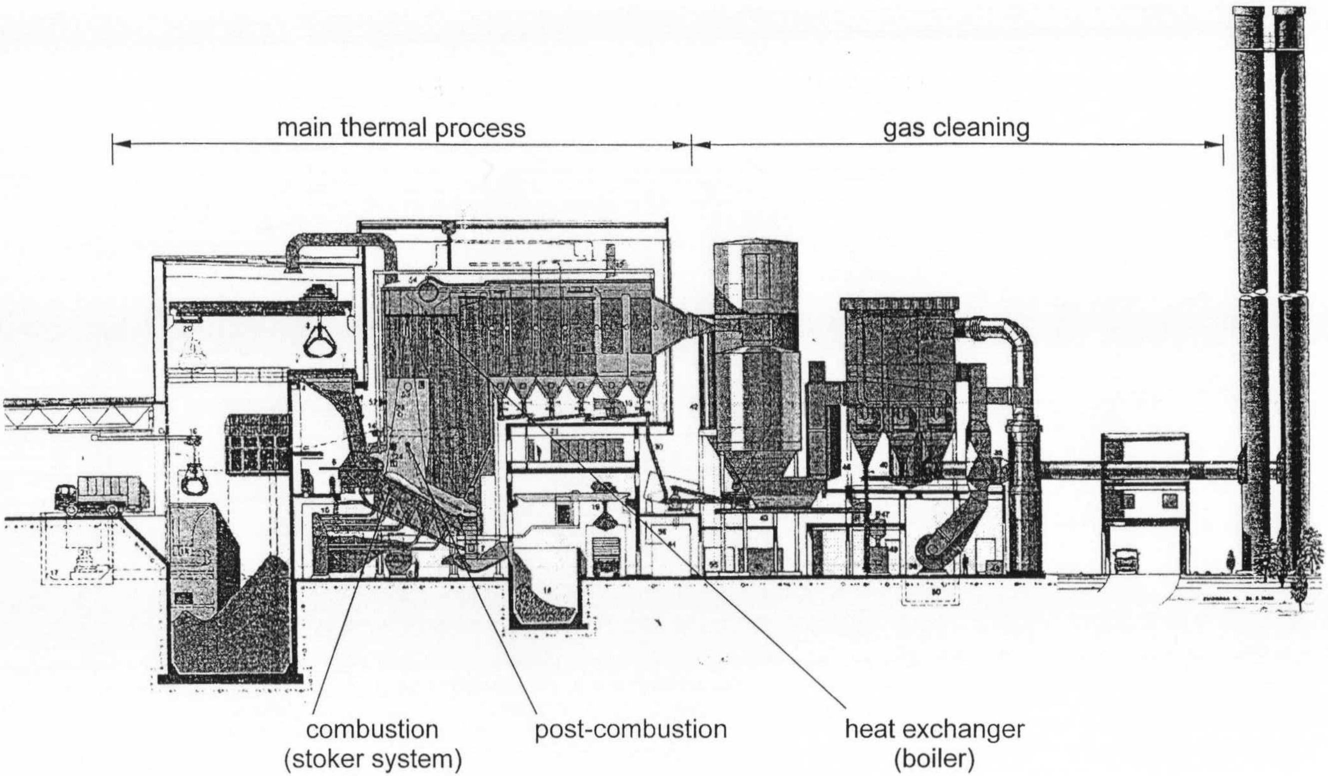


Figure 21: Schematic of a combustion - post-combustion process (household waste) [60].

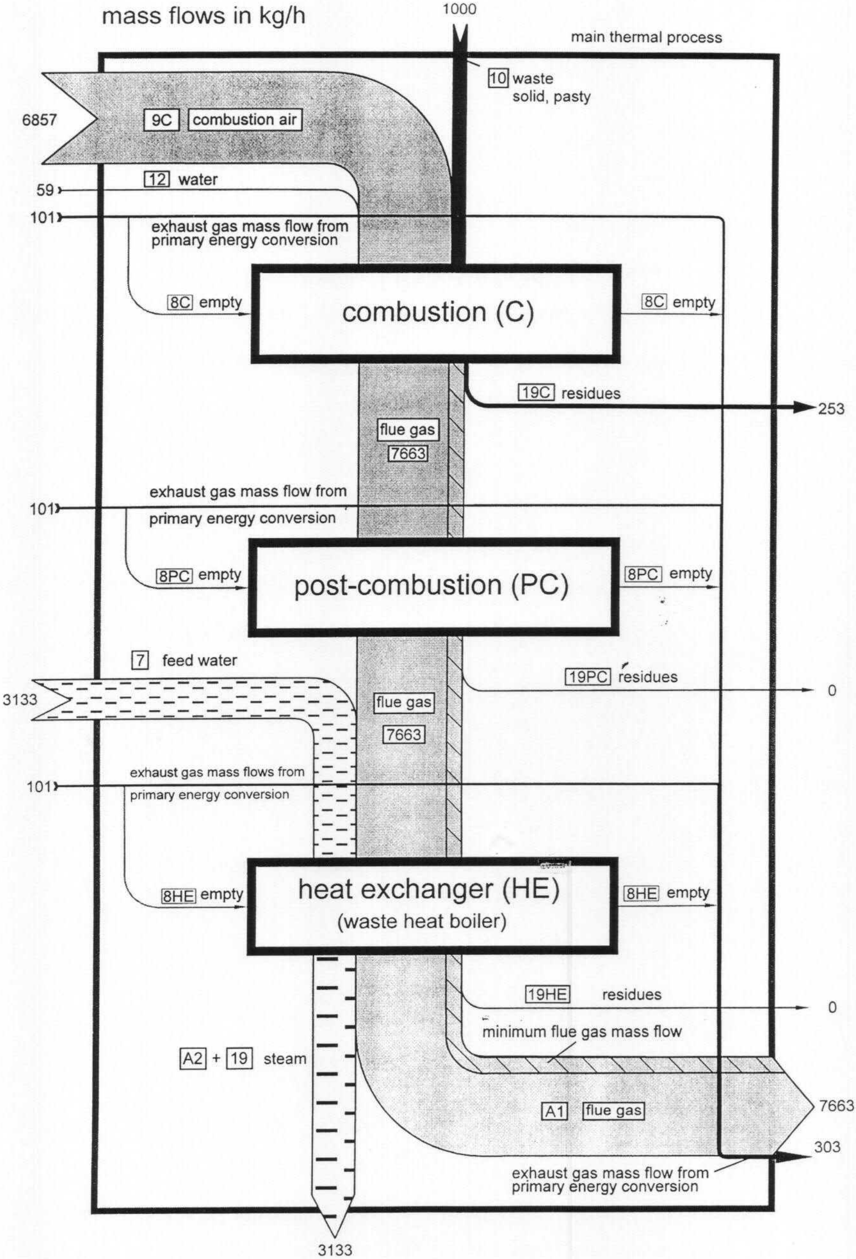


Figure 22: Mass flow diagram for a combustion - post-combustion process (main thermal process; houshold waste) [55] (see also fig. 15, 17, 18, 23).

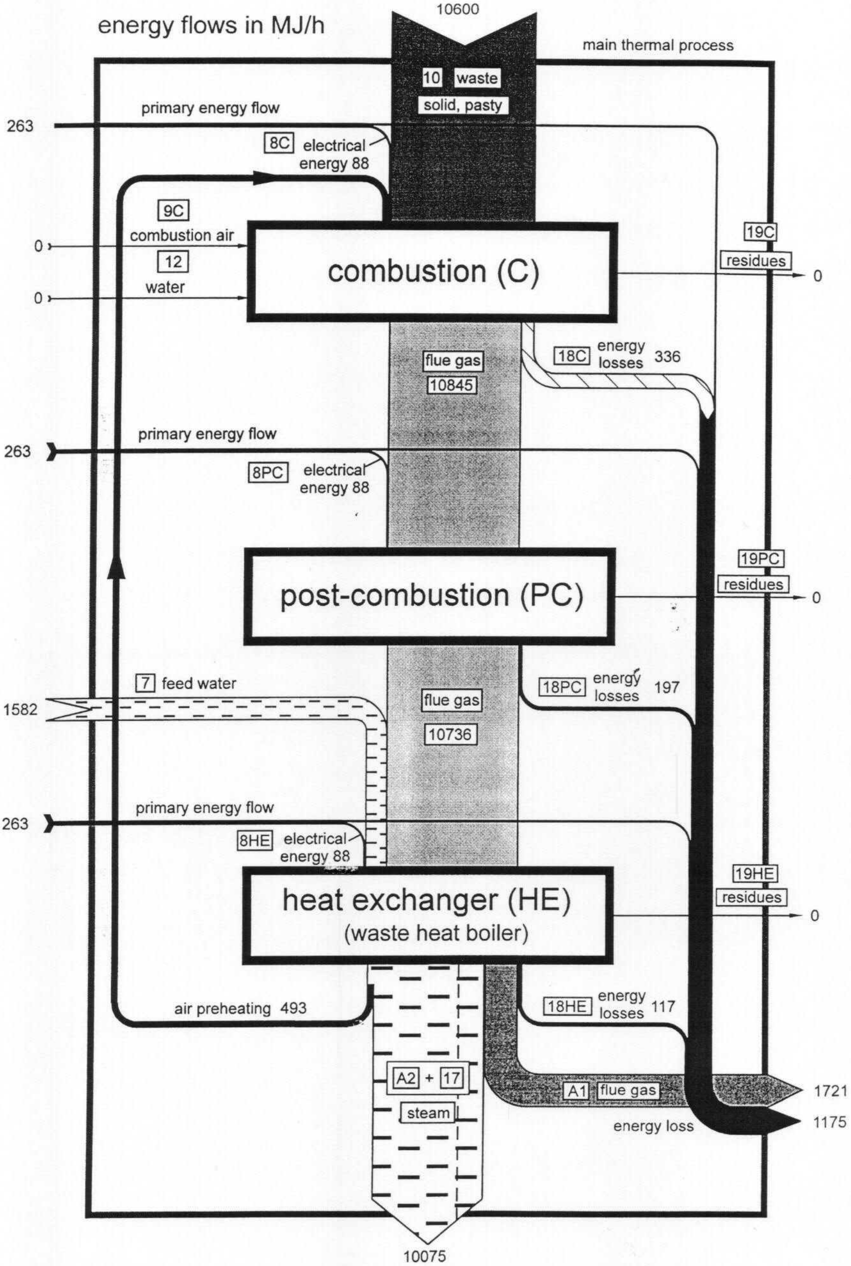


Figure 23: Energy flow diagram for a combustion - post-combustion process (main thermal process; household waste) [55] (see also fig. 15, 17, 18, 22).

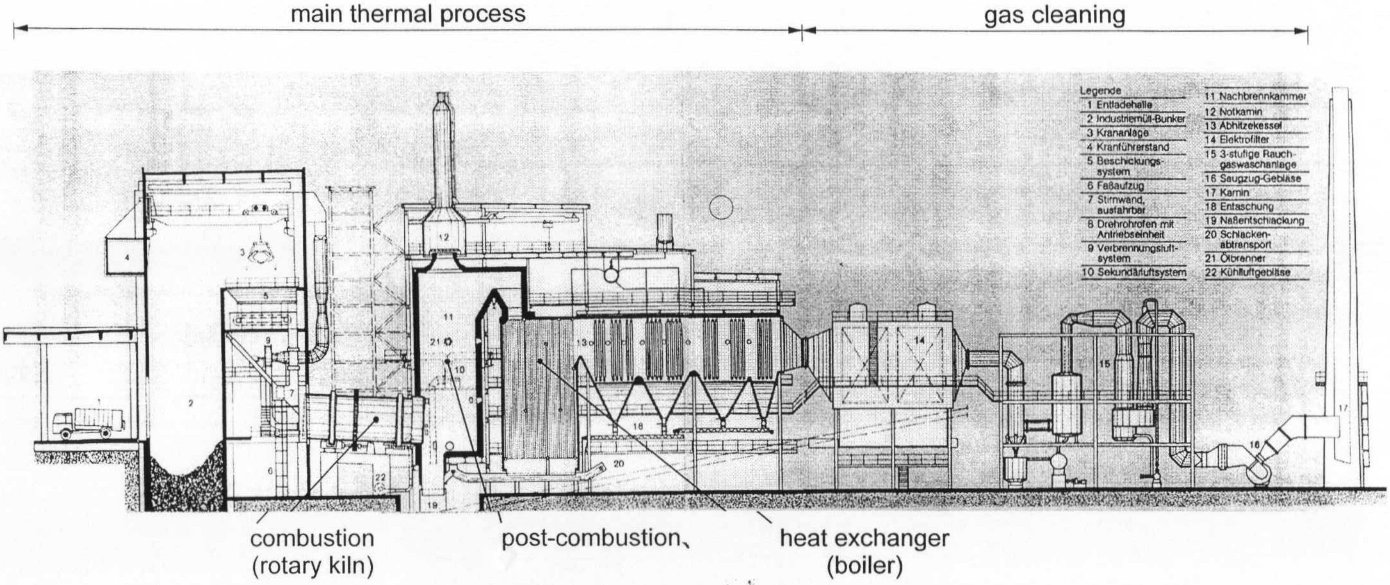


Figure 24: Schematic of a combustion - post-combustion process (hazardous waste) [69].

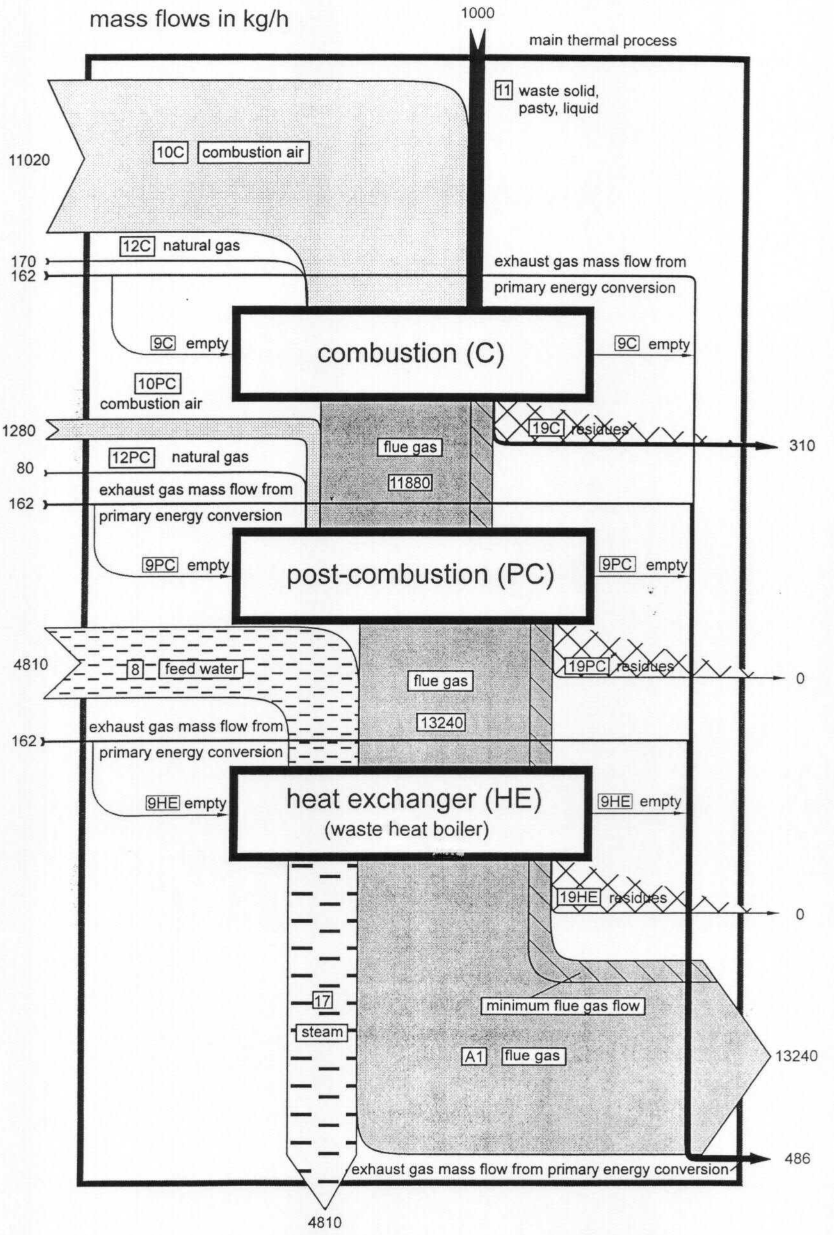


Figure 25: Mass flow diagram for combustion - post-combustion process (main thermal process; hazardous waste) [53] (see also fig. 15, 26).

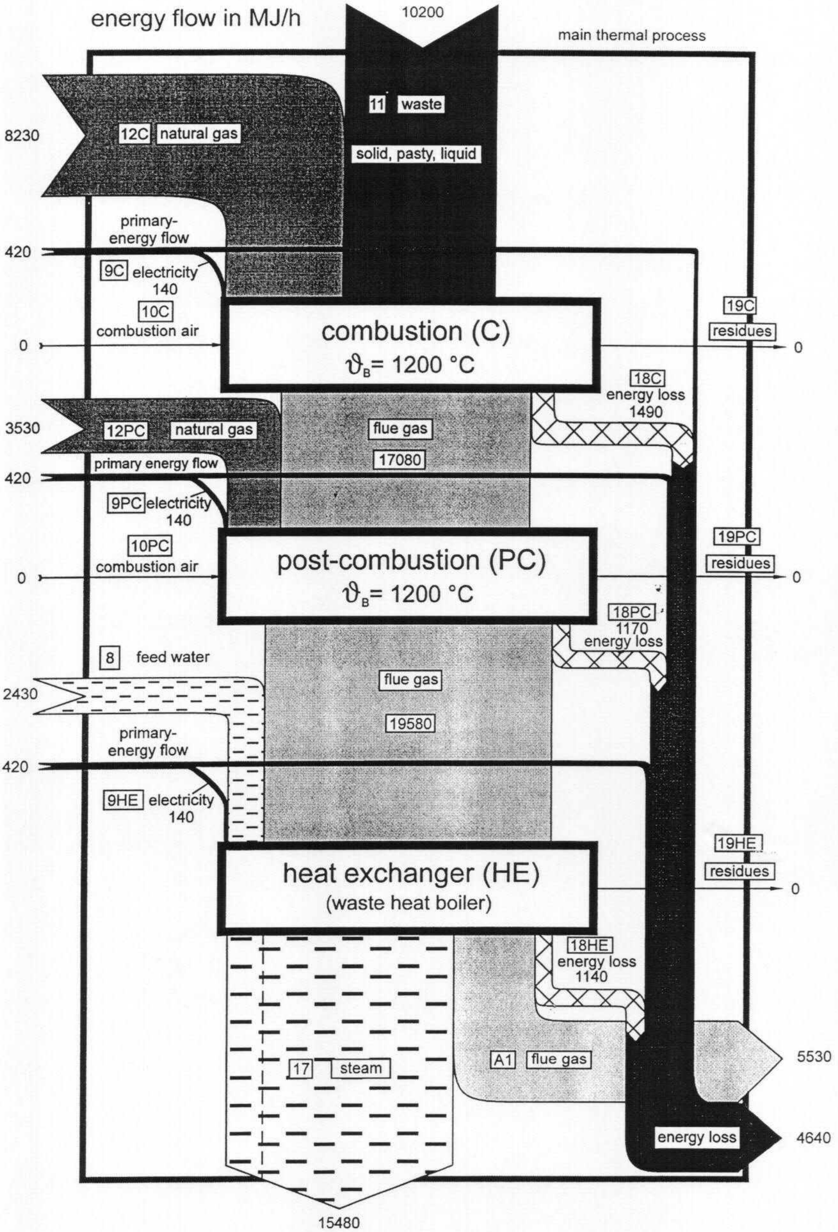


Figure 26: Energy flow diagram for combustion - post-combustion process (main thermal process; hazardous waste) [53] (see also fig. 15, 25).

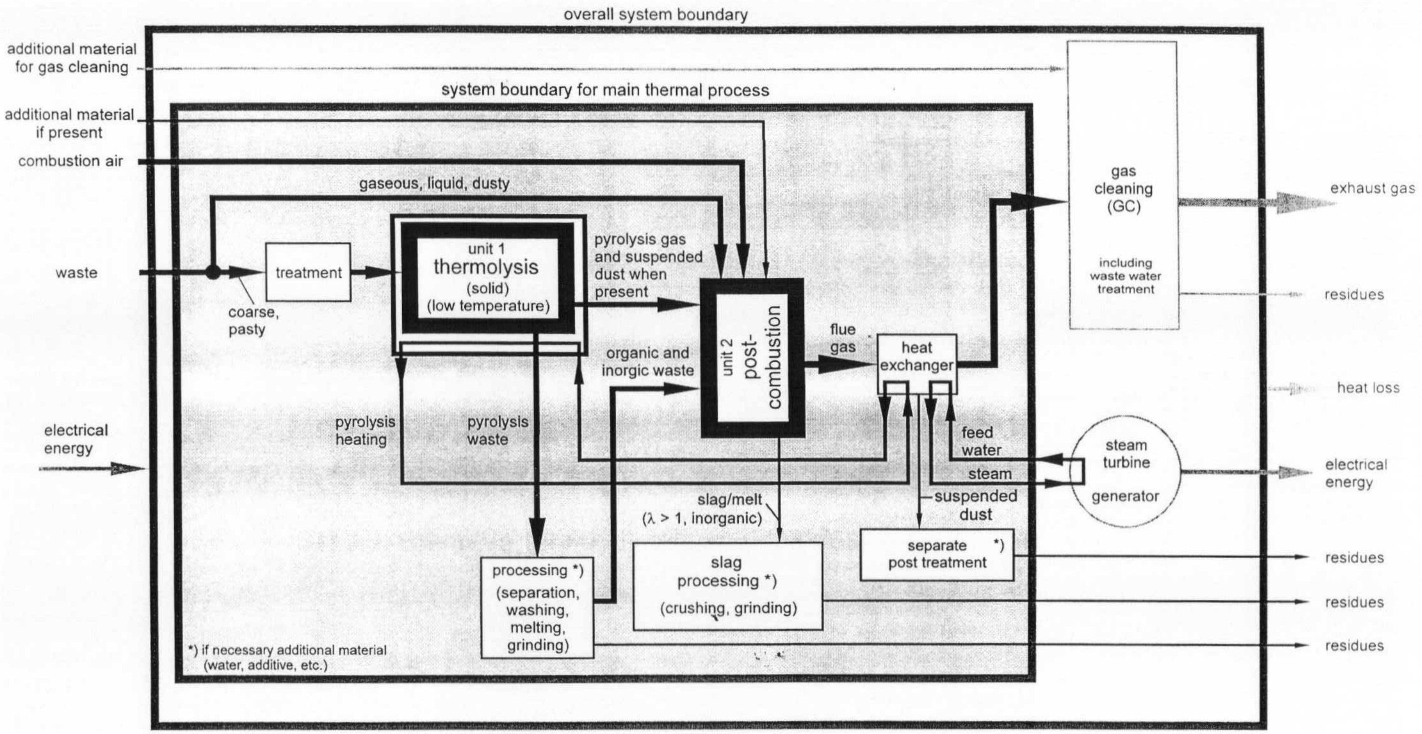


Figure 27: Block flow diagram for a thermolysis - post-combustion proess (Schwel-Brenn Verfahren Siemens KWU) [53].

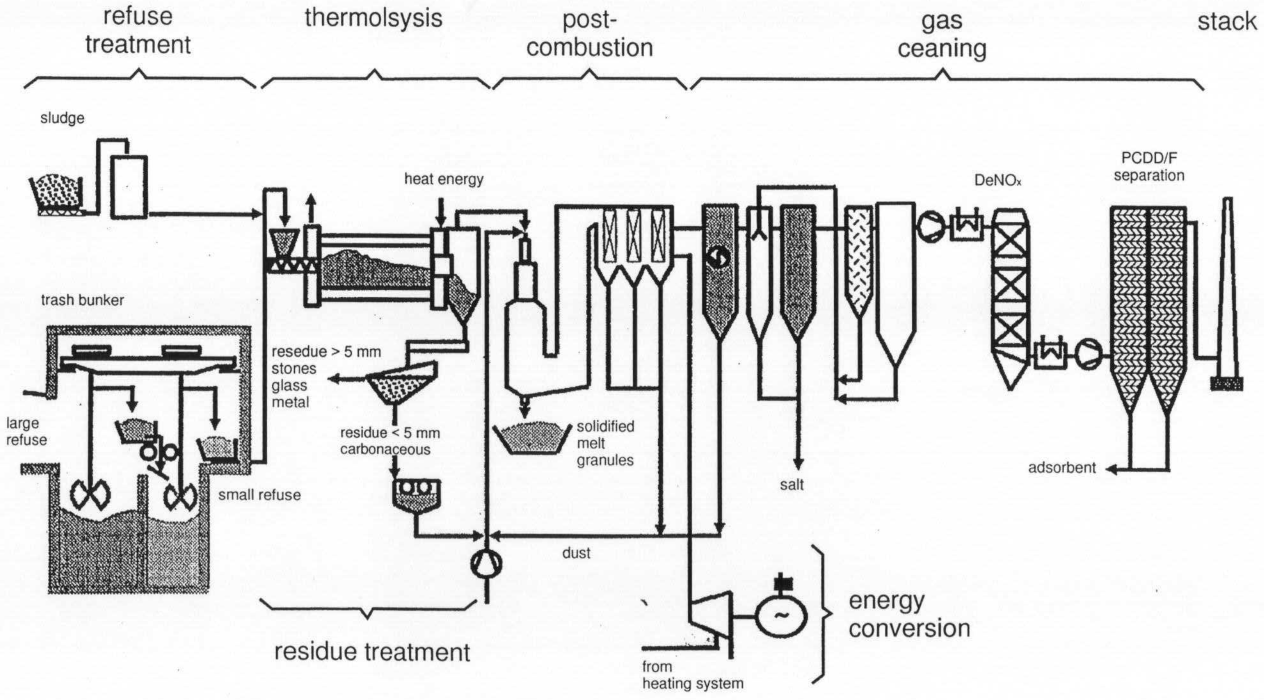


Figure 28: Schematic of Schwel-Brenn-Verfahren Siemens KWU [95, 96, 97, 98].

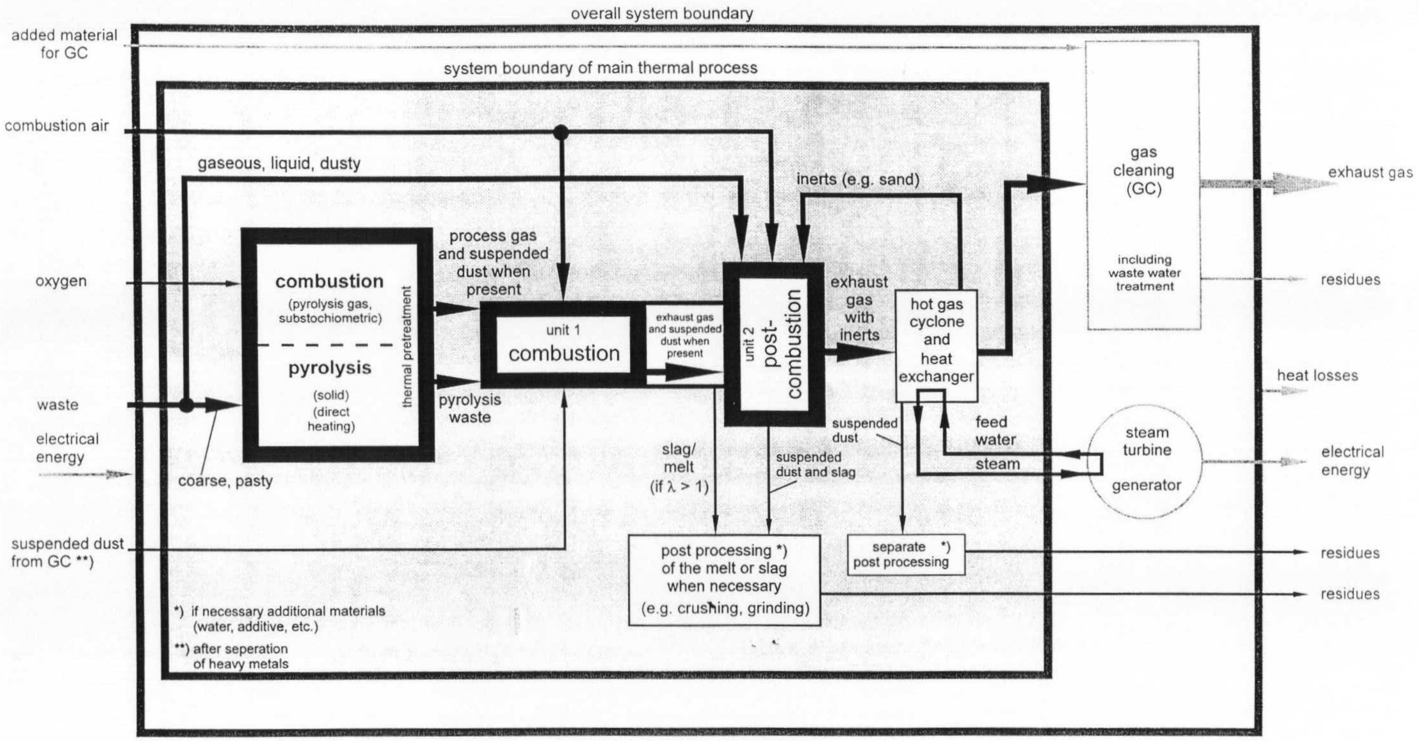


Figure 29: Block flow diagram for the Duotherm Verfahren, Von Roll [53].

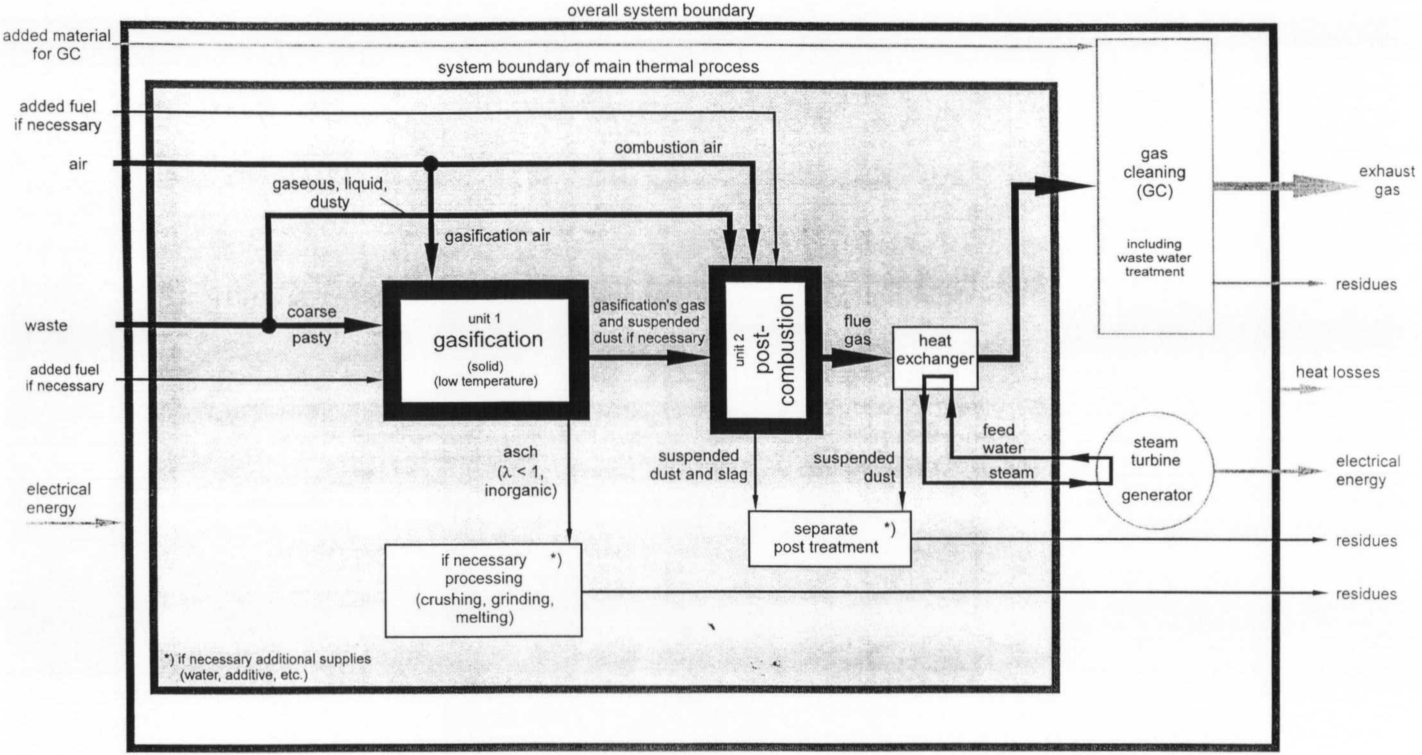


Figure 30: Block flow diagram for gasification - post-combustion process; advaced standard waste incineration (household waste) [53, 101].

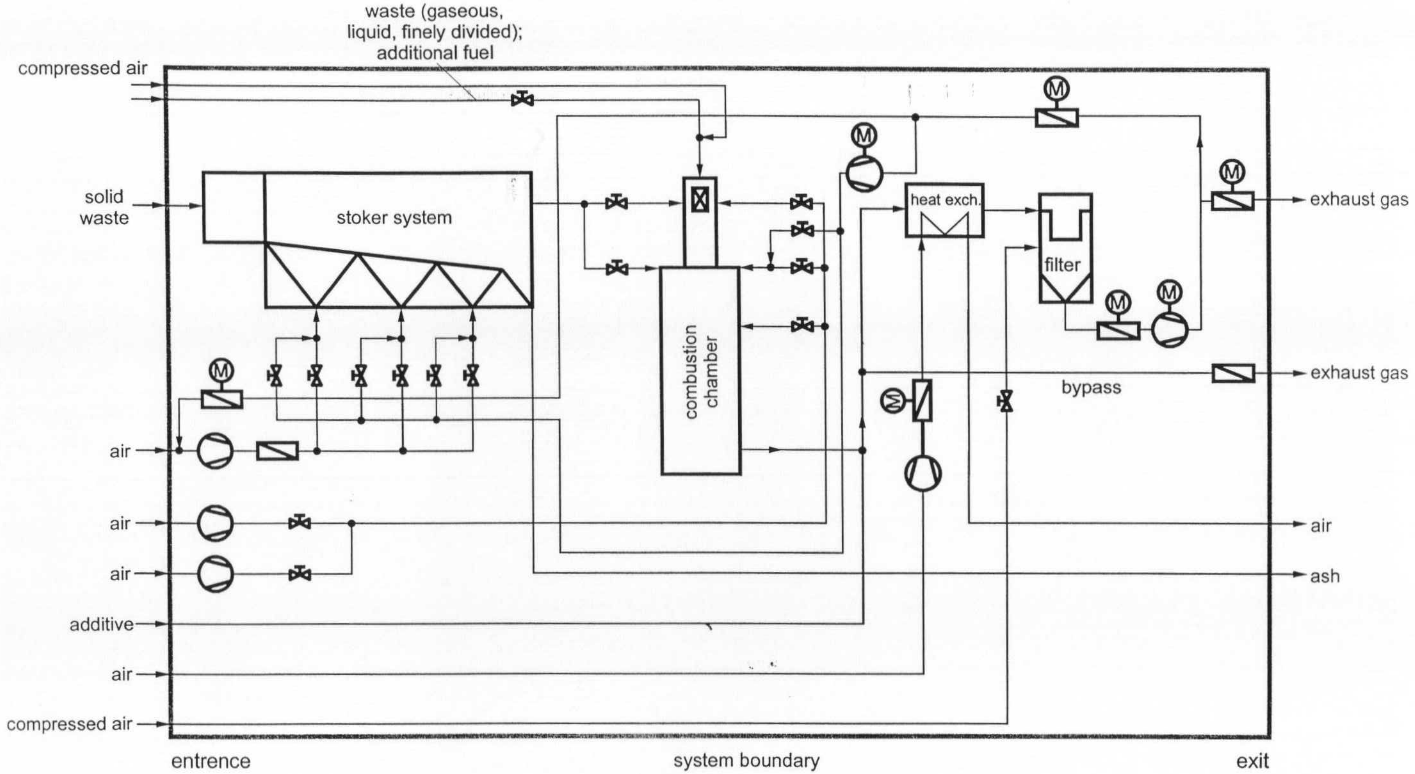


Figure 31: Thermal treatment of coarse solids (pilot-plant concerning to the fig. 10. and fig 30.) [101].

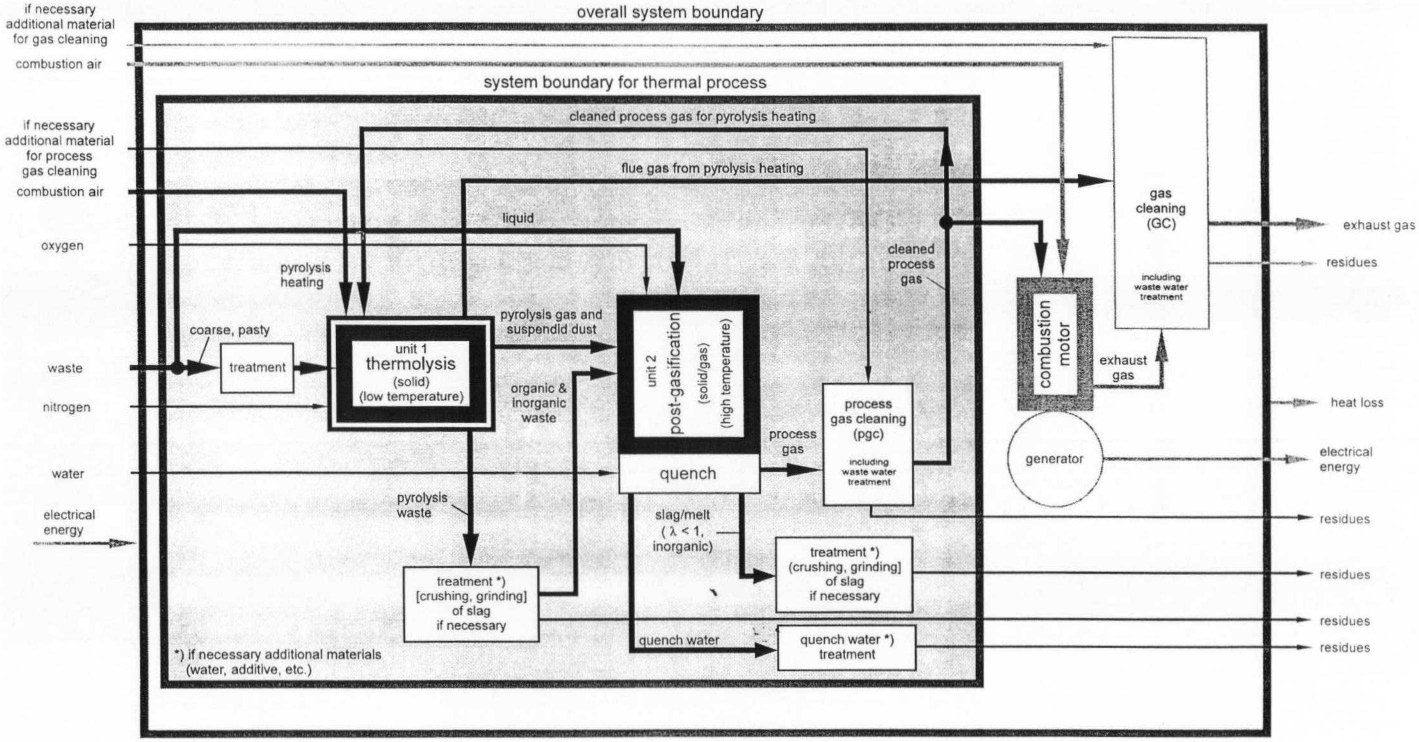


Figure 32: Block flow diagram for thermolysis post-gasification. (e.g. Konversionsverfahren nach NOELL) [53].

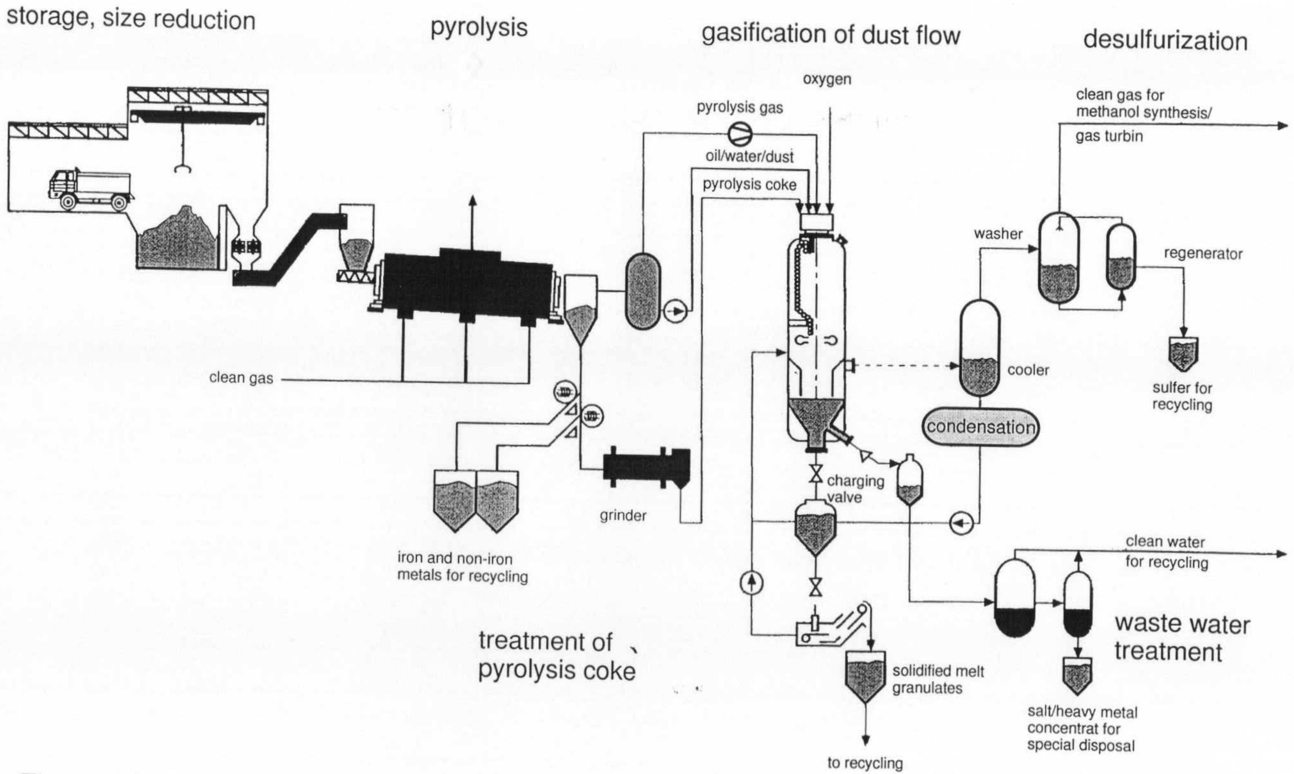


Figure 33: Schematic of the Konversionsverfahren nach NOELL (only main thermal treatment) [104, 105, 106].

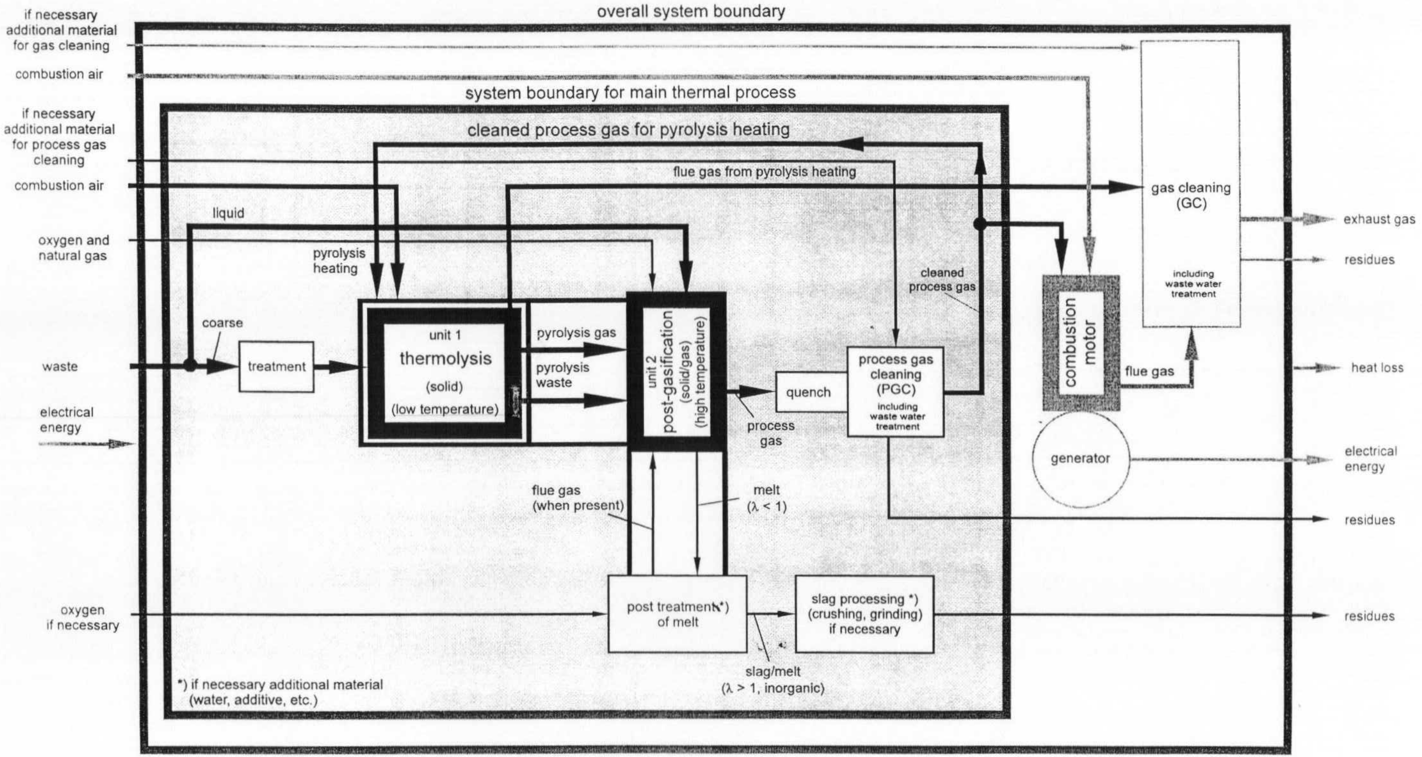


Figure 34: Block flow diagram for thermolysis-gasification (Thermoselect) [53].

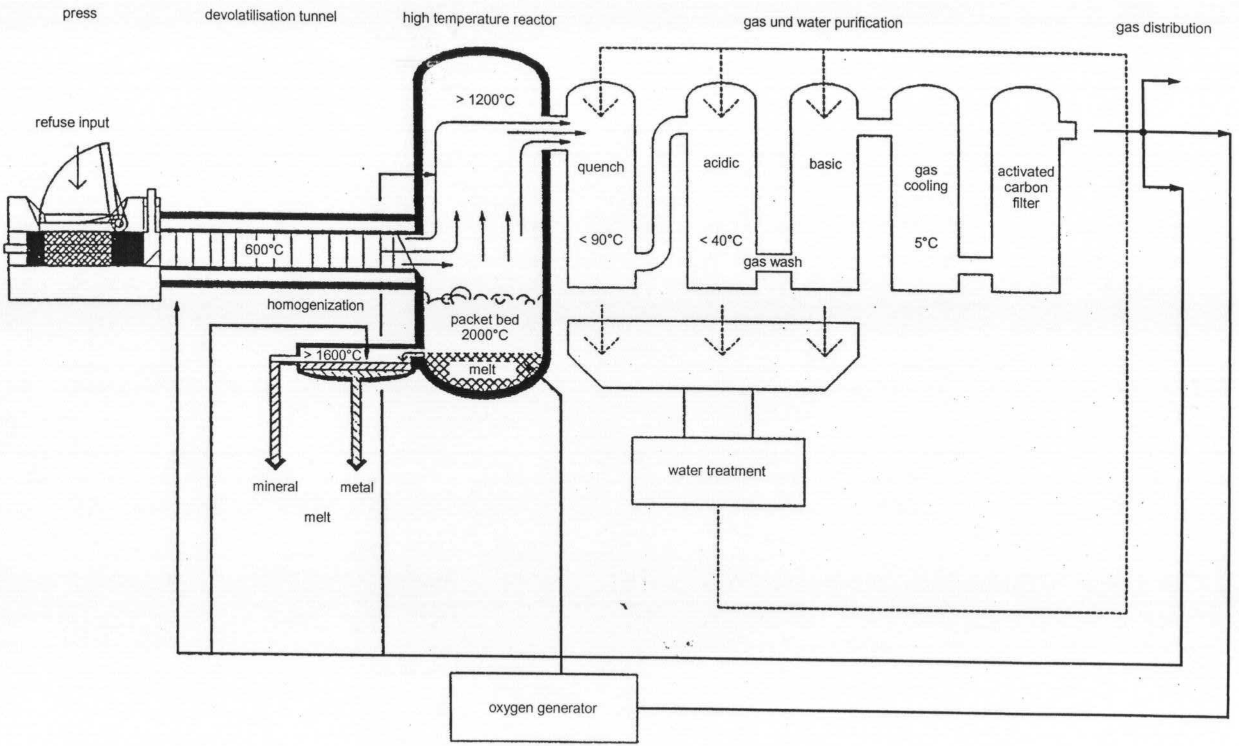


Figure 35: Schematic of the Thermoselect process [108, 109, 110].