

Expert Report

for the Federal Ministry for the Environment,  
Nature Conservation, Building and Nuclear Safety

Project No. Z 6 –30 345/18

Report No. 29217

Status of Alternative Techniques  
for Thermal Waste Treatment

– Final Report –

by

Prof. Dr.-Ing. Peter Quicker, Dipl.-Ing. Florian Neuerburg, Dipl.-Ing. Yves Noël, Adrianna Huras B.Sc.

Rheinisch-Westfälische Technische Hochschule Aachen  
Unit of Technology of Fuels (TEER)  
Wüllnerstraße 2 52062 Aachen

in cooperation with

Dipl.-Volksw. Dipl.-Geogr. Ralf Georg Eyssen  
Prof. Dr.-Ing. Helmut Seifert, Dr. rer. nat. Jürgen Vehlou  
Prof. Dr.-Ing. Karl Thomé-Kozmiensky

Translation

Dipl.-Ing. Heike Bär

ON BEHALF OF  
THE FEDERAL ENVIRONMENTAL AGENCY (GERMANY)

June 2015

## Report Cover Sheet

Report No.	29217
Report Title	Status of alternative techniques for thermal waste treatment Final report
Authors	RWTH Aachen, TEER: Quicker, Peter; Neuerburg, Florian; Noël, Yves; Huras, Adrianna Japan Consult: Eyssen, Ralf Georg KIT: Seifert, Helmut, Vehlow, Jürgen TK Verlag: Thomé-Kozmiensky, Karl
Performing Organizations	RWTH Aachen University Unit of Technology of Fuels (TEER) Wüllnerstraße 2 52062 Aachen  Japan Consult Poststraße 5 14943 Luckenwalde  Karlsruhe Institute of Technology, Institute for Technical Chemistry (KIT) Herrmann-von-Helmholtz-Platz 1 76344 Eggenstein-Leopoldshafen  TK Verlag Karl Thomé-Kozmiensky (TK Verlag) Dorfstraße 51 16816 Nietwerder
Funding Agency	Umweltbundesamt Postfach 14 06 06813 Dessau-Roßlau
Report Date (Year)	2014
Project No. (FKZ)	Project Z 6 -30 345/18
No. of Pages	195
Supplementary Notes	
Keywords	Pyrolysis, gasification, plasma processes, plasma gasification, plasma pyrolysis, depolymerization processes

## Executive Summary

Concerning both number and capacity of installations, incineration is the dominating process for thermal treatment of waste. Around the world, about 255 million Mg of waste are incinerated per year in approximately 2,200 installations.

Besides this established method for waste treatment, waste pyrolysis and waste gasification are offered on the market as additional thermal treatment processes. These processes - also called "alternative" thermal treatment - have been on the market since the 1970ies, presented by changing providers under different labels. Alternative processes are characterized by comparatively complex systems engineering. Suppliers state that in comparison to waste incineration, alternative processes show the advantage of higher electrical efficiency and/or produce higher quality conversion products, like liquid energy carriers to substitute other fuels or vitrified slag of very low leachability.

Marked by setback experiences, alternative thermal processes are not relevant in the Federal Republic of Germany. In other countries, though, discussion has intensified in the recent years, with lobby groups and some decision makers explicitly calling for application of these technologies. Supporters refer to long-term operating experience of installations in Asia, especially in Japan. Yet, general conditions there are completely different from those in Europe or North America. In particular, treatment costs are significantly higher whereas annual operation time is much shorter.

Practical experiences mentioned above mainly refer to gasification and pyrolysis plants. Besides these "classic" alternative thermochemical processes, there have been further alternative processes pushing into the market in recent years. Plasma processes (realized as plasma gasification) convert waste respectively its carbonization products by contact with plasma at temperatures of at least 2000 °C (partly ionized gas). According to suppliers this leads to low gaseous emissions and high quality conversion residue at the same time. Another alternative thermochemical process variation, (catalytic) liquefaction is supposed to convert waste to liquid carbohydrates, usually in a single-stage process frequently using catalysts. It is intended to obtain a product with fuel-like characteristics which can then be used to substitute diesel. The so-called HTC-processes (hydrothermal carbonization) are preferably used to treat (wet) biodegradable waste and (sewage) sludge. The input material is converted to carbonization product under pressure and in liquid aqueous phase. The product is meant to allow optimized energetic or material utilization.

There is little reliable data available on operating experiences from plasma and liquefaction processes, which are currently subject of intense discussion, as well as for hydrothermal carbonization, which is on the verge of being introduced to the market. For some of the discussed technologies, even mass and energy balances are not available. Treatment of problematic secondary material flows is often still on a conceptual level and not tested in practice.

The report „Status of Alternative Techniques for Thermal Waste Treatment“ aims to provide and evaluate information on the state of the art of alternative thermal processes for the treatment of mixed municipal solid waste.

Subject of this report are only processes for which a relevant timespan of continuous operation could be proved. Technologies currently not in operation, but with demonstrated practicability in the recent past, have been included. In addition, some newer developments have been considered which are - according to suppliers - about to be available on the market. Yet, a certain minimum stage of development was applied as criterion for inclusion.

Besides technological maturity of waste treatment technologies, the local legal and (socio-) political framework is crucial for success or failure of new technologies. For example, the wide-

spread use of alternative thermal processes in Japan cannot be understood without knowledge of the local situation. Therefore country specific conditions are also outlined and discussed in this study.

Information for this report was gathered from different sources. Basis is a comprehensive literature review. Information gathered here was supplemented and verified by questioning of operators. Technologies currently in operation in Germany or - due to development stage - presumably relevant for the market were subject to more detailed examination by visitation of installation sites. Basic process information and parameters as well as environmentally relevant indicators like emissions, energy demand or quality of recyclable materials reconditioned within the process were investigated. Where available, economic data and treatment costs were included. Literature was researched in the English, French, Japanese and German language area. Current developments and established processes currently in operation were considered as well as those "historic" processes which were in long-term operation on an industrial scale in the recent past and therefore also represent state of the art.

Based on gathered information, processes were classified respectively evaluated considering the following aspects:

- Development status of technology (classification according to VDI Guideline 3460)
- Necessary (pre-)treatment effort
- Nature and quality of products (eventually as input for follow-up process)
- Complexity
- Economic viability

The evaluation of alternative thermal waste treatment technologies shows a clear picture:

Of the many types of alternative waste treatment methods analyzed, some upstream facilities jointly operated with other thermal processes can be looked at as potentially reasonable and economic alternatives, even under European legal and market conditions. Alternative processes coupled to power-, cement- or lime plants allow direct utilization of generated products (gas, eventually coke) under optimized conditions (e.g. higher electrical efficiency in power plants).

Also, processes can be relevant that allow treatment of specific waste fractions like highly toxic, chlorine contaminated or low calorific value materials (e.g. contaminated soils) which are not combustible independently. The ecological necessity of high-grade treatment of these hazardous waste materials may justify higher treatment efforts as for example in plasma processes. Here, legal requirements are decisive.

Processes that do not achieve complete inertization of products must be assessed critically. According to the valid BREF-Documents on waste incineration, only those alternative thermal treatment methods can be state of the art, which are either equipped with a consecutive combustion stage with energy utilization or which recover or dispose products. This requirement is not met by methods that generate coke or residue with high ignition loss as "product" without a specified subsequent use. These processes frequently lead to high follow-up costs for product disposal. Given these conditions, profitable operation hardly seems possible.

Especially comparably simple processes (e.g. low-temperature pyrolysis or direct liquefaction) provoke high efforts for product processing (be it gas treatment after pyrolysis/gasification or fuel refinement after direct liquefaction). The alleged simplicity of the main process is generally at the expense of higher complexity in product post-treatment. Accordingly, post-treatment frequently is the weak point of these processes. In many cases, these problems are not considered during process development.

It must be emphasized that all alternative thermal processes considered in this study require significantly higher treatment effort than classic waste incineration. In general, a high effort for processing and conditioning of input material is mandatory. At least size reduction is necessary, often also fractionation and removal of metals and inert materials. Some processes even require pre-drying or pelletizing (briquetting) of input materials. Those few Japanese melting processes which - according to suppliers - can be operated without pretreatment of waste (but still with restricted particle size) are especially intricate to operate. Addition of coke and insertion of oxygen are common in these processes.

Operating efforts of complex alternative treatments cannot be reduced significantly with increasing experience in long-term operation. This can be learned from examples in Japan or the Secondary Raw Materials/Recycling Centre Schwarze Pumpe (SVZ). In Europe, sometimes the opinion is held that alternative treatment technologies are not on par with classic waste incineration only because of the latter's technological maturity. The conclusion that increasing operating experience and optimization could improve alternative processes leading to comparability with incineration therefore does not seem to be tenable.

In conclusion, it can be stated that alternative thermal processes are only operable and economically viable when the following requirements or conditions apply:

- Compliance with legal requirements (e.g. melting processes Japan)
- Attainment of special product properties (e.g. vitrified slag, low pollutant content)
- Treatment of special fractions (e.g. highly toxic or chloride containing materials, fractions with low calorific value)
- Operation of pre-treatment facilities to substitute fossil fuels (e.g. in power generation, cement and lime plants)

Hence, waste incineration is still state of the art to treat mixed municipal waste. None of the alternative processes has proved to be comparable in performance and flexibility. There are no alternative thermal processes available which are capable to compete with waste incineration considering both economic and ecological aspects. Because of their higher complexity, it is currently not to be expected that alternative methods can bridge this gap. In principle, treatment of mixed municipal solid waste should be reserved to established incineration processes, designed and well-tried for this purpose.

## Table of Contents

Report Cover Sheet .....	2
Executive Summary .....	3
Table of Contents .....	6
1 Project Information .....	8
1.1 Background .....	8
1.2 Aim of the Project .....	8
1.3 Thematic Focus .....	9
1.4 Methodology .....	9
1.5 Project Organization .....	12
2 Thermal Processes for Waste Treatment .....	13
2.1 Overview and Classification of Thermochemical Processes .....	13
2.2 Classic Alternative Methods for Waste Treatment .....	14
2.2.1 Pyrolysis .....	14
2.2.2 Gasification .....	16
2.3 Recent developments .....	18
2.3.1 Plasma Processes .....	18
2.3.2 Liquefaction of Waste .....	20
2.3.3 Hydrothermal Processes .....	21
3 Relevant Alternative Thermal Processes for Waste Treatment .....	24
3.1 Pyrolysis .....	24
3.1.1 Pyrolysis as Sub-Step of Combustion/Melting Processes .....	24
3.1.2 Stand-Alone Pyrolysis .....	38
3.1.3 Pyrolysis as Upstream Process .....	52
3.2 Gasification .....	54
3.2.1 Gasification as Part of Staged Combustion Processes .....	55
3.2.2 Gasification as Sub-Step of Combustion/Melting Processes .....	59
3.2.3 Gasification for Syngas Production .....	70
3.2.4 Gasification as Upstream Process .....	94
3.3 Plasma Processes .....	104
3.3.1 Alter NRG (Westinghouse) .....	105
3.3.2 C.H.O.-Power (Europlasma) .....	107
3.3.3 Advanced Plasma Power (Tetronics) .....	110
3.3.4 Plasco Energy (Phoenix Solutions Company) .....	112
3.4 Liquefaction Processes .....	114

3.4.1	Dieselwest .....	115
3.4.2	Logoil .....	118
3.5	HTC Process .....	119
3.6	Summarized Process Overview .....	121
4	Evaluation and Discussion .....	122
4.1	Political and Societal Framework of Waste Treatment .....	122
4.1.1	Europe.....	123
4.1.2	Asia .....	126
4.2	Assessment of Classical Alternative Thermal Waste Treatment Processes .....	130
4.2.1	Pyrolysis.....	130
4.2.2	Gasification.....	131
4.3	Evaluation of Recent Developments in Thermal Waste Treatment .....	132
4.3.1	Plasma Processes .....	132
4.3.2	Liquefaction Processes .....	133
4.3.3	Hydrothermal processes .....	134
5	Conclusion.....	135
6	Process Fact Sheets .....	137
6.1	Pyrolysis .....	137
6.1.1	Pyrolysis as Sub-Step of Combustion/Melting Processes .....	137
6.1.2	Pyrolysis as Stand-Alone Process .....	142
6.1.3	Pyrolysis as Upstream Process .....	148
6.2	Gasification .....	149
6.2.1	Gasification as Sub-Step of Staged Combustion Processes .....	149
6.2.2	Gasification as Sub-Step of Combustion/Melting Processes .....	150
6.2.3	Gasification for Syngas Production.....	155
6.2.4	Gasification as Upstream Process .....	163
6.3	Plasma Processes.....	167
6.4	Liquefaction Processes .....	173
	Literature .....	178
	Abbreviations .....	189
	List of Figures.....	190
	List of Tables .....	193

# 1 Project Information

## 1.1 Background

Considering the worldwide number of installations as well as their capacity, the most dominating treatment method for waste is incineration. Currently, 225 million Mg of waste are treated in 2,200 facilities [Döring 2014].

Besides this established and - concerning oxygen input - overall hyperstoichiometric treatment method (excess air conditions), the substoichiometric processes pyrolysis and gasification are also found in the market. These so-called alternative methods have been presented by different providers under varying names ever since the 1970s. They are characterized by comparably complex systems engineering and process equipment. According to operators, the advantage of substoichiometric processes lies in higher electrical efficiency and/or a higher quality of conversion products, for example vitrified slag of low leachability or non-fossil liquid fuels.

While alternative processes have gained no relevance in Germany due to experiences marked by setbacks, discussion abroad has intensified in recent times and some lobby groups and decision makers explicitly claim the use of these technologies for waste treatment. Supporters point out successful long-time operation of facilities in Asia, especially in Japan. Yet it must be considered that the general framework and waste treatment policy in this region differ significantly from that in Europe or North America.

Practical experiences mentioned above mainly refer to gasification and pyrolysis plants. Besides these “classic” thermochemical processes, other alternative processes have entered the market in the last few years.

Plasma processes (implemented as plasma gasification) convert waste respectively pyrolysis char by contact with plasma (partly ionized gas) at temperatures of at least 2,000 °C. According to providers of this technology, this leads to low gaseous emissions and, at the same time, high quality conversion residue.

Another alternative thermochemical process type is the catalytic direct liquefaction process. In this process - sometimes also referred to as “oilization” - solid waste is converted into liquid carbohydrates in a single-stage process often using catalysts. The intention is to generate products with fuel-like properties that can be used to substitute diesel.

The so-called HTC processes (hydrothermal carbonization) are preferably applied for (wet) organic waste and (sewage) sludge. Waste material in a fluid aqueous phase is converted to a carbonization product that is meant to allow improved energetic or material utilization.

Both plasma processes and liquefaction are currently subject of intense discussion, hydrothermal carbonization is about to be launched on the market. Yet, there is little reliable operating experience documented for all three processes. What is more, in some cases even plausible mass and energy balances are not available. Treatment of problematic secondary and minor material flows is often only laid out on conceptual level.

## 1.2 Aim of the Project

The report „State of the Art of Alternative Processes for Thermal Waste Treatment“ aims to provide and evaluate information serving to determine the state of the art in alternative thermal treatment processes of solid municipal waste.

Processes were considered when they had a proved record of relevant continuous operation under industrial conditions.

Technologies which are not in operation any more but have proved practicability in the recent past were also included. Some new developments with assumed short-term market availability have also been included. A certain minimum stage of development was prerequisite for processes to be selected for further consideration (see chapter 1.4).

Besides technological maturity, the local legal and (socio-) political framework is absolutely crucial for success or failure of new waste treatment technologies. For example, the great importance of thermal treatment processes in Japan cannot be understood without knowledge of the local situation. Therefore, also country specific conditions are described and discussed in this report.

The findings of this report serve to support the Federal Environmental Agency of Germany as knowledge base for further legal and technological measures for waste utilization and are meant to be considered in the Seville process to revise the BREF-document on waste incineration which is currently starting.

### **1.3 Thematic Focus**

The main focus of this report lies on classic and most widely spread thermochemical processes: pyrolysis and gasification.

In addition, technologies that have been developed more recently are considered as well, as being:

- Plasma processes
- Plasma gasification
- (Catalytic direct) liquefaction
- Hydrothermal carbonization

The introductory part gives a general overview and classification of basic thermochemical processes. Both process principles and essential process parameters are explained. Product properties and potential problematic issues of the processes are discussed.

A number of technologies which have been identified as relevant in consultation with the ordering party is explained in detail in the main section of the survey. For each process, characteristic process indicators and parameters are given (see chapter 6).

Since local policy has significant influence on implementation and dissemination of waste treatment technologies, information on policy framework and legal situation in certain regions of the world is included as well. Special attention is given to the Japanese market because regulations there have led to a comparatively far distribution of alternative treatment methods.

Finally, processes are evaluated regarding their technological maturity. The main intention here is to derive basic and universal statements for the different processes.

### **1.4 Methodology**

Information was gathered from different sources. First of all, the report is based on a detailed literature review. Information found here was supplemented and validated by interviewing operators based on a questionnaire. Installations which are either in operation in Germany or which are technologically mature enough to be of possible relevance for the German market were subject to one-day visits.

Basic process information, essential process parameters and environmentally relevant performance parameters like emissions, energy demand or properties of processed recyclables were researched. Where available, details on treatment costs and economic efficiency were included.

The literature review covered English, French, Japanese and German publications. Current development, established treatment methods and “historic” processes were included, the latter yet only in case of a successful long-term operation on industrial scale. In the course of research, more than 100 relevant processes were identified.

Installations and developments of high relevance for the German market were examined during on-site visits and in dialogue with the operators. On-site visits were carried out at following installations:

- Municipal waste pyrolysis plant Burgau
- Circulating fluidized bed gasification within the cement plant Rüdersdorf
- Lime bed shaft gasification Ecoloop located in the Harz mountains
- MEE pyrolysis process, Schwerin
- Catalytic depolymerization plant, Dieselwest, Ennigerloh
- Thermoselect plant, Karlsruhe (decommissioned)

In order to gather further information on the CONTHERM pyrolysis process that was in operation for several years as upstream facility to the hard coal power plant Hamm, the employee at the RWE power plant Westfalen who was formerly in charge was interviewed at length.

Suppliers respectively operators in Japan were contacted directly using the contractors’ professional network. Here too, depth of information was improved by repeated inquiry.

Literature data was used in case the operator of a relevant process did not reply to the questionnaire or to other attempts to gather further information. The same approach was applied for processes currently not in operation respectively operators which no longer exist.

Since all information was gathered from either literature or operators, the authors take no liability for their correctness. Inconsistencies or obviously suspicious information noticed within the research process is commented on in the text.

Based on information at hand, data was structured according to following criteria:

- State of the art (as in VDI 3460, see table 1.1)
- Necessary (pre-) treatment effort
- Type and quality of products (eventually as input for follow-up facility)
- Complexity
- Economic efficiency

Results were discussed and reconciled with selected members of the national expert group preparing revision of the BAT-Document on waste incineration.

Table 1.1: Development status of thermal waste treatment processes according to [VDI 3460] (simplified).

Devel. status	Status Regarding	Minimum Requirement
1	Plant/Process	bench-scale tests, mass and energy balance of core plant
	Input/Output Materials	descriptive analysis of input and output materials (quality, quantity)
	Market Potential	assessment of market potential of a full-scale plant based on bench-scale test results
	Scale-up	description of risks and opportunities of a scale-up, design of a pilot plant
2	Plant/Process	steady-state operation of a pilot plant, mass and energy balances of a core plant
	Input/Output Materials	analysis of input and output materials (quality, quantity); discussion of opportunities and limitations of input materials
	Market Potential	prediction of market potential of a full-scale plant
	Scale-up	description of technical conditions for a scale-up, further unit operations needed for material feeding and discharge, design pilot plant
	Operation	assessment of potential operating problems (corrosion, erosion, scaling...)
3	Plant/Process	steady-state operation of a pilot plant over a prolonged period, measurement of emissions
	Input/Output Materials	testing of the process-specific products concerning their environmental relevance and utilization options
	Market Potential	description of the market potential of a full-scale plant
	Scale-up	technical and economic interpretation of measurement and analysis results related to a full-scale plant, size of equipment, materials, expected construction and operating costs of a full-scale plant, costs per Mg of waste
	Operation	assessment of the expected run time, plant availability and service life a planned full-scale plant
4	Plant/Process	normal operation of full-scale plant over a period of one to two years, confirmation of mass and energy balances, emission values
	Input/Output Materials	demonstration of the suitability of the plant for then planned input materials, marketing potential of typical products generated by the process
	Market Potential	validation of capital and operating costs (business plan)
	Operation	demonstration of availability and runtime
5	Plant/Process	normal operation of full-scale plant over several years, assessment of environmental relevance of the process and plant
	Input/Output Materials	demonstration of disposal of input materials, demonstration of the marketing of process-specific products
	Market Potential	traceable description of capital and operating costs over several years
	Operation	optimization efficiency, availability, runtime

## 1.5 Project Organization

This report was subject to a public rendering process by the Umweltbundesamt, the German Federal Environmental Agency. Contractor is the Unit of Technology of Fuels (TEER) at the RWTH Aachen University.

The following table shows project partners involved in carrying out the research. Project manager was the Unit of Technology of Fuels.

Table 1.2: Project management and project partners

Institution	Editor
<b>Project Management</b>	
RWTH Aachen Unit of Technology of Fuels TEER	Prof. Dr.-Ing. Peter Quicker Dipl.-Ing. Yves Noël Dipl.-Ing. Florian Neuerburg Adrianna Huras B.Sc.
<b>Project Partners</b>	
Japan Consult	Dipl.-Volksw., Dipl.-Geogr. Ralf Georg Eyssen
Karlsruhe Institute of Technology Institute for Technical Chemistry	Prof. Dr.-Ing. Helmut Seifert Dr. rer. nat. Jürgen Vehlow
TK Verlag Karl Thomé-Kozmiensky	Prof. Dr.-Ing. Karl Thomé-Kozmiensky

## 2 Thermal Processes for Waste Treatment

The following section describes the basic principles of thermochemical conversion processes underlying those waste treatment processes discussed in this report, starting with an overview and a classification of processes for the treatment of waste.

### 2.1 Overview and Classification of Thermochemical Processes

As shown in figure 2.1, basic thermochemical processes can be classified regarding heat supply and reactant, distinguishing between

- Processes with external heat supply (pyrolysis)
- Processes with oxygen as reactant (autothermal gasification and combustion)
- Processes with water as reactant (allothermal steam gasification, hydrothermal processes)
- Processes in which a partly ionized gas of high temperature is generated by applying electrical voltage (plasma processes)

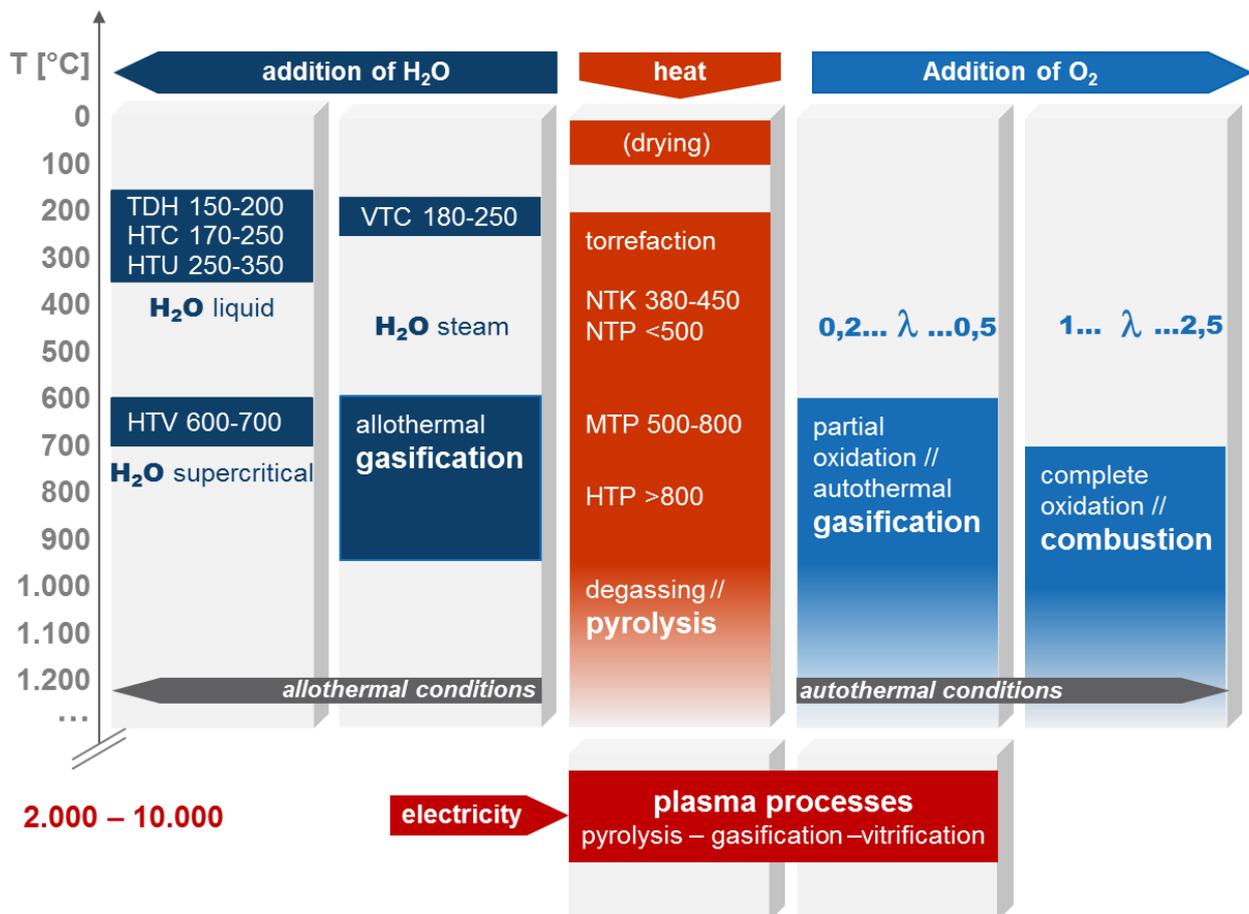


Figure 2.1: Overview of thermochemical processes (see annex for abbreviations)

The following chapters give further information on the processes introduced above.

## 2.2 Classic Alternative Methods for Waste Treatment

Both pyrolysis and gasification can be called classic alternative thermal waste treatment processes. Already by the end of the 19th century, gasification was tested in several European cities in order to generate illuminating gas for street lighting. In San Jose, California, gasification gas was even used as motor fuel. Yet, all attempts had to be given up in a short time (high ash content, uneconomic operation, explosions) [de Fodor 1911, Reimann 1991].

The basic processes taking place during pyrolysis and gasification are shown schematically in figure 2.2. In particular, the most important homogeneous and heterogeneous gasification reactions are shown.

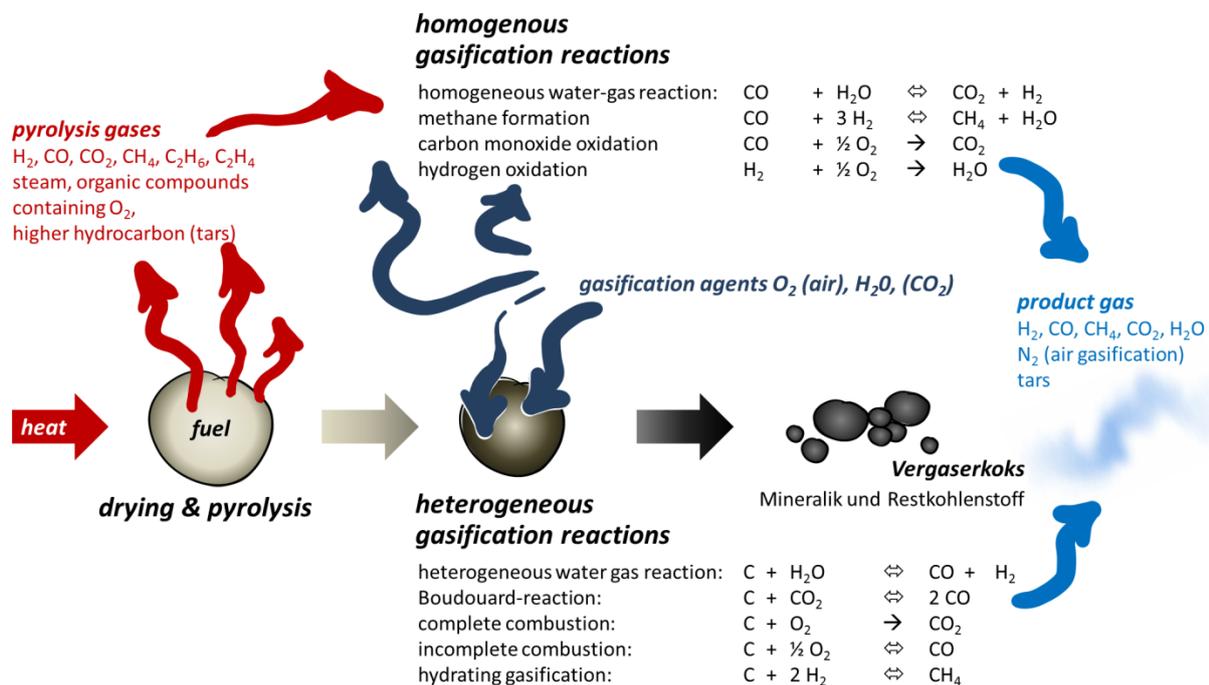


Figure 2.2: Pyrolysis and gasification in a simplified overview (heteroatoms not considered)

### 2.2.1 Pyrolysis

The term pyrolysis refers to the thermochemical decomposition of organic materials caused by external heat supply in the absence of either oxygen, other oxidizing agents or other reactants. In practice, introduction of small amounts of oxygen or air with input materials cannot be avoided. Depending on process temperatures, the following distinction is drawn:

- Low temperature pyrolysis (LTP)  $T < 500 \text{ }^\circ\text{C}$
- Medium temperature pyrolysis (MTP)  $500 \text{ }^\circ\text{C} < T < 800 \text{ }^\circ\text{C}$
- High temperature pyrolysis (HTP)  $T > 800 \text{ }^\circ\text{C}$

Recently, pyrolysis at temperatures between 250 and 300 °C is referred to as torrefaction. This low-temperature type of pyrolysis is traditionally applied in processing and refining of food and is currently discussed and tested as a means to customize biomass fuels, especially to raise calorific value and optimize physical properties (grindability, hydrophobicity).

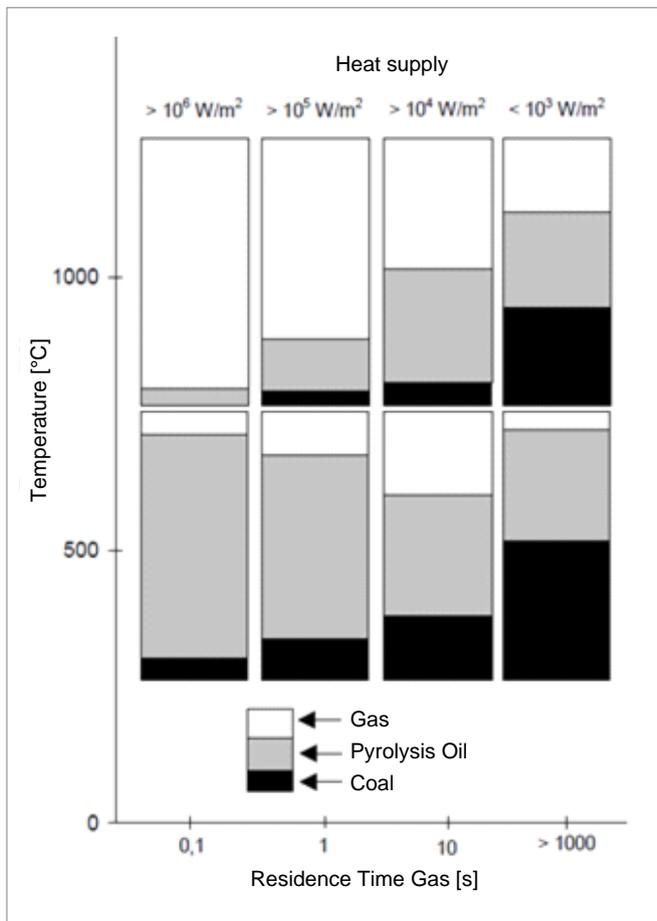


Figure 2.3: Pyrolysis of wood: product range as a function of temperature and residence time [Gerdes 2001; translated] (schematically)

mainly consists of  $\text{CO}_2$ ,  $\text{CO}$ , hydrogen, methane, ethane and ethene. Product properties are determined by waste composition. For example, different dominating plastic fractions in the input material cause a significantly altered composition of product gas. Another important factor influencing the product range of pyrolysis is the water content of input waste, because higher humidity leads to increasing relevance of the heterogeneous and homogeneous water-gas reaction (see figure 2.2) [Warnecke 1991].

The amount of hydrogen and carbon monoxide in the gas increases with temperature, while the concentration of carbon dioxide, methane and higher alkanes recedes [McIntyre 1974, Thomé 1979, Thomé 1985]. The mass fraction of condensable products decreases with temperature as well. However, due to the high calorific value of contained tars, the aqueous phase still holds a significant energy content.

Another criterion to differentiate pyrolysis processes can be (gas-) residence time. When input materials go through a rapid heating phase, the process is called flash-pyrolysis. This way a high yield of liquid products can be achieved, especially at low temperatures. Higher process temperatures lead to more gaseous components in the product range. Calorific values decrease with increasing temperature [Warnecke 1991]. The adjacent figure schematically demonstrates the interrelation between temperature, residence time and expected product range for the example of wood [Gerdes 2001]. Results can differ significantly for waste (especially waste with low cellulose content).

Torrefaction as well as flash pyrolysis are used to refine biomass. These processes are not relevant for the treatment of municipal solid waste and are therefore not discussed any further in this report.

For thermal treatment of waste, intermediate and slow rate pyrolysis methods in the medium and high temperature range are relevant. Products stripped under these conditions are mainly gaseous. Yet with sufficiently long residence time, aromatization and polymerization may lead to (re-)composition of liquid or solid reaction products. The gas

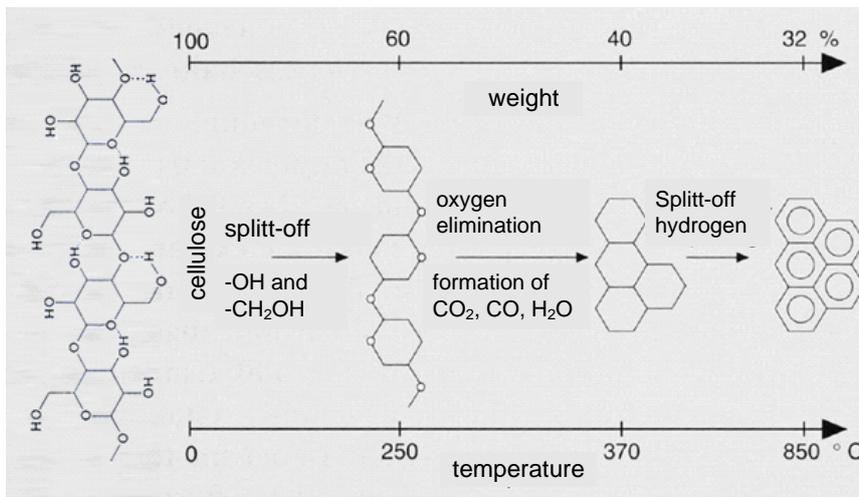


Figure 2.4: Processes and temperature dependency of pyrolytic decomposition of cellulose [Thomé 1994; modified]

Using the example of cellulose, the adjacent diagram shows the processes during degassing as well as generated products, the conversion of the material structure and mass loss of solid material as a function of temperature.

Residual coke mainly consists of carbon and inert materials contained in the feed material (mineral and metal components). Non-volatile heavy metals also remain in the coke fraction [Tabasaran 1977]. Heavy metals with higher volatility like mercury, cadmium and

lead and their chlorides and oxides are already transferred to the gaseous phase at moderate temperatures [Diepenseifen 2011]. At low temperatures, these heavy metals are partly bound to the coke fraction as metal sulfides.

Sulfur contained in the processed waste is transferred to the gaseous phase as hydrogen sulfide and eventually as carbonyl sulfide. A significant amount of sulfur remains within the solid coke residue fraction [Thomé 1979, Scholz 2001].

Nitrogen compounds in the waste are decomposed during pyrolysis and transferred to the gaseous phase as ammonia (NH<sub>3</sub>), hydrocyanic acid (HCN) and elementary nitrogen. Secondary reactions especially of ammonia may occur. Little nitrogen remains in the coke [Thomé 1979].

Organically bound chloride, e.g. PVC, passes into the gas phase as HCl. Unlike in incineration processes, chloride bound in salt (NaCl) remains - at least at moderate temperature - in the solid residue [Tabasaran 1977]. Fluoride on the other hand is converted to gaseous HF [Thomé 1985].

Depending on the properties of input material, the calorific value of pyrolysis gases fluctuates in a wide range. When condensable compounds (pyrolysis oil vapors) are included, very high calorific values between 12.5 and 46 MJ/m<sup>3</sup><sub>N</sub> can be obtained. The calorific value of non-condensable permanent gases lies between 12 and 16 MJ/m<sup>3</sup><sub>N</sub> [Thomé 1994].

## 2.2.2 Gasification

Gasification processes aim to convert mostly solid, sometimes also liquid or paste-like materials to a fuel or synthesis gas with the highest possible calorific value, hereby creating added value in comparison to the original solid material. The solid material is brought into contact with a reactive gasification agent which carries oxygen or - in the case of steam as agent - hydrogen into the process. Possible gasification agents are

- Air
- Oxygen
- Steam
- Carbon dioxide

Gasification is defined as autothermal when the gasification agent causes partial oxidation of the fuel, as is the case when using oxygen or air as gasification agent. Therefore, the necessary heat of reaction for the mainly endothermic gasification reaction is generated by the fuel. Energy content of the gas is reduced accordingly (cold gas efficiency usually about 80 % at most). The limitation of oxygen supply is crucial for gasification in order to prevent energy loss or complete oxidation of feedstock. Usual conditions imply an oxygen supply of 30 to 40 % of the total oxygen demand, synonymously given as air ratio of 0.3 - 0.4.

When steam is used as gasification agent, there is no heat released since no partial oxidation of fuel occurs. On the contrary, additional thermal energy is needed since water molecules are split generating oxygen and hydrogen. This operation mode is called allothermal gasification since necessary energy is supplied by external sources (Greek: állos = other, different). External heating on the outer surface of the reactor is usually not sufficient to maintain the gasification process. Therefore, several heating options are applied, e.g. hot sand (circulating bed), hot ceramic spheres or heatable built-in components.

Thermochemical gasification involves a number of stages: drying, degassing (pyrolysis), homogeneous and heterogeneous gasification reactions. Figure 2.2 shows these sequences schematically. In the heating phase, humidity is evaporated. First small amounts of carbon dioxide and carbonic acids occur already at temperatures below 200 °C. The degassing intensity of volatile components rises with temperature. Only after the main part of degassing is completed, gasification agents or process-generated gases (hydrogen, carbon monoxide) can be transported by diffusion or convection to the surface of the largely degassed solid material mainly consisting of fixed carbon. Then, the heterogeneous gasification reactions outlined in figure 2.2 can take place.

Stripped gases react among themselves and with the applied gasification agents. The most important homogeneous gasification reactions are also illustrated in figure 2.2 (see above).

The product composition in gasification processes depends on both temperature and pressure. Rising temperatures lead to an increase of carbon monoxide and hydrogen while the methane content decreases. Increasing pressure on the other hand promotes generation of methane and carbon dioxide. [Thomé 1994] The influence of pressure and temperature on the heterogeneous water-gas-reaction and hydrating gasification is illustrated in figure 2.5.

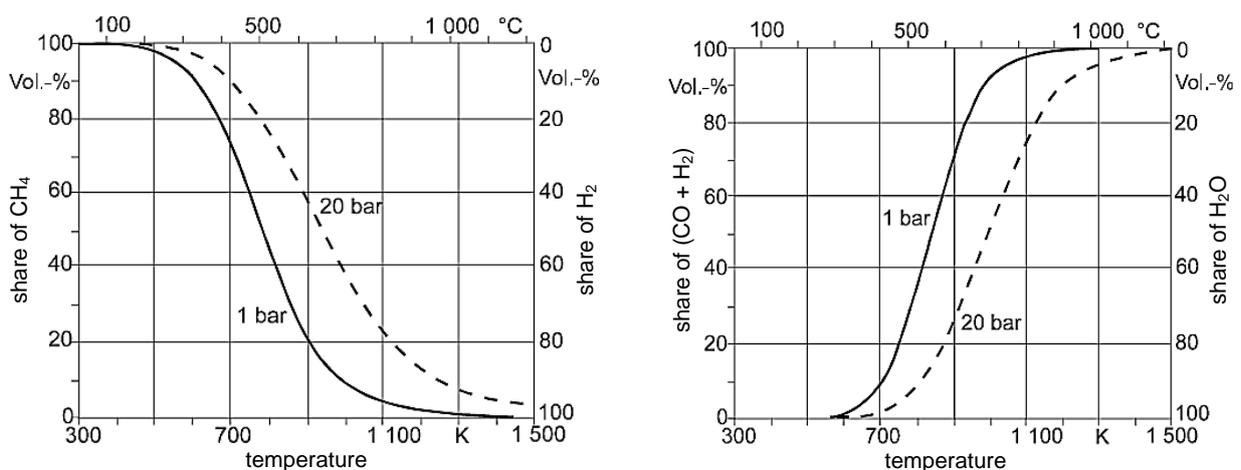


Figure 2.5: Temperature and pressure dependency (examples for 1 and 20 bar) for hydrating gasification reaction ( $C + 2H_2 \leftrightarrow CH_4$ , left) and heterogeneous water-gas-reaction ( $C + H_2O \leftrightarrow CO + H_2$ , right) adapted from [Kaltschmitt 2009].

Sulfur contained in the feedstock is mainly transferred to the gas phase as hydrogen sulfide. COS is hardly detected [Häßler 1995]. Nitrogen is detected as ammonia and small amounts of HCN. At

typical gasification temperatures, most of the ammonia is converted to elementary nitrogen. Chlorine occurs as HCl [Knoef 2012].

Generated product gases are very much determined by the gasification agent, they have a lower calorific value than pyrolysis gases. Calorific values of more than 12 MJ/m<sup>3</sup>N are achieved with allothermal steam-gasification [Thomé 1994]. When oxygen is used as gasification agent, calorific values range from 10 to 18 MJ/m<sup>3</sup>N. The lowest calorific values are found in autothermal air gasification since the product gas is diluted by the high inert nitrogen content of up to 60 %. [Wood 2013]

## 2.3 Recent developments

### 2.3.1 Plasma Processes

Primarily developed for aerospace and military applications, plasma processes are now used in metallurgy and waste treatment as well. Suitability of plasma processes for thermal waste treatment has been proved in the past for hazardous waste fractions like asbestos or chemicals. Vitrification of radioactive waste is another established application. Besides these treatment processes for mono-fraction wastes, plasma supported thermal waste treatment processes for municipal waste have been introduced to the market in recent years and are now offered by suppliers all over the world. [Fabry 2013]

#### 2.3.1.1 Principles of Plasma Processes

Classic alternative thermal processes generally obtain necessary temperatures by partial oxidation of fuel (direct heating) or by external heating of the reactor surface respectively by using a heat transfer medium (indirect heating). Plasma generation is yet another example for direct heat transfer. A process gas (either oxidizing or inert) is ionized by a large specific amount of thermal, electric or electromagnetic energy. Considering the level of energy, plasma is also considered the fourth state of aggregation. [Helsen 2010]

Plasma is generated in plasma torches by applying a voltage between two electrodes causing an arc discharge. Plasma arc torches can be divided into non-transferred and transferred arc torches.

In transferred arc torches, the arc is generated between a free cathode and an external anode. Working gas flows around the rod-shaped cathode which is surrounded by a cooled circular shell.

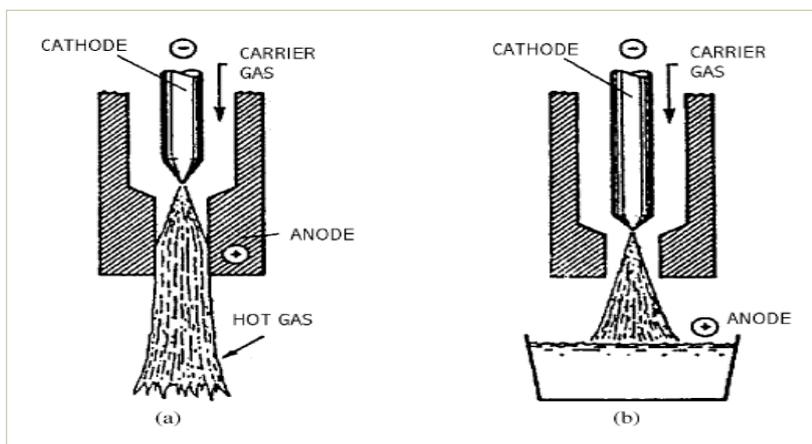


Figure 2.6: Plasma generation with non-transferred arc (left) and transferred arc (right) [Bonizzoni 2002].

The arc caused by voltage between cathode and anode provides the necessary energy to generate plasma. The gas flow through the shell causes the heated gas to leave the lance as plasma jet [Huang 2006]. Depending on the design, the distance between cathode and anode may amount to one meter. Due to extremely elevated thermal flux, minerals and metals contained in the treated materials are liquefied and vitrified [Bonizzoni 2002]. The melting bath is grounded electrically

at the walls of the reactor. In transferred arc torches, the melting bath takes on the function of anode for the arc [Gomez 2007].

When plasma is generated by a non-transferred arc, the electrodes are installed in a housing. In contrast to the transferred arc, in non-transferred arcs it is not the molten material that serves as anode but the burner lance itself. Just like in non-transferred arc torches, working gas flows around the rod-shaped cathode.

Plasmas generated for thermal waste treatment reach temperatures between 2,000 and 30,000 K [Huang 2007].

One aspect mentioned as advantage of plasma processes is the comparatively easy temperature regulation with electrical power as control quantity [Fabry 2013]. In the case of plasma gasification, this allows decoupling of heat release and oxidizing agent supply. Furthermore, plasma processes are characterized by high heat transfer to the treated substance, high heating rates in the starting-up phase and small size of installations. Plasma treatment leads to decomposition of high-molecular compounds (tars etc.) which are generated in classical alternative thermal processes. Due to high process temperatures and depending on process design, it is even possible to melt temperature resistant process residue. [Helsen 2010]

When process energy is provided exclusively by plasma, this results in high energy costs. Accordingly, most suppliers offer combined plasma processes. These include a “classic” pyrolysis respectively gasification step on a moderate temperature level combined with a downstream plasma step for gas treatment and/or vitrification of residual material. Differentiating factors of the offered plasma conversion processes are therefore mainly the design of the low-temperature conversion step and plasma generation, and not the plasma conversion itself. [Lamers 2013]

Just like classic alternative processes for thermal waste treatment, plasma processes are divided into pyrolysis and gasification processes. In plasma pyrolysis, inert gases like argon or nitrogen are utilized, whereas plasma gasification uses working gases containing oxygen. [Heberlein 2008]

### **2.3.1.2 Plasma Pyrolysis**

Plasma pyrolysis combines the inert process atmosphere of pyrolytic decomposition with energy supply through plasma. Correspondingly, waste feedstock is broken down into simple molecules at temperatures of 2,000 K or more under reducing conditions. [Dave 2010] Depending on whether the substance to be converted is heated radiantly by plasma or in direct contact with the plasma, two types of decomposition occur: radiative heating leads to thermal cracking of macromolecules. In direct contact between waste and plasma on the other hand, plasma molecules, ions and electrons in excited state interact on molecular level, hereby enhancing decomposition of the pyrolytic material. [Bonizzoni 2002]

A multitude of studies can be found on the treatment of diverse waste fractions by plasma pyrolysis on bench and pilot plant scale. In most cases, studies refer to mono-fraction waste (plastics, tires) or to waste fractions with high risk or contaminant potential (hospital waste, combustion ashes) [Helsen 2010]. Products of waste conversion are usually a gas with high calorific value and vitrified slag [Dave 2010]. Despite intensified research activities in the field of plasma pyrolysis, industrial applications to treat solid waste materials with this technology are not yet known [Helsen 2010].

In contrast, Plasma pyrolysis of liquid and gaseous hazardous waste materials is already applied on industrial scale. [Helsen 2010]. Two examples for providers of this technology are:

- PLASCON process by DoloMatrix, Australia  
number of facilities: 10, capacity: approximately 100 kg/h  
[Heberlein 2008] [Helsen 2010]
- Shinmaywa Auto Engineering (Japan)  
number of facilities: 5, capacity: approximately 10 kg/h  
[Heberlein 2008]

Since this report focusses on thermal conversion of solid waste respectively secondary fuels, plasma pyrolysis processes will not be considered any further.

### 2.3.1.3 Plasma Gasification

In thermochemical gasification, addition of an oxidizing agent allows partial utilization of energy bound in the feedstock as a source of energy. Plasma gasification processes use the generation of plasma as additional source of energy. According to suppliers, this allows gasification of low calorific waste [Helsen 2010]. For economic reasons, air is the most common gasification agent. To prevent input of nitrogen from air (resulting in increased gas flow volume), some processes use pure oxygen or steam as gasification agent. The most common type of plasma generation in plasma gasification processes for thermal waste treatment is the non-transferred arc. Yet, when the focus lies on the vitrification of process residue, transferred arc discharge is the preferred technology because of higher heat transfer into the slag.

Plasma gasification is implemented in two configurations: single-stage processes gasify and melt waste directly using plasma (Alter NRG, Europlasma, see chapter 3.3). The additional process energy supplied by plasma depends on the calorific value of the waste input. In some process concepts, the calorific value of waste is increased by addition of energy carriers (coal, coke) in order to reduce energy costs. Despite this measure, energy costs are still comparatively high. Therefore, single-stage processes are mainly used to treat small waste fractions with high hazardous potential (asbestos, filter dust, hospital waste). [Helsen 2010]

To achieve economic treatment of municipal solid waste with plasma processes, some suppliers offer two-stage processes (Plasco Energy, Advanced Plasma Power, Europlasma, see chapter 3.3). In the first step of the process, waste is gasified in a “conventional” reactor, for example on a grate. Generated Process gases are treated in a second stage using plasma. This process layout is to be considered as gas processing unit, used to condition the generated gas for an upgrade utilization (gas motor). Depending on process design, gasification residue may be molten in a plasma converter as well. According to suppliers, energy costs for a two-stage plasma gasification are significantly lower than for the single-stage process. [Helsen 2010]

## 2.3.2 Liquefaction of Waste

### 2.3.2.1 Basic Principle

Liquefaction of waste or biomass aims to generate a fuel product in a direct process. The output is to be a product that is either conforming to fuel standards or an intermediate product comparable to crude oil or gas oil. Technologies applied to produce syngas with subsequent oil synthesis are not object to further consideration at this point.

The possibility to liquefy waste fractions depends on their chemical composition. The target product consists of hydrocarbon chains, in simple terms:  $(-CH_2-)_n$ . Input materials with a comparable structure are polyolefins. Other plastic fractions and biomass contain an increased share of

heteroatoms (oxygen, nitrogen, sulfur, chloride) which either prevent direct formation of pure CH<sub>2</sub>-chains or significantly reduce the content of these chains in the product.

Polyolefins can be directly split thermally into short-chain paraffin waxes and olefins. High temperatures (> 600 °C) and short residence time lead to a higher content of short chain hydrocarbons, whereas low temperatures (< 400 °C) and longer residence time cause longer chains. Unless saturated with hydrogen, olefins tend to polymerize and therefore show low ageing stability. [Franz 2008]

Reaction pathways for the decomposition of heteroatom rich input fractions like biomass are by far more complex. To produce high value oils, it is indispensable to widely eliminate heteroatoms. What is more, the hydrogen/carbon ratio in biomass is about 1.4 and is therefore significantly lower than the ratio of the target product (H/C ratio approx. 2). Conversion to hydrocarbon can take place in the presence of hydrogen or hydrogen transferring substances. Advanced technologies claim to achieve high quality products solely using a catalyst. So far, scientific proof of this fact has not been provided. [Behrendt 2006]

When product oils shall be used as fuels, they must meet the specifications of respective standards. For diesel fuels, this is DIN EN 590, for petrol it is DIN EN 228.

### 2.3.2.2 Process Approaches

Process approaches for liquefaction can be distinguished as follows:

- High pressure hydrogenation
- Depolymerization
- Solvolysis:
  - Organic solvent
  - Water as solvent (hydrolysis)
- Combined processes

All treatment principles operate with a liquid phase. This is to enhance miscibility and allow rapid heating of input materials.

High pressure hydrogenation aims to generate saturated products with a low amount of heteroatoms. Pressure ranges from 100 to several hundred bar, temperatures are between 300 and 350 °C. The use of hydrogen as hydration agent leads to a comparatively high product quality at the price of high operating efforts.

Depolymerization is basically a thermal decomposition of the input material. A “start-up oil“ added in the start-up phase should not be converted within in the process or rather should the conversion rate not exceed fuel generation. The process is operated at 250 to 420 °C and slightly below atmospheric pressure. Liquefaction processes which are currently offered on the market and presented in this study operate based on the principle of depolymerization (see chapter 3.4).

In solvolysis, a solvent takes part in the reaction. Used solvents are either organic compounds (e.g. oils, ethylene-glycol or water/phenol) and/or a medium with either acidic, basic or neutral pH value. In literature, temperatures from 300 to 450 °C and pressures up to 200 bar are given as reaction parameters. [Behrendt 2006, Tukker 1999]

### 2.3.3 Hydrothermal Processes

Hydrothermal carbonization was discovered by Bergius at the beginning of the 19th century [Glasner 2001]. The use of this technology for the purpose of waste treatment has only recently

come into focus, going back to the work of Professor Antonietti at the Max-Planck-Institute of colloids and interfaces in Potsdam, Germany [Röthlein 2006]. Based on his research, this topic is downright booming at the moment and many research institutions and companies are working on this field.

By hydrothermal carbonization, biogenic materials like plant residue, biodegradable waste or sewage sludge can be converted to a carbonization product (also called hydrochar) with both high carbon content and calorific value (see fig. 2.7). Biomass is treated in an aqueous phase with a residence time of 2 to 16 hours at temperatures between 170 and 250° C and a pressure sufficient to maintain a liquid state of aggregation (10 - 40 bar). Citric acid is added frequently and usually denoted as catalyst.

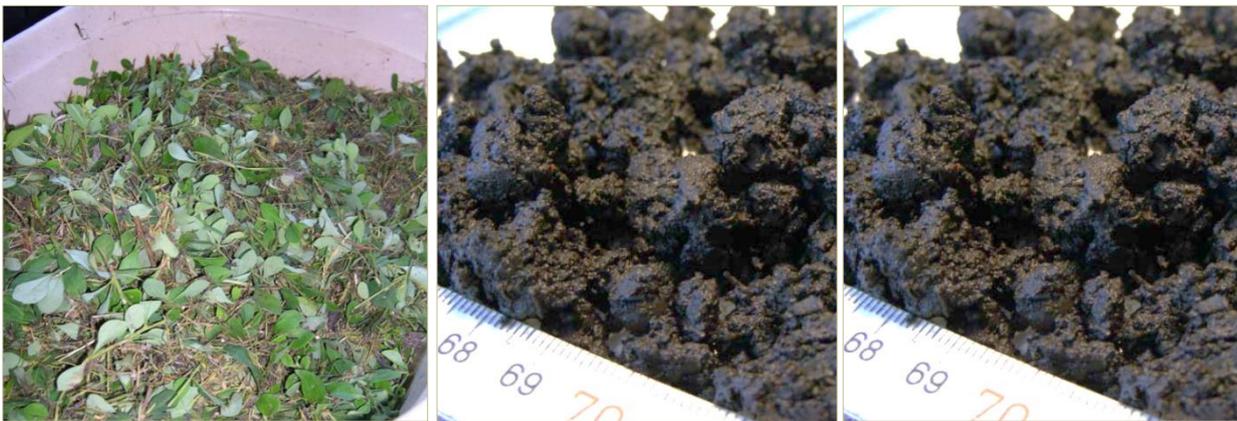


Figure 2.7: Hydrothermal carbonization; left: starting material, middle: product, right: (another) product magnified [Ramke 2011, Wallmann 2011].

Besides the desired carbonization product, permanent gases (up to 5-10 wt.-%) and wastewater (5-15 wt.-%) occur. Exhaust air frequently contains significant amounts of hydrogen sulfide. Carbon monoxide, methane and further volatile hydrocarbons occur, requiring mandatory waste-air purification. [Serfass 2014]

The wastewater pH shows acidic values (3.5-6.5) and is contaminated with high organic loads. Typical COD-values range from 30,000 to 100,000 mg/l. The COD/BOD ratio is 2 to 2.5 indicating refractory, i.e. non-degradable COD which causes problems in wastewater purification. Also, nitrogen loads of up to 5,000 mg/l require further treatment. [Serfass 2014]

Besides hydrothermal carbonization, two other hydrothermal processes exist: hydrothermal liquefaction (HTU - hydrothermal upgrading) and hydrothermal gasification. In contrast to hydrothermal carbonization, these two processes aim to enrich carbon in a liquid or gaseous product usable as fuel. Typical process parameters of hydrothermal processes are given in table 2.1.

Another technology to carbonize biomass currently in development is vapothermal carbonization (VTC). The main difference to HTC lies in the utilization of saturated steam instead of (liquid) water. Basic process parameters are included in Table 2.1. Both higher energy efficiency (no heating of water) and advantageous process management (no de-watering) are mentioned as advantages of this process in comparison with HTC. [EEK 2011] Another difference between the two processes is the influence on ash content.

While the ash content in HTC processes decreases because soluble components are washed out, ash content in VTC is higher, since the organic content of substrate decreases during treatment whereas the ash is not affected. Like HTC, VTC produces polluted exhaust air (H<sub>2</sub>S, CO, VOC) and highly polluted, acidic wastewater with a COD of up to 300,000 mg/l. [Spantig 2010, Serfass 2014]

**Table 2.1:** Basic process parameters of hydrothermal processes, adapted and amended from [Clemens 2011, Klemm 2009, EEK 2011].

	Hydrothermal Carbonization	Hydrothermal Liquefaction	Hydrothermal Gasification	Vapothermal Carbonization
Reaction Agent	water, liquid	water, liquid	water, hypercritical	saturated steam
Temperature	170 - 250 °C	250 - 350 °C	600 - 700 °C	180 - 250°C
Pressure	10 - 40 bar	50 - 200 bar	250 - 300 bar	16 - 42 bar
Residence Time	2 - 16 h	10 - 15 min	1 - 5 min	3 h
Additive/Catalyst	citric acid, FeSO <sub>4</sub>	alkali carbonates, alkali hydroxides	usually none	none
Main Product	carbonization product (coke)	oily liquid rich in phenols	H <sub>2</sub> , CO <sub>2</sub> , CH <sub>4</sub>	carbonization product
Product Separation	draining, drying	phase separation hydrophilic - hydrophobic	phase separation gaseous - liquid	drying

### 3 Relevant Alternative Thermal Processes for Waste Treatment

Processes with proved long-term and full-scale operation for which fully operational systems engineering is available are described and discussed in this chapter. Those processes under development that show the potential to enter the market before long are introduced as well, provided that sufficient data was available from either literature or suppliers in order to evaluate the process.

#### 3.1 Pyrolysis

Supporters of the application of pyrolysis to treat municipal waste postulate several advantages of pyrolytic treatment, especially in comparison to waste incineration. The following benefits are specified [Lamers 2013]:

- Energetic use of pyrolysis oil and gas can be more efficient in prime movers (gas turbine, combustion engine).
- Metal recovery from pyrolysis coke is facilitated and leads to higher quality recovery products; production and utilization of soot (“Carbon Black”) is considered to be beneficial.
- Reduced emissions

Yet, these technological advantages still have not been proved in in long-term operation. Information on (long-term) operation and economy on waste pyrolysis is rarely found in literature. It is known, on the other hand, that many attempts to implement the technology suffered from major problems. In general, the following aspects of pyrolysis processes are considered to be problematic [California 2007, Lamers 2013]:

- Reactors and process management commonly require high intensity material processing with according pre-treatment costs.
- Generated pyrolysis gases contain high concentrations of tars, impeding energetic utilization.
- Marketing of generated coke is hindered by low coke quality.
- Complex systems engineering requires high maintenance efforts.
- In some processes, fossil fuels are used for heating purposes.

In the following chapters, processes based on pyrolysis technology are explained. Processes were selected as relevant for state of the art according to the criteria introduced above (see chapter 1.4).

##### 3.1.1 Pyrolysis as Sub-Step of Combustion/Melting Processes

Distinguishing mark of processes explained below is the use of a pyrolysis step in a high-temperature process in which both pyrolysis gas and generated coke are combusted - frequently after removal of the metal fraction - at temperatures above the melting temperature of the slag. The generated slag is a vitrified product with favorable elution values.

###### 3.1.1.1 IHI Pyrolysis Gasification and Melting Systems

The company Ishikawajima-Harima Heavy Industries developed a process to treat municipal solid waste that combines a pyrolysis step in an externally heated rotary drum with high temperature combustion. The pilot plant was operated around the year 2000 with a capacity of 20 Mg/d.

## Technology

The following figure (3.1) schematically illustrates the process. First, waste is shredded, then dried and transferred to the pyrolysis drum. Pyrolysis gas is transferred to a downstream melting furnace with subsequent horizontal combustion chamber. The process ends with a heat recovery boiler and gas purification.

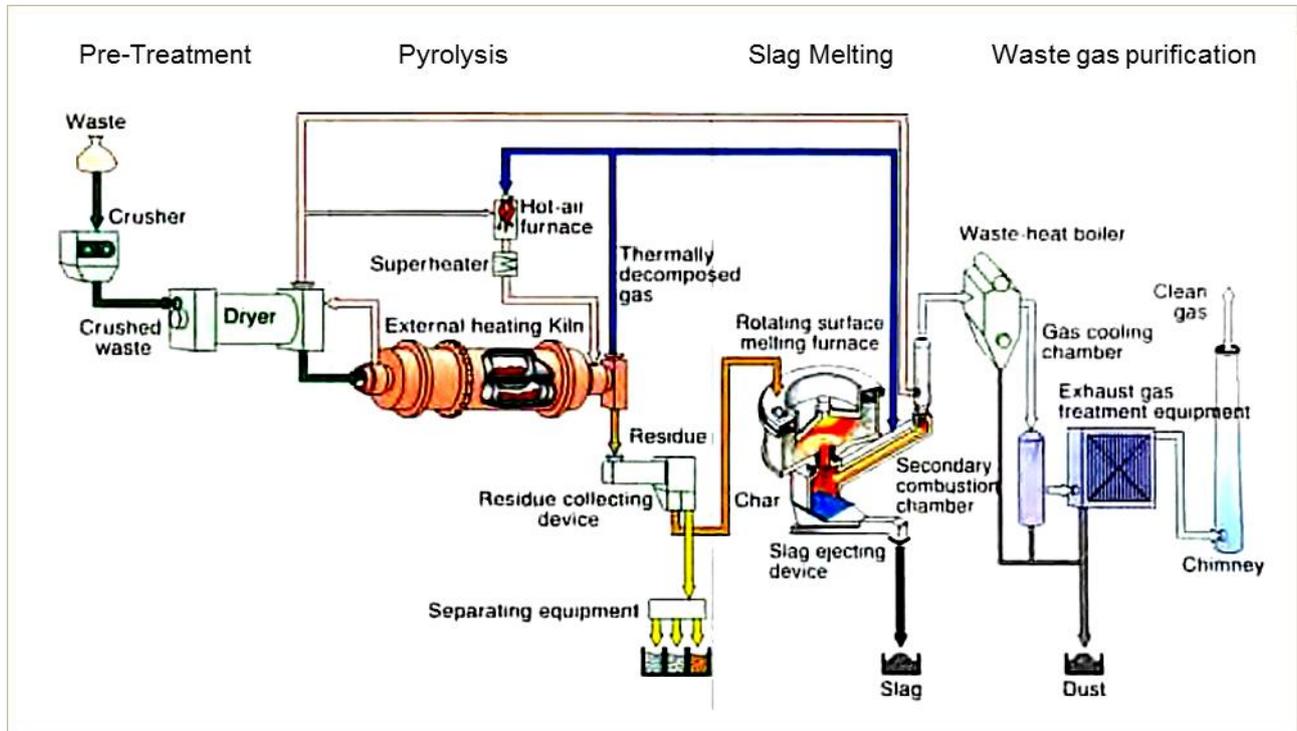


Figure 3.1: Schematic diagram of the IHI Pyrolysis Gasification and Melting System

## Development Status

A technical plant with two lines of 65 Mg/d each was handed over to the city of Chita in 2003. It seems that this process is no longer pursued.

### 3.1.1.2 Siemens Schwel-Brenn-Process

The Schwel-Brenn process was designed by the engineer Karl Kiener and was known as “Kiener-Pyrolysis”. Siemens-KWU refined the process based on experiences in power plant technology and launched it on the market. This process combines pyrolysis (low temperature carbonization in a rotating kiln) with high temperature combustion of pyrolysis gases and pyrolysis coke in a burning chamber. Besides household waste, household-like commercial waste and bulky waste, sewage sludge (drained or dried) can also be treated. It was the aim to convert waste almost completely into secondary raw materials and usable energy.

## Technology

Process design and flow pattern of the Schwel-Brenn process are shown in figure 3.2 and 3.3. In the following, the process is described by the example of the plant in Fürth, Germany.

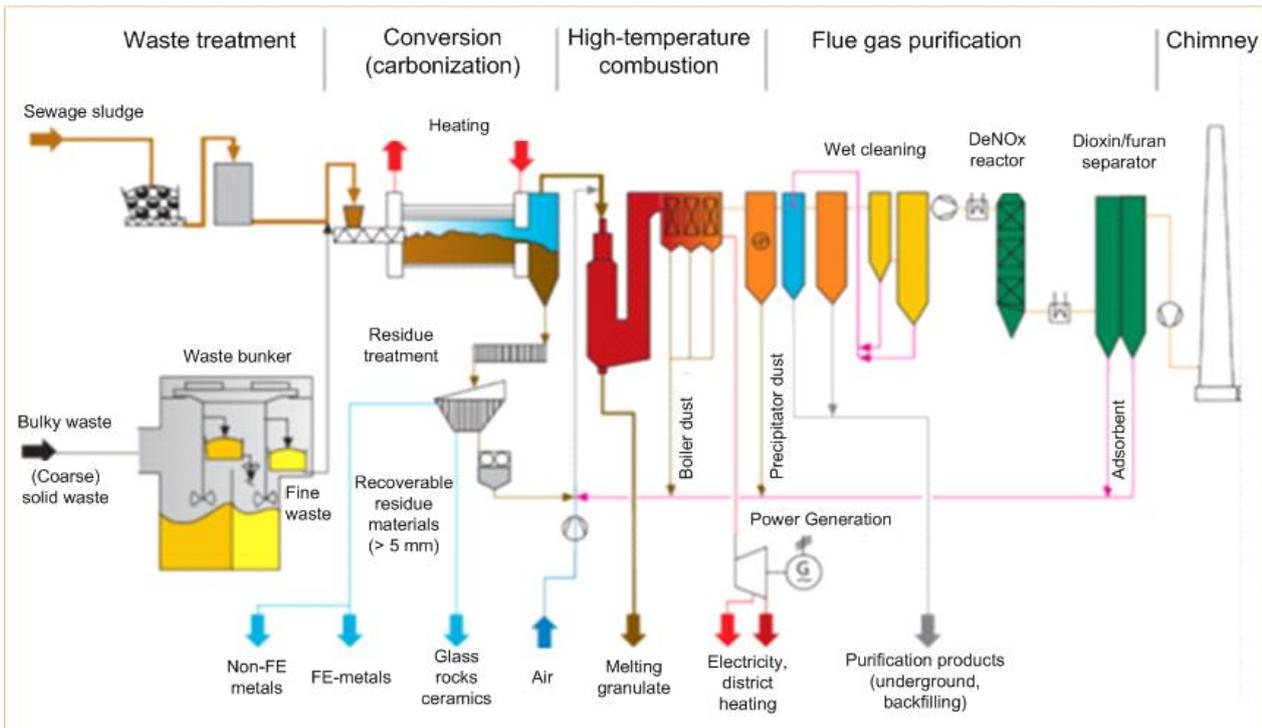


Figure 3.2 Process diagram Schwel-Brenn-Process by the example of the Fürth plant [Siemens AG, quoted in Thomé 1998; translated].

After delivery, the waste is initially shredded to an edge length less than 150 mm. Drained or dried sludge, which can be treated with this process, is dried separately to more than 90 % DM. The heating medium is low temperature steam originating from the water-steam-cycle of the plant. The obtained dry granulate can be fed directly to the carbonization process.

The mixture of fine waste and sewage sludge is homogenized in a slowly rotating drum (fig. 3.4 and 3.5) and heated up to about 450 °C under oxygen deficient conditions. Pipes arranged in the drum serve as heating device. A heating gas flows through the pipes in counter current to the waste passing the drum. Residence time of the waste in the drum is about one hour. In pyrolysis, a combustible pyrolysis gas and a dry, carbon containing residue are generated.

Pyrolysis gas is transferred directly to the high temperature combustion chamber. Solid residue is separated into a coarse fraction > 5 mm and a carbon containing fine fraction < 5 mm. Ferrous and non-ferrous metals are separated from the coarse fraction using magnetic and current separators. According to the supplier, the remaining mixture of glass, stones and ceramics can be marketed. The fine fraction containing carbon is ground to a particle size < 1 mm.

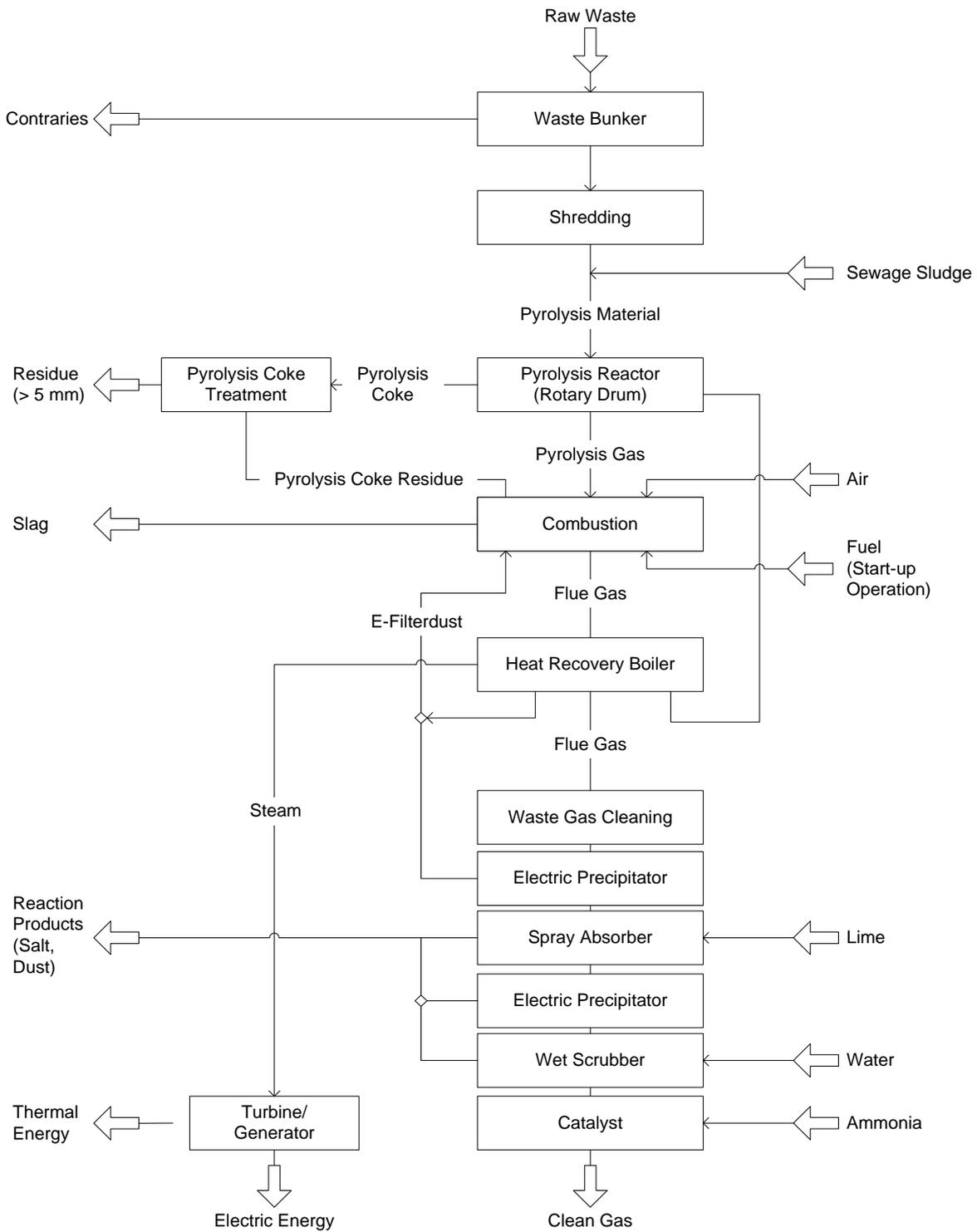


Figure 3.3: Process principle Schwel-Brenn-Process Siemens AG [according to Bischofsberger, cited in Heil 1990].



Figure 3.4: Conversion drum Schwel-Brenn plant in Fürth [Siemens AG 1997].

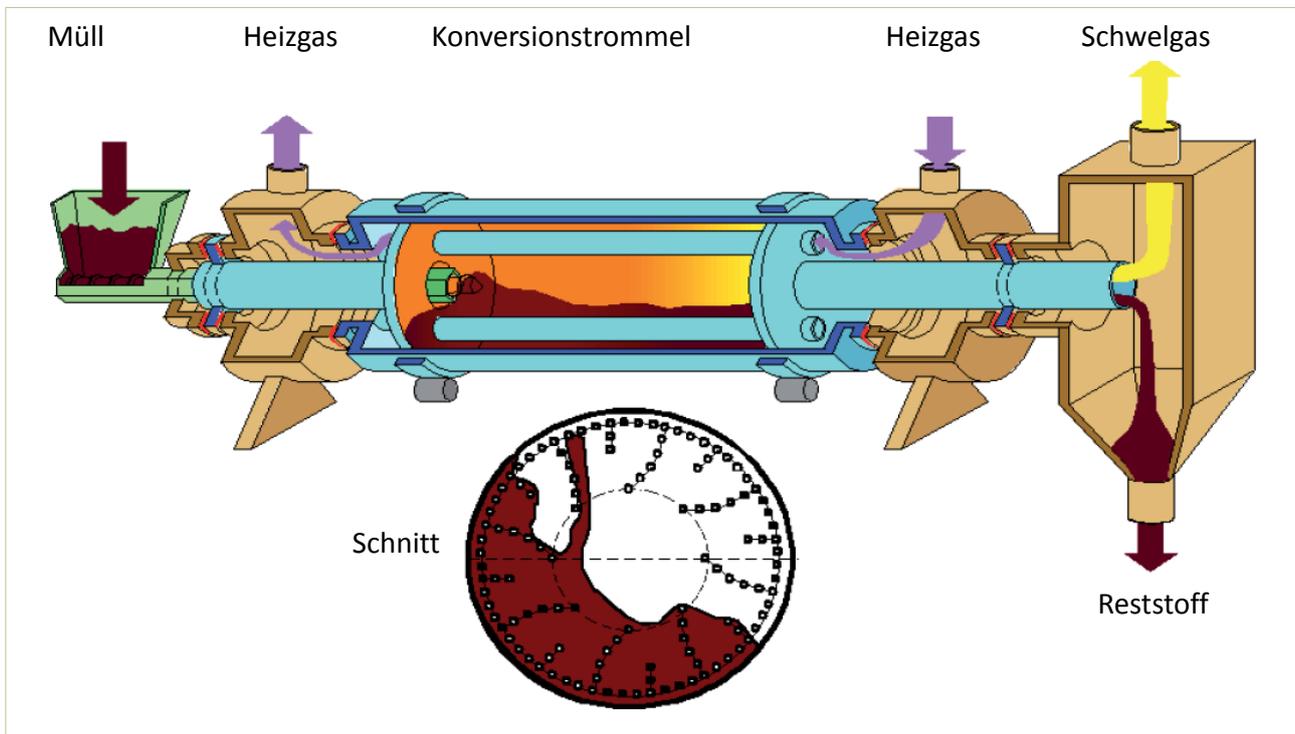


Figure 3.5: Conversion drum Schwel-Brenn Process with arrangement of heating pipes [Siemens AG, cited in Thomé 1998].

The fine fraction containing carbon is combusted together with the pyrolysis gas at temperatures of more than 1,300 °C. Therefore, the temperature is approximately 150 °C above the ash softening point. A liquid melt is formed which is then removed and solidified to a granulated melt.

Flue dust from the heat recovery boiler as well as the contaminated adsorbent from fine cleaning of flue gas are also combusted respectively molten in the high temperature combustion chamber.

Heat contained in the exhaust gases is transferred to the water-steam-cycle in the heat recovery boiler. With an extraction-condensing turbine and a generator, electricity can be generated or steam can be released (district heating, process steam).

Installations for waste gas purification consist of an electrical precipitator, a wet scrubber, SCR reactor and a fine cleaning stage (furnace coke fixed-bed filter). The latter removes dioxins, furans and remaining hydrogen chloride, sulfur dioxide and various heavy metals. [Thomé 1998]

### Operating Parameters

Table 3.1 lists fundamental technical data and operating parameters for the plant in Fürth.

Table 3.1: Technical data and operating parameters of Siemens Schwel-Brenn plant Fürth [Siemens AG 1996].

Parameter	Value	Parameter	Value
Number of Lines	2	Process Temperature	450 °C
Capacity	100,000 Mg/a	Heating: indirect; using natural gas in counter flow	
Calorific Value	8.4 - 10 MJ/kg	<b>Combustion Chamber (cooled)</b>	
Gross Heat Release	51.3 MW	Diameter	ca. 3.5 m
Gross Output Electricity	ca. 12 MW	Height	ca. 10 m
Efficiency	ca. 23 %	Process Temperature	ca. 1,300 °C
<b>Conversion drums (2 per line)</b>		<b>Heat Recovery Boiler</b>	
Throughput	5 Mg/h apiece	Steam Pressure	40 bar
Length	ca. 21 m	Steam Temperature	400 °C
Diameter	ca. 2.5 m	Mass Flow Steam	59.8 Mg/h
Weight	ca. 120 Mg		

According to the supplier, ferrous and non-ferrous metals are clean, dry and not oxidized due to prevailing conditions inside the conversion drum. Colors on the metals or plastic linings are removed during pyrolysis. Depending on the composition of input waste, the non-ferrous metal fraction is said to consist of 70 to 80 % aluminum with a rest of copper and other non-ferrous metals.

Due to conditions in the conversion drum, the fraction consisting of glass, stones and ceramic fragments is both sanitized and dewatered.

The melting granulate generated in the high temperature combustion chamber is a glass-like product similar to lava (see fig. 3.6). According to the supplier, both melting granulate and the glass/stone/ceramics fraction meet the assignment criteria of materials according to Z 1.1 of the “Requirements for the material recovery of mineral residues/waste” of the Joint Waste Commission of the Federal States of Germany (LAGA) and can therefore replace gravel and sand in the construction sector or be used as substitute for gravel and sand in construction and as insulation material (cellular glass, mineral wool). [Thomé 1998]

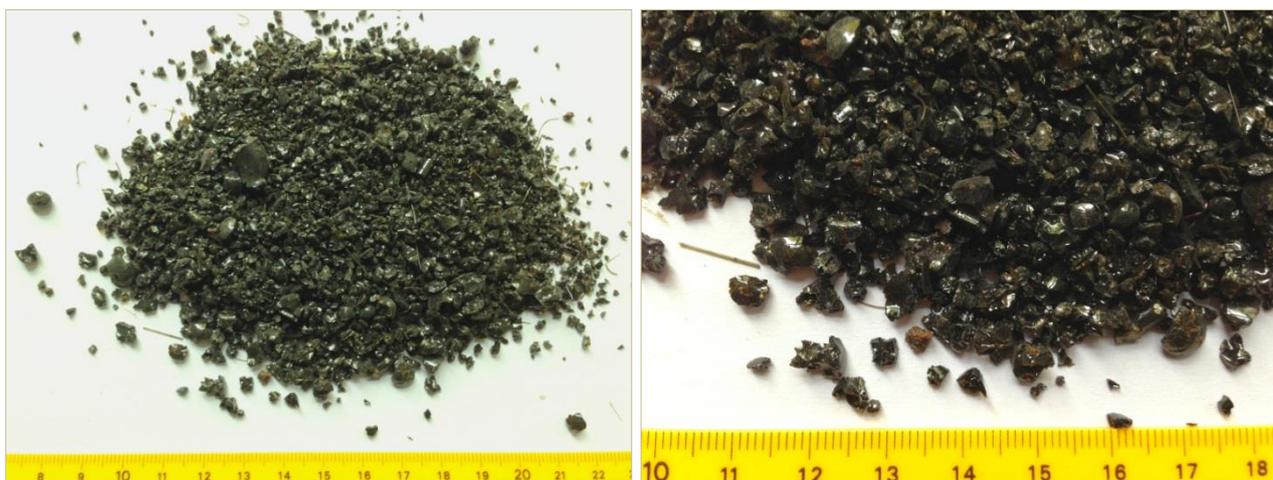


Figure 3.6: Granulate from Siemens Schwel-Brenn-process (own picture)

### Costs and Development Status

From 1988 to 1996, a demonstration plant was operated in Ulm-Wiblingen (Germany). An industrial size plant with a capacity of 100,000 Mg/a was built in Fürth (Germany) and started operation in 1997. It was shut down after serious operational problems in 1999. The process is not offered any longer in the German speaking area.

Table 3.2: Basic parameters of former Schwel-Brenn projects [Siemens AG 1996]

Location	Capacity	Operation
Ulm-Wiblingen	4 Mg/d (1 line) (demonstration plant) Household waste, commercial waste similar to household waste, bulky waste, sewage sludge, special batches (e.g. automobile shredder residue)	start-up pyrolysis 1984 start-up Schwel-Brenn process 1988 shutdown 1996
Fürth	100,000 Mg/a (2 lines) (industrial size installation) household waste, commercial waste similar to household waste, bulky waste, sewage sludge	construction 1994-1997 startup 1997 shutdown 1999
Neubrandenburg	150,000 Mg/a (2 lines) household waste, commercial waste similar to household waste, bulky waste, sewage sludge, hazardous waste	start-up was planned in 2004
Thun (Switzerland)	150,000 Mg/a (2 lines) household waste, commercial waste similar to household waste, bulky waste, sewage sludge	start-up was planned in 2002

Treatment costs were estimated to be about 235 DM/Mg for a Schwel-Brenn plant with a capacity of 160,000 Mg municipal waste per year with a calorific value of circa 10 MJ/kg, with costs depending on the general framework on site.



Figure 3.7: Schwel-Brenn plant in Fürth [Siemens AG, cited in [Thomé 1998].

### 3.1.1.3 MES R21

The Siemens Schwel-Brenn-process was marketed under license from 1991 on by the Japanese Mitsui Engineering and Shipbuilding Co. Ltd., Tokyo (MES), formerly Mitsui Babcock. Mitsui constructed and operated two demonstration plants in Yokohama and Chiba with a capacity of 1 Mg/h each from 1994 to 2000. The first commercial installation was the Yame Seibu Clean Center which started to operate in March 2000 with two lines of 110 Mg/day each.

#### Technology

This process (see fig. 3.9 and 3.10) allows waste with a maximum size of 20 cm. Thus, a shredder is usually installed upstream to the waste bunker. Waste is transferred to the feeding hopper of the pyrolysis drum by crane.

The pyrolysis drum is more than 20 m long with an internal diameter of over 3 m. Pyrolysis is operated at approximately 450 °C. The drum is heated by an internal pipe system (see figure below) with hot air of 520 °C. The air is heated in the first boiler pass after the burning chamber. The residence time of waste inside the drum is 1-2 hours.

Generated pyrolysis gas is transferred directly and without further treatment from the drum to a combustion chamber where it is oxidized. Solid residue from the combustion chamber passes a magnetic and a fluidized bed separator for metal recovery. Pyrolysis coke is then extracted in an air separator and the coke is transferred to the combustion chamber.

Combustion takes place at 1,350 °C. Flue gas is directed to a boiler for energy recovery, usually with a (semi-)dry gas purification downstream. In the installation in Koga, the so-called Neutrec®-process was implemented, a dry gas purification with NaHCO<sub>3</sub> as neutralizing agent.



Figure 3.8: External view of pyrolysis drum (left) and arrangement of steam-heated pipes inside the drum (right) in the MES R21 plant Toyahashi

The following flow diagram (fig. 3.9) shows the complete run of process as applied at Toyahashi, where 200 Mg/d of waste are treated in two lines. Figure 3.10 gives a picture of the same installation as three-dimensional illustration. Figure 3.11 shows photographs of the installations in Koga and Toyahashi.

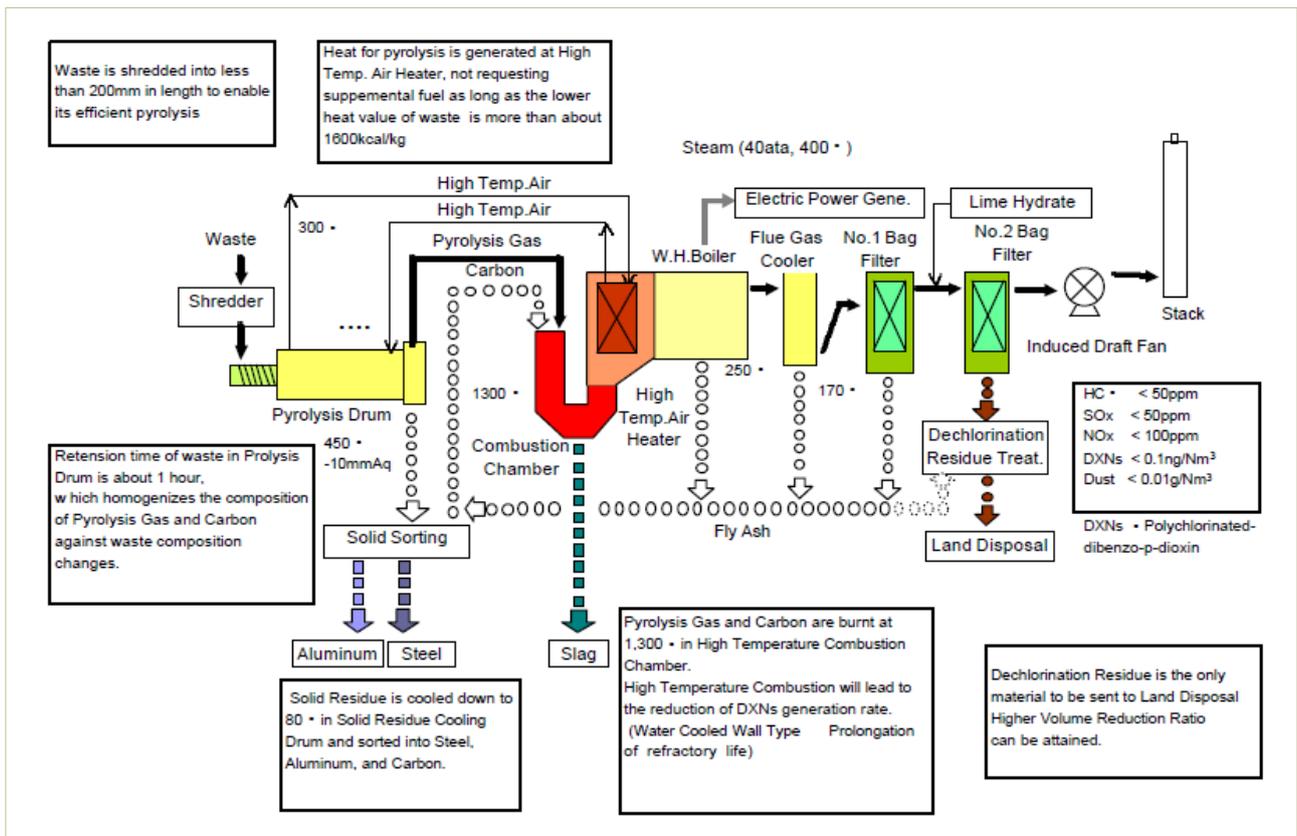


Figure 3.9: Process diagram with process explanations of the MES R21 installation in Toyohashi

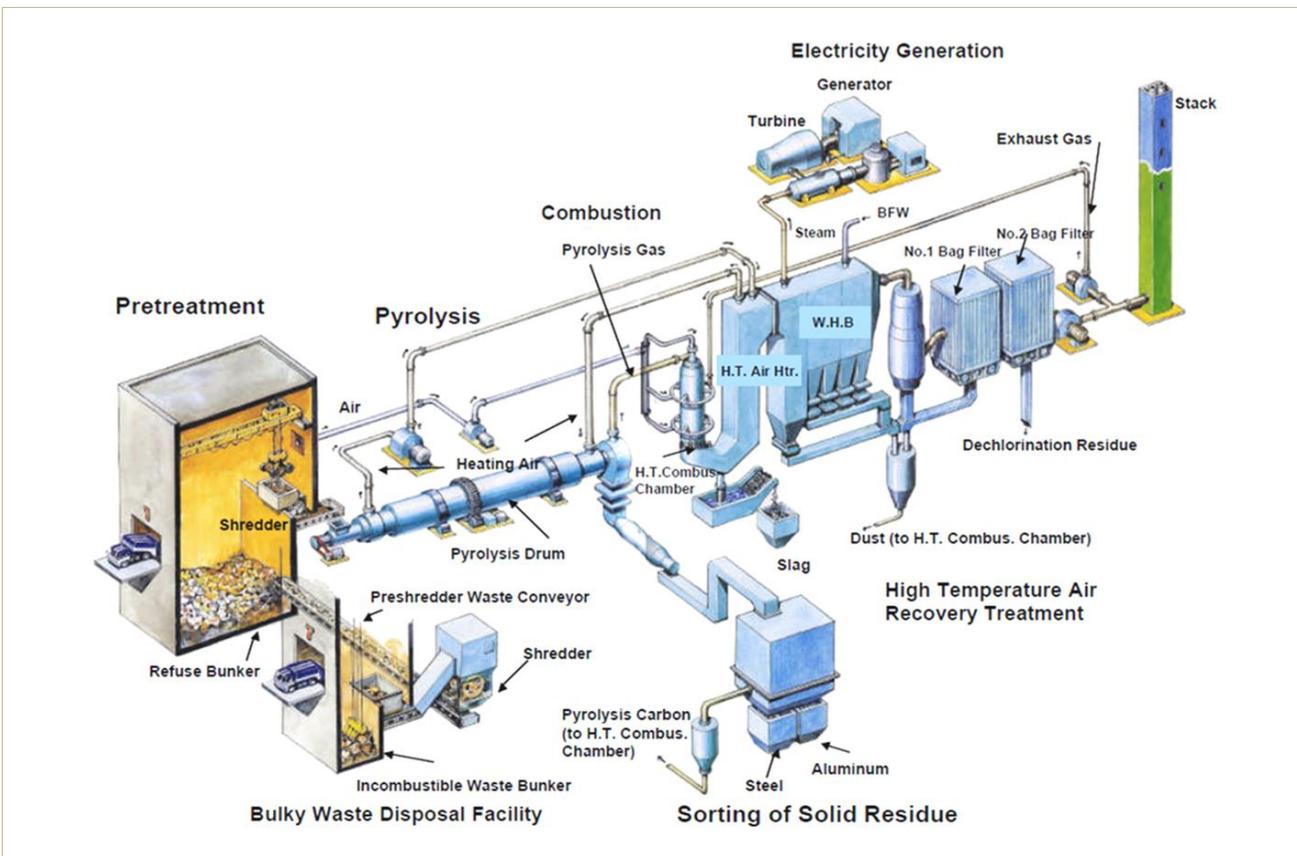


Figure 3.10: Illustration of the MES R21 installation in Toyohashi.

## Operating Parameters

Operating parameters of the MES R21 process are exemplified by data from the plant in Koga, which was built between November 2000 and March 2003.

Table 3.3: Operating Parameters of MES R21 plant in Koga

Parameter	Value	Parameter	Value
Lines	2	Combustion Temperature	1,300 °C
Capacity	2 x 130 Mg/d	Steam Pressure	4 MPa
Availability	300 d/a per line	Steam Temperature	400 °C
Length of Pyrolysis Drum	23 m	Electricity	4.5 MW
Internal Diameter of Drum	3.1 m	Efficiency	≈ 15 %
Residence Time Pyrolysis	1-2 h	Internal Consumption	1.8/0.7 MW
Pyrolysis Temperature	450 °C	Electricity Export	≈ 2 MW
Hot Air Temperature	520 °C		

## Emissions and Residues

In the year 2009, Japanese limits required by authorities exceeded European limit values. Limits given for the Koga plant were as follows:

- Dust: 20 mg/m<sup>3</sup>
- HCl: 100 ppm
- SO<sub>2</sub>: 100 ppm
- NO<sub>x</sub>: 100 ppm
- Dioxins 0.05 ng(I-TEQ)/m<sup>3</sup>

Measured values have not been made public. For the Yame Seibu plant, the following values were published as medium emission data for 2002:

- Dust: < 10 ppm
- NO<sub>x</sub>: 47 ppm
- Dioxins: 0.007 ng(I-TEQ)/m<sup>3</sup>

Pyrolysis processes are particularly well-suited for metal recovery. As demonstrated in the flow diagram of the R21-installation, metal recovery from pyrolysis residue is made up of a magnetic separator and a fluidized bed separator. Ferrous scrap and especially aluminum are sold. Inert fractions from pyrolysis and slag from the combustion chamber can be utilized in the construction sector, residue from gas purification is disposed.

## Costs and Development Status

Investment costs of approximately 105 Million € have been published for the Koga installation. For the Yame Seibu site, Mitsui specified operation costs of circa 24 €/Mg, which cannot be considered a realistic amount. Supposedly, this amount only includes operating materials.



Figure 3.11: View of the MES R21 installation at Koga (left) and Toyahashi (right)

Until 2009, seven plants with 15 lines and an overall capacity of 1,840 Mg/d were constructed in Japan. The largest plant with a capacity of 2 x 20 Mg/h is located at Toyahashi and started operation in 2004. According to [Lamers 2013], the worldwide capacity amounts to less than 1 Million Mg/a in about 25 installations.

Higher investment and operating costs than for conventional waste incineration led to the fact, that obviously this technology is no longer marketed at this time.

### 3.1.1.4 Takuma Pyrolysis Melting System

Besides Mitsui Engineering and Shipbuilding Systems Co. Ltd, the Takuma Co. Ltd. in Osaka obtained a license for the Siemens Schwel-Brenn process as well.

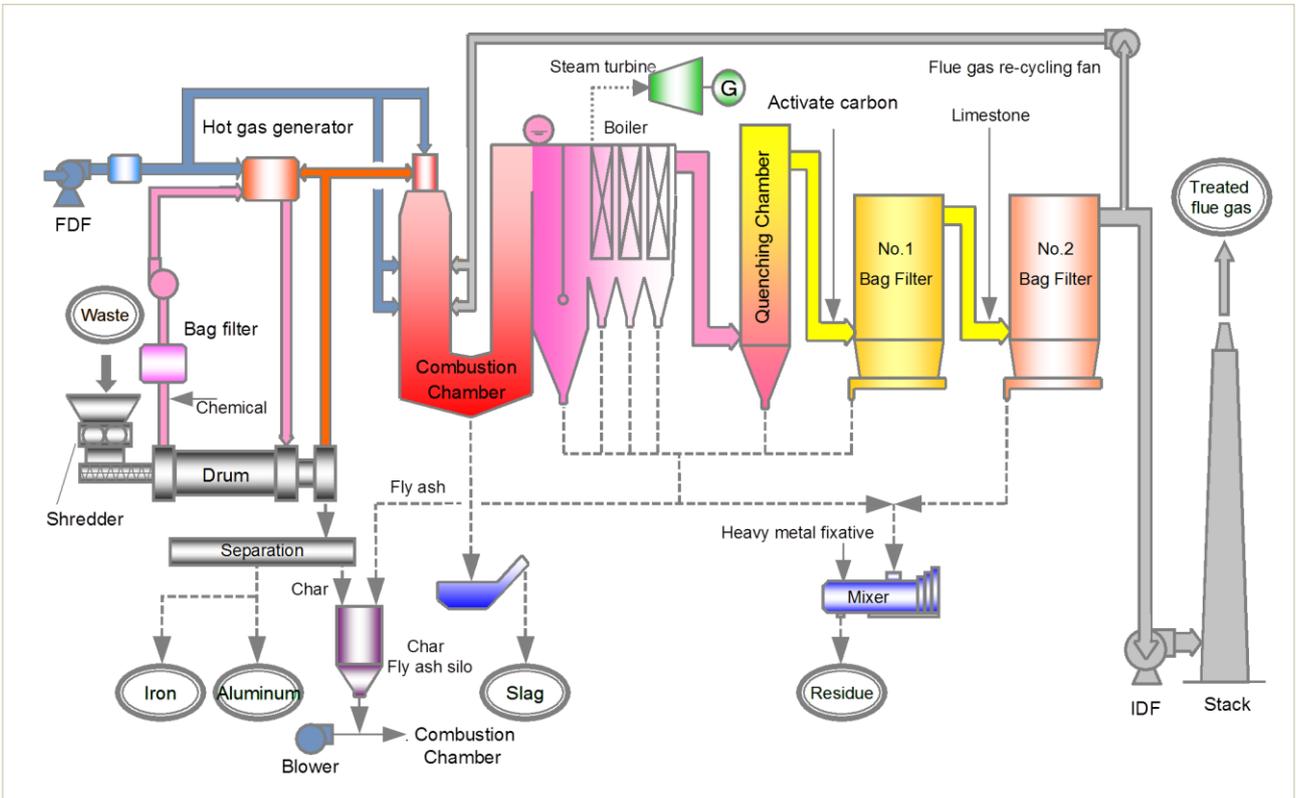


Figure 3.12: Process diagram Takuma Pyrolysis Melting System [Takuma 2014].



Figure 3.13: Picture of Takuma pyrolysis gas melting system

### Technology

The process technology is very similar to the MES R21 (see above) as apparent from the process diagram (fig. 3.12). Presumably, operating parameters are comparable as well and residue materials are treated likewise.

### Development Status

Until 2012, five plants with 10 lines and an overall capacity of 776 Mg/d have been built by Takuma, of which the last has been in operation since 2012 at

the city of Moriya in the Ibaraki prefecture (capacity: 258 Mg/d, 3 lines).

#### 3.1.1.5 Von Roll INOVA RCP process

During the 1990s, when slag melting became increasingly popular in Europe, von Roll INOVA developed the Recycled Clean Products (RCP) process. It is made up of three stages: pyrolysis and partial gasification on the grate, combustion of solids in a melting furnace and a circulating fluidized bed for gas burnout, with an optional Holderbank Smelting Redox process for slag treatment. The RCP process was designed to maximize the production of reusable products, utilizing all substances in the waste to the greatest possible extent. In 1997, an RCP plant was installed at the waste incineration facility of Bremerhaven, Germany.

### Technology

This process was designed to work with municipal waste as well as slag and flue ashes from conventional waste incineration. That is why the first facility with a capacity of 6 Mg/h and thermal output of 17.5 MW was built next to an existing waste incineration plant with 3 lines of 15 Mg/h each, located in Bremerhaven. The following process diagram (fig. 3.14) shows the thermal core components as realized in Bremerhaven.

Passing through a lock, waste is fed to a pyrolysis chamber, which resembles the combustion chamber of a conventional grate furnace. Nitrogen is injected at the front of the chamber. Oxygen is injected in the rear part to oxidize part of the pyrolysis gas, hereby supplying the necessary energy for pyrolysis. In the subsequent melting furnace, again, oxygen is injected for further combustion of pyrolysis gas as well as pyrolysis coke. Mineral residue which occurs together with the coke is molten. An additional oil burner is installed inside the melting furnace.

Flue gas with a temperature of about 1400 °C containing a remainder of pyrolysis and synthesis gas is directed to a circulating fluidized bed operated with sand, where oxygen and air are added to achieve complete burnout of gas. At the end of the cyclone used to separate sand, a fluidized bed heat exchanger is installed, transferring part of the combustion energy to a water-steam cycle. Positioning of the heat exchanger in the sand bed prevents direct contact of the reactor with flue gas containing chloride and hereby reduces the risk of corrosion. The sand cooled down in the fluidized bed heat exchanger reduces the temperature of gas flowing from the furnace into the fluidized bed from circa 1400 °C to 1000 °C.

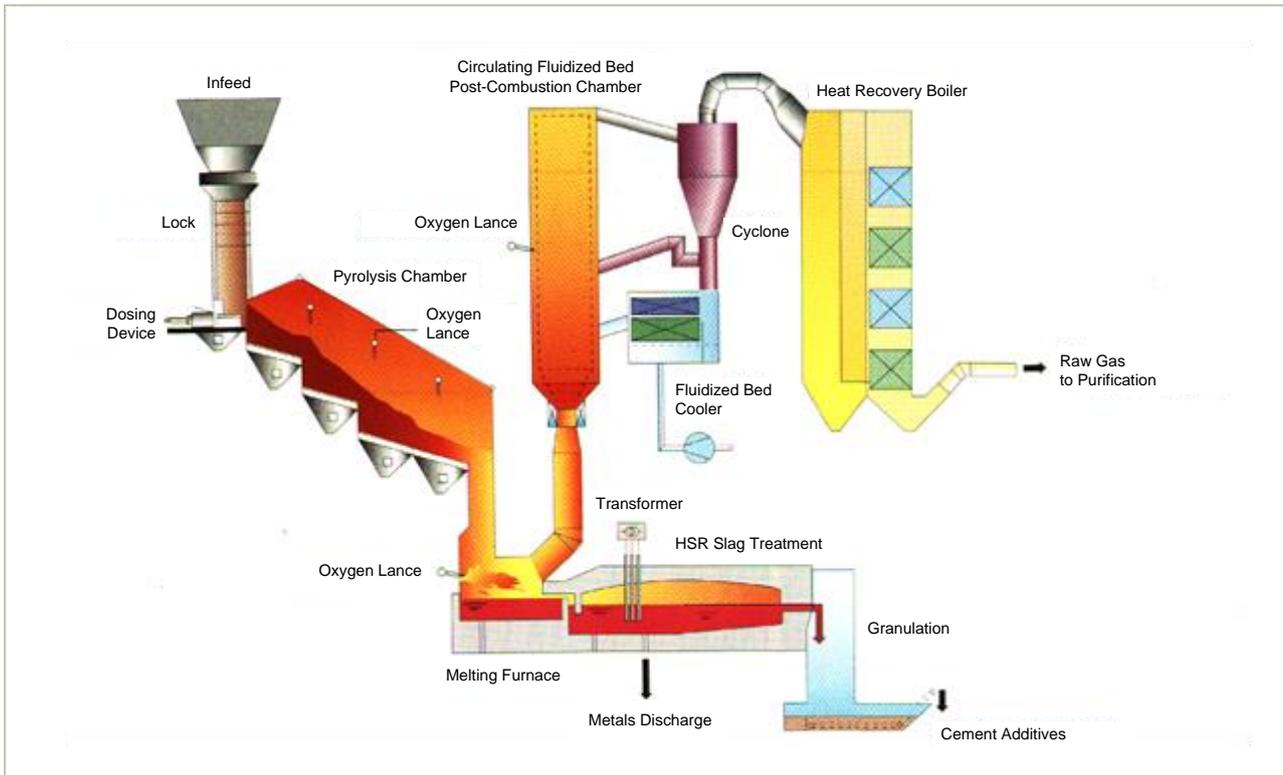


Figure 3.14: Process diagram RCP-Process [von Roll 1999; translated]

To remove SO<sub>2</sub> from the flue gas, lime is added to the sand. Generated gypsum is then separated in the sand processing step. In addition, an SNCR-plant using ammonia is integrated for denitrification.

After passing the cyclone, the flue gas enters a steam boiler followed by conventional flue gas purification. On the Bremerhaven site, flue gas was divided passing the purification lines of two boilers from the waste incineration plant. Generated steam was fed to the existing steam circle of the waste-to-energy facility.

A Holderbank Smelt-Redox process, optionally offered for the RCP process, was integrated in Bremerhaven. It is a resistance-heated melting chamber as known in the glass industry. An additional oil burner is built into the chamber.

Volatile heavy metals contained in the slag vaporize under reducing atmosphere and high temperatures around 1,500 °C. An iron-copper alloy is drawn off at the bottom of the melting tank.

### Operating Parameters

Operating parameters which have been made public are summarized in the following table.

Table 3.4: Operating data of the RCP Plant in Bremerhaven.

Parameter	
Capacity	6 Mg/h
Thermal Capacity	17.5 MW
Steam Pressure/Boiler	40 bar
Steam Temperature	400 °C

During trial operation over a 90 day period (with many interruptions), information on input and auxiliary materials was gathered.

Table 3.5 Trial operation RCP-plant Bremerhaven –input and auxiliary materials

Input and Auxiliary Materials		Products / Residue Materials	
Waste	4 Mg/h	Cu/Fe-Alloy (87%/10%)	60 kg/h
Oxygen	4.274 Mg/h	Granulate	1.2 Mg/h
Nitrogen	1.010 Mg/h	Flue Dust	190 kg/h
Air	0.864 Mg/h	Flue Gas	18.19 Mg/h
Lime	80 kg/h		
Sand	80 kg/h	<b>Energy efficiency</b>	
Electrode Graphite	25 kg/h	Boiler Efficiency	70 %

### Emissions and Residue Materials

Flue gas passes through the flue gas treatment of the waste-to-energy facility, so that emissions meet all legal requirements.

Residue materials respectively products are the metal alloy discharged from the Holderbank Smelt-Redox process and the melting granulate quenched in water. The metal alloy mainly consists of iron and copper. The iron content can be reduced by increasing the partial pressure of oxygen in the HSR-plant. Analysis of the alloy generated during the operating test in Bremerhaven showed about 87 % iron, 10 % copper and scarcely 1 % nickel. In Bremerhaven, the alloy was sold to Aurubis (formerly known as Norddeutsche Affinerie) where copper was regenerated.

The granulate is a calcium aluminosilicate with high iron content. Elution tests according to the Swiss TVA-protocol showed values significantly below limit values for deposition on landfills for inert matter. This confirms a quality of the material which should allow utilization as construction material or in the cement industry.

### Costs and Development Status

In 1999, the supplier stated that investment costs for an RCP-plant without HSR-process are comparable to conventional waste-to-energy facilities. Disposal prices ranging from 250 CHF for a plant with HRS-process to 225 CHF without HSR-Process were given. For a 16 MW standard plant - which was never built - disposal prices were said to be 160 CHF. In comparison, disposal costs in Swiss waste-to-energy facilities in 1999 ranged from 170 CHF to 340 CHF.

The RCP plant in Bremerhaven, which has to be considered as pilot plant, was in operation for several years but never continuously and under full load. Around 2000, an RCP license was given to Hitachi-Zosen, but the technology has not been applied in Japan. [Hesseling 2002, Stammbach 1999, HZI 2011]

## 3.1.2 Stand-Alone Pyrolysis

This section deals with those pyrolysis processes which use the pyrolysis gas - usually in a combustion chamber with steam generator - but not the pyrolysis coke, which is then to be considered as product respectively process residue. This approach is currently chosen by several processes on the verge of entering the market and was applied in the waste pyrolysis plant in Burgau, Bavaria.

### 3.1.2.1 Destrugas

The Destrugas process was designed to pyrolyze household waste, commercial waste similar to household waste, bulky waste, waste tires, waste oil and sewage sludge in a directly heated shaft reactor. It was the aim to generate a gas with the quality of town gas, electricity and py-

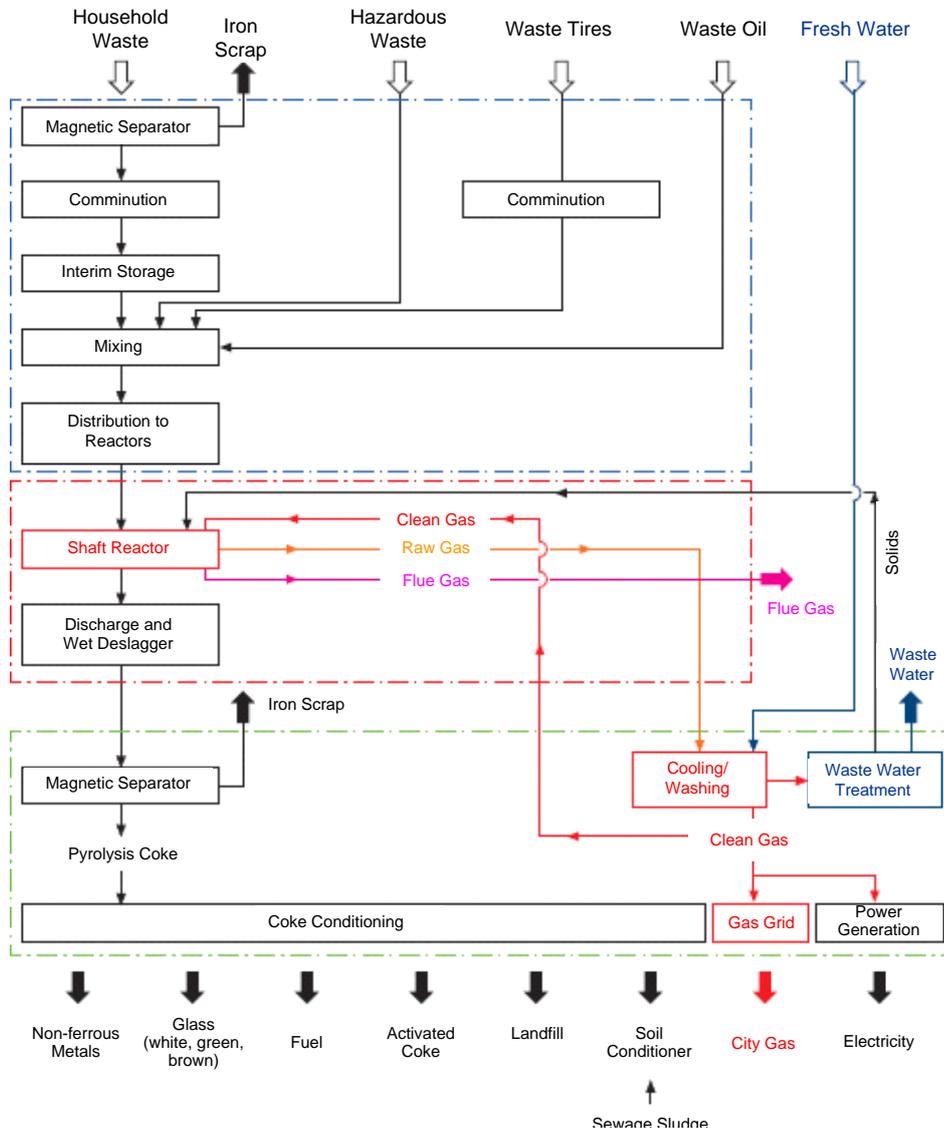
rolysis coke. The inventor of the process was Karl Kroyer. Pollution Control Ltd. constructed two plants in Denmark, at Kalundbord and Kolding. The Technische Universität Berlin did the basic research using a pilot plant located at the site of the waste incineration plant Berlin-Ruhleben which was operated by the Berliner Stadtreinigungsbetriebe (BSR). A demonstration plant was constructed by Hitachi Engineering & Construction C. Ltd. in Hitachi City, Japan. All plants have been shut down. The process is no longer offered on the market.

**Technology**

The following figure shows the process diagram of this process, figure 3.17 illustrated the process at the Kalundborg plant.

In downstream conditioning, the delivered waste is treated with magnetic separators to remove iron scrap and is then minimized to a particle size less than 100 mm. The waste is stored temporarily in a bunker and may then be mixed in defined proportion with liquid or pasty waste and crushed waste tires. This mixture is then allotted to the reactors.

Through a feed hopper, conditioned waste is fed to the top of the pyrolysis reactor, also called “retort” by the supplier. Each retort chamber is 300 mm in breadth, about 3 m long and 7 m



high and has a capacity of 5 Mg/day. It is heated indirectly using gas. Meander-shaped hot gas flues are placed on the outside of the chamber walls, hot gas flows downwards. Per narrow side in the lower part of the hot gas flues, two burners are installed which can be fired with purified pyrolysis gas. The hot gas flues are led from the narrow ends to the middle of the chamber and then redirected outwards. Vertical heat distribution and temperature profile of the furnace walls can be regulated with additional heating and air feed on different height levels of the chamber.

The aim is to completely carbonize waste in the furnace and to split long-chain carbohydrates.

In the bottom region of the retort, tempe-

Figure 3.15: Process Diagram Destrugas Process [Rymssa 1977, modified]

atures should stay below 1,050 °C to avoid caking. Pyrolysis coke is discharged with a rotary valve. The residence time in the retort is regulated by variation of the rotating speed of the valve. By increasing residence time, the carbonization of waste can be optimized. The ash discharge hopper leads to a wet deslagger. Pyrolysis gas is extracted by suction above the rotary valve (see figure below). [Rymssa 1977]

Per Mg of raw waste, the Destrugas Waste Pyrolysis generates around 660 kg wet pyrolysis coke with a water content of about 47 %.

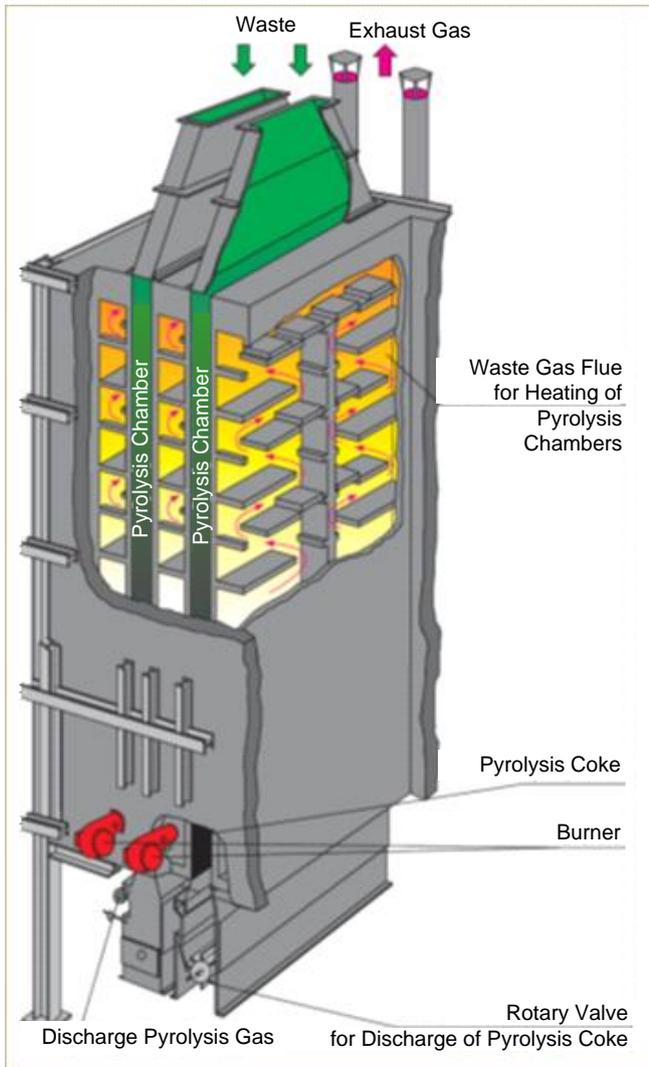


Figure 3.16: Destrugas-Process; Detail showing two indirectly heated retorts within a battery of retorts [adapted from Rymssa 1977]

### Products and Residue Materials

According to the supplier, generated pyrolysis coke can be treated with different conditioning processes in order to gain activated coke or fuel respectively recover glass, ferrous and non-ferrous metals. In Denmark, tests were carried out with a “soil improvement material”, made up of a granulated mixture of pyrolysis coke and sewage sludge.

The extracted raw syngas is cooled down and transferred to a venturi scrubber. Dust as well oils and tars which have been condensed due to pre-cooling are precipitated in the gas scrubber. Contaminants are washed into a decanter using a rinsing fluid. Separated thick matter may be mixed with waste and then returned to the pyrolysis reactors. Product gas is transferred to a storage tank.

Per Mg of municipal solid waste, 330 kg (this corresponds to 412 m<sup>3</sup><sub>N</sub>) purified pyrolysis gas with a calorific value of about 1,400 kJ/m<sup>3</sup><sub>N</sub> is produced. Gas composition is given in table 3.6.

In order to heat the pyrolysis chambers, about 200 m<sup>3</sup><sub>N</sub>/Mg waste are required. Combustion gases are drawn through the hot gas flues into the chimney by a fan.

According to manufacturers, excess gas - amounting to circa 212 m<sup>3</sup><sub>N</sub> per Mg municipal waste - is stored and meant to be used for heating purposes or production of town gas. Conversion into electricity in gas engines should be possible.

Table 3.6: Destrugas process - composition of purified syngas [Rymssa 1977].

Parameter	Value	Parameter	Value
Hydrogen	45 %	Carbon Monoxide	13 %
Methane	10 %	Carbon Dioxide	19 %
Ethene	3 %	Steam	8 %
C <sub>n</sub> H <sub>m</sub>	2 %		

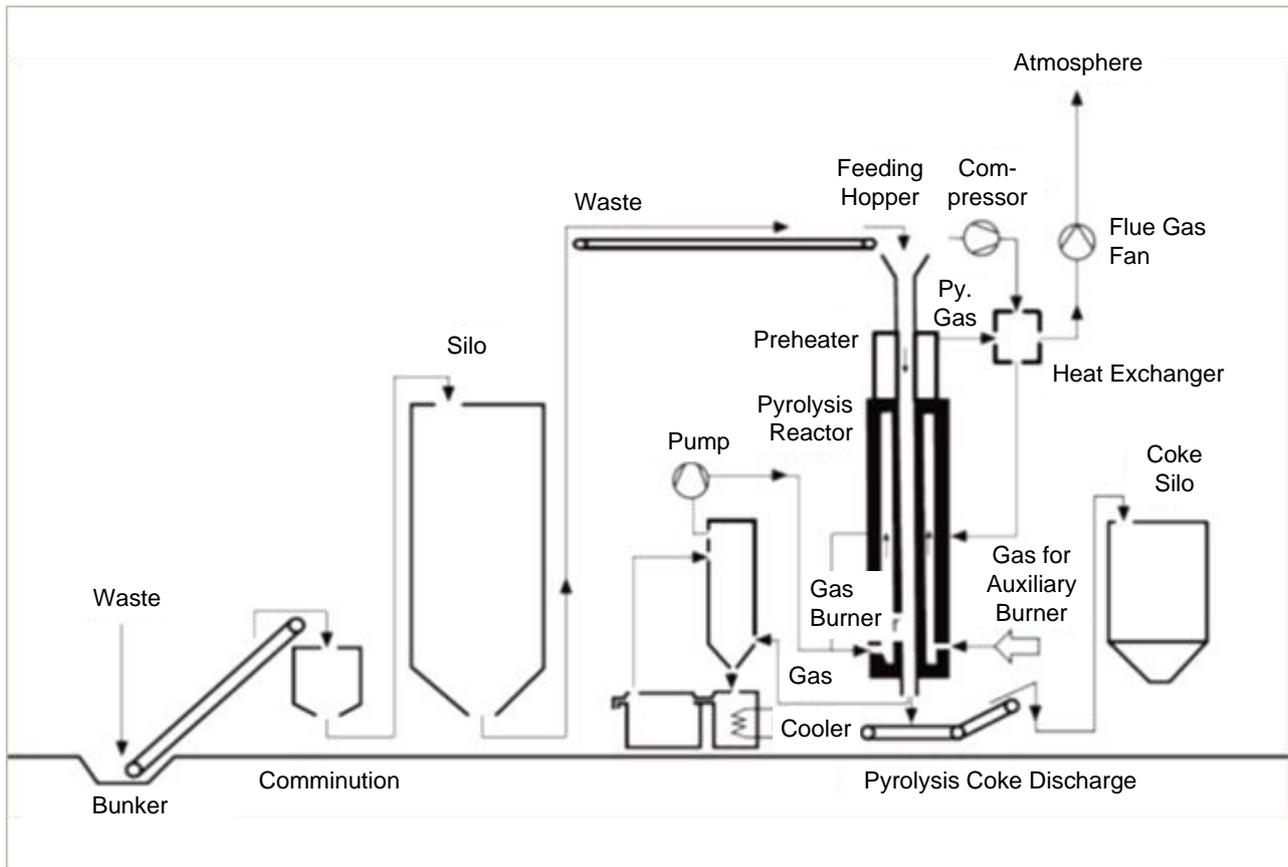
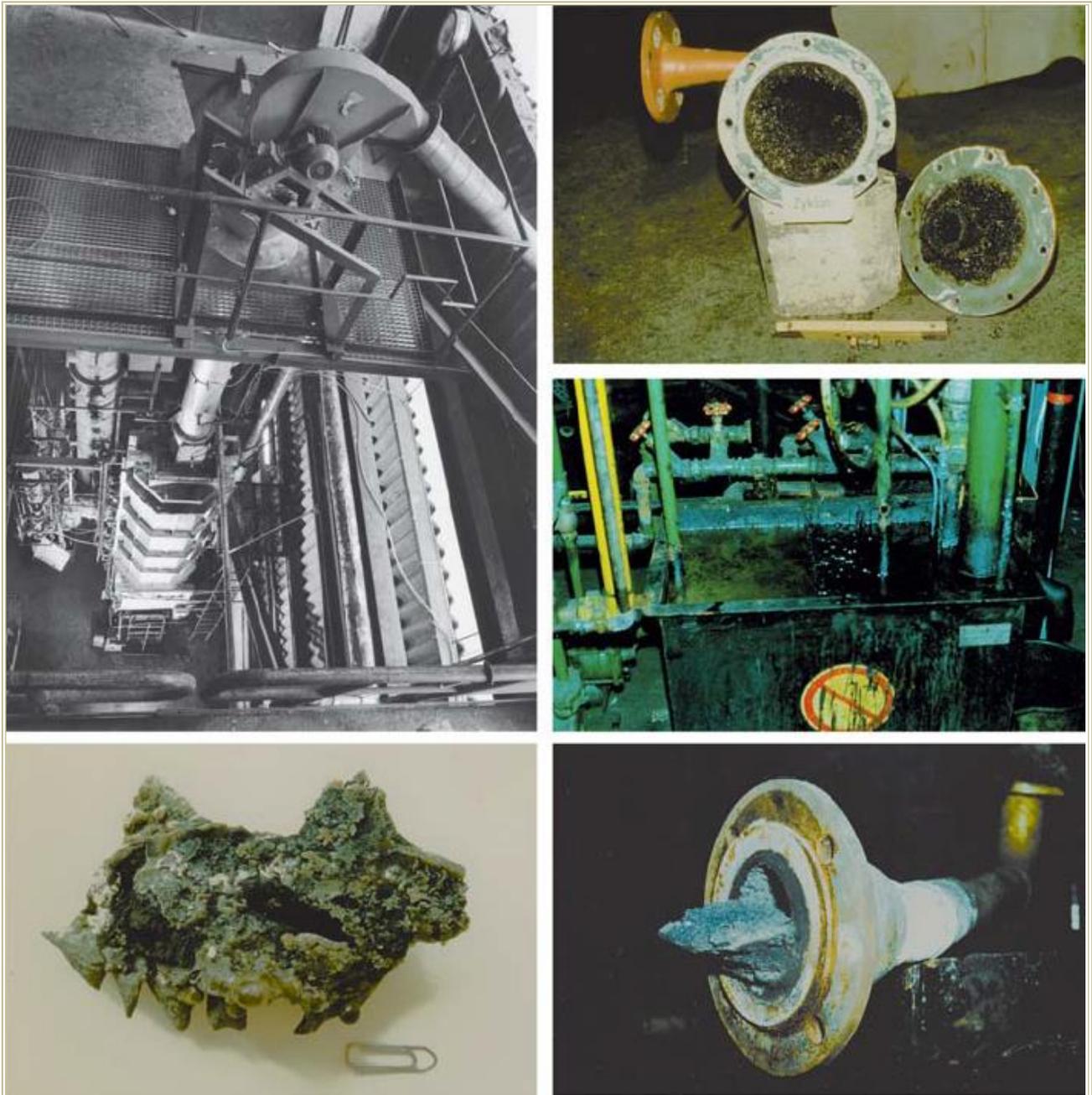


Figure 3.17: Process schema Destrugas plant in Kalundborg [adapted from [Douglas n.d.]].

Pyrolysis gas is cooled in the cooler using circulating water. The water accumulates dust, tar and oil. This mixture can be separated using a decanter. Downstream gas scrubbers wash the gas with water in reverse flow. Dust, tar and oil are separated from the scrubber water using a decanter as well.

Regarding pollution, scrubber water from Destrugas plants is comparable to water from quenching water from coke ovens and gas coolers in coking plants. Based on experience, the Berliner Stadtreinigungsbetriebe, participating in the research project of the TU Berlin, developed a waste water treatment process for scrubber water. [Rymssa 1977]

Figure 3.18 shows a picture of the pilot plant operated by the TU Berlin (top left) as well as different areas and components of the plant. Trouble spots are clearly visible



**Figure 3.18** Details pilot plant Destrugas process  
 Top left: Pyrolysis shaft reactor with exhaust fan at site of MSW Berlin-Ruhleben of the Berliner Stadtreinigungsbetriebe (BSR). / Top right: open cyclone – inner surfaces misted with naphthalene. / Middle right: partial view washing system – overflow basins with refloating tar.  
 Bottom left: slag agglomerate found in pyrolysis coke. / Bottom right: Segment of emergency gas pipe – with deposition of solidified flue ash. [Thomé 1979].

### 3.1.2.2 Burgau Municipal Waste Pyrolysis

The Municipal Waste Pyrolysis Plant in Burgau (Bavaria) (MPA Burgau) is the only industrial size pyrolysis plant for residual waste operated in Germany. Constructed and built by Babcock, it started operation in 1983. Approximately 26,000 Mg residual waste and sewage sludge are treated per year [Meier 2014, Frede 1996]. Figure 3.19 shows the facility. The decision to construct a waste pyrolysis plant as novel treatment process was influenced by a policy willing to try alternatives to waste incineration. Also, the plant was intended to treat sludges containing chromium

coming from a local industrial site. Due to reducing conditions during pyrolysis, oxidation from chromium to highly toxic chromium IV is prevented.



Figure 3.19: Waste pyrolysis plant in Burgau [DGE 2010]

Prior to pyrolysis treatment, municipal and commercial waste are coarsely shredded to a particle size below 300 mm. Dewatered sewage sludge is fed directly to the fine sludge material bunker. Bulky waste is conditioned as well. Wood is separated for recycling outside the pyrolysis process whereas mattresses and upholstery are removed in order to prevent blockage of the feeding screws (see below). Both raw and conditioned waste and separated upholstery can be seen in figure 3.20.

Shredded waste is fed to the pyrolysis reactor using a dosing screw. These screws are the bottleneck of the process and require that spiral springs are completely removed from the waste input. Figure 3.25 (left side) shows a dismantled dosing screw. During infeed, about 1 weight % lime (CaO) is added to the feedstock to bind acid components in situ. The plant consists of two lines in which the treated waste is outgassed at 470-500 °C for about one hour. Pyrolysis residue makes up ca. 40 % of the feedstock and is removed with wet deslaggers and cooled down to 40-50 °C. [Meier 2014]



Figure 3.20: Raw waste, shredded waste, separated upholstery at MPA Burgau

The structure of the MPA Burgau can be seen in figure 3.21. Characteristics of waste input as well as process parameters are summarized in table 3.7.

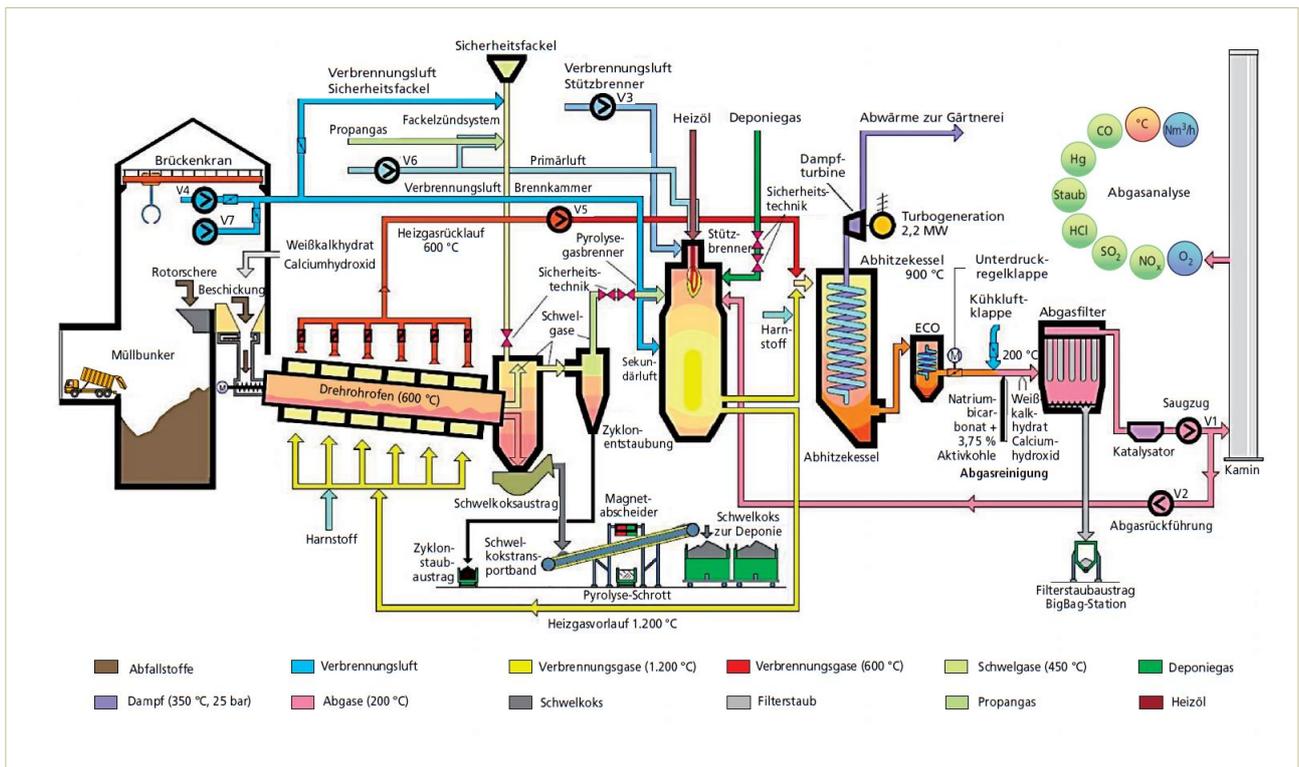


Figure 3.21: Process diagram MPA Burgau [Meier 2014]

Table 3.7: Input properties and process parameters of MPA Burgau [Meier 2014]

Average Input Properties		Process Characteristics Rotary Drum Pyrolysis	
Input	mixed MSW (household/commercial)	Throughput	2 x 2 Mg/h
Particle Size	< 300 mm	Number of Rotary Drums	2
Water Content	20 %	Diameter	2.2 m
Ash Content	25 - 30 %	Heated Length	21 m
Calorific Value	9 MJ/kg	R.P.M.	1.5 min <sup>-1</sup>
M <sub>residue</sub> /m <sub>input</sub>	0.45	Temperature	470 - 500 °C
LOI <sub>residue</sub>	35 %	Residence Time	ca. 60 min.
		Pressure	ambient pressure

Following pyrolysis, ferrous metals are removed from the residue material (pyrolysis coke). Non-ferrous metals are not separated. The coke is then disposed of to a category II landfill despite its high calorific value. Because of the high loss on ignition (LOI), a special permit is necessary for disposal. The landfill capacity will be exhausted around the year 2020. Further operation of the MPA beyond this time is uncertain. [Meier 2014]

The quality of recycled ferrous metals separated from the pyrolysis residue as well as the nature of the residue can be seen in figure 3.22.



Figure 3.22: Overbelt magnetic separator, Fe-Product and residual coke landfill with visible amounts of non-ferrous metals, MPA Burgau.

Carbonization gases generated in the pyrolysis drums are drawn off in concurrent flow at the head of the rotary kiln and then combined in a product gas flow. After primary dust removal in a hot gas cyclone, product gases are led to a combustion chamber and combusted at circa 1,200 °C. Part of the hot flue gas is used to heat the rotary drums. The remainder is led to a waste heat boiler. Flue gas used to heat the rotary drums is also fed to the boiler. Behind the boiler, dry flue gas cleaning with catalytic denitrification follows. Both internal and external view of the heating chamber of one of the two pyrolysis reactors can be seen in figure 3.23. Figure 3.25 shows details of the extensive sealing at the head of the rotary kiln (left picture). The middle picture shows the so-called rumble-stones, added to the waste to remove depositions on the inner side of the reactor walls.



Figure 3.23: Pyrolysis rotary kiln MPA Burgau.  
Left: external view including heating chamber and discharge pipe; right: internal view

Steam that is generated in the boilers is led to a turbine to generate electricity. Limited by turbine size, the electrical output of the plant does not exceed 2.2 MW. Part of the exhaust heat is delivered to an adjacent market garden.

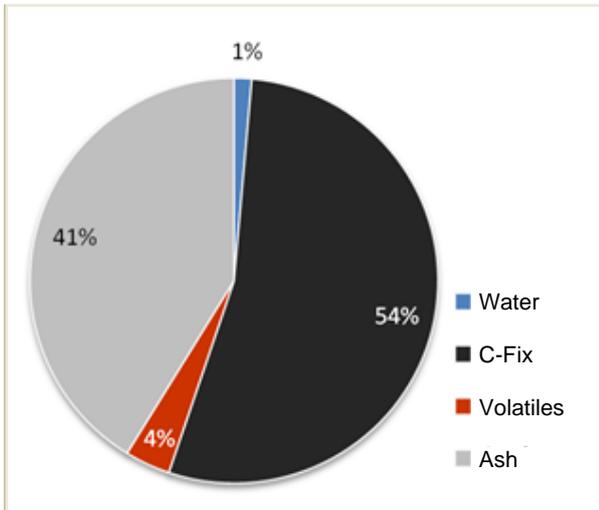


Figure 3.24: Proximate analysis of pyrolysis coke MPA Burgau (wt.-%)

### Energy Efficiency and Treatment Costs

Regarding the energy efficiency of the Burgau process, it has to be considered that this plant was designed solely for disposal, while energy efficiency was not the issue in focus. This is underlined e.g. by the fact that in the disposal concept, generated coke with high calorific value is landfilled. As visible in the adjacent figure, the landfilled residue consists of more than 50 % fixed carbon (C-fix). Energetic use of chemical energy bound in the process residue would influence the energy efficiency of the whole process significantly.

Values in table 3.8 give basic information on mass and energy balance of the Burgau plant.

Table 3.8: Mass- and energy balance MPA Burgau, according to [Meier 2014]

Mass Balance				Energy Balance			
Input	[wt.-%]	Output	[wt.-%]	Input	[%]	Output	[%]
MSW	100	Syngas	~ 60	Waste	100	Electricity (gross)	~ 22
CaO	0,5-1	Pyrolysis Coke	~ 40			Heat	N/A
Sum	~ 100	Sum	~ 100	Sum	100	Sum	N/A



Figure 3.25: Details MPA Burgau (left to right) Rotary drum transition with insulation, „rumble stones“ to remove deposition on inside walls and disassembled feeding MPA Burgau (own pictures).

### Costs and Development Status

The facility in Burgau is one of a kind, no further plants of this type have been built. The process has been optimized and enhanced over decades by the staff so that now a stable well-performing process is obtained. Yet, the basic concept of the process is no longer up to date. Landfilling of coke, especially without prior removal of non-ferrous metals, is not state of the art of modern resource economy. In addition, landfill capacity is limited. Accordingly, conceptu-

al, technical and administrative measures are currently being examined in order to enhance sustainability of the facility.

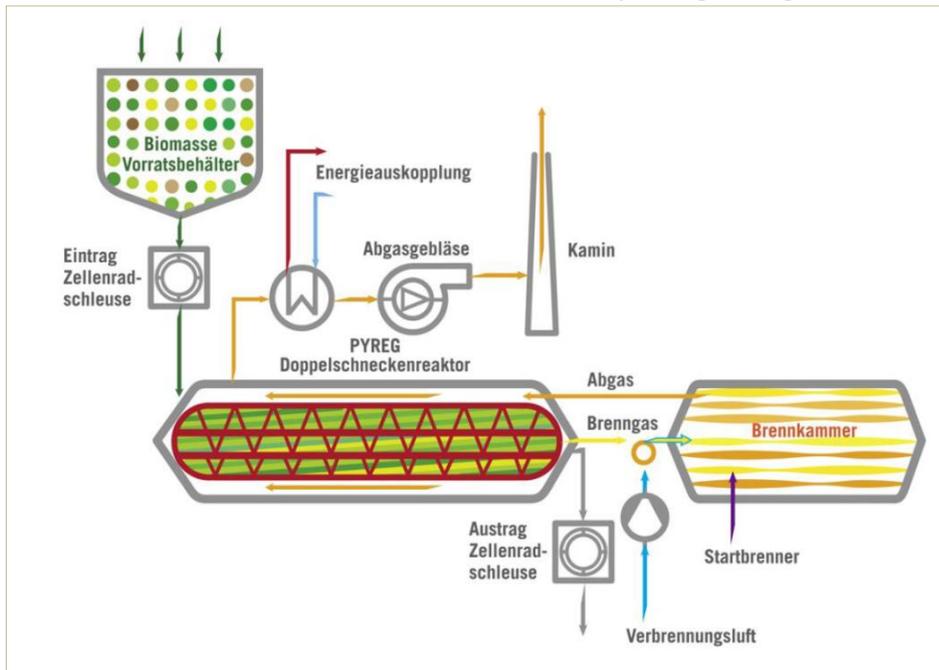
Process expenses as given by the operator amount to about 200 € per Mg of waste treated, plus costs for landfilling of pyrolysis residue of circa 100 €/Mg.

### 3.1.2.3 Pyreg-Process

This process was developed by the Pyreg Company and has been marketed since 2009. Biogenic materials are in focus as input material, since it is intended to use generated coke as fertilizer, soil additive or adsorbent. Possible input materials from the waste sector are sewage sludge, screenings, slaughterhouse waste or green cuttings. Municipal waste or fractions thereof are not destined as input material. Since this study focuses on treatment of municipal waste, the Pyreg process is of minor interest.

#### Technology

The input material undergoes thermochemical conversion in two linked process steps. First, degassing happens in a twin-screw reactor, secondary combustion of the generated combustible gases takes place in a downstream combustion chamber. Feedstock comes into the twin-screw reactor from a storage tank with push floor via a screw feeder. Rotary valves at the entry and discharge of the reactor serve as backfire safety device and prevent oxygen inflow. The input material is continually fed to the reactor and once inside the reactor it is heated up, dried and degassed. Two electrically powered counter-rotating twin screws guarantee forced conveying of the feedstock. The reactor is heated externally using flue gas with temperatures of up to 800 °C



originating from the combustion of pyrolysis gas. The whole process is run under moderate underpressure to prevent leakage of combustible gases. Combustion temperature is about 1250 °C. For start-up from cold state, the process is heated up for 0.5 - 1 hour using natural or liquified gas. Flue gas leaving the heating jacket is cooled down with a flue gas heat exchanger allowing decoupling of up to 150 kW<sub>th</sub>.

Figure 3.26: Process schema Pyreg process [Pyreg].

## Operating Parameters

Table 3.9: Process parameters Pyreg plant and mass balance for feedstock pig slurry

Parameter	Value	Parameter	Value
Fuel Power	500 kW	Pyrolysis Temperature	500 – 800 °C
Throughput	180 kg/h	Temp. Combustion Chamber	ca. 1,250 °C
Heating Power	max. 150 kW	Residence Time	15 – 30 minutes

## Costs and Development Status

According to the supplier, seven reference plants have been constructed with an overall operating time of 25,000 hours. In future, it is intended to offer an additional module to generate electricity.

The supplier quantifies treatment costs of 100 to 150 €/Mg dry matter.

### 3.1.2.4 Intermediate Pyrolysis

Intermediate Pyrolysis with integrated reforming has been tested successfully since 2011 at Harper Adams University and Aston University (Great Britain) using the so-called Pyroformer (see figure 3.27). The reactor has a capacity of 100 kg/h with an electric power of circa 75 kW.

Like the Pyreg-process, intermediate pyrolysis was primarily designed for biogenic input material and therefore cannot be considered for treatment of municipal waste.

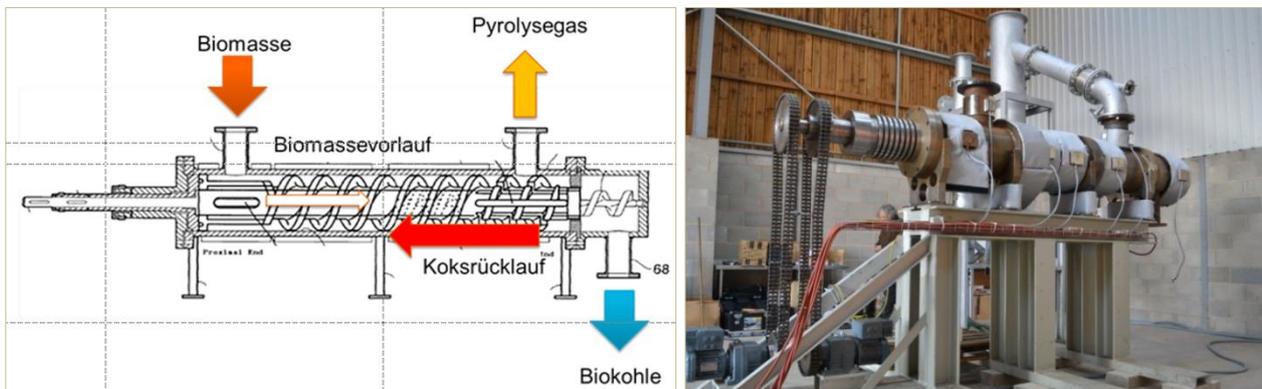


Figure 3.27: : Pyroformer. Left: schema; right: on site at Harper Adams University [Hornung 2014]

## Technology

In a first step, feedstock is separated into solid and liquid components at medium temperatures. These intermediate products are then reformed catalytically at circa 700 °C in a second step. The generated coal serves as catalyst to decompose long-chained organic compounds and to promote reforming reactions at low temperatures. In product purification downstream the reactor, the liquid phase is condensed and aerosols in the remaining gas are removed using a bio-diesel/RME scrubber.

The process generates three products:

- Product gas made up of H<sub>2</sub> (up to 40 wt.-%), CO, CO<sub>2</sub>, N<sub>2</sub>, CH<sub>4</sub>, small amounts of higher hydrocarbons
- Product oil with high calorific value and low acid content
- Coke with high carbon content

The produced gas and oil are meant to be used to generate electricity on site in a combined heat and power unit. Currently, a 50:50 mixture with biodiesel is pursued. In future, other utilizations are planned.

When only biogenic material is used as feedstock, it is intended to use the generated coke as soil conditioner.

### Operating Parameters

Intermediate pyrolysis with integrated reforming is operated in a temperature range from 400-500 °C with a residence time of 5 to 30 minutes. Biomass with a dry matter content of 70 % and higher can be processed. Table 3.10 gives information on products and energy supply for processed digestate.

Table 3.10: Products and supply of energy from intermediate pyrolysis [Binder 2014]

Starting Material	raw	dry	Product	Percentage	Calorific Value	Energy Supply
Digestate	30 kg/h	11 kg/h	Carbonization Product	32 wt.-%		50 % biodiesel admixture
Dry Matter Content	30 %	80 %	Gas	38 wt.-%	11 MJ/m <sup>3</sup> <sub>N</sub>	11 kW <sub>el</sub> (net)
			Product Oil	10 wt.-%	34 MJ/kg	14 kW <sub>th</sub>

### Costs and Development Status

Gases and oils generated with this process have been tested successfully for over 500 h in a modified Cummins motor. Gas was used directly; oil was mixed with biodiesel in a ratio of 70:30 and both tested in a Dual-Fuel Common Rail Diesel motor. In future, it is intended to optimize the mixture rate with biodiesel in favor of the product oil. Suitability for motors is currently researched at the Ostbayerische Technische Hochschule Amberg (Germany).

At present, the Pyroformer reactor is tested in combination with a fluidized bed gasifier at the Biomass Research Institute in Birmingham.

In 2013, the Fraunhofer Institute for Environmental, Safety and Energy Technology (UMSICHT) in Sulzbach-Rosenberg, Germany, developed an advanced process called Thermo-Catalytic Reforming (TCR). According to the developers, this process with new reactor design allows a wider range of both input materials and products.

The developers claim that the high oil quality achieved is supposed to allow direct utilization as fuel without a further complex synthesis step. Application as marine diesel or fuel oil and also blending with automotive fuels are mentioned as future perspectives.

Treatment costs of around 110 €/Mg Input have been published. Calculated investment costs for a TCR plant to treat separated digestate with a dry matter content of 30 % amount to circa 1.3 million €. [Binder 2014]

#### 3.1.2.5 M.E.E: Intermediate Pyrolysis

M.E.E. GmbH, a daughter of Maplan GmbH, was founded in 2011 and is operating a pyrolysis pilot plant in Schwerin (Germany) with a capacity of up to 750 kg/h. In absence of air, the plant operates at temperatures of up to 550 °C, with a maximum internal energy consumption of 20 %. According to the supplier, this installation is an enhancement of the intermediate pyrolysis process (see chapter 3.1.2.4). Different waste streams can be treated with this process. The installation currently in operation serves to develop both concept and process for a planned serial production. A capacity of 5 Mg/h is planned for installations delivered in series. The plant in Schwerin was visited by the project team on November 27<sup>th</sup>, 2013.

In contrast to the two processes described above which were designed to treat mainly biogenic materials (see chapter 3.1.2.3 and 3.1.2.4), the M.E.E. pyrolysis process is suitable for typical waste fractions like plastic waste (e.g. lightweight packaging), shredder fractions, reject or residues from chemical industry. Yet, treatment of unprocessed municipal waste is not considered by the developers.

### Technology

Suitable input materials as specified by the supplier are - among others - sewage sludge, digestate, poultry manure, bones, scrap tires, shredder fractions, Tetra Pak, rejects. Also ash containing materials with up to 70 % mineral components are supposed to be suitable. A Water content of less than 15 % is necessary. Higher water contents require pre-drying. Pelletizing can be necessary when materials are difficult to handle. Depending on the favored residence time, a particle size up to 40 mm is specified.

The installation is shown in figure 3.28. This process concept, too, is based on a screw reactor.



Figure 3.28: left: MEE-plant Schwerin, combustion chamber in the foreground, feeding system and transverse reactor in the background; right: back view reactor with fuel feeding [own pictures].

The input material is fed to the reactor by a double gate lock feeding device with ball valves. The reactor is heated by molten salt flowing through the screws plus external electrical heating. Downstream the reactor is a carbon reformer. The supplier does not publish information on the geometry of this unit. It is meant to prevent further conversion of organic components and therefore to obtain a coke product with low tar content by using water as gaseous reactant. Coke is discharged with a screw. Currently, product gas is burned in a combustion chamber without further condensation of volatile components. Application of condensable components as liquid fuel has been subject to further research and it is intended to continue development in this direction.

### Operating Parameters

During the visit to the installation, pig manure was used as input material. According to the operators, throughput was 150 kg/h, while a throughput of 750 kg/h had been achieved with other input materials. The reactor is designed for process temperatures between 350 and 550 °C and is operated at an overpressure of 300 mbar. Operating data of the M.E.E. plant can be found in table 3.11. The mass balance is exemplary for pig manure. Values of immediate and elementary analysis are displayed in figure 3.29.

Table 3.11: Operating parameters of the M.E.E. plant and mass balance by the example of pig manure as input material

Parameter	Value	Mass Balance (100 % Input Pig Manure)	
Throughput	up to 5 Mg/h	Pyrolysis Gas	10.8 %
Thermal Capacity	up to 20 MW	Pyrolysis Coke	42.0 %
Residence Time	6 - 12 min	Pyrolysis Oil	3.5 %
Filling Degree	50 %	Water	43.7 %
Pyrolysis Temperature	350 to 550 °C		

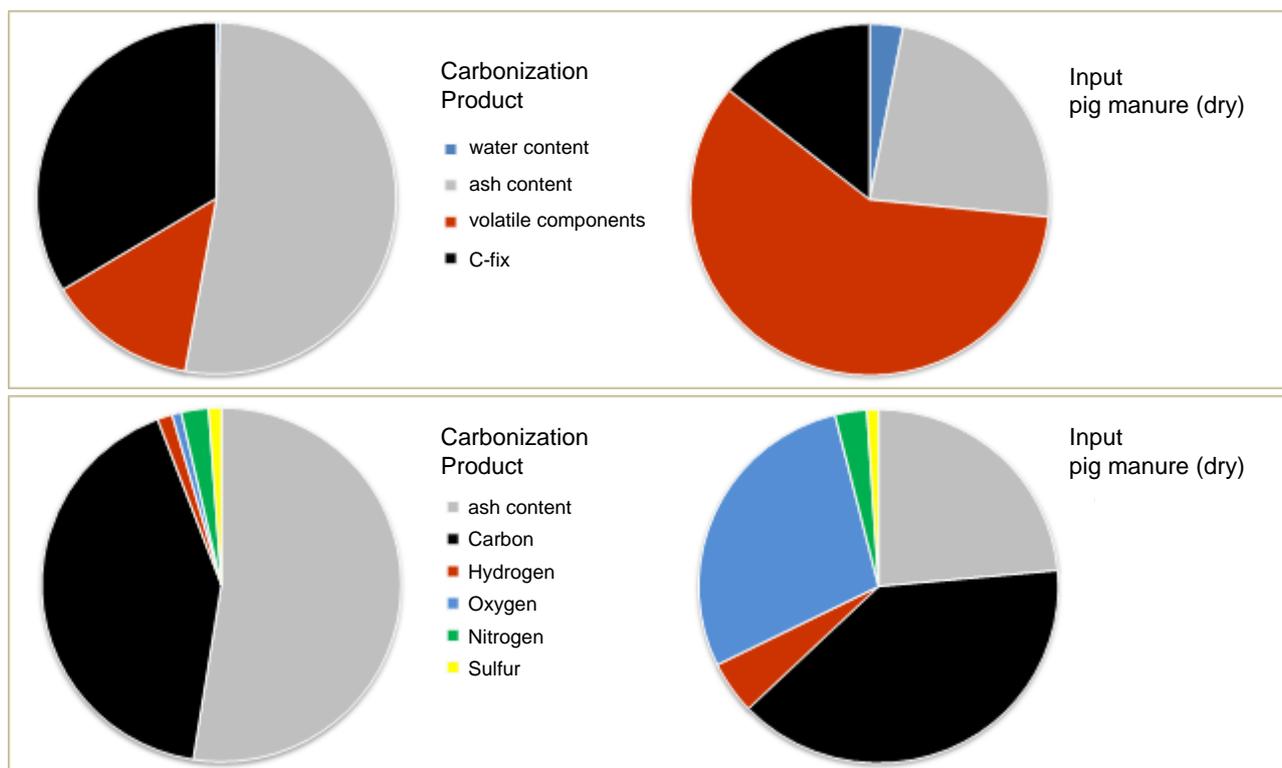


Figure 3.29: Immediate- (top) and elementary analysis (bottom) of input material and carbonized pig manure from MEE-plant Schwerin (own data; oxygen content calculated; reference: wt.-%).

### Costs and Development Status

According to the operator, the installation has been in operation for about 4,000 hours with a throughput of 500 Mg. Continuous operation with the intended throughput has not been proved so far. The longest operating period was achieved in the context of a four-week experimental campaign. Due to the development status, reliable data regarding maintenance efforts is not available so far. The operator expects a maintenance interval of one year. Gaseous products are not yet used energetically. Current planning includes diverse applications like heat, steam, steam turbine or ORC process.

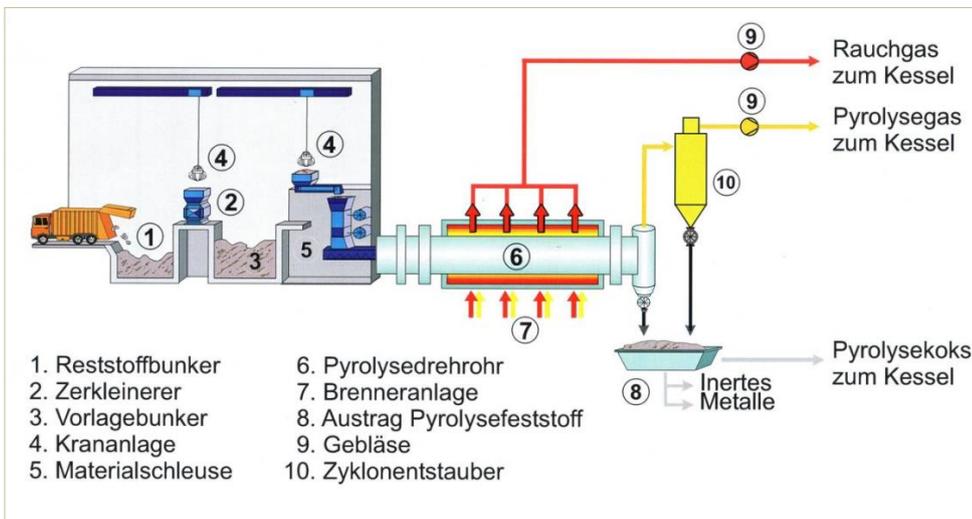
The supplier calculates investment costs of about 6.2 million € for a plant with a capacity of 2 Mg/h. Treatment costs are estimated to be between 59 and 81 €/Mg depending on input material. The calculation made available to the authors includes depreciation, interest (both for 20 years), maintenance, electricity and personnel.

### 3.1.3 Pyrolysis as Upstream Process

#### 3.1.3.1 ConTherm Process

The ConTherm plant was designed by PLEQ and after takeover by Mannesmann MDEU/Technip it was constructed between August 2000 and September 2001. The installation was used as upstream pyrolysis of high calorific refuse derived fuels in the Westfalen power plant near Hamm (Germany). Pyrolysis gas and coke were co-combusted in block C of the power plant. Plant acceptance operation continued until the end of 2003, modifications were necessary. The plant was shut down due to economic reasons in December 2009 after the emergency stack broke down.

#### Technology



As shown in figure 3.30, refuse derived fuel is first shredded and then transferred to a rotary drum where degassing takes place. The drum is heated by natural gas. Pyrolysis gas is drawn off and then lead to the power plant burners passing a cyclone and a blower.

Solid residue is conditioned externally and separated into pyrolysis coke, a metal and an inert fraction.

Figure 3.30: Schematic view ConTherm process [Spindeldreher 2004].

The coke was also used in the power plant, metals were marketed and the inert fraction was landfilled. The power plant is equipped with a gas purifying system. The ConTherm installation consists of two parallel pyrolysis rotating drums. Figure 3.31 shows the drums before assembly and the generated coke after external conditioning.



Figure 3.31: ConTherm-process - rotary drums and generated pyrolysis coke after post-treatment [Spindeldreher 2004].

## Operating Parameters

The two-line ConTherm facility was planned for a throughput of 100,000 /Mg/a with a maximum of 120,000 Mg/a corresponding to an hourly throughput of 6.7 to 8 Mg per line. This had to be reduced to 70,000 Mg/a because the rotary drums were undersized and therefore temperatures achieved in the center of the drums was not sufficient for pyrolysis.

Yet, operating data published in 2010 is still based on an overall throughput of 100,000 Mg/a and can therefore only be considered as design data.

Table 3.12: Operating parameters ConTherm facility.

Parameter	Value	Parameter	Value
Throughput	13,3 Mg/h	Residence Time	90 min
Thermal Capacity	66,9 MW	Availability, planned	85 %
Number of Rotary Drums	2	Availability, reached	> 90 %
Length Rotary Drums	20 m	Input Natural Gas	690 kg/h
Diameter Rotary Drums	2.8 m	<b>Products</b>	<b>Mass Flow</b>
Filling Degree	15 %	Pyrolysis Gas	8,940 kg/h
Pyrolysis Temperature	500 °C	Pyrolysis Coke	3,300 kg/h
Shell Temperature	750 °C	Metals	1,060 kg/h

The following data on the energy balance was published in 2010, it can also be considered only as design data [DGE 2010].

Table 3.13: Energy balance ConTherm facility

Input		Output	
RDF	240.7 GJ/h (89,2 %)	Pyrolysis Gas	232.8 GJ/h (86,2 %)
Natural Gas	29.2 GJ/h (10,8 %)	Pyrolysis Coke	28.3 GJ/h (10,5 %)
		Flue Gas	5.1 GJ/h (1,8 %)

According to this data, the ConTherm facility would have been operated with a thermal efficiency of 96.7 %.

## Costs and Development Status

There is no data available on process costs.

The facility had to be modified significantly during trial operation. The undersized rotary drums were a fundamental issue, causing a decrease in throughput of 30 %. Statements speaking of a filling degree of 15 % therefore seem far from reality. In addition, problems occurred at the sealing of the rotary drums. They showed a tendency to release pyrolysis gas when underpressure was too low, and allowed air intrusion when underpressure was too high. It took several years to improve underpressure regulation.

Another substantial weak point was the pyrolysis gas pipe. Severe deposition of dust and tars occurred, even leading to blockages, caused by insufficient performance of the cyclone (see figure 3.22). The original pipe was replaced by a shorter one with external heating (up to 400 °C).



Figure 3.32: ConTherm process – Pyrolysis gas pipes blocked by depositions [Spindeldreher 2004].

Sieving of residue materials also caused problems. In consequence, after metal removal, the remainders were handed over to an external service provider who returned the pyrolysis coke after conditioning.

The steel emergency stack was not designed properly. When in use, it became so hot that its structural stability was affected and finally, the stack broke down. In the end, material failure of the stack led to the shutdown of the whole facility. A reconstruction of the plan would have cost around 1 million Euros. Falling prices for RDF, which was no longer available as desired in quality and on requested terms, finally tipped the scales not to reconstruct the plant. [ConTherm 2004, DGE 2010, ConTherm 2010]

Experiences made with the ConTherm facility can be summarized as follows:

- Severe problems occurred in the first year, yet over time these problems were solved.
- The installed system is operable in principle and could likely be operated successfully in long-term operation.
- The technology is complex and requires high maintenance effort, therefore, unmonitored operation is not possible.
- Given attractive market conditions, this downstream process could be interesting for further application.

### 3.2 Gasification

When evaluating gasification processes, it is necessary to distinguish whether gasification is only one step within a staged combustion process or if it is a “sole” gasification, meaning that the target product allows variable use as (fuel)gas.

In fact, it is only the first treatment step that is operated under oxygen deficiency conditions in staged combustion processes. Gases produced are subsequently oxidized completely, frequently in downstream reactor areas (secondary combustion chamber) which are hardly spatially separated from the first step. Technically, these processes are to be classified as combustion processes with lower energetic efficiency than in classical waste incineration [Lamers 2013].

Especially melting-gasification processes offered by different Japanese companies are principally staged (high temperature) combustion processes. Added value can be obtained by slag melting which is achieved at the cost of a high energy demand.

The following section focusses on gasification processes aiming to produce syngas or fuel gas. Major advances are postulated for these processes in comparison to incineration. They are as follows [Lamers 2013]:

- Higher electric efficiency caused by utilization of the gases in combustion engines
- Lower emissions
- Vitrifying of slag with outstanding eluate values for high temperature processes ( $T > 1500 \text{ }^{\circ}\text{C}$ )

Similar to pyrolysis processes, available information for gasification processes is limited. Especially data on operation experiences, energy efficiency, emissions, costs and long term operation are barely published [Lamers 2013].

Gasification technology faces several challenges, most of which refer to the quality of the generated product gas:

- Detailed specification for waste conditioning and elimination of troubling materials
- High contents of tar and dust hinder motoric utilization of the gases, accordingly extensive gas purification is required
- High maintenance efforts

### **3.2.1 Gasification as Part of Staged Combustion Processes**

Some staged combustion processes are marketed as gasification process. This has both political and financial reasons. In some countries, “alternative” treatment technologies are supported by government funding. In addition, it is presumed that these “alternative” technologies have a better image in public than conventional waste incineration. Besides these aspects, technological advantages are considered as well [Lamers 2013]:

- Smaller facilities for the same amount of waste
- Economic solutions possible for smaller capacities
- Nitric oxide reduction due to staged combustion

Processes available on the market are for example grate technologies by Energos [Energos 2014], the Slovenian company KIV [KIV 2014], and the Australian Entech company [Entech 2014], or the fluidized bed technology by EPI Energy Products of Idaho, now taken over by Outotec [Outotec 2014]. In the following, the most well-known staged combustion process will be presented, the Energos technology.

#### **3.2.1.1 Energos**

From 1990 to 1997, the Norwegian research organisation SINTEF in Trondheim developed a two-stage process for thermal waste treatment, designed for small and medium throughput, which was then marketed by Energos.

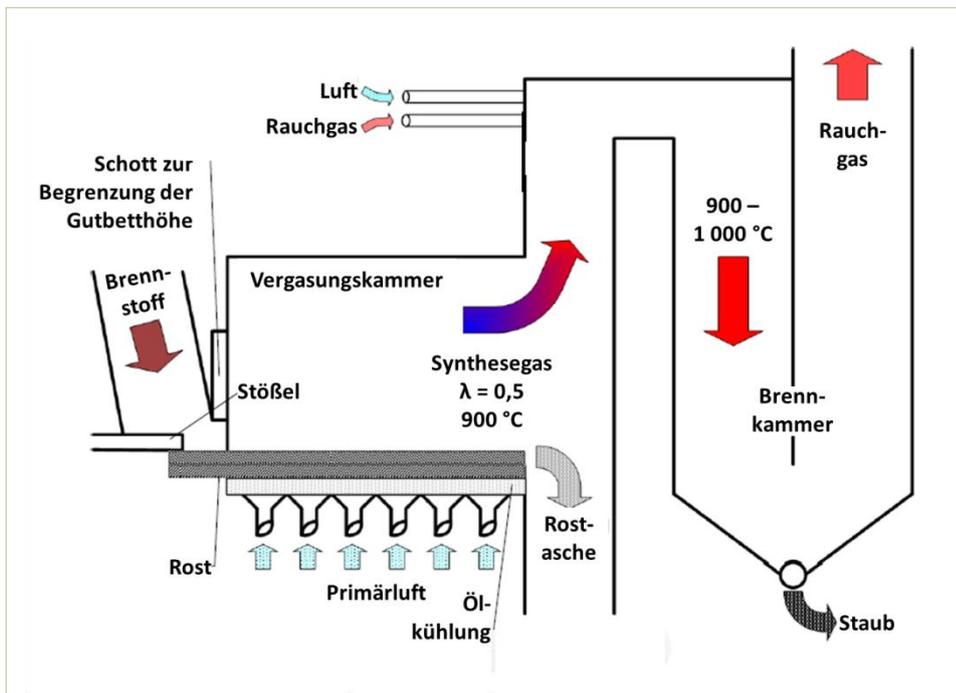


Figure 3.33: Energos process – schematic diagram of gasification and post-combustion chamber

The process includes a gasification chamber, where waste is directly gasified on a grate. Above the gasification chamber is the oxidation chamber. Here, air is injected and the generated syngas is combusted. The process was designed for residual waste that is to be conditioned on site, i.e. shredding and elimination of troubling materials. Yet in the only facility of this kind in Germany, located in Minden, only externally conditioned

RDF is incinerated. Accordingly, there was no waste conditioning unit installed in this facility.

It is subject to occasional discussion whether this process is to be classified as gasification or two-stage combustion, since many conventional technologies for waste incineration are also operated under oxygen deficiency conditions. The difference lies in the fact that in conventional waste incineration, the post-combustion chamber is connected directly to the primary chamber. In Energos installations, the post-combustion chamber is structurally separated from the combustion chamber. Nevertheless, this technology is to be classified as staged combustion process.

### Technology

Core items of this process are the two reaction chambers. Waste is conveyed into the first chamber using a hydraulic stoker. Syngas flows directly into the oxidation chamber for combustion.

Waste is transported through the gasification chamber with an oil-cooled grate, constructed similar to a conveyor band. Poking or other influences on the fuel bed are not possible with this construction. Stoichiometry should be set to  $\lambda = 0.5$ . From operation in Minden, air ratios of 0.5 and 0.6 are known. However, operators in Minden admit that determination of the air ratio is not reproducible due to obstructed measurement instrumentation and systems control. The gasification temperature is about  $900\text{ }^{\circ}\text{C}$ . An oil- respectively gas burner is installed for start-up, shutdown or breakdowns/disturbances in operation.

Air and re-circulated flue gas are added to the syngas inside the channel that leads to the post-combustion chamber. Within the combustion chamber, syngas is then combusted at  $900-1000\text{ }^{\circ}\text{C}$ .

A complete Energos facility can be seen in the following figure.

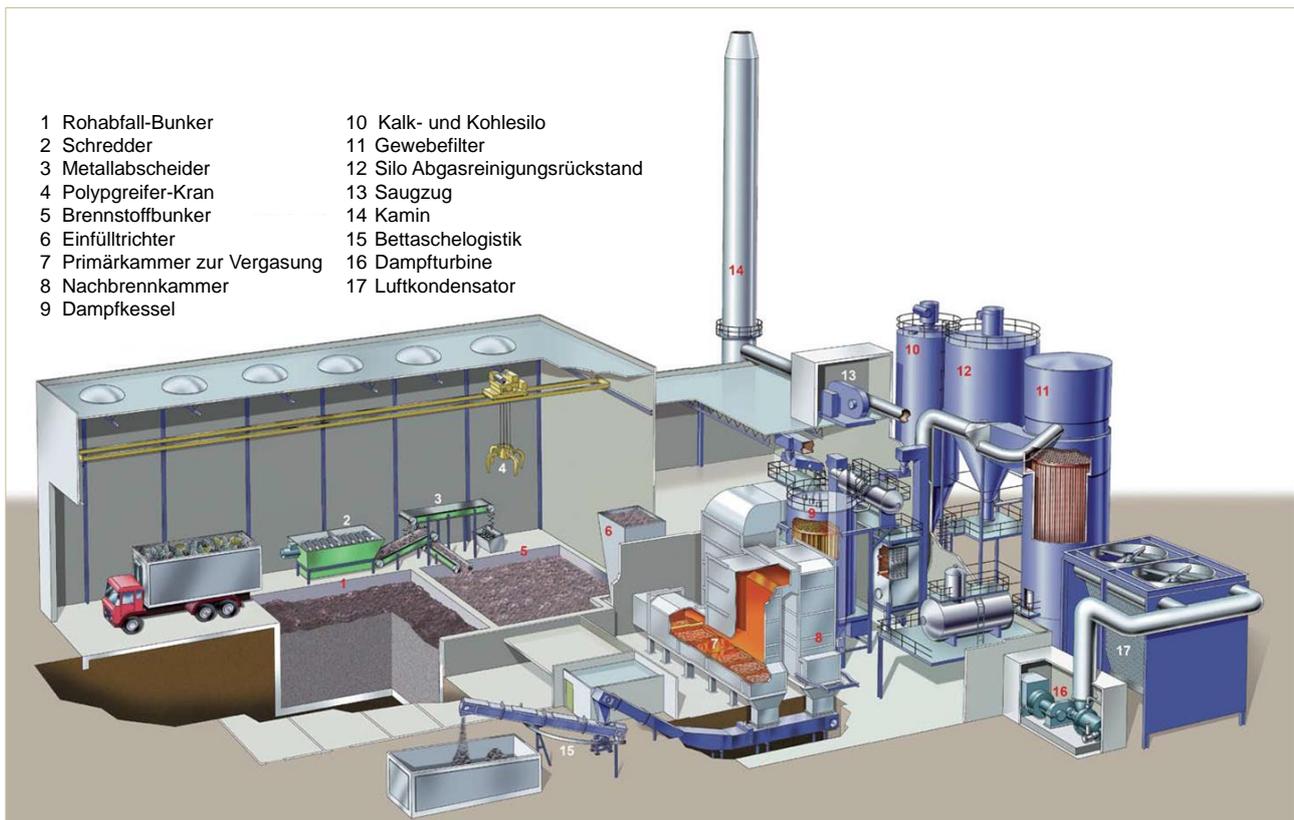


Figure 3.34: Energos process: three-dimensional sectional view

Residual waste is delivered to a bunker. The waste passes a magnetic separator and a shredder into a second bunker and is then transferred to a charging hopper with a crane. The material is then conveyed to the grate (where it is gasified) using a hydraulic slide. Grate ash is discharged at the end of the grate.

As clearly visible in figure 3.34, the combustion chamber is positioned directly above the gasification chamber, hereby minimizing thermal loss. Syngas passes through a vertical channel into the combustion chamber where it is combusted under addition of air and re-circulated flue gas.

Downstream the combustion chamber follows a heat recovery boiler, succeeded by a flue gas purification system. The latter does not include a denitrification device, but does still meet the limit values because of the staged combustion.

### Operating Parameters

The process is offered in two standardized sizes with 5 or 6 Mg/h per line. Basic operating parameters are summarized in table 3.14.

Table 3.14: Operating Parameters of the Energos process

Parameter	Wert	Parameter	Wert
Throughput per Line	5 or 6 Mg/h	Air Ratio	0.5
Calorific Value	10 - 14 MJ/kg	Calorific Value Product Gas	4 - 4.5 MJ/m <sup>3</sup>
Gasification Agent	air	Combustion Temperature	900 - 1,100 °C
Gasification Temperature	900 °C	Oxygen Content Off-Gas	7 vol.-%

The composition of the syngas was analyzed in 2011 during tests in an Energos facility in Norway. Results are shown in table 3.15. Main components of the generated low amounts of tar are aromatic and polyaromatic hydrocarbons.

Table 3.15: Composition and Gross Calorific Value of gas from the first stage of the Energos process

Composition and Gross Calorific Value							
N <sub>2</sub>	65,97 %	CH <sub>4</sub>	7,12 %	C <sub>2</sub> H <sub>6</sub>	0,15 %	Tars	0,0025 %
CO <sub>2</sub>	20,25 %	H <sub>2</sub>	4,55 %	C <sub>2</sub> H <sub>4</sub>	0,27 %	H <sub>o</sub>	4,34 MJ/m <sup>3</sup>
O <sub>2</sub>	0,50 %	CO	0,97 %	C <sub>3</sub> H <sub>8</sub>	0,20 %	λ	0,55

Existing plants with standardized dry flue gas cleaning technology easily meet the requirements of the waste incineration directive. This applies in particular to NO<sub>x</sub> emissions which show yearly average values of 60-65 mg/ m<sup>3</sup><sub>N</sub> even without secondary mitigation measures.



Figure 3.35: External view of the Energos plant in Minden (own picture).

Loss on ignition of the grate ash usually lies under 5 %, values of up to 10 % occur occasionally, higher values are rare. Considering the low air ratio in the primary zone, LOI values appear to be rather low, yet values are confirmed with a large number of analyses over a timespan of several years. It is possible that air ratios during operation are higher than indicated by the system control.

#### Costs and Development Status

The Energos process can be considered as established thermal waste treatment process for small and medium throughput. The first Energos facility, which started operation in Ranheim close to Trondheim in 1997, was shut down in 2012. Until 2002, four more facilities

with an overall throughput of 186,000 Mg/a were built. The first and so far only Energos facility in Germany was constructed in 2001, when a former power plant was rebuilt into an Energos facility with a nominal throughput of 39,000 Mg/a. With input showing an average calorific value of 13 MJ/kg, this plant has a de facto throughput of 32,000 to 33,000 Mg/a.

It took until 2009 when the next plant began to operate, located on the Isle of Wight (30,000 Mg/a). In 2010, a plant in southern Norway with 78,000 Mg/a followed. Currently, six facilities with an overall capacity of 636,000 Mg/a are under construction in Great Britain. The Energos technology is especially interesting in Great Britain because the process is approved as gasification and therefore earns two ROCs (Renewable Obligate Certificates) for exporting electricity into the grid. This might be one reason why Energos markets the process as gasification.

So far and with an operating experience of more than 550,000 hours, Energos plants have proved their suitability to recover energy from municipal waste.

Yet, it must be considered that this less costly treatment technology is subject to certain restrictions. Adequate preconditioning of municipal waste is indispensable for this grate type. The infeed system constructed in Minden is prone to disturbances (see figure 3.36) because there is no direct connection between feeding hopper and grate. Instead, a feeding conveyor was built in between the two. Bands as well as long pieces of foil or materials with a tendency to agglomerate cause blockages of the screw. [del Alamo 2012, Energos 2013, Sanquist 2011]

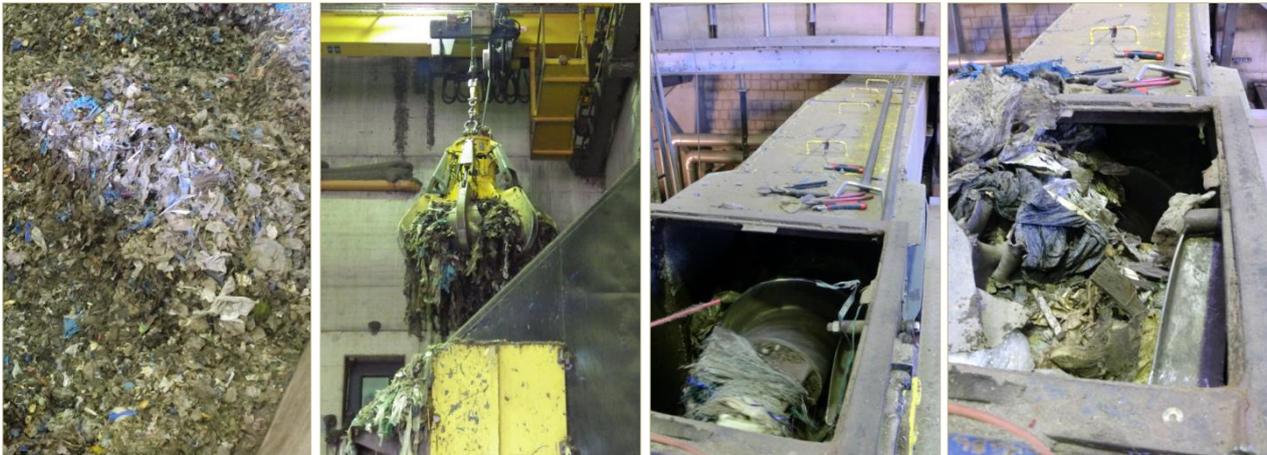


Figure 3.36: Infeed of waste at the Energos plant in Minden: Input of RDF, feeding hopper loaded with crane, screw between hopper and grate, blocked screw (from left, own pictures)

According to the operator, treatment costs at the Minden plant lie between 60 and 70 € per Mg of RDF.

### 3.2.2 Gasification as Sub-Step of Combustion/Melting Processes

Especially in Japan, different suppliers developed staged incineration processes which allow melting of mineral components (ash) due to high temperatures in the combustion stage. At the end usually stands a solid, vitrified product which is barely leachable and can therefore be used as building material.

#### 3.2.2.1 Ebara TwinRec Process (TIFG)

In the beginning of the 1990s, the Ebara Corporation began to develop a gasification process -

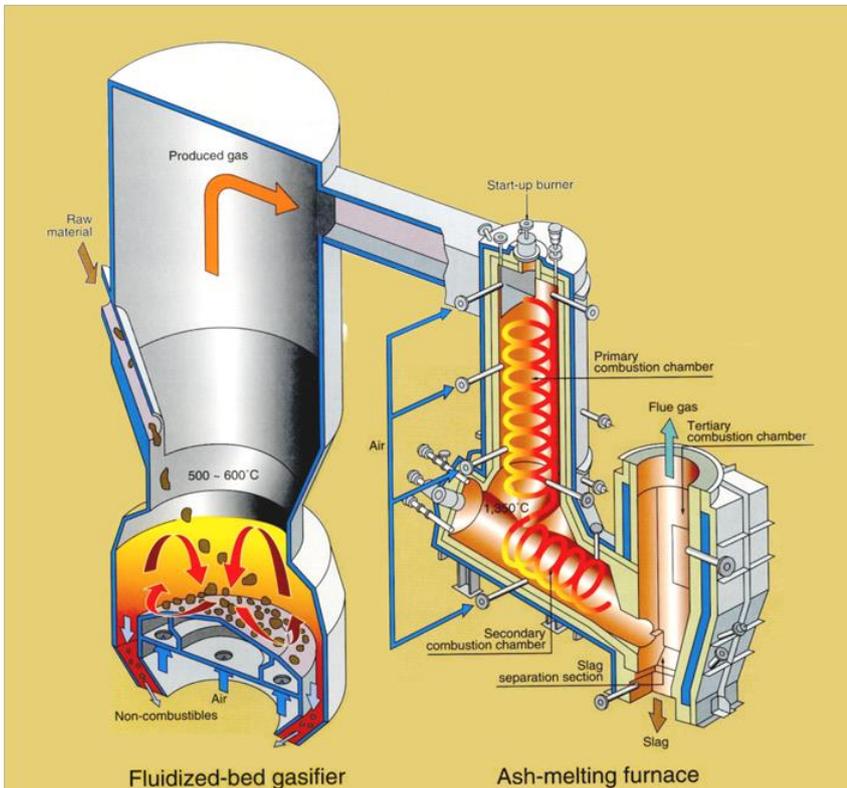


Figure 3.37: Schematic diagram Ebara process

based on their waste incineration plants with rotating fluidized bed - in which syngas was supposed to be combusted directly in swirl combustion chambers at high temperature with immediate melting of fly ash.

Besides municipal waste, TwinRec plants are used to treat sewage sludge, hospital waste, shredder residue and all kinds of plastic waste.

#### Technology

Waste is gasified in a circulating fluidized bed at temperatures of 500 to 600 C. Air is used as gasification agent. The synthesized gas flows directly

and without further treatment into a vertical swirl combustion chamber and from there into a second swirl combustion chamber which is inclined downward. For complete burnout, a vertical combustion chamber is attached. The maximum combustion temperature in the first chamber is 1,350 - 1,450 °C.

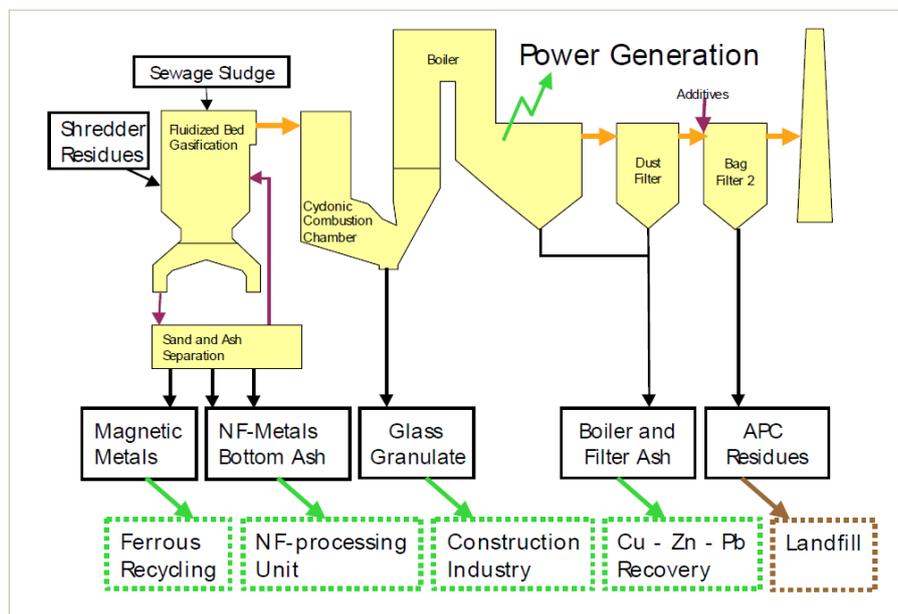


Figure 3.38: Flow chart Aomori TwinRec plant with residual materials and their recycling pathways respectively disposal measures

The adjacent process diagram shows the set-up of a complete TwinReg plant by the example of the first commercial plant in Aomori. Preferred fuel in this plant is the shredder light fraction (SLF), also called automobile shredder residue (ASR), from end-of-live vehicles.

Like in all combined processes, a steam boiler and conventional gas cleaning are found downstream the combustion.

### Operating Parameters

Information exceeding the data mentioned above is fragmentary. Published data from the Kawaguchi plant with 3 lines à 144 Mg/d documents very stable operation already in the first two months after start-up.

Table 3.16: Operating Parameters Ebara TwinRec

Parameter	Value	Parameter	Value
Capacity (per line)	144 - 225 Mg/d	Gasification Temperature	500 - 600 °C
Operating Time	240 - 280 d/a	Combustion Temperature	1,350 - 1,450 °C
Gasification Agent	air		

### Emissions and Residue Materials

Conventional dry flue gas cleaning guarantees compliance with authorized limits and would also be able to meet European limit values. In Japan, emission limits for dioxin are particularly important. Values measured in a demonstration plant over a period of 100 days were always lower than 0.01-0.05 ng(I-TE)/m<sup>3</sup>.

Since gasification residue is not molten in the TwinRec process, metal recovery is both possible and reasonable. In the Aomori plan, too, metals are recovered, since the shredder light fraction treated in this facility contains high amounts of metal. The inert fraction from the gasification as well as residues originating from the combustion chamber can be used in the construction sector. Flue gas treatment residues are disposed.

### Costs and Development Status

A small test plant with a throughput of 7 Mg/d was started up in Sodegaura in November 1995, followed by a pilot plant with 20 Mg/d in Fujisawa in July 1997. The first commercial size facility with two lines of 225 Mg/d each was handed over in Aomori in February 2000.

After this first plant, 12 installations with 21 lines and an overall capacity of 3,100 Mg/d were built in Japan until 2009. Information on plants in operation implies high availability.

There is no data available on process costs.

### 3.2.2.2 Hitachi Zosen Gasification and Melting System

In the 1990s, Hitachi Zosen developed a waste treatment system which combines gasification in a fluidized bed and high temperature combustion. A demonstration plant with a throughput of 33 Mg/d started operation in the end of 1998 in Yore Town.

#### Technology

As shown in the following process schema, waste is gasified with air in a stationary fluidized bed of sand at 500-600 °C. Synthesized gas is directed to a slag tap furnace where it is combusted at 1,200-1,400 °C with simultaneous melting of fly ash. An additional post combustion chamber is operated at temperatures above 850 °C for complete burnout. A downstream waste heat boiler and gas cleaning system follow.

Since the gasification stage is operated at moderate temperatures, iron and aluminum can be recovered from the solid gasification residue. A downstream waste heat boiler and gas cleaning system follow. Since the gasification stage is operated at moderate temperatures, iron and aluminum can be recovered from the solid gasification residue.

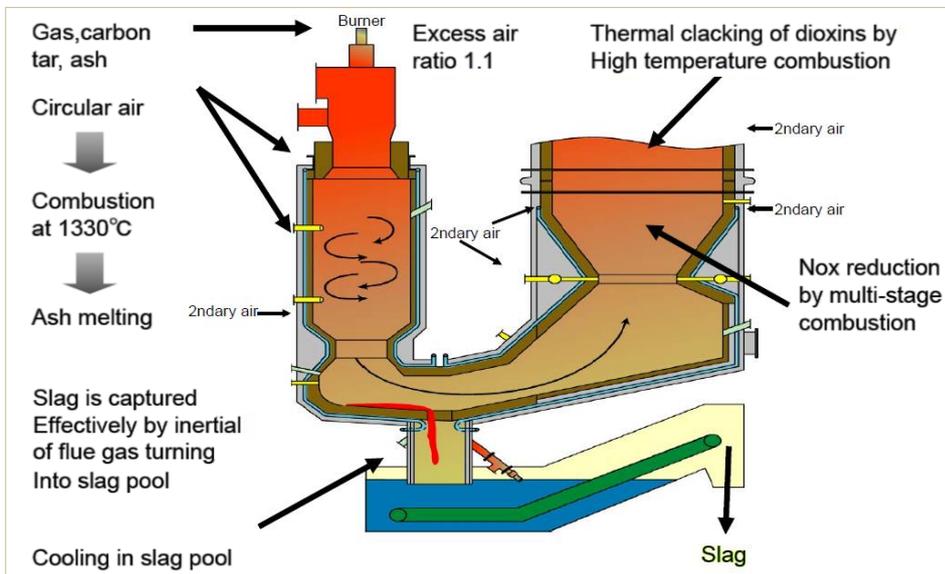
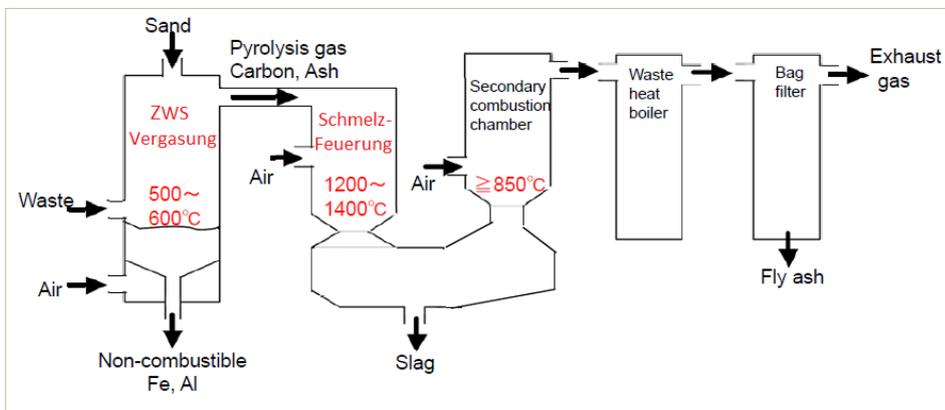


Figure 3.39: Hitachi Zosen Gasification and Melting System. Top: process schema; bottom: slag tap furnace [HZI 2011].

#### Development Status

After the demonstration plant, at least one more plant with two lines and a throughput of 75 Mg/d each was built in Sakurai City in 2002. Information on treatment costs or further developments after 2002 is not at hand. [HZI 2011]

### 3.2.2.3 JFE High-Temperature Gasifying and Direct Melting Furnace System

In the year 1992, the JFE Engineering Company began to develop the High Temperature Gasifying and Direct Melting Furnace System to gasify preconditioned waste and coke in a combination of shaft furnace and fluidized bed. Synthesized gas is combusted in an attached post combustion chamber.

Operation of a pilot plant, required for certification in Japan, started in 1995. System approval followed in 1998. In 2000, an order was placed for the first commercial size plant with three lines in Kagamigahara.

#### Technology

The central gasification reactor is loaded from above with preconditioned waste (only in Fukuyama, RDF is used as fuel), coke and limestone. A coke layer emerges at the bottom of the furnace. It is oxidized at 2,000 °C and higher with air that is enriched to an oxygen content of 35 % and injected at the main tuyere. At these temperatures mineral components are molten, carbon is combusted and because of the Boudouard equilibrium (see figure 2.2.), CO prevails as combustion product of coke.

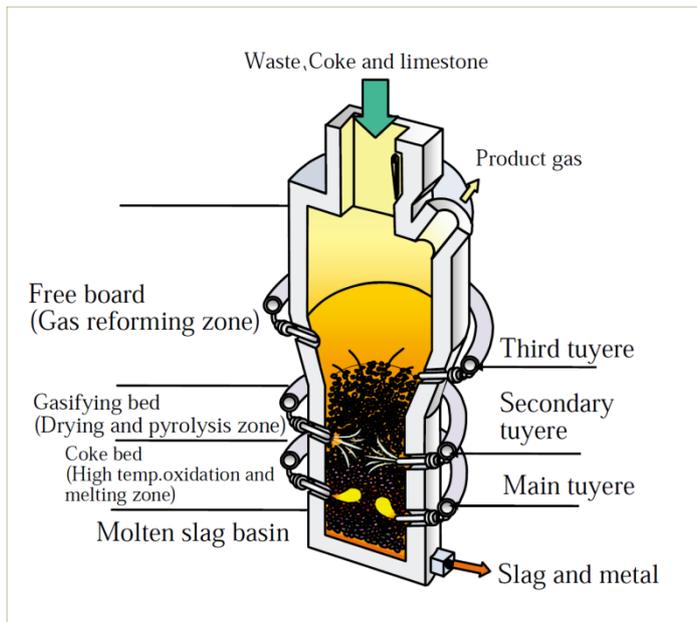


Figure 3.40: Gasification reactor of the JFE High-Temperature Gasifying and Direct Melting Furnace System with presentation of reaction zones [Nishino 2009].

The CO-rich product gas from this area reaches Zone 2 of the furnace. Both upper nozzle rings inject further air into the furnace, hereby fluidizing the bed material. Controlling of material and air supply makes sure that gasification conditions are maintained in the reactor despite fluidization. Temperatures in zone 2 and in the free board are between 700 and 850 °C. The reactor with construction and reaction zones as shown in the adjacent figure differs from the DMS process by Nippon Steel (see chapter 3.2.2.5) in the fluidization of the gasification good. While the DMS process is a fixed-bed gasification, the JFE process combines fixed bed gasification in the lower part of the reactor with fluidized bed gasification in the upper part.

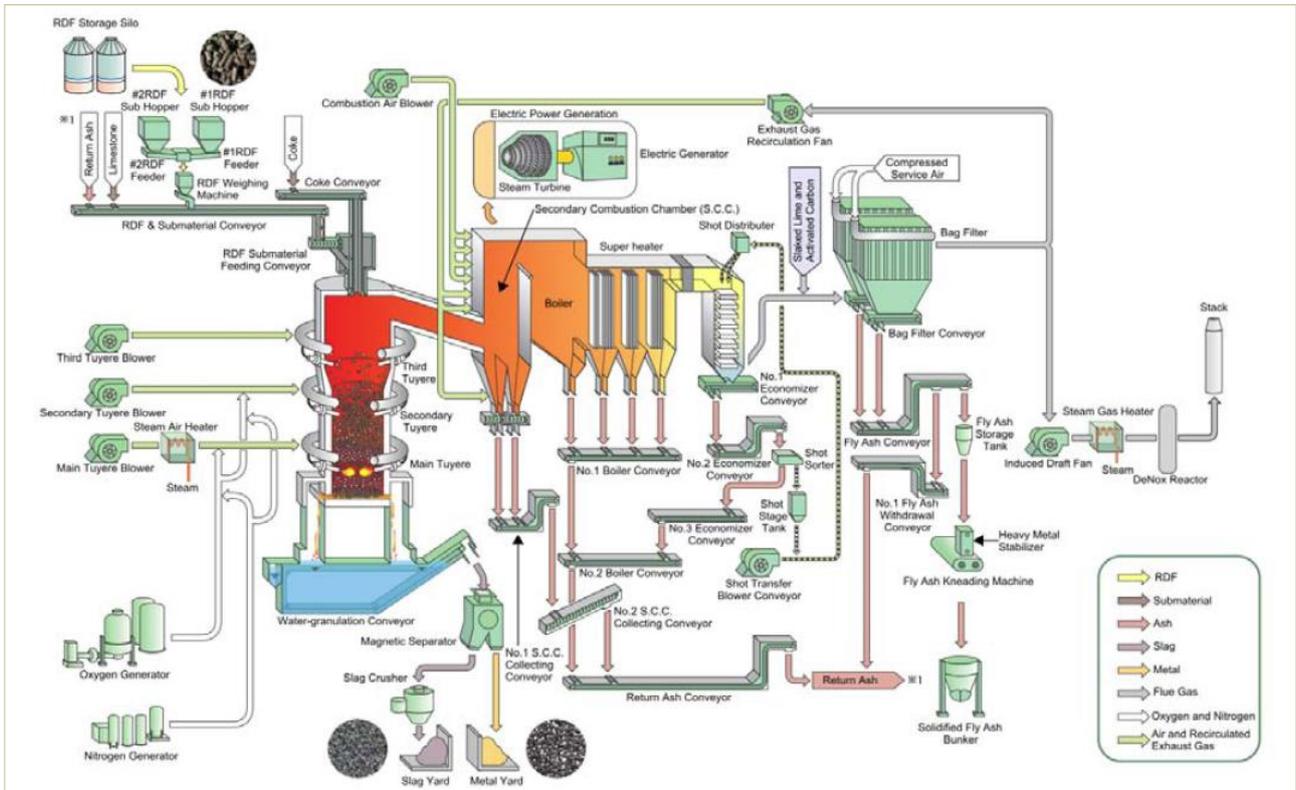


Figure 3.41: Process schema JFE High-Temperature Gasifying and Direct Melting Furnace System in Fukuyama

In contrast to the DMS process, syngas is led to a combustion chamber and combusted without prior dust removal. Downstream the combustion chamber, a waste heat boiler with steam turbine and generator, a semi-dry flue gas cleaning to remove acid gases and an SCR-unit for denitrification are installed. Figure 3.41 shows the process diagram for the Fukuyama plant. The facility has one line with a capacity of 314 Mg/d, start-up was in 2004.

**Operating Parameters**

Operating parameters for a JFE facility are exemplified by data from the Fukuyama plant. This facility was built to treat pelletized RDF which is produced from municipal solid waste in nine preparation plants located in different cities. Table 3.17 presents design data and the fluctuation range of several fuel parameters. Yearly throughput is given as well. Referring to the design capacity of 314 Mg/d, a yearly capacity utilization rate of about 60 % was achieved.

Table 3.17: Characteristic fuel parameters of RDF treated in a JFE plant

Parameter	Unit	Design Data	Operational Data 2004-2011
Calorific Value	MJ/kg	18.2	16.16 - 19.72
Water Content	wt.-%	8.0	2.2 - 5.8
Combustibles	wt.-%	81.4	78.7 - 86.5
Ash Content	wt.-%	10.6	9.9 - 15.5
Throughput (2009)	Mg/a	-	70,753

Operating Parameters of the Fukuyama facility are given in table 3.18

Table 3.18 Operating parameters of the JFE plant in Fukuyama [Suzuki 2011].

Parameter	Value	Parameter	Value
Capacity	314 Mg/d	Combustion Temperature	1,000 °C
Lines	1	Steam Temperature	450 °C
Coke Content Feed	≈ 5 %	Steam Pressure	60 bar
Lime Content Feed	≈ 3 %	Boiler Efficiency	83 %
Typical Operation Time (since 2004)	250 d/a	Generator	20 MW
Gasification Temperature	700 - 2,000 °C	Electric Efficiency	30 %
O <sub>2</sub> -Enrichment	35 % in bottom zone	Internal Electricity Consumption	≈ 20 %

Electric efficiency refers to the fuel materials RDF and coke. When comparing this process with conventional incineration plants, at least the energy demand for RDF production has to be included into consideration.

### Emissions and Residue Materials

The flue gas cleaning following the boiler reduces emissions so that they comply with legal limits in Japan. Authorized limits for the Fukuyama plant as well as emissions measured during operation are given in table 3.19.

Between 2004 and 2011, around 7,000 Mg vitrified slag and about 440 Mg magnetic metal fraction were recovered per year from an annual throughput of 70,000 Mg. The inert fraction from gasification shows the expected leachability values that allow further utilization in the construction sector or cement industry. Flue gas treatment residues are stabilized and either stored in big bags or disposed of in hazardous waste landfills.

Table 3.19: Authorized limits and measured emissions JFE plant Fukuyama

Parameter	Unit	Authorized Limit Value	Measured in 11/2009	2010 - 2012
Dust	mg/m <sup>3</sup> <sub>N</sub>	11	< 5.6	
HCl	mg/m <sup>3</sup> <sub>N</sub>	89	46.7	11 - 35
SO <sub>2</sub>	mg/m <sup>3</sup> <sub>N</sub>	63	< 31.7	
NO <sub>x</sub>	mg/m <sup>3</sup> <sub>N</sub>	114	75.2	21 - 34
PCDD/F	ng[ <i>l</i> -TE]/m <sup>3</sup> <sub>N</sub>	0,06	0.0019	0.00014 - 0.0062

### Costs and Development Status

There is no information at hand concerning costs. It is assumed that treatment costs are similar to those of the DMS process (see chapter 3.2.2.5).

Between 2003 and 2008, JFE constructed 10 plants with 20 lines and an overall capacity of circa 1,500 Mg/d. In seven years of operation, no unscheduled shutdowns due to technical failures occurred in the Fukuyama facility. Yet it has to be considered that a comparatively short yearly operating time leaves much time for maintenance. [Nishino 2009, Nagayama 2010, Suzuki 2011]

#### 3.2.2.4 Kobelco Gasification and Melting System

In the 1990s, Kobelco Eco Solution Co. like many other companies in Japan developed a process for combined gasification and incineration of municipal solid waste. Despite its origin in the steel sector, the company did not choose a shaft furnace but began the development process

based on a fluidized bed reactor. The company's experience with this technology for waste incineration goes back to 1983.

Synthesis gas is combusted in a downstream combustion chamber. In October 2000, the Chubu-Kamikata plant with a capacity of 60 Mg/d located in Aomori started operation.

**Technology**

Center piece of the installation is a stationary fluidized bed with an attached swirl combustion chamber for burnout of syngas, as shown in figure 3.42.

Initially, incoming municipal solid waste is shredded and fed to the fluidized bed with a screw conveyor. Gasification takes place at temperatures of 500 - 600 °C, air is injected into the reactor. Coarse materials like scrap are discharged underneath the nozzle floor. This material is separated in the grit classifier; metallic components are retrieved and marketed. Finer ashes are returned to the fluidized bed together with the sand.

Dust-laden syngas flows into the swirl combustion chamber without further treatment. Air is injected at the head of the chamber and the syngas is combusted at about 1,350 °C. For safety reasons, an auxiliary burner is installed with an average fuel demand of circa 4 l fuel per Mg of waste.

Fly ash is molten in the combustion chamber and then discharged to a slag cooler, generated granulate is crushed. Because of the high-temperature treatment, excellent elution values can be assumed for this material. It is doubtful whether this material could be marketed in Europe at prices as high as those indicated for Japan.

A waste recovery boiler is found downstream the combustion chamber. It is operated at 420 °C and 60 bar. For a facility with a throughput of 100,000 Mg/a, an electrical efficiency of 27 % is stated. Less internal consumption, a net efficiency of 23 % is expected.

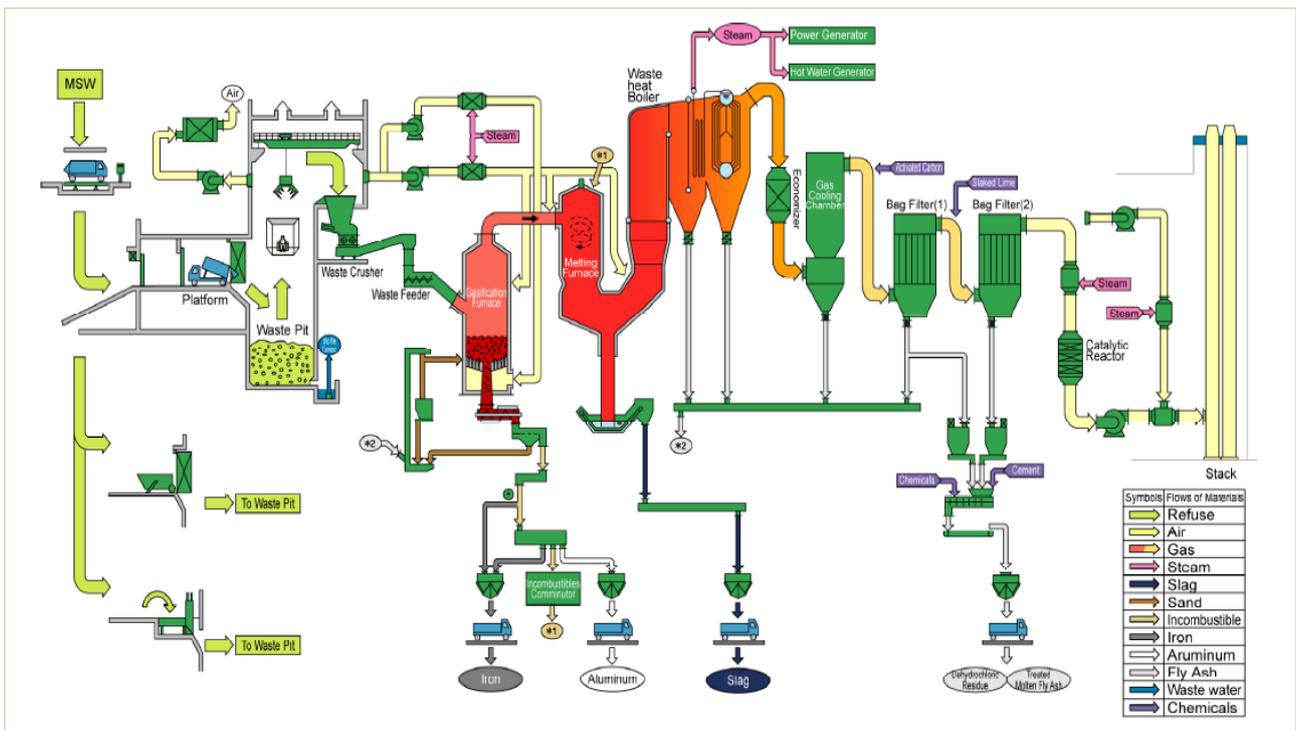


Figure 3.42: Process schema of the Kobelco plant in Ishinomaki

The process diagram shows that the plant in Ishinomaki comes with conventional gas purification. Fly dust and flue gas purification residues are removed with fabric filters, an SCR-plant is installed for denitrification.

### Operating Parameters

Basic operating parameters at hand are given in table 3.20. Kobelco states a maximum throughput per line of 330 Mg/d, a maximum throughput of 175 °Mg/d has been implemented in the Sagamihara installation in 2010.

Table 3.20: Operating parameters of the Kobelco-plant in Ishinomaki

Parameter	Value	Parameter	Value
Capacity	230 Mg/d	Combustion Temperature	1,350 °C
Number of Lines	2	Auxiliary Fuel Demand	4l/Mg waste
Availability (Technical Data)	280 d/a	Steam Temperature	300 °C
Operation 1 / 2	> 300 d/a	Steam Pressure	30 bar
Gasification Agent	air	Generator	1.3 MW
Gasification Temperature	550 - 600 °C	Efficiency	25 %

In standard operation, maintenance shut downs are scheduled about every three months. The longest shut down period published by the operator was 308 days long. Figure 3.43 shows the operating times for the two lines in Ishinomaki from December 2002 until June 2006. Beneath the throughput-graphic, the yellow resp. grey bar diagrams with interruptions show the shut down intervalls. These were usually scheduled but could also be unscheduled, for example because of an earthquake. In this case, the two lines in Ishinomaki were re-started within 24 respectively 72 hours.

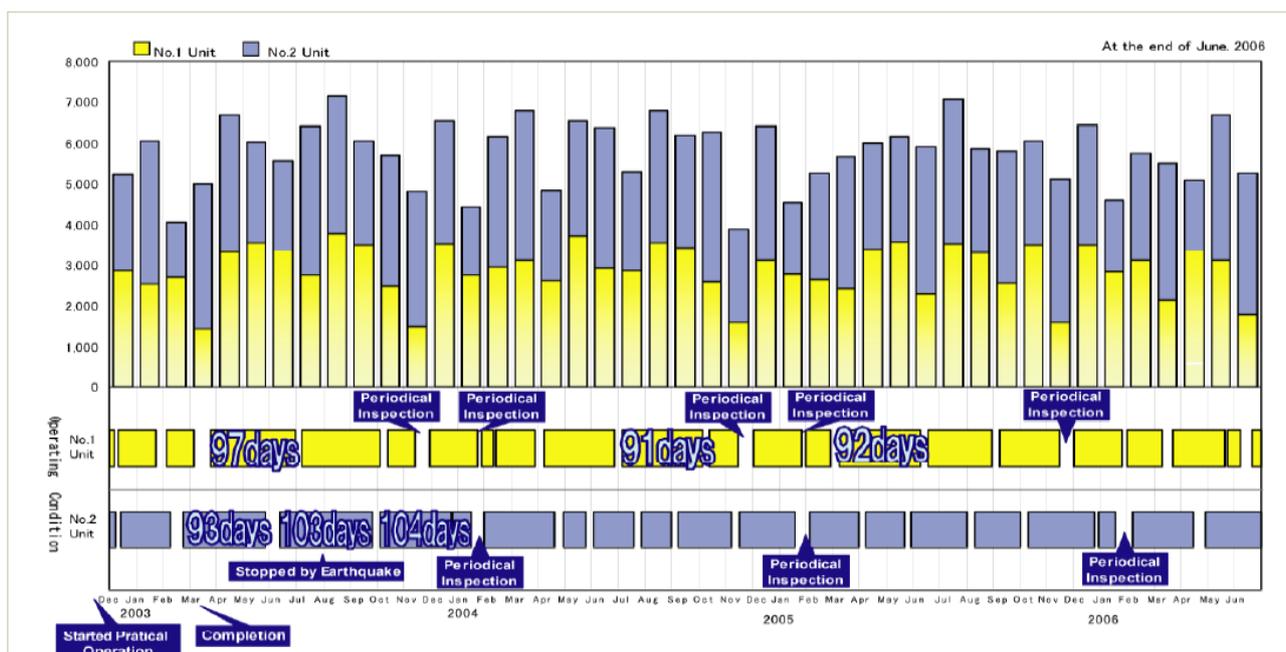


Figure 3.43: Operation and shut-down periods of the Kobelco plant in Ishinomaki (yellow: line 1; grey: line 2)

### Emissions and Residue Materials

The customary dry flue gas cleaning meets the rather moderate Japanese authorized limits. European limits could be met as well with adjusted operation mode.

Residues from gasification in the fluidized bed reactor are not molten. They pass a magnet separator and an eddy current separator. Recovered metals, iron and especially aluminum, are sold. Inert materials generated in the combustion chamber can be used in the construction sector. Prices around 150 ¥/Mg ( $\approx 1,10$  €/Mg) are achieved in Japan when the material can be used as aggregate in asphalt products. Residue materials from flue gas cleaning are disposed of.

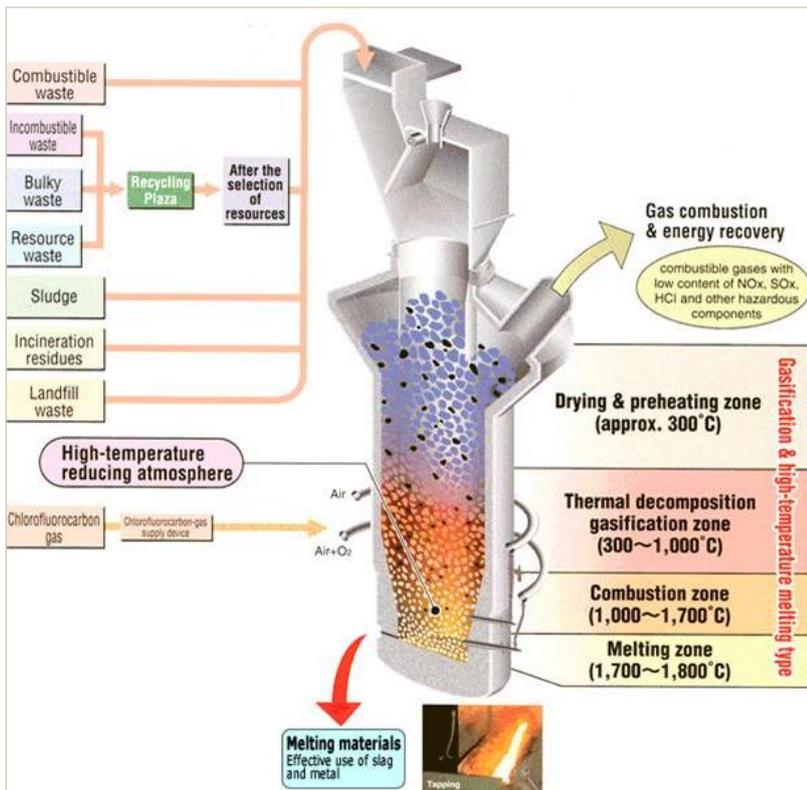
### Costs and Development Status

Overall costs for waste treatment in this process are not at hand. Operating costs for the Ishinomaki plant have been published for the timespan of April to October 2005. An average value of 1,200 ¥/Mg ( $\approx 8,50$  €/Mg) is given. However, this information only refers to operating materials (auxiliary fuel, additives for flue gas cleaning, water, electricity) and disposal of flue ash. Neither labor and maintenance costs nor write-off or investment costs are considered.

Until 2013, 14 plants with an overall capacity of 2,589 Mg/d have been constructed in Japan and South Korea by a licensee. With operating times of up to 13 years and stable operation, the process has proved its long-term stability.

#### 3.2.2.5 Nippon Steel Direct Melting Systems (DMS)

Based on the shaft furnace technology used in smelting, Nippon Steel & Sumikin Co. in Fukuoka started to develop a combined stationary gasification of coal and municipal waste at the beginning of the 1970s. Nowadays, the developed MSW Direct Melting System DMS is widely spread in Japan. The first plant started operation in 1979 with a capacity of 2x50 Mg/d.



### Technology

Process principle is the combined fixed bed gasification of municipal solid waste or other combustible and non-combustible (e.g. ashes) waste and coke in a shaft furnace. Coke percentage ranges from 5 to 10%. Untreated waste (maximum edge length of 800 mm) is loaded from above to the shaft furnace together with coke and the fluxing compound limestone used for internal desulfurization. The adjacent figure shows temperature and reaction zones in the reactor.

Combustion of the waste-coke-mixture in the lower part of the furnace supplies the required energy for gasification. Temperatures at the base of the furnace rise up to 1,800 C, causing melting of the mineral fraction of the waste. Combustion temperatures above the melting zone are 1,000

to 1,700 °C. Further up the material bed, gasification takes place at temperatures between 300 and 1,000 °C. In the upper area of the furnace, the waste is dried.

Figure 3.44: Shaft furnace of the Nippon Steel DMS process with display of reaction zones

Air is enriched to an oxygen content of 36 % and used as gasification agent. Syngas is drawn off at the head of the furnace, molten residue materials discharged at the bottom.

The process diagram of a complete DMS facility as operated e.g. in Munakata Eco Park in Kyushu is displayed below.

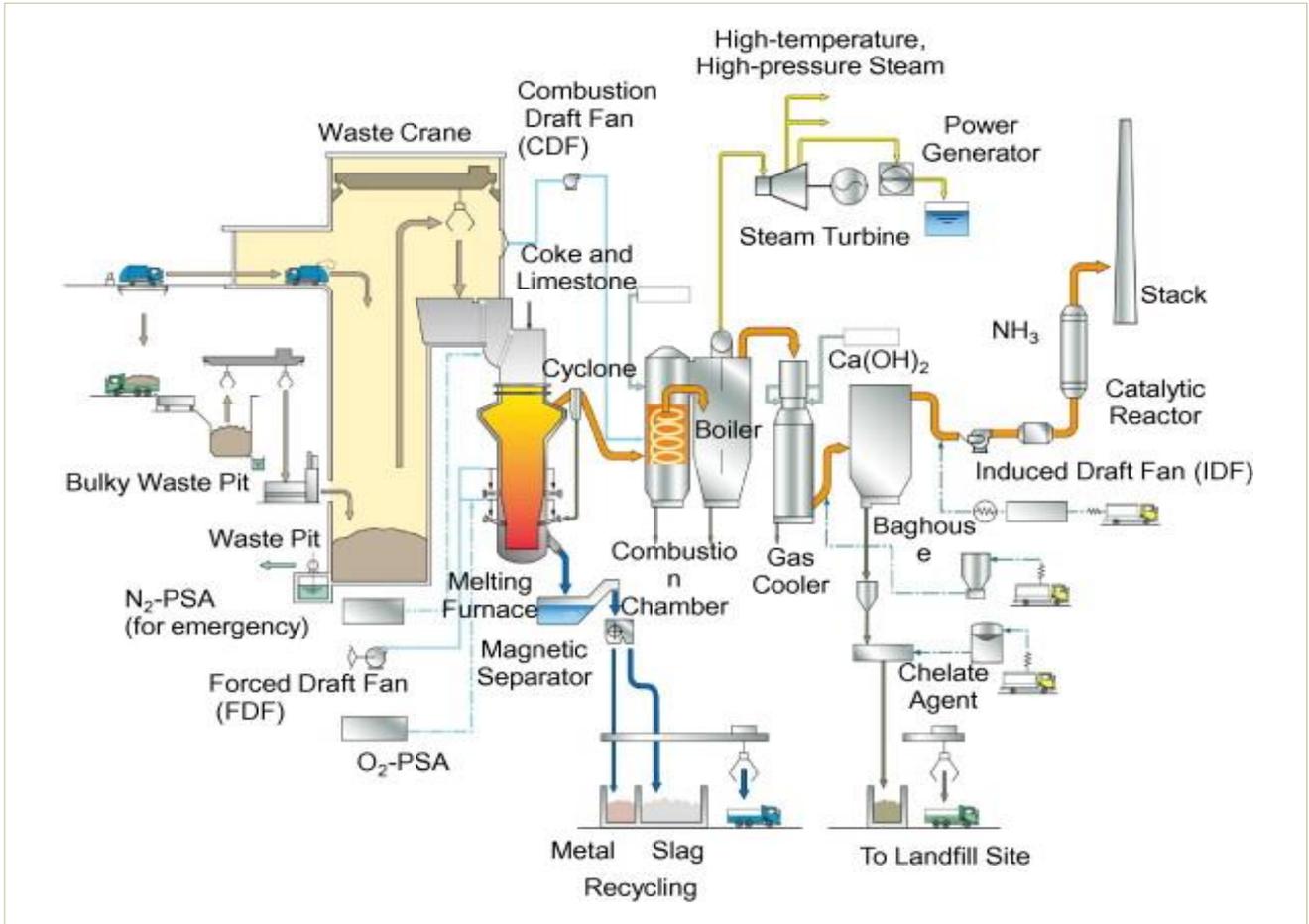


Figure 3.45: Process schema Nippon Steel DMS process.

As demonstrated in the diagram, syngas passes a cyclone for dedusting and is then combusted in a swirl combustion chamber at 940 °C. Downstream the combustion chamber, a waste heat recovery boiler and a calcium-based semi-dry flue gas cleaning unit with an SCR-facility for catalytic denitrification are installed.

## Operating Parameters

Operating parameters for DMS processes are exemplified with data from the facility in Mukata Eco Park.

Table 3.21: Operating parameters Nippon Steel DMS facility in Mukata Eco Park, Kyushu

Parameter	Value	Parameter	Value
Capacity	44,000 Mg/a	Waste Humidity	50-55 %
Number of Lines	2	Residence Time	4 h
Capacity per Line	80 Mg/d	Gasification Temperature	300 – 1,000 °C
Throughput Coke	61 kg/Mg waste	O <sub>2</sub> -Enrichment	36 Vol.-%
Throughput Waste 2008	32,177 Mg	Combustion Temperature	≈ 940 °C
Throughput Coke2008	1,954 Mg	Steam Pressure	40 bar
Operating Time (Design Data)	240 d/a	Steam Temperature	400 °C
Operating Time Line 1, 2008	183 d	Generator	2.4 MW
Operating Time Line 2, 2008	202 d	Typical Electricity Generation	1.2 MW
Parallel Operation of Lines	28 d	Export to Grid 2008	722 MWh

## Emissions and Residue Materials

Gaseous emissions identified for 2009 in the Mukata plant are demonstrated in table 3.22. The table also includes authorized limit values. It is obvious that only European emission limits for HCl would have been exceeded. This could be optimized by increased addition of reacting agents.

Table 3.22: Emissions Nippon Steel DMS facility in Mukata Eco Park, Kyushu.

Parameter	Unit	Authorized Limit Value	Measured Value 11/2009
Dust	mg/m <sup>3</sup> <sub>N</sub>	10	< 1
CO	ppm	30	< 1
HCl	ppm	50	18
SO <sub>2</sub>	ppm	50	2
NO <sub>x</sub>	ppm	50	19
PCDD/F	ng [I-TE]/m <sup>3</sup> <sub>N</sub>	0.1	0.000046

Molten slag is first quenched and the crushed. Metal scrap is recovered with a magnetic separator. The mineral fraction is used in road construction.

Residue materials from flue gas cleaning are stabilized using a chelator and then disposed of in a special landfill. In Mukata, these materials are stored in big packs in large halls.

## Costs and Development Status

Operating costs for the installation in Mukata Eco Park for 2009 are given as circa 160 €/Mg waste. Information on included cost types is not available.

The first commercial plant with a capacity of 2 x 50 Mg/d started operation in 1979 in Kamaishi. The second installation with 3 x 150 Mg/d was started up in Ibaraki in 1980. Until 2009, 28 DMS plants with 57 lines and an overall capacity of 6,200 Mg/d were installed in Japan. The facilities seem to have a high availability. Comparably short operating times in Mukata were determined by the availability of waste. [IEA 2009, Tanagaki 2012]

### 3.2.3 Gasification for Syngas Production

#### 3.2.3.1 Ebara UBE Process (EUP)

Together with Ube Industries Ltd. and based on the TwinRec process, the Ebara Corporation developed a process for a two-staged pressure gasification of plastic waste from the packaging sector. Gasification is operated at 10 bar pressure. Synthesis gas is not burned to melt fly ash like in the Ebara TwinRec process but purified and can either go into energetic or material utilization. A demonstration plant with 30 Mg/d was commissioned in 2000.

#### Technology

Figure 3.46 shows a schema of the Ebara-UBE plant. The first gasifier is a circulating fluidized bed which is operated at 600-800 °C under a pressure of 10 bar. The gasification agent is a mixture of oxygen and water. Gas from the first stage flows into a second high-temperature gasification chamber which is operated at temperatures of 1,300 to 1,500 °C.

Product gas is purified and, in the case displayed below, it is transferred to an ammonium synthesis.

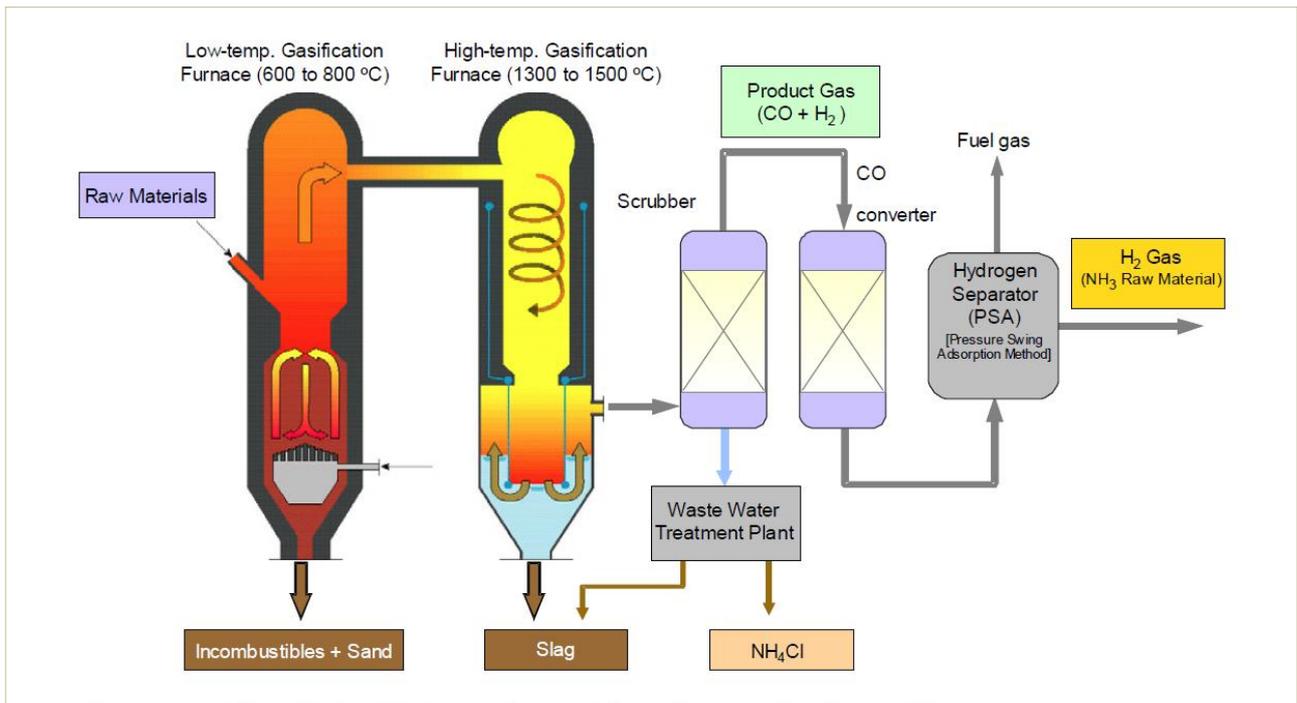


Figure 3.46: Process diagram of the Ebara UBE-process

#### Operating Parameters

An EUP plant treating 30 Mg/h of plastic waste with a net calorific value of 27-37 MJ/kg generates an amount of 3,350 m<sup>3</sup>/h synthesis gas consisting of 40-45 vol.-% H<sub>2</sub> and 25-30 vol.-% CO. After conversion of CO, 2,000 to 2,200 m<sup>3</sup>/h H<sub>2</sub> with a purity of 99.99 vol.-% are obtained.

#### Costs and Development Status

A second plant with a capacity of 65 Mg/d was installed in 2002 at the same site as the demonstration plant, followed by a two-line plant with a capacity of 98 Mg/d in each line.

Data on further operating parameters as well as costs were not found in literature. [Steiner 2002, Ebara 1999]

### 3.2.3.2 Kopf Gasification

The Kopf process is a fluidized bed process tailored for the gasification of sewage sludge. The energy content of the product gas is to be converted into heat and power in a combined heat and power plant (CHP). In 2011, a pilot plant with a capacity of 1,200 Mg/a located at the town of Balingen, Germany, was commissioned. Capacity was extended to 2,200 Mg/a in 2011. An industrial size plant of 5,000 Mg/a was supposed to start operation in Mannheim in 2010 [Delavelle 2012]. At the moment, it seems that this facility has not yet reached standard operating mode.



Figure 3.47: Sewage sludge gasification plant in Balingen

#### Technology

The process principle of this process is displayed in figure 3.48. Input material is sewage sludge with a dry matter content of 85 to 96 %. Feedstock is initially delivered to a gas cooler. Here, hot product gas is cooled by quenching with water and is drawn through the sewage sludge bed. The intention is to remove tars from the product gas and deposit them in the sewage sludge, this way returning tars to the gasifier. The sewage sludge is then fed to the stationary fluidized bed reactor. Preheated air is used as gasification agent. The gasifier is operated autothermally at

temperatures just below 900 °C. Product gas flows to a recuperative heat exchanger used to preheat gasification air. After quenching as described above and gas cleaning (dedusting and condensate separation) the product gas is utilized in the CHP unit.

#### Operating Parameters

The reactor is operated at 850 to 880 °C. A residence time of circa 30 minutes is supposed to ensure complete disintegration of organic compounds. The product gas is made up of 6-10 % H<sub>2</sub>, 6-10 % CO and 3-5 % CH<sub>4</sub>. The facility has a performance of 140 kW<sub>th</sub> and 70 kW<sub>el</sub>. [Delavelle 2012].

#### Costs

For a plant with a capacity of 667 kg<sub>DM</sub>/h (5,000 Mg/a, 7,500 hours in operation), the operator calculated investment costs of 6.8 million € for technical equipment and construction. Treatment costs are not specified.

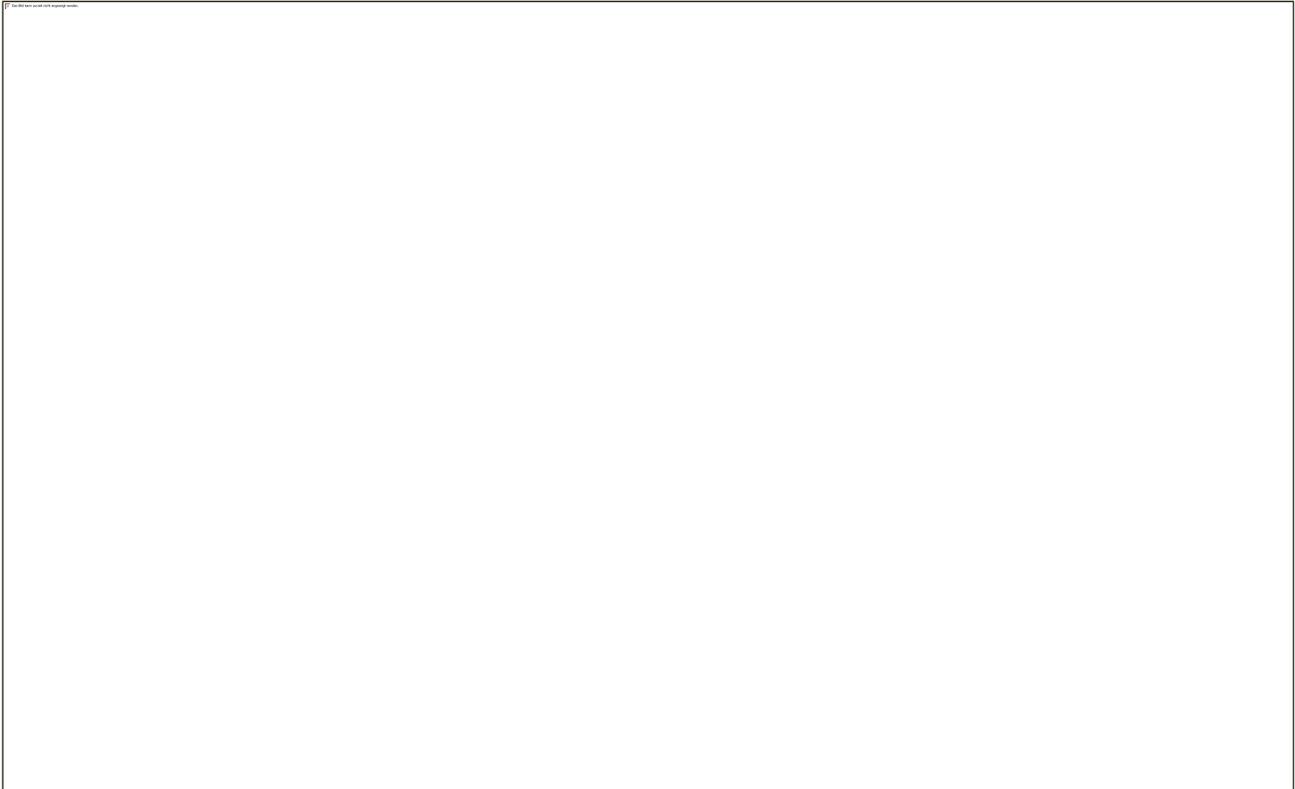


Figure 3.48: Kopf process: Process diagram for gasification of sewage sludge [Kopf 2014].

### 3.2.3.3 Noell Conversion Process

The Noell conversion process was developed for heterogeneous waste materials. It is made up of two stages of thermal treatment: pyrolysis in an indirectly heated rotary drum followed by an entrained-flow gasifier. Waste is pre-treated thermally in the pyrolysis stage and converted to syngas in the gasifier. Mineral components are molten and hereby rendered inert.

#### Technology

Figure 3.49 illustrates the process principle. With its modular design, the process was supposed to be applied with increased flexibility concerning feedstock and site conditions. Figure 3.50 shows the pyrolysis stage of the process.

Waste passes through the inclined drum and is degassed meanwhile. Residue from pyrolysis is drawn off with a wet deslagger. Sealings ensure that even large pressure fluctuations do not cause inflow of oxygen or outbreak of pyrolysis gas.

The rotary drum is heated with several burners which also divide the reactor into several controllable burner zones adjustable to process requirements.

Volatile compounds are drawn off the reactor as pyrolysis gas with a temperature of up to 650 °C. The gas is quenched in two water spray coolers to separate condensables. Division of the pyrolysis oil/water emulsion is achieved in two static decanters. Waste water is cooled down and then returned to the sprayer. After separation of condensable hydrocarbons, the cooled pyrolysis gas passes a pressure intensifier and is then led to the entrained-flow gasifier.

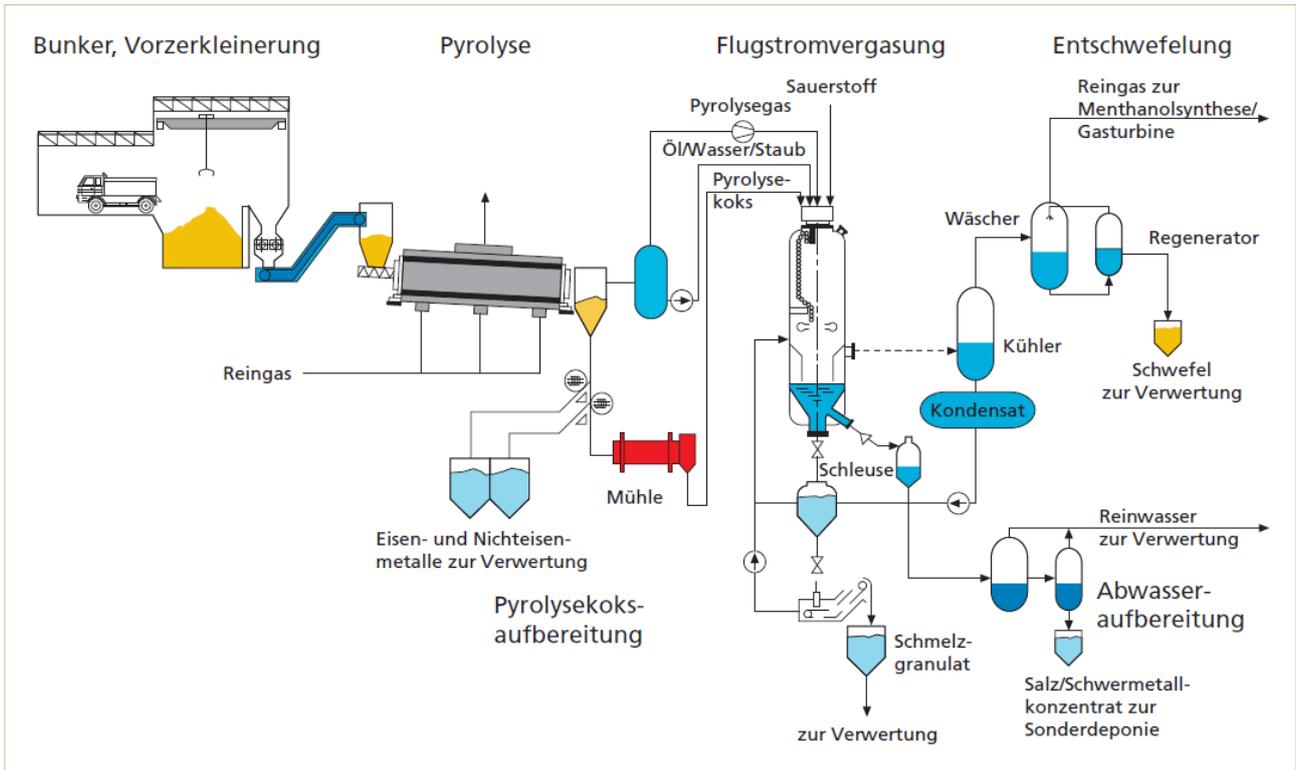


Figure 3.49 Process diagram Noell Conversion Process [Thomé 1994]

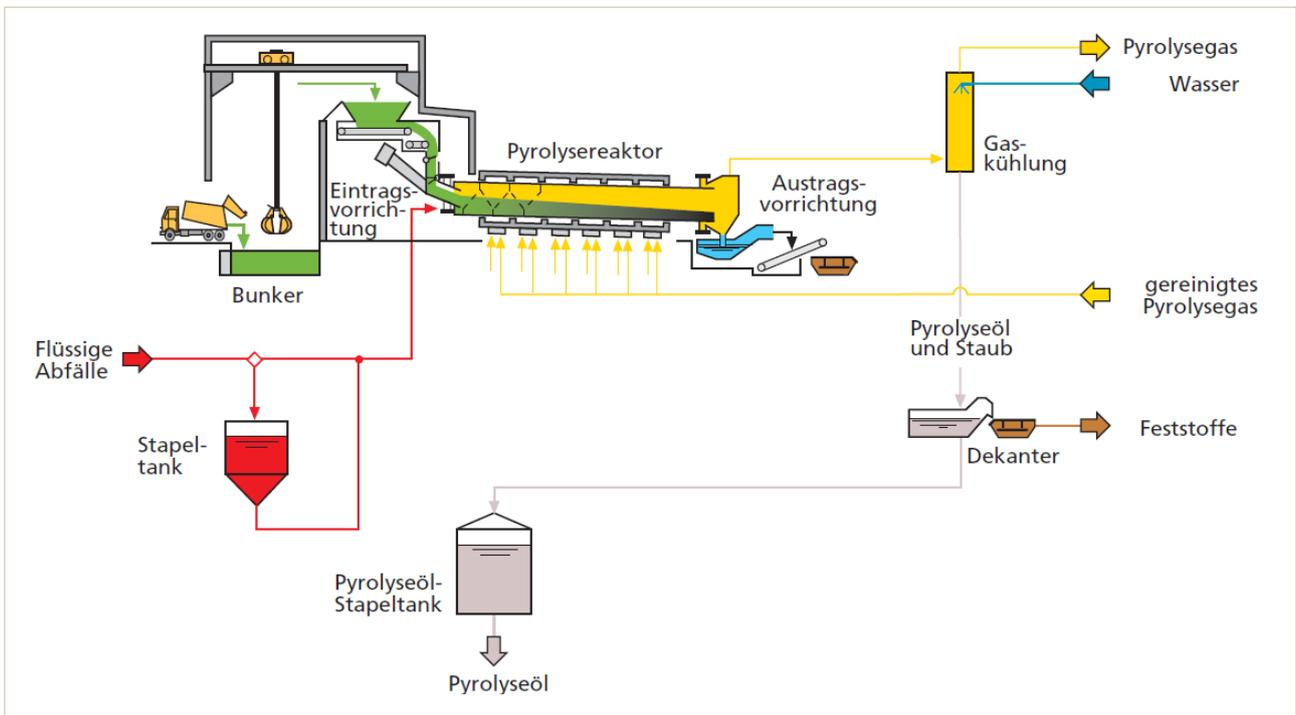


Figure 3.50: Noell conversion process - pyrolysis stage [Thomé 1994,changed].

Pyrolysis coke from the reactor is cooled and then conditioned by mechanical separation processes. Iron- and non-ferrous scrap are separated and transferred to recycling facilities.

The technology of the gasification stage was developed based on the GSP-process for gasification of dusty fuels [Schingnitz 1993]. The principle of this process is illustrated in figure 3.51.



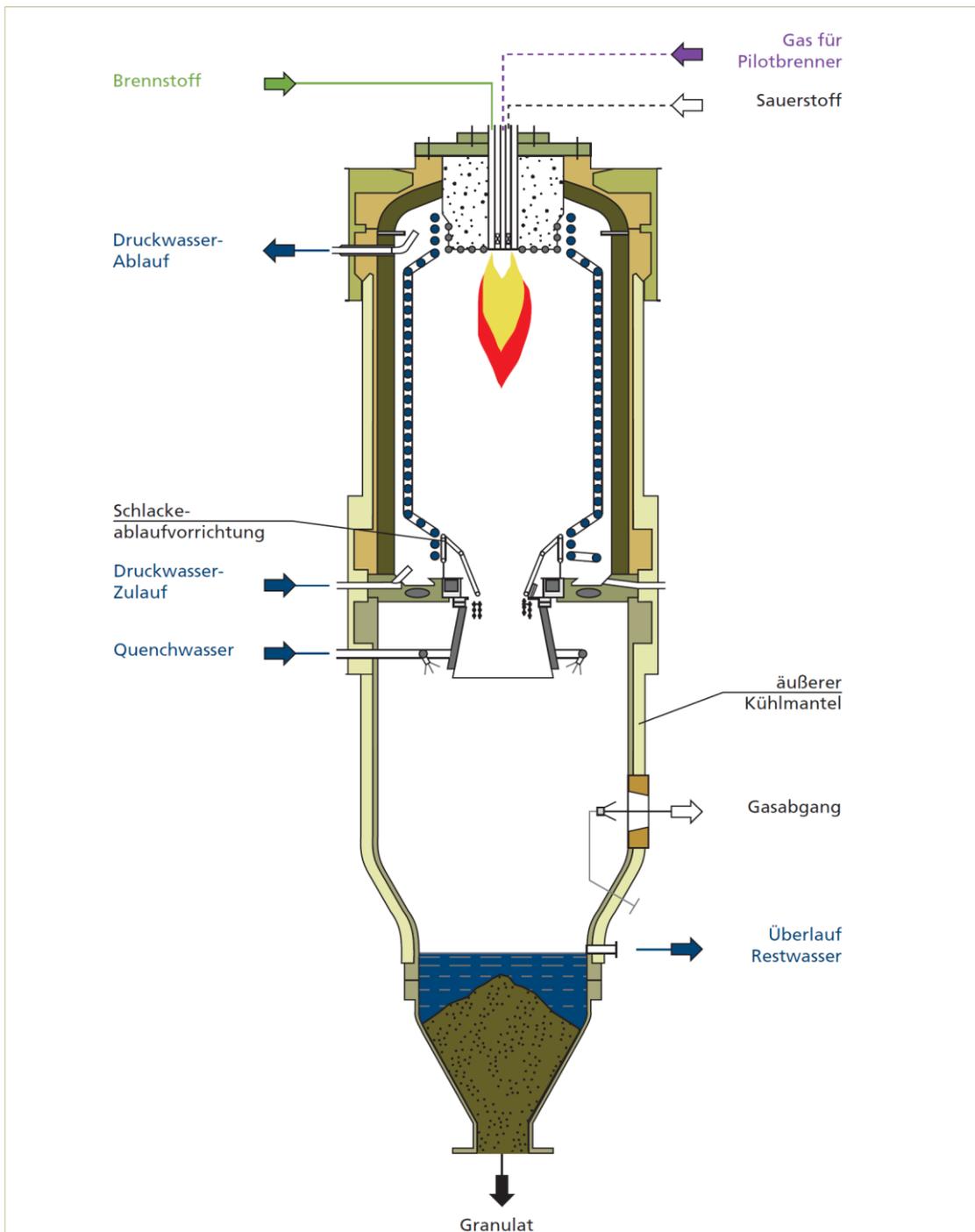


Figure 3.52: Schematic diagram of an entrained-flow gasifier [Schingnitz 1994].

To promote the reaction of organic substances with oxygen, the mass flow ratio of oxygen and input material is adjusted to obtain a reducing gas rich of CO and H<sub>2</sub> but free of hydrocarbons at temperatures of 1,400 to 1,700 °C. In this temperature range, mineral components are molten. Generated slag flows downwards along the reactor walls lined with fireproof ramming mass and protected by a thin layer of solidified slag.

Hot gas and liquid slag are drawn off together through a central opening at the bottom. In a cooling zone beneath the reactor, gas and slag are brought in contact with water. The slag solidifies and crumbles away to a granulate of vitric structure which is discharged through a lock and with a scraping conveyor.

Depending on system pressure, the gas is cooled down to 150 to 200 °C and saturated with steam. The saturated gas which is pre-cleaned by contact with water is cooled further, generating low pressure steam. Sulfur contained in the fuel is converted to hydrogen sulfide, which is separated from the gas and processed to elementary sulfur.

Waste water derived from the cooling zone contains a major part of contaminants of the hot gas like alkali chlorides, ammonia and traces of H<sub>2</sub>S and heavy metals. Waste water is either treated externally after removal of dissolved gases and solid particles or it is boiled down. Condensate from the different stages of gas cooling is returned to the cooling zone for hot gas and slag.

### Operating Parameters

Basic technical data and operating parameters of the Noell conversion process are listed in table 3.23.

Table 3.23: Technical data and operating parameters Noell conversion process

Parameter	Value	Parameter	Value
Pyrolysis		Entrained-Flow Gasification	
Capacity	6 Mg/h (Salzgitter)	Capacity	30 Mg/h (Schwarze Pumpe)
Temperature	up to 650 °C	Temperature	1,400 - 1,700 °C
Residence Time	≈ 2 h	Pressure	2 - 25 bar
		Reacting Agent	oxygen

The raw gas generated by gasification can be conditioned to be used as synthesis gases or for energetic utilization. Similar to gasification of coal, small amounts of COS, NH<sub>3</sub> and HCN occur which must be removed. The clean gas is supposed to be used as synthesis gas for methanol production. Yet, this requires installation of an additional process step for catalytic conversion of CO to H<sub>2</sub> with steam plus - if necessary - a further step for complete removal of CO<sub>2</sub>.

Clean gas can also be used in a gas motor or -turbine or to heat drying devices. Furthermore, the clean gas could be fed to the city gas grid after conditioning with natural gas and nitrogen to adjust combustibility. Excess heat is used for district heating. Alternatively, production of low pressure steam for industrial purposes is possible.

### Emissions and Residue Materials

Products of the gasification process are vitrified granulated slag, process water which mainly contains soluble salts and solids filtered from process water which contain superfine dust and heavy metal sulfides.

Analysis of process input and products show a high degree of destruction of organic substances. Values measured in process waste water and gasification gas are below authorized limits.

The behavior of heavy metals depends on their vapor pressure during high temperature gasification. Semi-volatile heavy metals are mainly fixed in the slag, whereas heavy metals with higher volatility (except for arsenic) are hardly fixed in the slag, mercury is not fixed at all. The latter are mainly precipitated as sulfides from process water and separated as solids. About 92 % of the phosphorus input are transferred to the granulate. Part of the alkali metals sodium and potassium are bound in the slag by relatively high amounts of SiO<sub>2</sub>. Chloride and Fluoride are completely transferred to the process water.

The leaching behavior is essential for recycling of slag granulate. Since elution values are lower than limits for category I landfills, the granulate can be used as construction material for landfills.

## Development Status

Development of the two main process stages pyrolysis and entrained-flow gasification started simultaneously in the middle of the 1970s. In 1984, an industrial size pyrolysis plant with a capacity of 6 Mg/h in Salzgitter/Lower Saxony as well as a gasification plant with a capacity of 30 Mg/h in Schwarze Pumpe (German Democratic Republic) were put into operation.

The pyrolysis facility in Salzgitter shut down temporarily as scheduled after a four year period of test and pilot operation. The entrained-flow gasifier in Schwarze Pumpe was operated to generate city gas in the German Democratic Republic. Planning content was granted to the pyrolysis in Salzgitter. The site was retrofitted and started operation in 1995 as the first facility for thermal treatment of hazardous waste in Lower Saxony.

### 3.2.3.4 SVZ Fixed Bed Gasifier

Fixed bed pressure gasifiers - shaft gasifiers equipped with a rotary grate - proved themselves at the industrial site Schwarze Pumpe in the former German Democratic Republic. They were used to gasify lignite for the supply of city gas in the former GDR.

After dismissing city gas production, the fixed bed pressure reactors were retrofitted to treat different waste mixtures with added coal. Waste types treated in Schwarze Pumpe included pelletized refuse derived fuels from processed household waste and commercial waste similar to household waste, compacted mixtures of plastic waste, woodchips, sewage sludge briquettes, tar sludge pellets and shredder light fraction (see figure 3.53). Facilities were shut down in 2007 and have been dismantled.



Figure 3.53: Input materials of the fixed bed pressure gasifier in Schwarze Pumpe  
left: refuse pellets; 2nd from left: paint sludge pellets (produced with Herhof Dry Stabilat process),  
2nd from right: plastic briquettes, right: briquettes of shredder light fraction; [own pictures (taken 2003)]

## Technology

Three reactor types had operating permits in Schwarze Pumpe:

- Fixed bed pressure gasifier (presented in this chapter)
- Entrained-flow gasifier (see chapter 3.2.3.5)
- British-Gas-Lurgi (BGL-) gasifier (described in chapter 3.2.3.6)

Fixed bed and BGL gasifier were intended to treat solid input materials while the entrained-flow gasifier was to be operated with liquid waste. The following picture (figure 3.54) gives an overview of the whole SVZ-site in 2003.

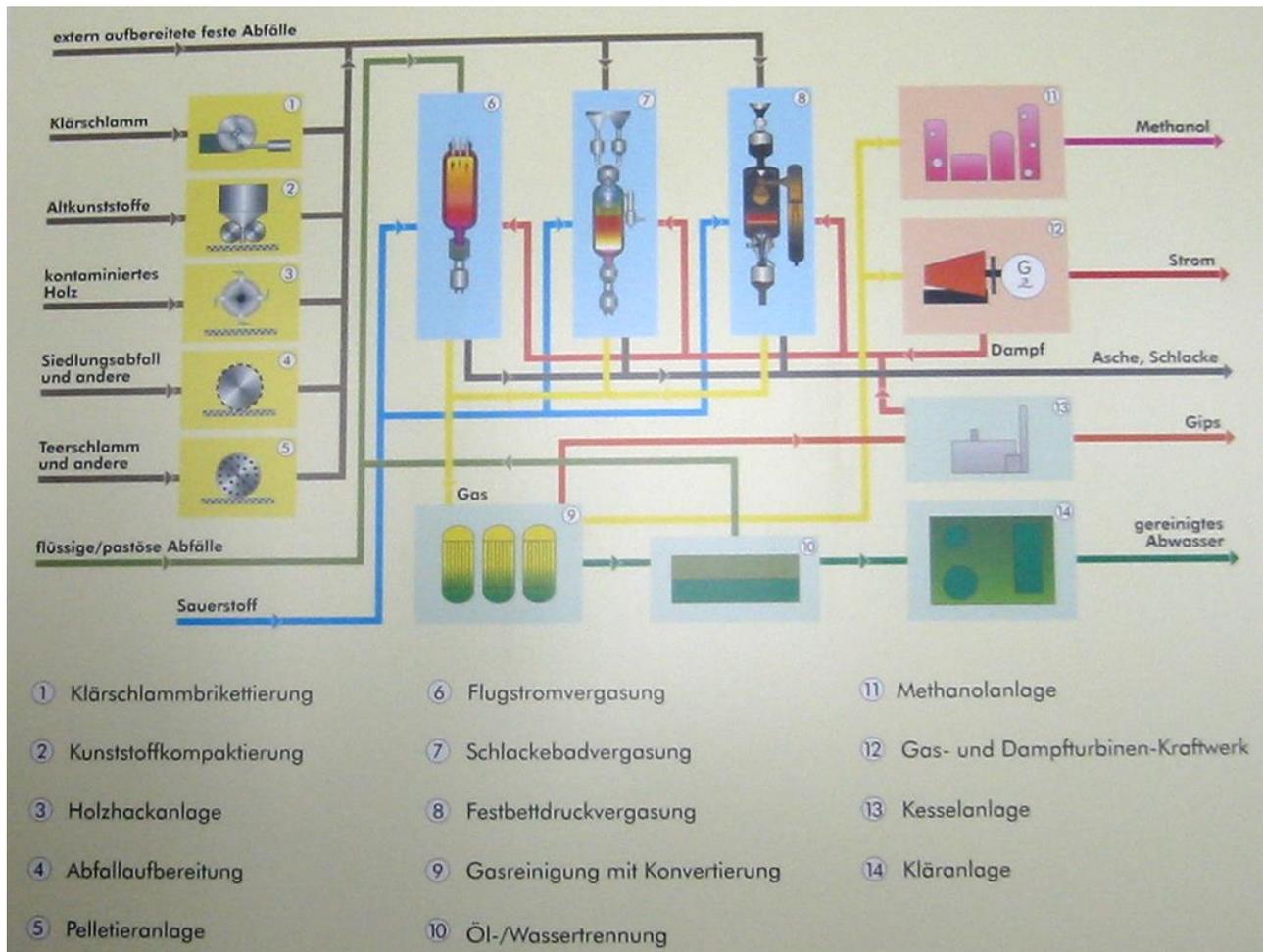


Figure 3.54: Plant overview of gasification and secondary installations at SVZ Schwarze Pumpe (picture taken of display board on site in 2003)

Household waste and commercial waste similar to household waste were subject to complex pre-treatment and conditioning in several stages to produce a loose refuse derived fuel with high calorific value. Waste was shredded, dried to a water content of circa 10 %, classified and finally sorted to eliminate disturbing substances as well as ferrous and non-ferrous scrap and inert materials (see figure 3.35). Before being fed to the fixed bed reactors, this mixture was pelletized, cooled and the fine fraction removed. Combustible small pieces of heavy matter were fed to the gasifier without prior pelletizing.

In the compacting unit, mixed plastic was shredded, iron scrap removed and then pressed in extruders. Waste wood like sleepers, wood poles, beams, demolition wood and others were chopped to woodchips. Dry sewage sludge was delivered to the briquetting plant and briquettes were produced under addition of dry lignite and/or water. Alternatively, sewage sludge could be pelletized together with tar sludge. This took place at the installation for tar sludge pelletization under addition of coal and/or animal meal.

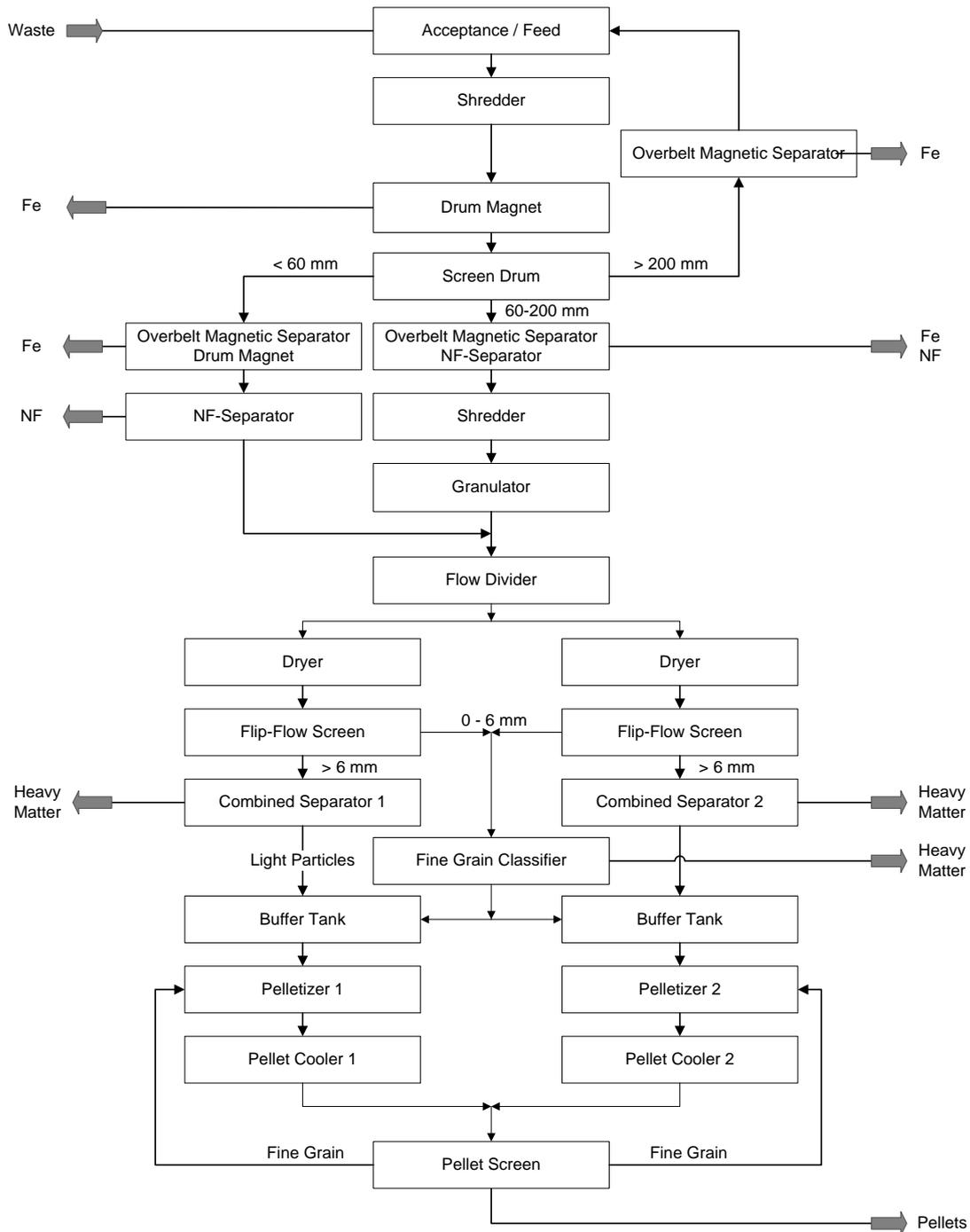


Figure 3.55: Conditioning of household waste and commercial waste similar to household waste at SVZ [adapted from Obermeier 2001; translated].

Gasification of solid waste materials and lignite/hard coal in variable mixing ratios was only allowed in four of the seven existing fixed bed gasifiers at a time or in the BGL gasifier and two entrained flow gasifiers with a maximum share of 85 % waste in the feedstock.

The fixed bed pressure gasifier had an available capacity of 12.5 Mg/h each with an annual maximum capacity of 444,000 Mg of solid waste and lignite/hard coal in various mixing ratios (see figure 3.56).



Figure 3.56: Fixed bed pressure gasification unit with surroundings at Schwarze Pumpe. Gasifiers were located in the building with the blue roof [own picture, taken 2003]

A mixture of lignite briquettes and/or hard coal was gasified in the fixed bed reactors (3.6 m diameter) together with pre-treated waste materials. Steam and oxygen were used as gasification agents, they were mixed using the injector principle and injected through the rotary grate with a pressure of 27 bar. Reactors were operated at about 75 % of the available filling height. This was achieved by systematic interruptions of the fuel feed to achieve better flow through the combustion bed. A slurry product containing up to 30 % solids and consisting of water and hydrocarbons was added to the solid gasification good from the upper part of the reactor. Normally, the slurry input amounted to a maximum share of under 20 % of the feedstock. Gasification temperatures in the oxidizing zone of the reactor were between 1,200 and 1,300 °C and dropped to around 450 °C at the raw gas discharge because of heat loss and reduction processes.

Ash was removed by a rotary grate, an ash lock, a drop shaft and a scraping conveyor.

Raw gas from the fixed bed pressure gasifiers was cooled and condensed in four parallel condensation lines (see figure 3.58).

In a scrubber, the gas was washed and cooled down with water.

Furthermore, waste steam recovery units were installed in each line, consisting of two parallel heat exchangers, four coolers connected in series and a mist collector. Condensation products - tar oil and middle oil phenolic water - were discharged for tar separation. Cooled raw gas was transferred to gas cleaning through pipes.

For gasification itself and utilization of the generated gas, a wide range of peripheral equipment was necessary, which is listed below but will not be explained in detail. Peripheral devices included:

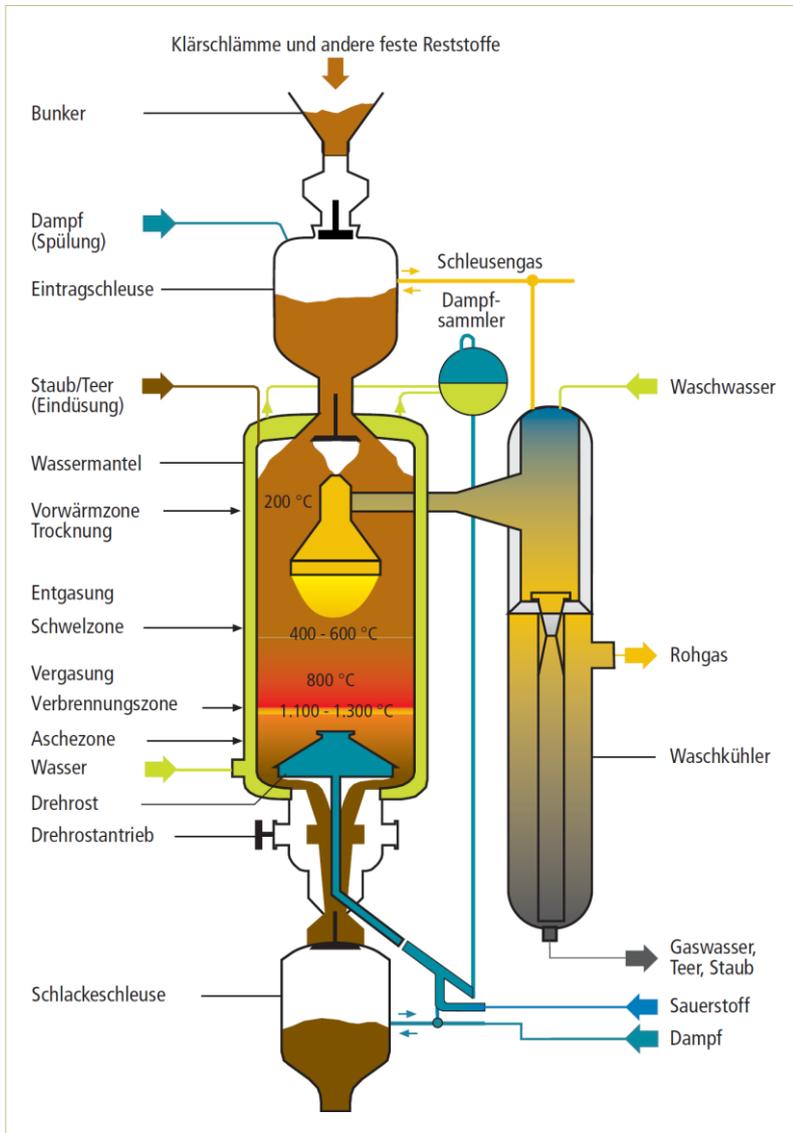


Figure 3.57: Fixed bed reactor with rotary grate for gasification of solids and tar at SVZ Schwarze Pumpe [Thomé 1998, modified].

- Production of oxygen in the air separation installation
- Partial conversion of CO in the raw syngas  
In the conversion facility, a partial flow of raw gas was treated: carbon monoxide was converted to CO<sub>2</sub> and H<sub>2</sub> using steam in order to achieve the optimum ratio of CO<sub>2</sub>/CO/H<sub>2</sub> for synthesis of methanol.
- Gas cleaning  
Raw synthesis gases were cleaned using the RECTISOL process.
- Methanol plant  
In this unit, conditioned syngas ran through a fine cleaning process to remove remaining impurities and catalyst poisons and was then compressed. Raw methanol generated in methanol synthesis was distilled to produce high purity methanol.
- Gas and steam turbine power plant with boiler system and desulfurization  
Decompression gas from gas cleaning was combusted in the boiler system, purge gas from methanol synthesis was combusted in the gas and steam turbine power plant

Methanol produced at Schwarze Pumpe was sold, for example to a refinery in Schwedt or to the furniture industry in nearby Poland.

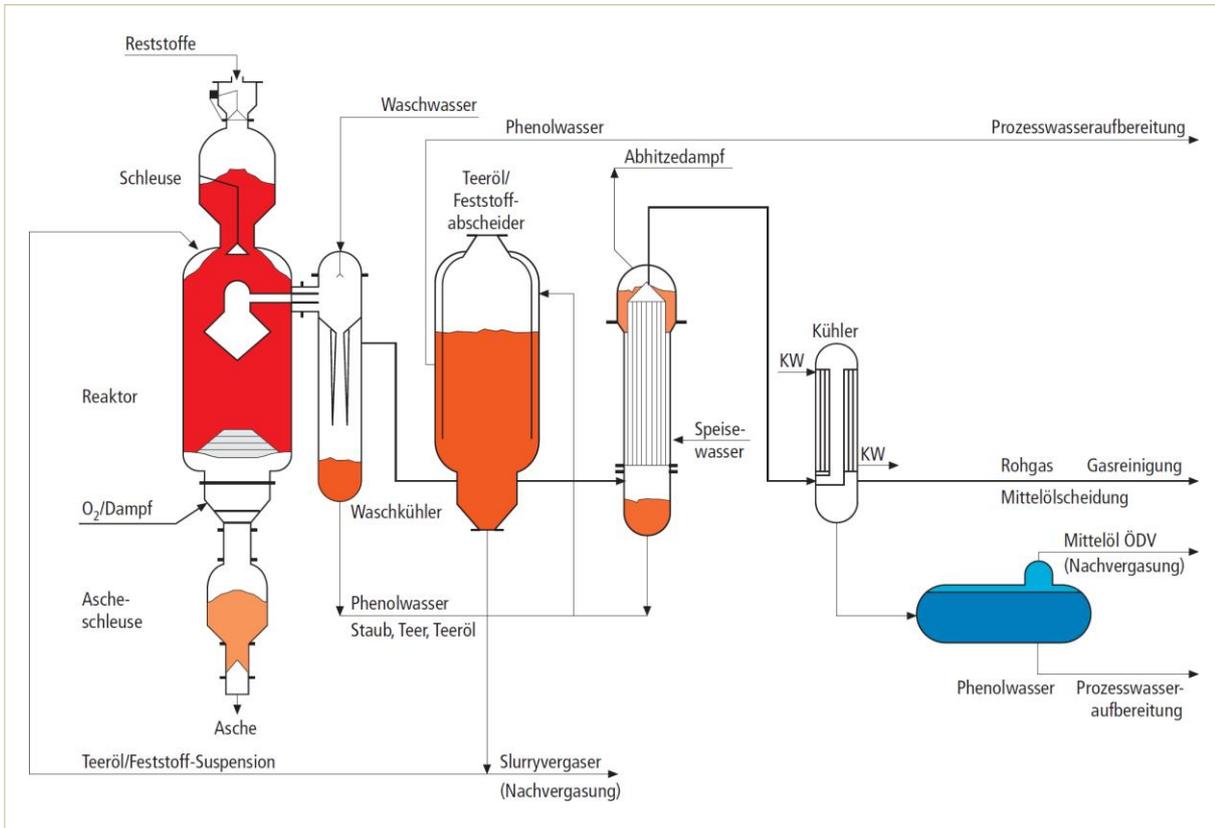


Figure 3.58: Process diagram of fixed bed gasification at SVZ Schwarze Pumpe [Thomé 1994].



Figure 3.59: SVZ Schwarze Pumpe with gas and steam turbine power station (middle) and methanol plant (right) [SVZ 2003, from Thomé 1998].

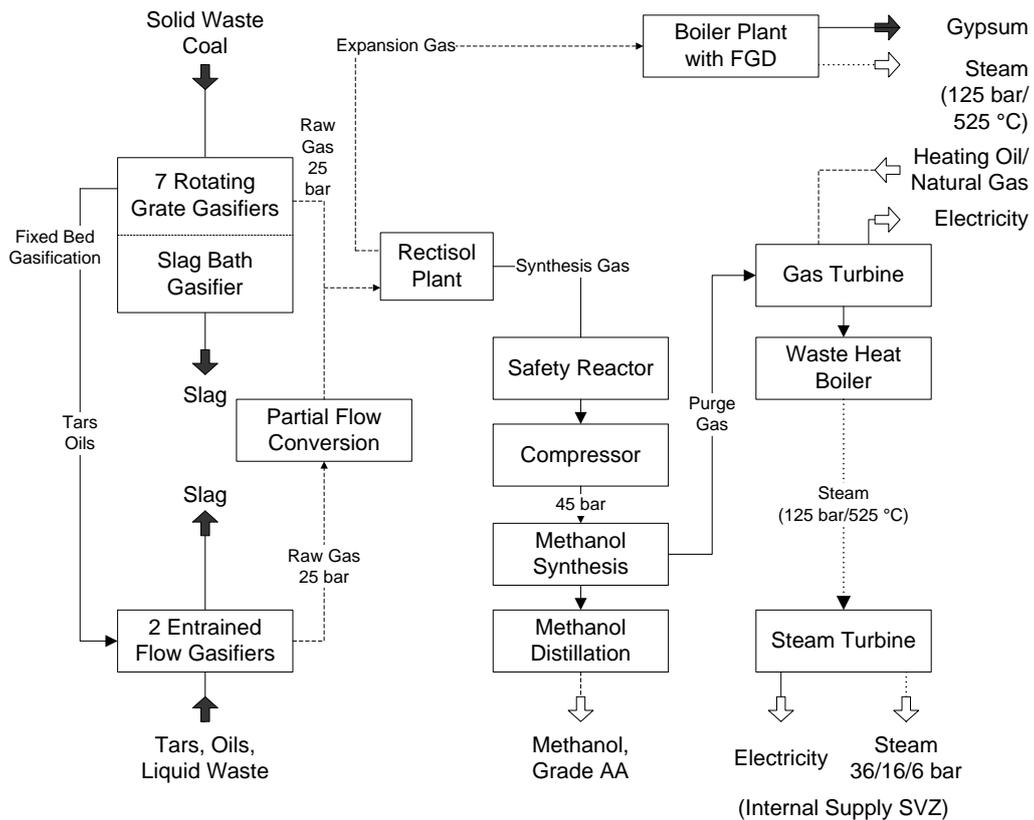


Figure 3.60: Gasification and gas utilization at SVZ Schwarze Pumpe [Seifert 2001; translated]

### Operating Parameters

The following table (3.24) gives essential technical data, operating parameters and requirements for refuse derived fuel to be gasified.

Table 3.24: Technical data, operating parameters and RDF requirement for fixed bad pressure gasification at SVZ Schwarze Pumpe

Technical Data Installation	Wert	RDF Requirements	Wert
Available Capacity	12.5 Mg/h each	Texture	solid, fragmented
Height	9 m	Particle Size	min. 16 x 16 x 16 mm
Diameter	3.6 m		max. 80 x 80 x 120 mm
Utilization of Maximum Filling Height	≈ 75 %	Water Content	< 20 %
Temperature Oxidation Zone	1,200 – 1,300 °C	Ash Content	< 20 %
Temperature at Raw Gas Discharge	450 °C		

### Development Status

After the political turn in 1989, the plant was first owned by the Berliner Wasserbetriebe. In the middle of 1997, commercial operation started in the recycling chain of conditioning - gasification - methanol synthesis - power generation. After temporary ownership by several companies with little success, Sustec took over in October 2005. Due to many problems, the necessary permanent availability of the plant could not be achieved. The whole site could not be operated economically. Despite massive government aid, Sustec had to shut down the waste gasification in the middle of 2007. Sales could not prevent bankruptcy. The gasifiers have been dismantled.

### 3.2.3.5 SVZ Entrained-Flow Gasification

The former splitting plants 1 and 4 were used as entrained flow gasifiers for liquid and pasty wastes (see figure 3.62). Input materials for gasification ranged from light to heavy gasification oils, in addition, slurry products containing water or tar-oil-solid-mixtures could be injected with atomizer nozzles.

#### Technology

Prior to gasification, liquid waste was pre-treated in order to separate water and coarse solids, hereby producing oil which could be gasified.

Liquid intermediate products from installations on site generating and conditioning gas were conveyed to tanks and passed a filter before entering a raw product tank. Quality was adjusted with dewatering and desludging. Oil and water were separated by sedimentation in raw product tanks. Water sinking downwards was pumped into an intermediate tank or directly into the storage tank for the phenolic water treatment unit. Refloating oil was removed and conveyed to the middle oil station. Here, pre-dewatered raw oil was further dewatered in a one stage distillation under atmospheric pressure. Gasification oil accumulated in the sump and was then conveyed to the gasification oil tanks.

The light-oil/water phase from the head of the reactor was re-circulated to dewatering, the water subsequently discharged to the phenolic water treatment and refloating oil mixed with the gasification oil.

Gasification oil was a mixture of

- Water-free waste oil products which could be instantly used in the process and which were purchased on the market
- The oil phase separated from liquid wastes (oil/water mixtures)
- Middle oil from fixed bed pressure gasification

Within the splitting plant, a collecting and conditioning facility for sludge-like slurry products containing oil or water was operated. Sludges were delivered with tank trucks and passed a filter before entering a delivery tank where gasification oil and/or tar-oil-solid-product could be added. Sludges and added product were mixed with a stirring device.

The suspension out of the delivery tank was then pumped (volume-controlled) into the mixing tank. Once more, gasification oil or tar-oil-solid product could be added to produce a uniform feedstock. The different substances were mixed using a jetstream mixer. For disintegration of solids found in the suspension and to generate a homogeneous suspension, a wet crusher was located downstream the mixing tank.

The slurry product was pumped to the pressure increaser unit through a pressure controlled internal circulation and finally fed to the entrained-flow gasifier with an atomizer nozzle. For further maceration of solids, a gorator (wet crusher with inclined rotating disc) was installed upstream the booster pumps.

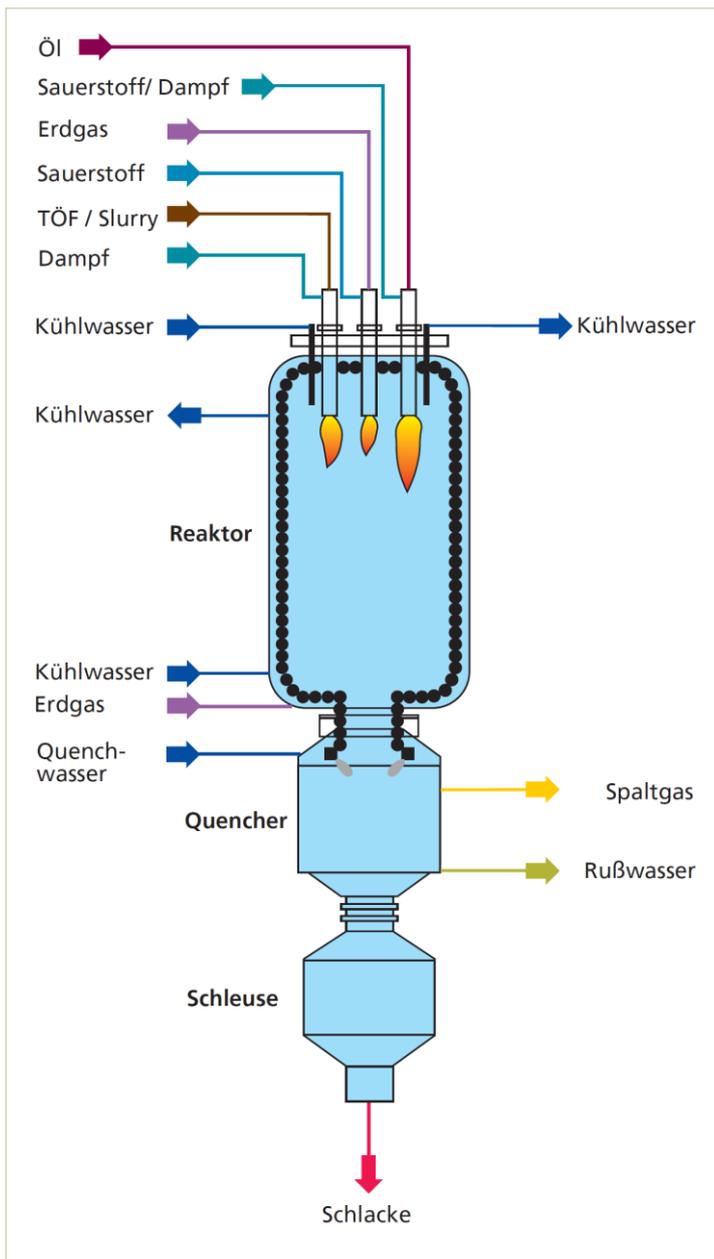


Figure 3.61: Fixed bed reactor with rotary grate to gasify solid materials and tar at SVZ Schwarze Pumpe [Thomé 1998, altered].

The two entrained-flow gasifiers (see figure on the left) had a capacity of 15 Mgs of liquid and pasty wastes per hour. In the splitting plants, oils and liquids containing hydrocarbons were gasified. In addition, slurries, tar sludges and tar-oil-solid-mixtures could be utilized. The composition of hydrocarbons in the input materials was irrelevant for the process, so oils of different origin could be used.

The gasification oil to be split was pumped to the oil burners through three pipes. The oxygen-steam-mixture serving as gasification agent flowed through a joint pipe which was then divided into three branches to feed the three burners. The burners were spread evenly over the circumference of the reactor. Inside the reactors, temperatures reached about 1,500 °C. One reactor was lined with refractory brick, the other equipped with a cooling screen. Splitting gas left the reactors in concurrent flow with slag and was lead through the quencher. Subsequently, the raw gas ran through different washing stages before being lead to the CO-partial-flow conversion (see figure 3.63). A granulated slag was left as gasification residue.

Residual water with fine particles and carbon black components was transferred to the treatment plant for soot water. The purified water could then be reused as quenching water in the splitting plant.



Figure 3.62: Entrained flow gasifier at Schwarze Pumpe. Top left: overview, top right: head of gasifier, bottom: burner - assembled and dismantled (own pictures, 2003)

The oil splitting process is split up into four stages:

- Partial oxidation of hydrocarbons
- Satiation and cooling of cracked gas in the quenching nozzle
- Gas scrubbing in the venturi scrubber
- Cooling and condensate deposition in heat exchangers

The gasification process and gas utilization required extensive peripheral installations like air fractionation to produce oxygen, conversion and cleaning of raw synthesis gas, methanol plant, gas and steam turbine plant and others (see chapter 3.2.3.4).

### Operating Parameters

Essential technical data and operating parameters of the entrained flow gasifiers as well as requirements for input materials are summarized in table 3.25.

Table 3.25: Technical data and operating parameters of entrained flow gasifiers at SVZ Schwarze Pumpe

Parameter	Value	Parameter	Value
Capacity	15 Mg/h each	Water Content	≤ 1.0 wt.-% in main oil flow
Temperature	ca. 1,500 °C	Solid Content	≤ 10.0 wt.-% in main oil flow
Reacting Agent	oxygen, steam		

### Costs and Development Status

Already in the former GDR, city gas was generated at the Schwarze Pumpe site using entrained flow gasifiers to utilize liquid and paste-like waste materials. The “Secondary Resource Utilization Center” SVZ Schwarze Pumpe could not be operated economically after the German reunification.

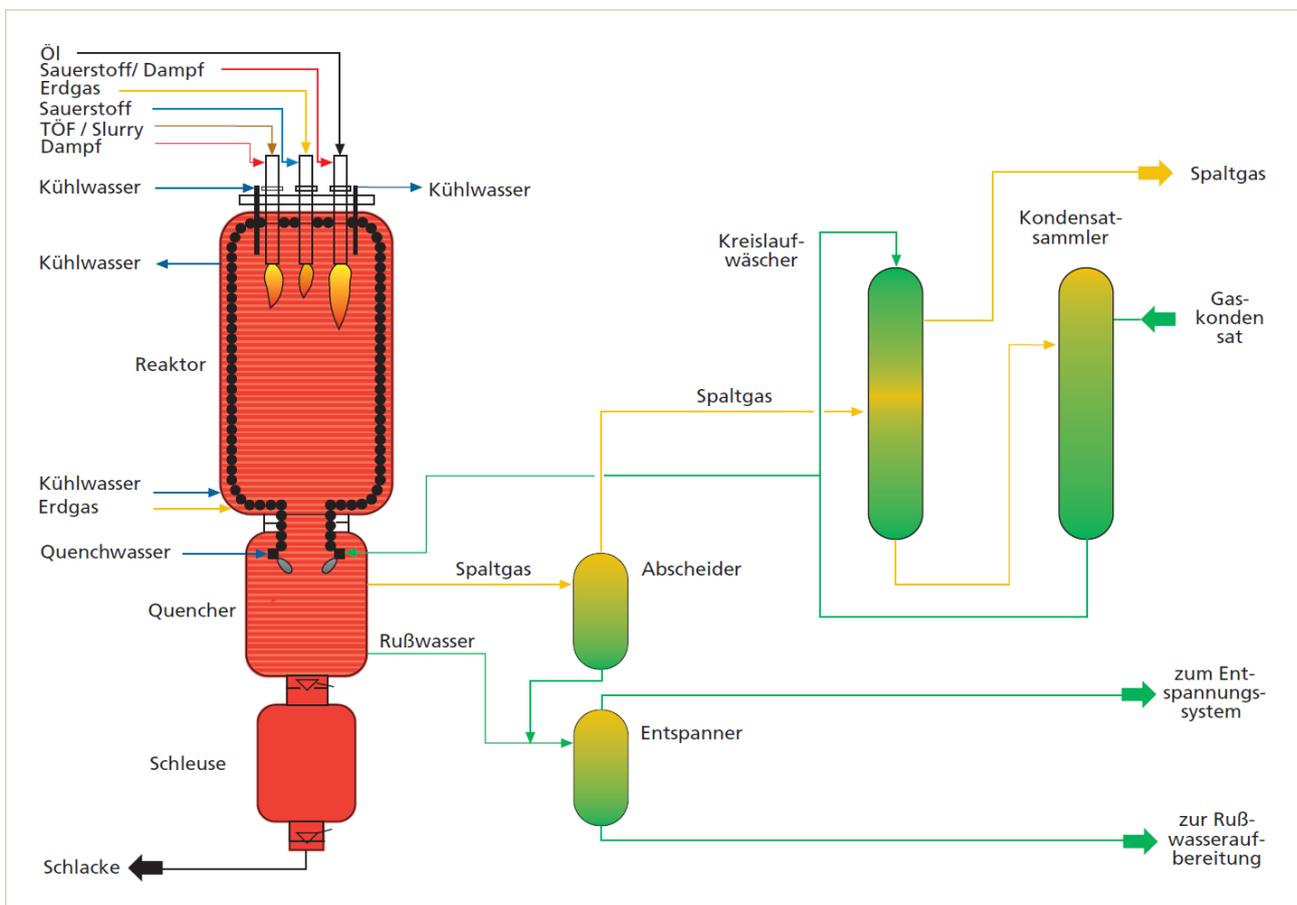


Figure 3.63: Process principle entrained flow gasification at SVZ Schwarze Pumpe [Thomé 1998].

### 3.2.3.6 SVZ BGL Fixed Bed Slagging Gasification (British Gas Lurgi)

The SVZ fixed bed slagging gasifier was a shaft gasifier with discharge of molten slag. Gas generation technology was developed in the 1970s by the two companies British Gas and Lurgi (BGL-gasification) to generate gas from coal. The technology was first used for gasification of waste by Lurgi Energie und Entsorgung GmbH.

Mixtures of different waste materials like pellets from pre-treated household and commercial waste similar to household waste, waste wood chips, sewage sludge briquettes, sewage sludge pellets, plastic compactates, shredder light fraction and tar-oil-solid-mixtures were used in the BGL-gasifier under addition of coal (see figure 3.53).

## Technology

Processing of waste input for fixed bed slagging gasification was identical to pre-treatment for entrained flow gasification, therefore it is referred to the explanations in chapter 3.2.3.4.

The BGL-gasifier (figure 3.64) had a capacity of 39 Mg/h and a yearly capacity of 312,000 Mg of solid waste materials in variable mixing ratios, including lignite and hard coal or crushed railway ties containing tar oils.

Input materials passed the BGL-gasifiers top-down in counter current to the generated gas. Gasification agents - oxygen and steam - were injected into the gas generating bottom part. They were discharged at the head of the gasifier after passing the fuel bed and reacting with the input material.

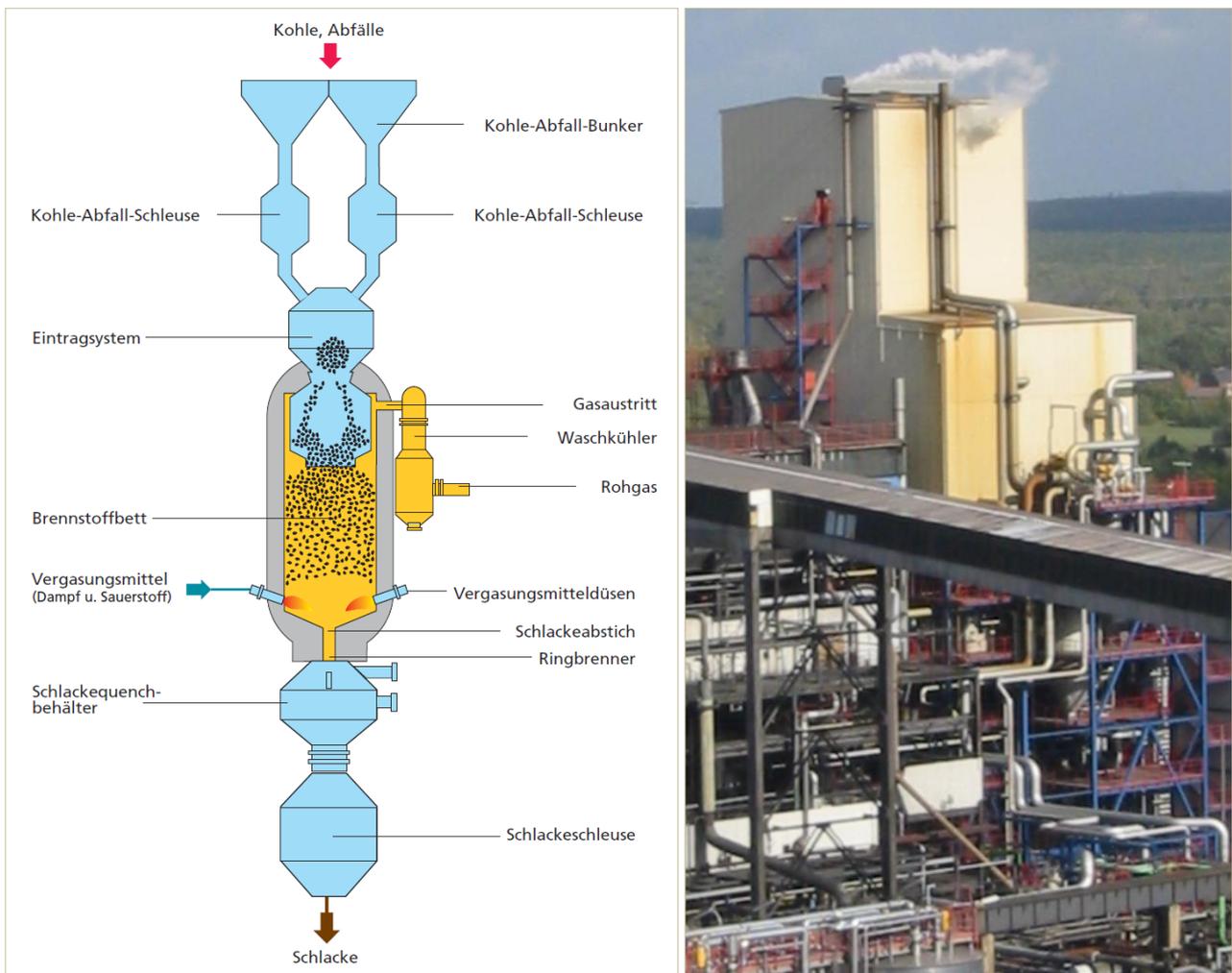


Figure 3.64: British-Gas-Lurgi (BGL)-Reactor for gasification of solid materials at Schwarze Pumpe. Left: process schema [Seifert 2001], right: picture of the installation (own picture, 2003)

The high-temperature reactor was operated at 25 bar and temperatures of up to 1,600 °C. These temperatures ensured destruction of organic hazardous substances. Inorganic pollutants were fixed in the slag, which was drawn from the reactor in molten state. Limestone was added as fluxing agent in the reactor to regulate slag viscosity.

The following processes took place in the reactor (top-down):

- Drying of input material
- Degassing of input material and generation of coke
- Gasification of coke from degassing
- Combustion of residual coke
- Slagging of ash constituents
- Cooling and solidification of slag in the water bath, forming granulate

Input material and granulated slag were loaded respectively discharged using pressure locks.

Raw gas generated in the upper part of the gas generator was conditioned with raw gas coming from entrained flow gasification and fixed bed gasification and was then transferred to gas cleaning. The synthesis gas was then used to produce methanol and generate electricity.

The gasification process itself as well as gas utilization required extensive peripheral installations (see chapter 3.2.3.4).

### Operating Parameters

Basic technical data and operating parameters of the fixed bed slagging gasifier as well as requirements regarding refuse derived fuel used in the process are given in table 3.26.

Table 3.26: Technical data and operating parameters fixed bed slagging gasifier (BGL) at SVZ Schwarze Pumpe

Parameter	Value	RDF Requirements	Value
Capacity	39 Mg/h	Texture	solid, fragmented
Diameter	3.6 m	Particle Size	min 16 x 16 x 16 mm
Temperature	up to 1,600 °C		max 80 x 80 x 120 mm
Pressure	25 bar	Water Content	< 20 %
Reacting Agent	oxygen, steam	Ash Content	< 20 %
Fluxing Agent	limestone		

### Costs and Development Status

The BGL reactor at Schwarze Pumpe was the first industrial scale fixed bed slagging gasification reactor for waste worldwide. Operational tests started in 2000, the performance test was in January 2002 and commercial standard operation started in February 2003.

The reactor cost about 45 million DM.

It was intended to build two more BGL-gasifiers until 2005, depending on operating success and the acquired amount of waste.

Yet, the SVZ Schwarze Pumpe could not be operated economically. Despite massive government support, gasification of waste was closed down. The slag bath gasifier was dismantled.

#### 3.2.3.7 Thermosteact Process

Thermosteact is a continuous degassing and gasification process with integrated direct melting of inorganic constituents. It was designed for combined treatment of municipal waste like household waste, commercial waste similar to household waste, bulky waste and dewatered or dried sewage sludge.

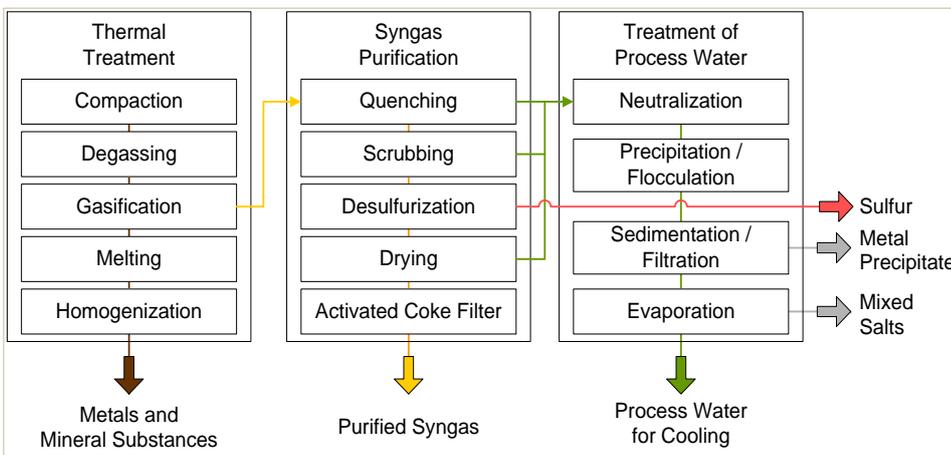
After shutdown of the first commercial plant in Karlsruhe, this process never gained foothold in Europe.

**Technology**

Waste is compressed and pressed into a heated degassing duct. Partly degassed material and enclosed inorganic material - minerals and metals - are continuously fed to a high temperature reactor. Organic compounds are gasified under addition of oxygen. Mineral and metallic components are molten. According to the supplier, these two fractions are separated into stable mineral and metallic products which are supposed to allow industrial utilization.

Reaction gases are converted to synthesis gas in the upper part of the reactor. The raw gas passes a multi-stage gas cleaning where contaminants are absorbed or condensed. The cleaned synthesis gas is utilized energetically.

The following two figures show the principle of the whole process and a process diagram.



Using a waste press, density of the input material is increased from circa 200 kg/m<sup>3</sup> to circa 1.200 kg/m<sup>3</sup>. This measure aims to reduce residual air (N<sub>2</sub>-reduction), crush brittle waste particles, reduce volume, distribute water contained in the waste, generate gas-tight waste plugs and increase thermal conductivity.

Figure 3.65: Process concept Thermoselect process [Thomé 1994; translated]

In each line, every three minutes about 500 kg are pressed and shifted into the degassing duct. Compression of waste prevents noise emissions and leakage of liquids and press water. The pressed waste serves as gas tight plug that prevents backflow of process gases.

The degassing duct is designed as pusher kiln with rectangular profile and is made of corrosion resistant alloyed steel. The kiln is heated externally using part of the cleaned synthesis gas as fuel. Starting in the outer layers, waste is dried, partly degassed and partly coked at temperatures of up to 800 °C. Released gas escapes through the channel and a gas collecting system and is then led into the high temperature reactor.

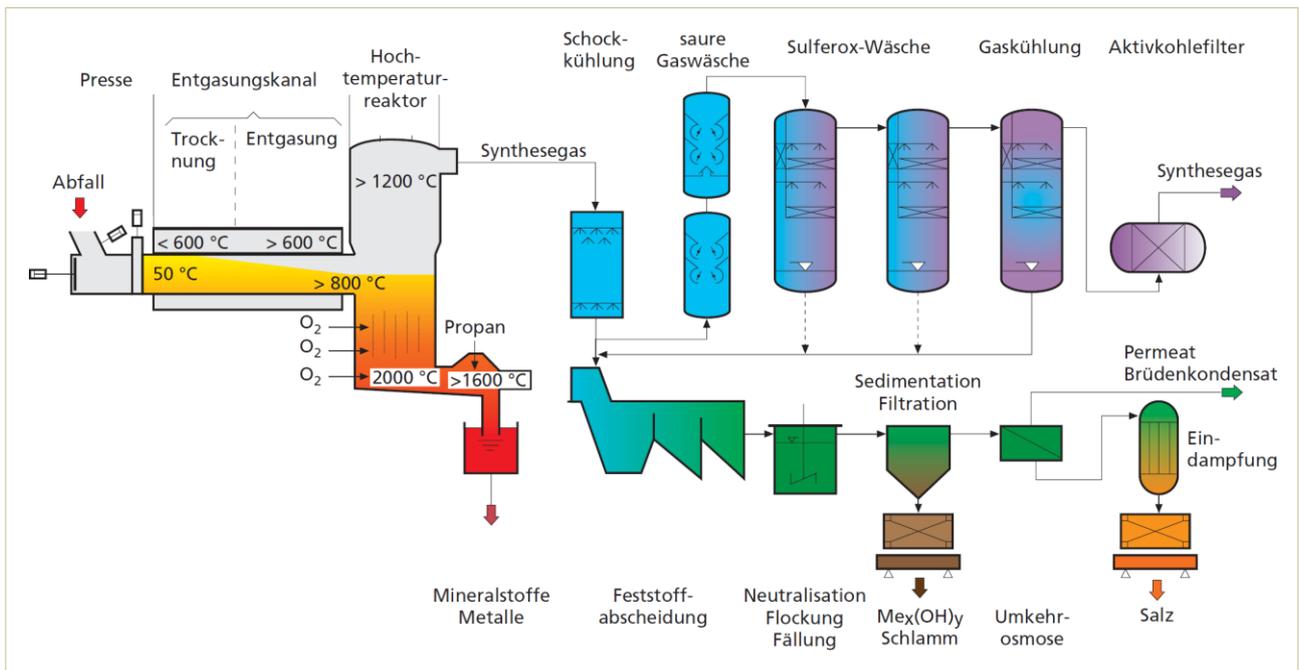


Figure 3.66: Overview of the Thermoselect process [Thomé 1994].

The vertical high-temperature shaft furnace is connected (gas-tight) to the degassing duct, also serving as anchoring device for the movably mounted parts of the press and the degassing duct. The pressure-resistant high-temperature reactor is operated at 0.3 bar above ambient pressure. Partially degassed waste, continuously transported from the degasification duct into the reactor, is gasified under dosed addition of oxygen at temperatures up to 2,000 °C.

Hot gas from the degassing duct and from waste in the reactor is converted to synthesis gas in the upper part of the reactor at 1,200 °C. Oxygen and generated steam serve as reacting agents. At high temperatures and with sufficient residence time, higher molecular carbonization products (char) decompose to low molecular substances  $H_2$ ,  $CO$ ,  $CO_2$  and  $H_2O$  as main components of the synthesis gas. Dosed injection of oxygen promotes exothermic reactions that guarantee an outlet temperature of the raw gas of 1,200 °C.

Due to high temperatures in the reactor - locally over 2,000 °C - and with sufficient residence time, mineral and metallic components are molten and unfixable volatile metals are cast out. In a downstream homogenizing reactor in which synthesis gas - or alternatively natural gas - and oxygen are used to maintain temperatures, two melting phases are formed.

It is intended that, because of their different density and surface characteristics, mineral and metallic melt separate in the homogenizing reactor at about 1,600 °C. Drawn off melts are granulated by water injection. Products are discharged from the granulating tank with a bucket conveyor. Figure 3.67 shows pictures of the granulate.

Raw syngas leaves the reactor with an excess pressure of 0.1 to 0.2 bar. Besides the main constituents  $CO$ ,  $H_2$ ,  $CO_2$  and steam, the gas contains small drops of molten minerals, volatile heavy metals as well as  $HCl$ ,  $H_2S$  and  $HF$ . The gas is cleaned in a multi-stage gas cleaning unit.

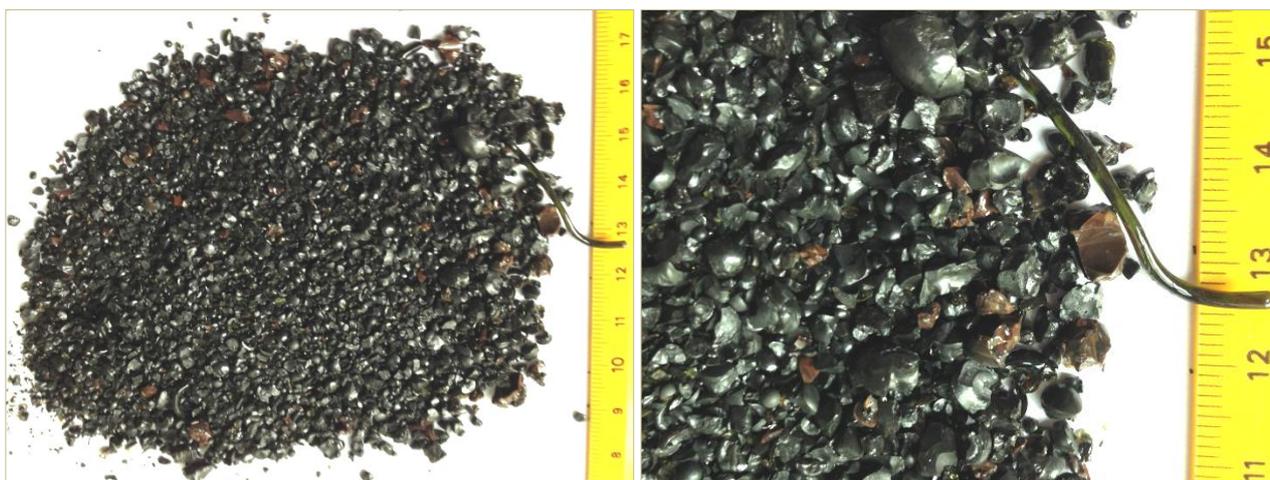


Figure 3.67: Granulated melt from the Thermoselect process (own pictures)

In the first stage, water is injected, abruptly cooling down the raw gas from 1,200 °C to 70 °C. In the absence of oxygen, regeneration of organic pollutants like dioxins and furans is prevented. Simultaneously, drops of molten minerals in the gas solidify. They are collected together with produced carbon in a sedimentation tank, then discharged and returned to the process. Highly acidic components are removed from the synthesis gas by acidic scrubbing, further acidic liquid drops are removed in the following basic scrubbing. The following fine cleaning includes particle separation, desulfurization, drying/cooling and reheating of the synthesis gas using waste heat. Dust and carbon particles still contained in the gas are first separated with a special scrubbing process using a soluble wetting agent and are then returned to the process. By separation and chemical conversion in an iron chelate solution, H<sub>2</sub>S is removed from the synthesis gas and converted to elementary sulfur, which can be used industrially after separation from the suspension. In the drying stage, the synthesis gas is cooled down to 8 °C, decreasing the water content in order to prevent condensation in the subsequent stage. The gas is then reheated to 50 °C and passes an activated carbon filter which serves as emergency filter.

The Thermoselect process recycles water from the waste feedstock and the gasification process and is therefore free of waste water. After cleaning and separation of residual and hazardous materials, process water is reused for cooling purposes, evaporated via coolers and discharged to the atmosphere. Process water is generated within gas cleaning stages by condensation of steam contained in the synthesis gas. It contains pollutants transferred from synthesis gas into the water. It is collected in a central sedimentation tank where solids are removed and then returned to the thermal treatment process. In a first step, the water is neutralized with sodium hydroxide solution. Due to the alkaline pH, metals predominantly fall out as hydroxides. By addition of Na<sub>2</sub>S, dissolved heavy metals are converted into sulfides of low solubility. Precipitated heavy metal compounds are flocculated by addition of FeCl<sub>3</sub> and polyelectrolytes and then separated in a sedimentation and a filtration stage.

Overflow from the sedimentation stage passes a reverse osmosis system into a multi-stage evaporation. The generated salt mixture is mainly made up of sodium chloride and a small amount of other alkali and earth alkali compounds. [Thomé 1998]

### Operating Parameters

Basic operating parameters of the industrial size Thermoselect plant in Karlsruhe are summarized in table 3.27.

Table 3.27: Operating parameters of the Thermostelect plant in Karlsruhe

Parameter	Value	Parameter	Value
Number of Lines	3	Thermal Power Steam Generator	63.1 MW
Nominal Capacity per Line	10 Mg/h	District Heating Power	50 MW
Availability	7,500 h/a	Internal Demand Process Heat	5.7 MW
Capacity	225,000 Mg/a	Number of Steam Generators	2
Thermal Output	100 MW	Number of Steam Turbines	1
Thermal Output (Including Natural Gas)	104.2 MW	Electricity Generation (gross)	12.7 MW
Synthesis Gas Output (gross)	67.6 MW	Excess Electricity (net)	2.7 MW

The composition of synthesis gas is determined by the composition of waste input, its calorific value and the operational mode of the high-temperature reactor. With calorific values of 9 to 12 MJ/kg in the infeed and recirculation of syngas to the high temperature- and the homogenizing reactor, calorific values of the resulting synthesis gas range from 6.7 to 8.7 MJ/m<sup>3</sup><sub>N</sub>.

Volume shares of combustible components are 33 to 41 vol.-% CO and 24 to 32 vol.-% H<sub>2</sub>. The share of Carbon dioxide ranges from 23 to 38 vol.-%. Minor components are residual nitrogen (ca. 3 vol.-%) and steam (ca. 1 vol.-%).

### Residual Materials

The Thermostelect process generates vitrified mineral materials which can be used as aggregates in concrete, hereby replacing natural minerals. Residual waste (e.g. municipal solid waste) contains mineralizing components which lead to non-degradable materials with low leachability. A low amount of residual carbon and fixation of heavy metal traces are important for the quality of the mineral materials. Vitreous state and a high level of inertization determine leachability (see figure 3.67).

The accrued metal is a low-alloy iron (> 90 wt.-%) with accompanying elements copper (ca. 5 %), nickel (ca. 0.6 %), chrome (ca. 0.3 %), tin (ca. 0.4 %) and phosphor. The metal granulate is meant to be returned to metallurgical processes.

The residual materials sulfur, mixed salt and product from metal precipitation show compositions that should allow further industrial utilization (sometimes after further treatment). The discharged sulfurous product contains about 70 % sulfur. Mixed salt is made up of 90 to 98 % NaCl plus alkali and earthalkali chlorides. Zinc is found in the metal precipitation product with a share of 80 to 130 g/kg, the content of lead is 50 to 100 g/kg. [Thomé 1998]

### Costs and Development Status

In 1992, a pilot plant was constructed in Fondotoce (Italy). In 1999, two industrial size plant started operation in Karlsruhe (Germany) and Chiba (Japan). The plants in Karlsruhe and Fondotoce have been shut down. Figure 3.68 shows pictures of the shut-down plant. Construction of a further plant in Ansbach (Germany) was stopped in 2002. Further projects in Hanau and Herten (Germany) and Giubasco (Switzerland) were cancelled.

Treatment costs in Karlsruhe exceeded the calculated costs of 250 DM/Mg significantly.



Figure 3.68: Thermoselect plant in Karlsruhe after several years of downtime [own pictures, 2014]

### 3.2.4 Gasification as Upstream Process

#### 3.2.4.1 Ecoloop

The Ecooop process is classified as upstream process since the main application of the process is to generate fuel gas for lime kilns and the only existing installation is currently used for just this purpose. According to the supplier, the process could also generate gases for other purposes.

Ecooop GmbH developed a counter current moving bed gasification process to generate synthesis gas from diverse carbon containing materials like plastic waste, refuse derived fuel, lignite or biomass. The first commercial size reference plant with a capacity of 32 MW was constructed at a lime plant in the Harz Mountains (Germany). Generated synthesis gas is supposed to substitute natural gas or other fossil fuels for lime burning in the plant on site.

#### Technology

The heart of the installation is a counter current moving bed gasifier. The reactor is designed as shaft furnace similar to those used in lime production. The feedstock, carbon carriers like RDF, enters the reactor at the top in an inert circulating material (moving bed), mainly consisting of CaO and eventually shares of CaCO<sub>3</sub> in a mixing ratio of circa 1 to 3. The alkaline material does not only serve as reaction carrier but also to remove contaminants like chlorine or sulfur from the process.

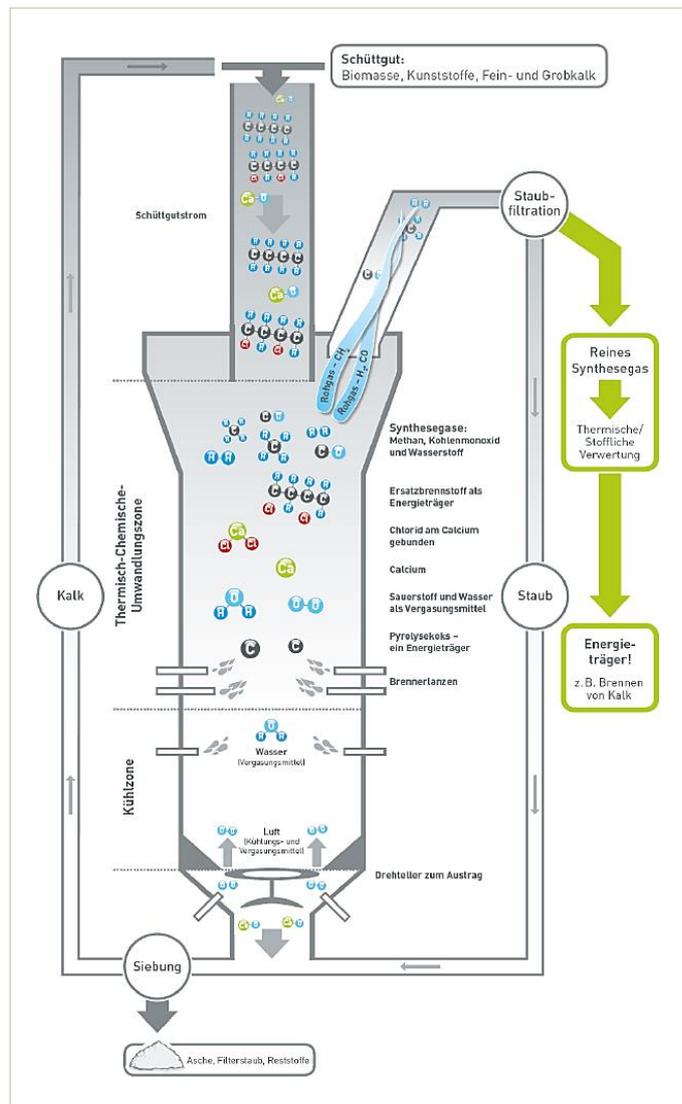


Figure 3.69: Schematic View of the Ecooop gasification reactor

The material continuously sinks downwards the reactor by gravitational force. As shown in the adjacent figure, air as gasification agent is injected bottom up. In the lower part of the vessel, the air also serves as cooling agent for the moving bed and the ash within the bed. The air is heated and hereby enables gasification.

Further up the reactor, burner lances fired with natural gas are used for process start-up. The lances also allow dosage of water or steam as gasification agent. In addition, they serve to recirculate organic condensate of high calorific value, originating from gas cooling.

In the hot part of the kiln, where combustion and gasification reactions take place, temperatures rise up to 1,200 °C. Further up, pyrolysis reactions take place at temperatures above 450 °C.

The raw gas, a mixture of synthesis and pyrolysis gas that may contain dust and tars, is discharged at the head of the reactor. In two parallel muffles, oxygen is injected into two raw gas muffles using special burners, leading to post-gasification of the raw gas.

In the next process step, the gas with a temperature of 400 to 500 °C is dedusted in two parallel ceramic filters and then cooled down to less than 50 °C. Condensation products (water, oils, tars) are separated and returned to the reactor using the burner lances mentioned above. Synthesis gas is stored in gas tanks from where it is drawn off into the lime kilns. Filter dust is transferred to the reconditioning of gasification residue.

### Operating Parameters

Since so far only one reference plant has been constructed, the following table only gives design data.

Table 3.28: Design data of the Ecoloop reference plant

Parameter	Value	Parameter	Value
Capacity RDF	ca. 40.000 Mg/a	Temperature Post-Gasification	> 600 °C
Thermal Capacity	32 MW	Temperature Filter	400-500 °C
EBS : Ca-Carrier Material	1 : 3	Temperature Clean Gas	< 50 °C
Gasification Agent	Air & Water	<b>Products</b>	
Residence Time	ca.12 h	Gas	ca. 15,000 m <sup>3</sup> <sub>N</sub> /h
Gasification Temperature	450-1,200 °C	Tar	≈ 20 kg/h
Pyrolysis Temperature	≈ 450 °C	Oily phase	≈ 50-150 kg/h



Figure 3.70: Ecoloop plant – general view (left) and gasification reactor (right) [own pictures]

## Emissions and Residue Materials

Synthesis gas is dedusted and then cooled down to less than 50 °C. In cooperation with the German Federal Environmental Agency and the Environmental Authority of Saxony-Anhalt, a measuring program is planned. Inter alia, fate and behavior of volatile heavy metal compounds generated in reducing atmosphere will be researched. Most of these heavy metal compounds occur as oxides and are separated during filtration together with fly ash. Sulfur and chloride are fixed as chlorides and Ca-S compounds in the lime bed due to excess CaO.

Residues from gasification are discharged together with the CaO moving bed at the bottom of the reactor and then reconditioned together with fine dust from synthesis gas cleaning. Fuel ashes are usually small-grained and are sifted together with fine lime which contains CaCl<sub>2</sub> and Ca-sulfur compounds resulting from chloride and sulfur contained in the fuel. Coarse lime is returned to the reactor, residual materials are disposed of.

## Costs and Development Status

So far, only one commercial size reference plant has been built. The technology is based on experiences from calcination and other high temperature processes and shows a certain potential for further application. One reason is the wide range of input materials, some of which are considered “critical”. Especially fractions with high chloride content without reasonable possibilities for re-utilization seem interesting.

The process requires approximately 10-15 % lime based on the mass flow of RDF input.

At the end of 2012, the gasifier was tested with anthracite and in 2013, in seven one- to two-week campaigns, RDF was tested as fuel. A thermal output of 15 MW was achieved. Downtimes were used for adjustments. The next intended steps are to increase the thermal output to 32 MW and to recirculate the condensate fraction from gas cooling (oil and water) (Status 2013).

Altogether, the technology is still under development and has to provide evidence of process stability in appropriate operation timespans under full load.

According to the supplier, even under conservative assumptions, production costs for the synthesis gas are significantly lower than expenses for natural gas.

### 3.2.4.2 Envirotherm – ZWS Rüdersdorf

Envirotherm is a plant manufacturer that offers decentralized and industrial size plants for a variety of energy carriers. Applications on offer include gasification plants based on fixed bed or circulating fluidized bed. So far, nine industrial size plants with a throughput between 16 and 210 Mg/h have been built respectively are about in the implementation stage. [Envirotherm 2013, Envirotherm 2014]

One of the industrial size plants of this supplier is operated by Cemex Deutschland AG in Rüdersdorf (Germany). The plant serves as upstream plant to provide fuel gas for a cement kiln. Both reconditioned municipal solid waste and carbon-rich mineral fractions are used. At present, the installation in Rüdersdorf is the only fluidized bed gasifier by Envirotherm operated with waste derived fuels.

At the Rüdersdorf site, Cemex processes about 2.5 million Mg limestone per year. Fossil fuels are used in the furnace system, for both the main burner of the rotary kiln and the calciner at the kiln inlet. Direct (partial) feeding of RDF into the furnace system is possible, but it is mainly refuse derived fuel gas from the downstream gasification unit that is used. The required fuel amounts to 70,000 Mg/a fossil fuels and 250,000 Mg/a RDF.

This upstream process was integrated in 1996, aiming to promote the use of fuels of low and middle calorific value as well as soils and sands with combustible components for the production of cement. On one hand, waste materials can be used as raw material in cement production. Since they are already added to raw material conditioning for the production of raw meal, they must be widely inert and free of volatile organic components. On the other hand, Waste fractions can be used as fuels. In order to maintain process conditions, a high calorific value respectively good reactivity and homogeneous material properties are required. In this context, the downstream circulating fluidized bed in Rüdersdorf is to be considered a reprocessing facility. Energy contained in organically contaminated mineral waste and RDF is concentrated in a product gas. What remains is a widely inert mineral fraction which can be utilized in the process. [Scur 2005]

### Technology

The gasification device operated in Rüdersdorf consists of a gasification reactor with a downstream hot gas cyclone. Organic substances in the feedstock are converted to gas and fed directly to the calciner of the cement furnace without further treatment (see figure 3.71). Besides substitution of raw materials in the cement production, it also serves to compensate losses of bed material. [Cemex 2013]

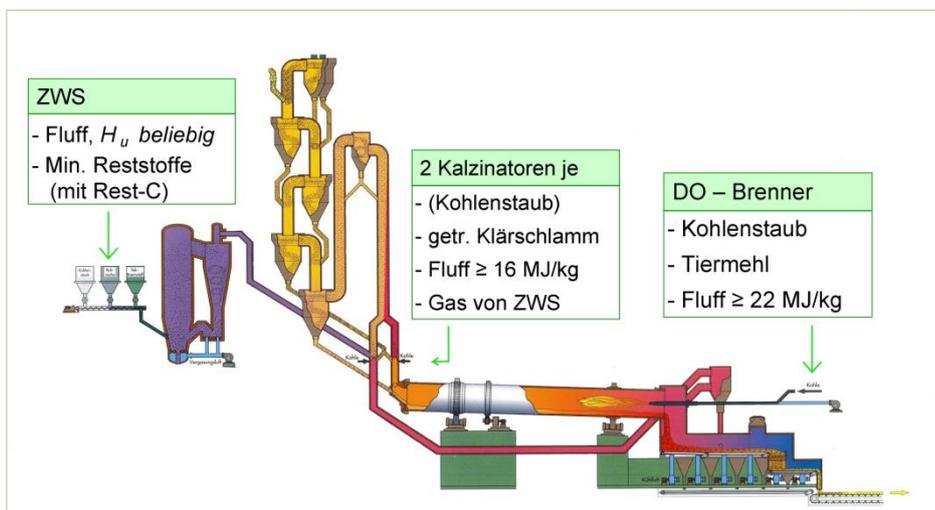


Figure 3.71: Integration of the ZWS-gasfier into the production of cement at Rüdersdorf site [Cemex 2013].

The gasification plant was designed for a firing capacity of 100 MW; depending on calorific value, throughput can reach 30 Mg/h. The plant excels in high tolerance regarding material properties of input. Calorific values can range from 1 to 35 MJ/kg with water contents of up to 50 %. The ash content is not limited by equipment but by the energy balance of the system. Particle size of the

input material should not exceed 100 mm, with feedstock ranging from low calorific power plant ashes and reject from papier plants to high calorific plastic waste [Cemex 2013]. Table 3.29 shows the properties of input material and process characteristics of the ZWS-gasfier.

Table 3.29: ZWS-gasifier in Rüdersdorf: process characteristics and properties of input material

Properties Input Material (average)		Process Parameters	
RDF	diverse, free of disturbing material (metals)	<b>Gasification Reactor</b>	
Particle Size	< 100 mm (mineral particles < 6 mm)	Design Power	100 MW
Water Content	< 50 %	Throughput	20-30 Mg/h
Ash content	not limited	Temperature	900-960 °C
Calorific Value	1-35 MJ/kg	<b>Gasification Products</b>	
Bulk Density	preferably > 300 kg/m <sup>3</sup>	Volume Flow Gas	62,000 m <sup>3</sup> <sub>N</sub> /h
		Calorific Value Gas	3-5 MJ/m <sup>3</sup>
		Temperature Gas	900-950 °C
		Residence Time Gas	4 s
		Mass Flow Residue	< 12 Mg/h
		C-Content Residue	< 1.5 %



Figure 3.72: ZWS Gasifier (left) and hot gas cyclone (bottom) before assembly in Rüdersdorf [Cemex 2013].  
Top middle: internal view ash cooler, top right: feeding screw [own pictures].

Air is used as gasification agent in the reactor and a product gas volume of 60,000 m<sup>3</sup>/h with a calorific value of 3,000-5,000 kJ/m<sup>3</sup> is generated. This gas leaves the hot gas cyclone at circa 8,000 °C. It is transferred to the cement kiln calciner through an unheated hot gas pipe of 50 m length. By integrating the gasification reactor into the process of cement production, the product gas pipe is relatively short. This prevents gas cooling and accordingly, condensation of long chained hydrocarbons (tars) is prevented. The gasification residue contains less than 2 wt.-% fixed carbon. Degassed material is added to the raw limestone and the mixture is ground. The gasification reactor and the hot gas cyclone while under construction are shown in figure 3.72, which also displays the ash cooler and the feeding screw.

### Costs

In the upstream facility in Rüdersdorf, more than 3 million Mg of RDF were utilized from 1996 to 2013. Due to plant layout, no gas treatment is necessary. Therefore, investment and operating costs are rather low compared to other alternative processes.

Table 3.30: Average treatment costs of ZWS gasification in Rüdersdorf [Scur 2014].

Costs	€/Mg
Operating Costs	10
Investment and Capital Costs*	20
<b>Sum</b>	<b>30</b>

\*Capital costs are estimated

### 3.2.4.3 Lahti Kymijärvi I

In order to meet the demand for decentralized thermal waste treatment caused by the low population density in Finland, a fluidized bed gasification was built in Lahti, Finland, to supply a major part of the firing power of the Kymijärvi power plant by gasification of biomass and plastic waste. The plant was dismantled after 10 years of successful operation because it was not licensable and was replaced by the advanced Kymijärvi II plant (see chapter 3.2.4.4).

### Technology

The gasification facility was operated using residue materials from forestry, waste wood and a high calory fraction from processed waste (see figure 3.73) all of which were gasified in a fluidized bed at temperatures between 850 and 1,000 °C. Synthesis gas was burned immediately in the combustion chamber of the adjacent coal power plant.

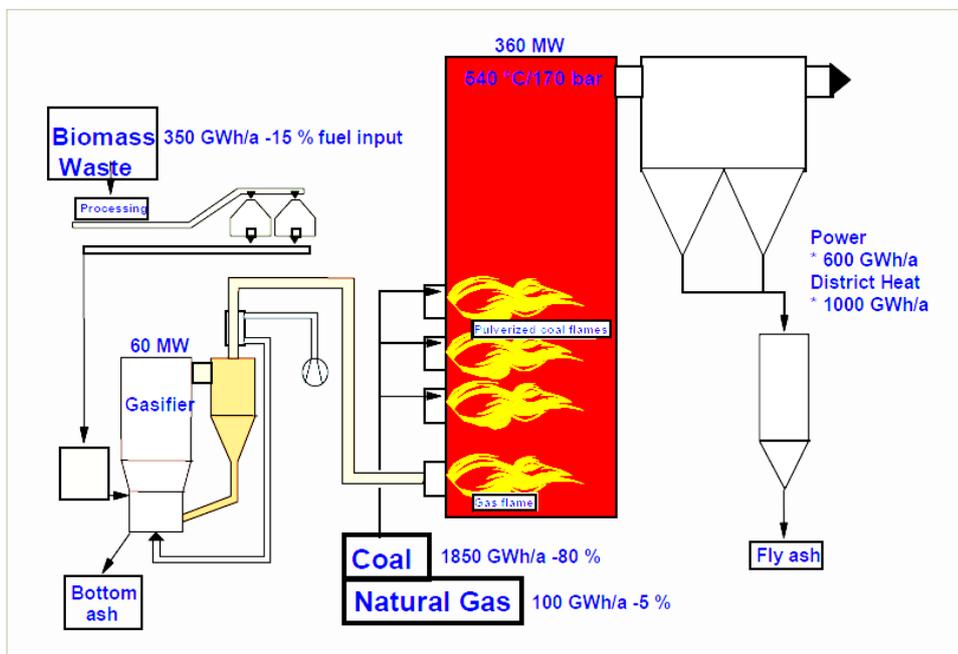


Figure 3.73: Process diagram of the Kymijärvi plant including performance data.

Fuel was fed to the reactor using a screw. Air was used as gasification and fluidizing agent (nozzle floor), it was preheated at the gas exit of the cyclone prior to entering the gasification reactor. The fluidized bed was operated without additional bed material.

The fuel input as reference variable determined air injection. Fly ash was separated in a cyclone and then returned to the reactor. Synthesis gas loaded with fine dust was directly fed to a pulverized-fuel burner within the power plant.

### Operating Parameters

Main fuel components were:

- Residue materials from forestry, like branches, bark
- Contaminated waste wood
- A processed high calorific waste fraction with a particle size of 5 cm, which was collected separately in Lahti and consisted of plastic (5-15 wt.-%), paper and cardboard (30-70 wt.-%) and wood (30-60 wt.-%).

Composition of the fuel mixture used for gasification varied over time. The share of biomass from forestry stabilized at 20 % between 2002 and 2005, contaminated waste wood had a share of circa 30 %, the high calorific fraction rose to 40 %. Hardly any other fuels (turf, paper) were used.

For the years from 1998 to 2001, the following data on availability, throughput and supplied energy were published.

Table 3.31: Operating data of the Lahti Kymijärvi I plant

Parameter		1998	1999	2000	2001
Operating Hours	h/a	4,730	5,460	4,727	7,089
Availability	[%]	81.8	98.9	97.1	96.1
Energy	[GWh]	225	342	295	445
Throughput	[Mg/a]	79,900	106,200	91,800	116,100
Share of High-Calorific Fraction	[wt.-%]	15	23	29	34

For the year 2002, the following information on composition and calorific value of synthesis gas was published (see table 3.32).

### Emissions and Residue Materials

Since the gasification facility does not emit substances into the atmosphere, only changes in the overall emissions of the power plant can be considered as reference for emissions of the gasification process. Possible influences on emissions can be estimated from contaminant contents in the synthesis gas. Yet, the following table does not show any critical pollutant content.

Table 3.32: Synthesis gas composition from Lahti Kymijärvi I

Parameter	Unit	Value	Parameter	Unit	Value	Parameter	Unit	Value
CO	[Vol.-%]	9.6	NH <sub>3</sub>	[mg/m <sup>3</sup> ]	800 - 1.000	Tars	[mg/m <sup>3</sup> ]	7 - 12
H <sub>2</sub>	[Vol.-%]	6.7	HCN	[mg/m <sup>3</sup> ]	25 - 45	Alkali Metals	[mg/m <sup>3</sup> ]	< 0.1
CH <sub>4</sub>	[Vol.-%]	3.3	HCl	[mg/m <sup>3</sup> ]	30 - 90	Dust	[mg/m <sup>3</sup> ]	6 - 10
CO <sub>2</sub>	[Vol.-%]	12.3	H <sub>2</sub> S	[mg/m <sup>3</sup> ]	50 - 80			
H <sub>2</sub> O	[Vol.-%]	35.0	C <sub>2</sub> H <sub>6</sub>	[mg/m <sup>3</sup> ]	7 - 12	Calorific Value	[MJ/kg]	2-3.5 (4.5)
N <sub>2</sub> (calc.)	[Vol.-%]	53.3						

Accordingly, alterations in power plant emissions were marginal. Of the heavy metals, copper and zinc contents were increased occasionally, this also applied for the sum parameter of heavy metals relevant for approval. The limits of the EU waste incineration directive were always underrun significantly. Utilization of synthesis gas even caused a slight emissions reduction for some contaminants. Alterations in comparison to standard operation with coal are as follows:

Table 3.33: Alterations in emissions from Lahti Kymijärvi I caused by utilization of product gas from gasification

Parameter	Increase	Parameter	Reduction
Heavy Metals	slight increase	NO <sub>x</sub>	30 mg/m <sup>3</sup> (5 %)
HCl	10–30 mg/m <sup>3</sup>	SO <sub>2</sub>	60–75 mg/m <sup>3</sup> (10 %)
Parameter	Unvaried	Dust	15 mg/m <sup>3</sup> (30 %)
CO	0		
PCDD/F	0		

### Costs and Development Status

The investment costs of the gasification facility amounted to 12 million Euros of which 3 million were funded by a EU-THERMIE program. In addition, the constructor Foster Wheeler obviously subsidized the gasification as reference plant. Further details on costs have not been published.

As mentioned above, the operational stability was high over several years. Changes in legislation led to the shutdown of the gasification since according to the new waste incineration directive, the installation would have required flue gas cleaning. Retrofitting was not possible at reasonable costs. Operation only with residue materials from forestry was not considered attractive in future since prices for this feedstock had been rising significantly. The necessity to provide waste management in Lahti then led to planning and construction of the gasification plant Kymijärvi II at the same site with the difference, that synthesis gas was to be purified before utilization in the power plant (see following chapter). [Palonen 1998, Granatstein 2002, Kivela 2006]

#### 3.2.4.4 Lahti Kymijärvi II

Lahti Kymijärvi II is a fluidized bed gasification for refuse derived materials. The generated synthesis gas is first cleaned and then transferred to a gas power plant which is not operated with a gas turbine but with a combustion chamber and water-steam-cycle. The plant substitutes Lahti Kymijärvi I (see chapter 3.2.4.3).

Starting in the years from 2000 on, Lahti Energia and the public research institution VTT planned a new technology and in 2005, the building application to construct an industrial size reference plant was submitted. Objections from environmental organization delayed the permit. At last, construction contracts were concluded in 2009. Construction was supported by the European Union.

The reference plant started demonstration operation in 2012 with two gasification lines, normal operation began in 2013.

### Technology

As in Lahti I, the core piece of the plant is a circulating fluidized bed which is operated with refuse derived fuel. Generated gas is dedusted and transferred to a gas plant with combustion chamber and water-steam-cycle. The following figure displays the plant layout.

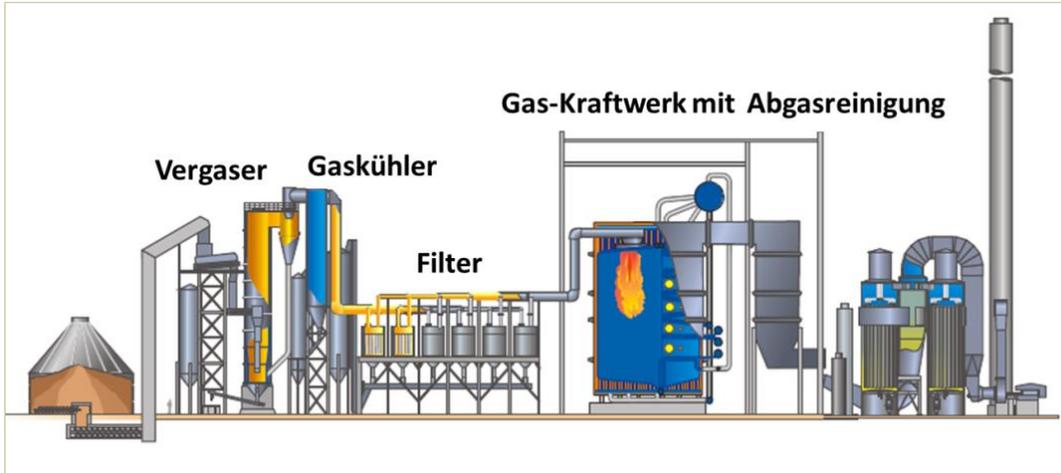


Figure 3.74: Plant layout Kymijärvi II

Refuse derived fuel is stored in a housed bunker. It is transferred to the fluidized bed reactor via an intermediate bunker and transported into the reactor with a feeding screw. Sand with added limestone is used as bed material. Gasification takes place at 850-900 °C. Synthesis gas is cooled in an upright cooler and dedusted with ceramic filters. The filtering device consists of 6 filter units per line with approximately 4.000 filter elements. Temperatures in the filtering device are chosen high enough to prevent tar condensation.

Dust-free gas is fed to the gas burners of the power plant. A dry flue gas cleaning with addition of  $\text{NaHCO}_3$  and activated coke to remove acid gases and mercury as well as an SCR-plant to reduce nitrogen oxides are found downstream. The configuration of the whole plant without gas cleaning as well as performance data is demonstrated in the following diagram.

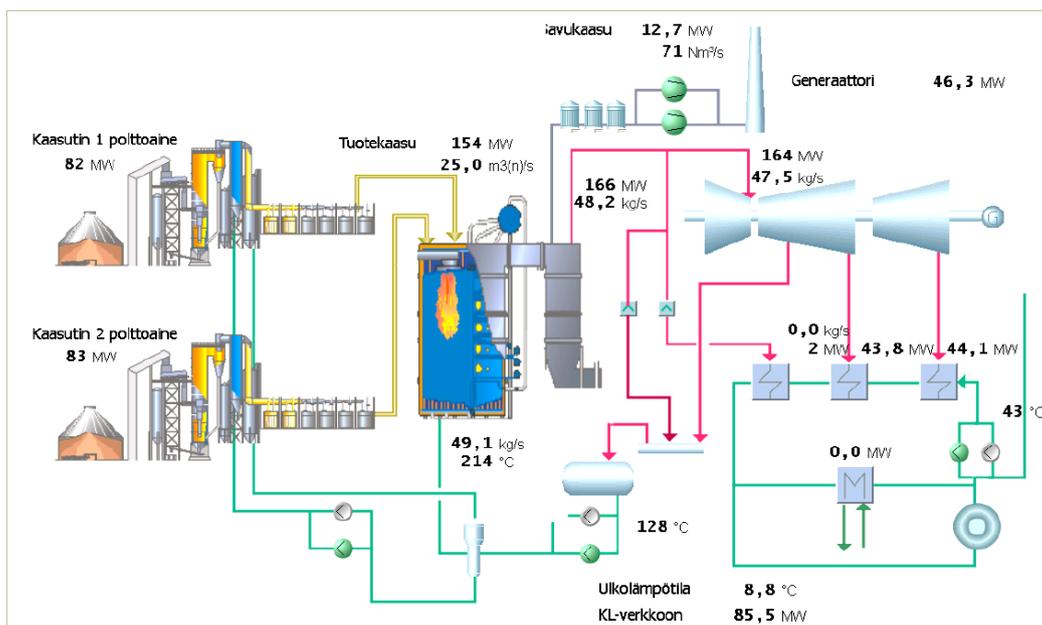


Figure 3.75: Process diagram Kymijärvi II (gas cleaning not included)

## Operating Parameters

The following operating parameters are to be considered as design data, data on standard operation is not yet available.

Table 3.34: Composition of synthesis gas from Lahti Kymijärvi I

Parameter	Value	Parameter	Value
Capacity RDF	250,000 Mg/a	Volume Synthesis Gas	≈ 25 m <sup>3</sup> /s
Thermal Capacity	2 x 80 MW	Combustion Temperature	> 850 °C / 2 s
Height Gasifier	≈ 30 m	Steam Temperature	540 °C
Diameter Gasifier	≈ 5 m	Steam Pressure	121 bar
Gasification Agent	air	Electric Power	50 MW
Gasification Temperature	850-900 °C	Thermal Power	90 MW
Filter Temperature	400 °C	Electric Efficiency	31 %

Energy export goes to the electric grid respectively the district heating system of the city of Lahti.

## Emissions and Residue Materials

So far, no information has been published on emissions; yet, it can be expected that the installed gas cleaning systems meets all emission limits. There is also no information available on residual materials.

## Costs and Development Status

The investment costs of the whole plant amounted to 160 million €. There is no data available on operating costs.

The installation has been operated for more than 5,000 hours. No information has been published on availability or operational disturbances. After 4,500 hours, there was no corrosion detectable on the boiler tubes. The technology is offered on the market, especially in the United Kingdom. [Isaksson 2012, Honkola 2013]

### 3.3 Plasma Processes

Technologies to generate plasma are currently mainly offered by the four companies Europlasma, Westinghouse, Phoenix Solution Company (PSC) and Tectronics. For thermal treatment of waste, providers active in the market are Westinghouse and Europlasma with their subsidiaries Alter NRG respectively CHO-Power. Tectronics and the company Advanced Plasma Power act as joint provider. Providers mentioned offer plasma technology both via subsidiary companies and third-party suppliers. In addition, third-party suppliers integrate the technology into their own process concept and then offer this on the market. [Helsen 2010]

A number of industrial scale installations for plasma gasification with capacities of less than 10 to more than 250 Mg/d is currently in operation. They are mainly located in Asia and America. CHO-Power is represented with one industrial size installation in France. Figure 3.76 shows both plants in operation (in 2012) and planned projects. Process concepts of currently relevant manufacturers are described in the following chapters.

Location	Raw material	Capacity (TPD)	Start Date	Production	Plasma Technology	Company
Mihama-Mikata, Japan	MSW/WW Sludge	25	2002		DC, Westinghouse	Hitachi Metals Ltd.
Utashinai, Japan	MSW/ASR	300	2002		DC, Westinghouse	Hitachi Metals Ltd.
Yoshi, Japan	MSW	151	1999		DC, Westinghouse	Hitachi Metals Ltd.
Pune, India	Hazardous Waste	68	2009	1,6 MWe	DC, Westinghouse	Maharashtra Env. Pow.
Nagpur, India	Hazardous Waste	68	2010	1,6 MWe	DC, Westinghouse	Maharashtra Env. Pow.
Shanghai, China			Project		DC, Westinghouse	
Tallahassee, USA	MSW	910	Project	35 MWe	DC, Westinghouse	Green Power Systems
Morcenx, France	Industrial/Biomass	137	2012	12 MWe	DC, Europlasma	CHO-Power
Hull, Sunderlan, Barry & Barrow, UK	Industrial/Biomass	107 x 4 plants	Project	37.5 MWe	DC, Europlasma	CHO-Power
Port Hope, Canada	MSW/TDF	400	Project	26 MWe	DC, Europlasma	Sunbay Energy Corp.
Hirwaun, UK	MSW/industrial	~750	Project (2015)	20 MWe	DC, Europlasma	EnviroParks Limited
Ottawa, Canada	MSW	85	Demonstration facility	1 MWe/ton	DC, PSC	Plasco Energy Group Inc.
Trail Road, USA	MSW		Demonstration facility	0.88 MWe/ton	DC, PSC	Plasco Energy Group Inc.
Los Angeles, USA	MSW		Project		DC, PSC	Plasco Energy Group Inc.
Beijing, China	MSW	200	Project		DC, PSC	Plasco Energy Group Inc.
Tainan City, Taiwan	Hazardous Waste	3-5	2005		DC, Homemade	PEAT International
Izuka, Japan	Industrial Wastes	10	2004		DC, Homemade	InEnTec
U.S. Navy	Shipboard Wastes	7	2004		DC, Pyrogenesis	Pyrogenesis
Hurlburt Field, USA	MSW/Hazardous	10.5	2011		DC, Pyrogenesis	Pyrogenesis
Faringdon, UK			Demonstration facility		DC, Tectronics	Advanced Plasma Power
Swindon	MSW	91,000 t/year	2008	16.3 MWe	DC, Tectronics	Advanced Plasma Power
South Wales	MSW		Project		DC, Tectronics	Advanced Plasma Power
North of England	MSW		Project		DC, Tectronics	Advanced Plasma Power
South West England	MSW		Project	17 MWe	DC, Tectronics	Advanced Plasma Power
Scotland – East Coast	MSW	91,000 t/year	Project		DC, Tectronics	Advanced Plasma Power
Brazil	MSW		Project		DC, Tectronics	Advanced Plasma Power
Brazil	ASR		Project		DC, Tectronics	Advanced Plasma Power
Belgium	Landfill	246 x 5 plants	Project	100 MWe	DC, Tectronics	Advanced Plasma Power
Swindon	Residual wastes		Demonstration facility	BSNG	DC, Tectronics	Advanced Plasma Power

ASR: Auto Shredder Residue, WW Sludge: Waste Water Sludge, TDF: Tire Derived Fuel, BSNG: Bio Substitute Natural Gas, TPD: Metric Tons Per Day

Figure 3.76: Industrial size plants for plasma gasification of waste built and planned [Fabry 2013].

### 3.3.1 Alter NRG (Westinghouse)

In the 1980s, Westinghouse/ Alter NRG developed a process for the pyrolysis of waste materials. Currently, the company is represented on the market with plasma gasification plants with capacities between 40 and 620 Mg/d (municipal solid waste) respectively 30 to 540 Mg/d (hazardous waste). According to the supplier, utilization of pure oxygen as gasification agent allows capacities of up to 1,000 Mg/d. [Westinghouse 2013]

#### Technology

The gasification process as developed by Westinghouse / Alter NRG is based on a counter-current gasifier in which part of the required thermal energy is supplied by plasma burners. Temperatures within the plasma jet are between 5,000 and 7,000 °C, the mean reactor temperature is about 2,000 °C. The gasification reactor (figure 3.77) is a shaft furnace and is loaded with a coke bed before start-up. Coke supplies the energy needed to melt gasification residue. During operation, the waste feedstock is mixed with coke so that the latter makes up 4 % of the energy input [Heberlein 2008].

As can be seen in the figure below, there is no direct contact between plasma and waste in the reactor. Due to reactor layout, the plasma underneath the waste stack provides a high energy level, hereby promoting gasification reactions. [Wood 2013]

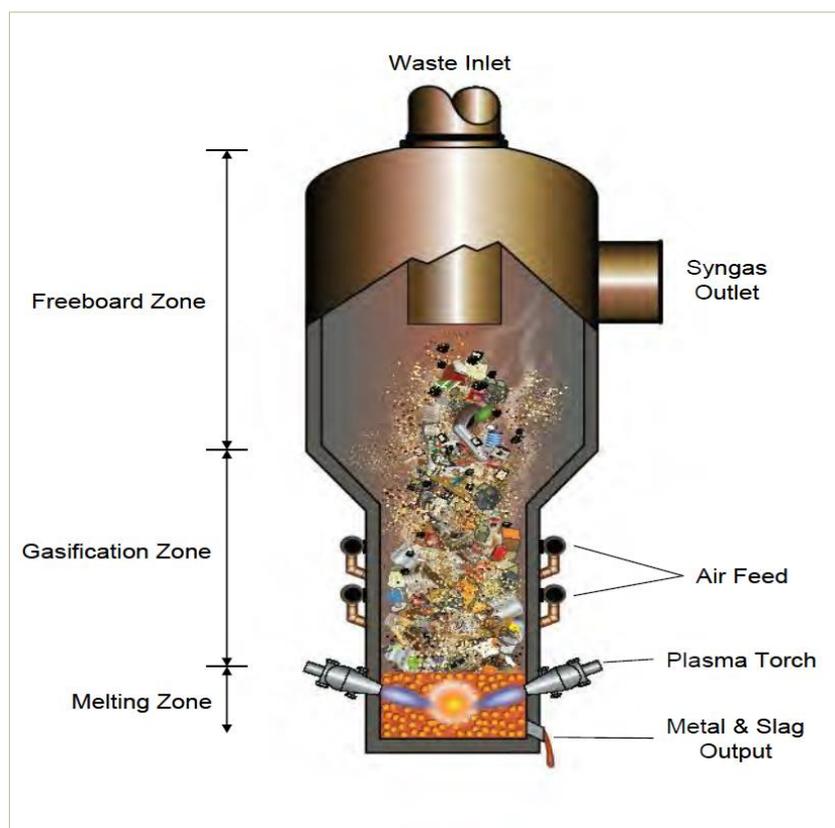


Figure 3.77: Alter NRG gasification reactor [Wood 2013]

Organic components of treated waste are converted into a high-energy synthesis gas. It leaves the reaction chamber in the upper area and is then cooled and purified for further utilization. Inorganic components are molten at high temperatures in the lower part of the reactor. This slag of about 1,650 °C is discharged at the bottom of the reactor. A long residence time in the device promotes complete decomposition of tars and prevents carryover of (soot-) particles. According to literature, the process is designed for a wide spectrum of input materials of heterogeneous

particle size and composition. It is operated with municipal solid waste (with and without conditioning), waste tires, shredder light fraction, biomass and hazardous waste. [Helsen 2010]

Purification of synthesis gas includes quenching, scrubbing with sodium hydroxide, an electrostatic precipitator and an activated carbon filter.

Inert waste components and metals are discharged as slag at the bottom of the reactor. Limestone is added and the slag is then cooled down abruptly with water causing formation of a fine-grained granulate. In literature, it is claimed that ferrous metals are recovered and that the inert fraction is used as construction material. This utilization is limited, depending on input material. [Helsen 2010]

A mass and energy balance of the Alter NRG plasma gasification process is given below. It was calculated in 2008 by the consulting company Juniper Consultancy and is based on operating parameters which were determined and supplied by Alter NRG. The balance refers to a plant with a capacity of 740 Mg/d of a mixture of municipal waste considered representative for the United States of America, together with 40 Mg/d waste tires.

Table 3.35: Mass- and energy balance of the Alter NRG plasma gasification process [Juniper 2008].

Mass Balance				Energy Balance			
Input	wt.-%	Output	wt.-%	Input	%	Output	%
Municipal Waste	62.3	Synthesis Gas	82.1	Waste	92.7	Synthesis Gas (sens.)	15.1
Waste Tires	3.5	Metals	5.5	Coke	4.2	Synthesis Gas (latent)	0.7
Steam	3.4	Slag	12.4	Limestone	-0.1	Synthesis Gas (chem.)	80.3
Coke	2.7			Air Preheating	1.2	Slag	0.2
Limestone	4.8			Electrical Energy	2.0	Loss	3.7
Air	20.0						
Plasma Gas (Air)	3.3						
<b>Sum</b>	<b>100</b>	<b>Sum</b>	<b>100</b>	<b>Sum</b>	<b>100</b>	<b>Sum</b>	<b>100</b>

Compared to conventional thermal waste treatment (incineration), the energy balance shows a lower demand of electrical energy. Other sources report a demand of 100 to 250 kWh/Mg waste respectively 312 kWh/Mg [Heberlein 2008, Ducharme 2010]. Initial assessment reveals that these values are significantly higher than those given by Alter NRG.

Since little information has been published on treatment costs in practice, it is referred to design data from literature at this point. In a study carried out at Columbia University based on the same data as given in table 3.35, cost calculations result in average treatment costs of 123 US-\$/Mg. Depending on the type of energy utilization, it can rise to 152 respectively fall to 105 US\$/Mg (75-100 €/Mg, exchange rate 04/2014). [Ducharme 2010]

Table 3.36: Average treatment costs of Alter NRG plasma gasification [Ducharme 2008].

Costs	US-\$/Mg
Personnel	10
Other Costs	32
Capital Expenditures and Other Costs (averaged)	81
Capital Expenditures and Other Costs (Steam Cycle)	63
Capital Expenditures and Other Costs (Combined Cycle)	110
<b>Sum</b>	<b>123</b>

## Development Status

According to Westinghouse/Alter NRG, there are currently three commercial plasma gasification plants and one demonstration plant in operation. The latter is operated by Alter NRG in Madison (USA) for research purposes. This facility with a capacity of 48 Mg/d serves to generate synthesis gas. According to the operator, more than 100 different waste fractions have been tested in this plant [Westinghouse 2013].

The biggest commercial plant is located in Utashinai (Japan) and was constructed in 2003 by Hitachi Ltd. It has a capacity of 165 Mg/d and is used to treat shredder light fractions from end-of-life-vehicles. The installation has two gasifiers and allows substituting the intended feedstock with 300 Mg/d MSW. Each reactor is equipped with four plasma burners with a power of 300 kW each. Air is used as carrier gas. The amount of coke and gasification agent varies with waste composition. Product gas energy is used in a steam process to generate electricity. [Heberlein 2008] According to Westinghouse, the facility has been closed down recently because of fuel shortage.

A second installation is located in Mihama-Mikata (Japan) and was erected by Hitachi Ltd. in 2002. Per day, 20 Mg municipal solid waste and four Mg of sewage sludge from surrounding communities are gasified. Generated synthesis gas is used to provide thermal energy for sewage sludge drying.

A third plant is located in Pune (India). It is operated by the company SMSIL, 72 Mg/d hazardous waste are gasified at this site.

### 3.3.2 C.H.O.-Power (Europlasma)

The company group Europlasma, consisting of INTERAM, TORCH & PROCESS, C.H.O.-POWER and Europe Environment, offers plasma burners and reactors for different applications. Plasma burners are based on the non-transferred arc generated by direct current between two electrodes. The offered capacity lies between 100 kW and 4 MW [Torchprocess 2013].

At the moment, Europlasma is on the market with three different products. One is the reactor to vitrify fly ash offered by Europlasma. Furthermore, the subsidiary companies INERTAM respectively C.H.O.-Power offer a process to vitrify waste containing asbestos respectively a two-stage process to gasify municipal solid waste [CHO 2014, Heberlein 2008]. Due to the focus of this report, the first two processes mentioned are only explained in brief whereas the C.H.O. process is described in greater detail.

#### Europlasma Melting Reactor for Incineration Residues

The technology to vitrify incineration residues developed by Europlasma is applied in several industrial size plants and was already installed in 1997 in a facility in Cenon (France). Inert vitrified product is primarily used as aggregate in road construction. The process is mostly applied in Japan to densify respectively vitrify fly- and grate ashes from waste incineration. Plants constructed in Japan were erected mainly in 2002 and 2003 in cooperation with local companies like Kobesteel and Hitachi Zosen. Another installation of this type is located in South Korea. [Torchprocess 2014]

The heart of the Europlasma process is a melting reactor in which a non-transferred arc operated with air supplies the necessary energy to melt ashes. The process was realized for an input of fly ash of 10 to 42 Mg/d. Depending on plant size, the specific energy demand ranges from 800 to 1,300 kWh/Mg treated material. Figure 3.78 shows the process setup. A downstream burning chamber is used for burnout of product gases.

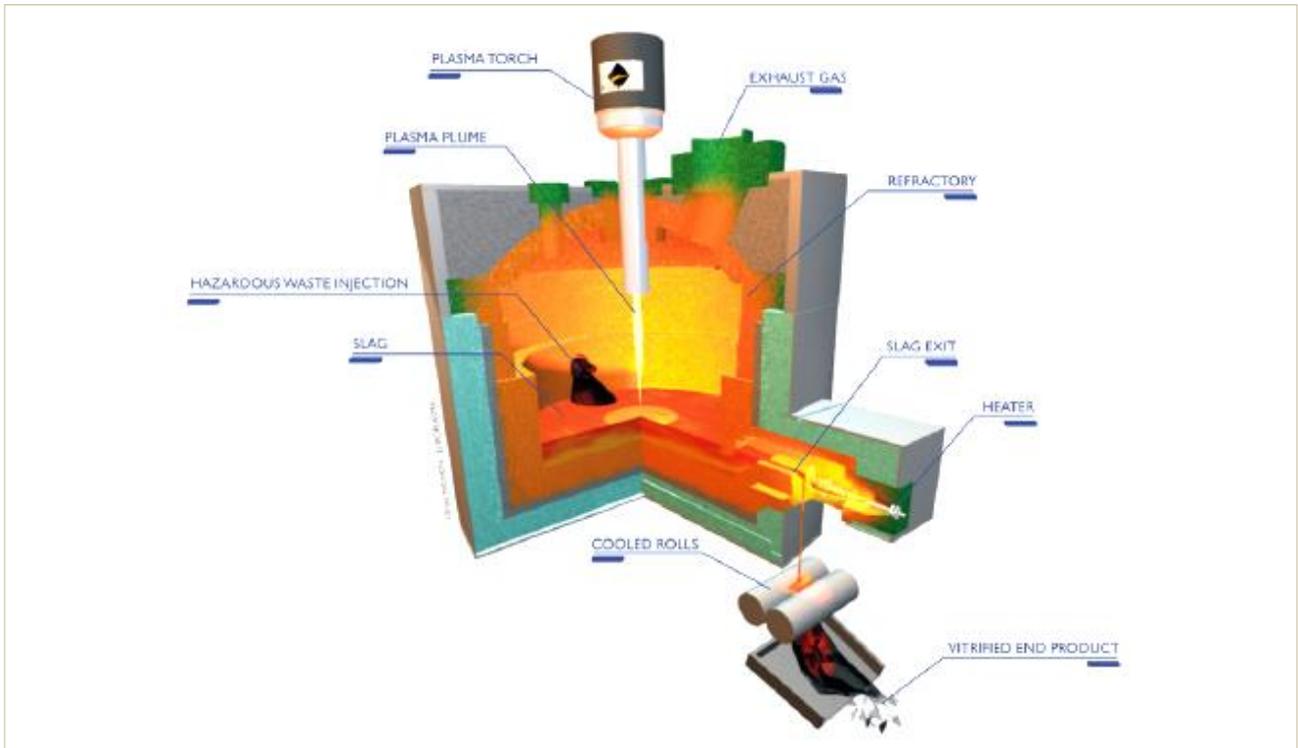
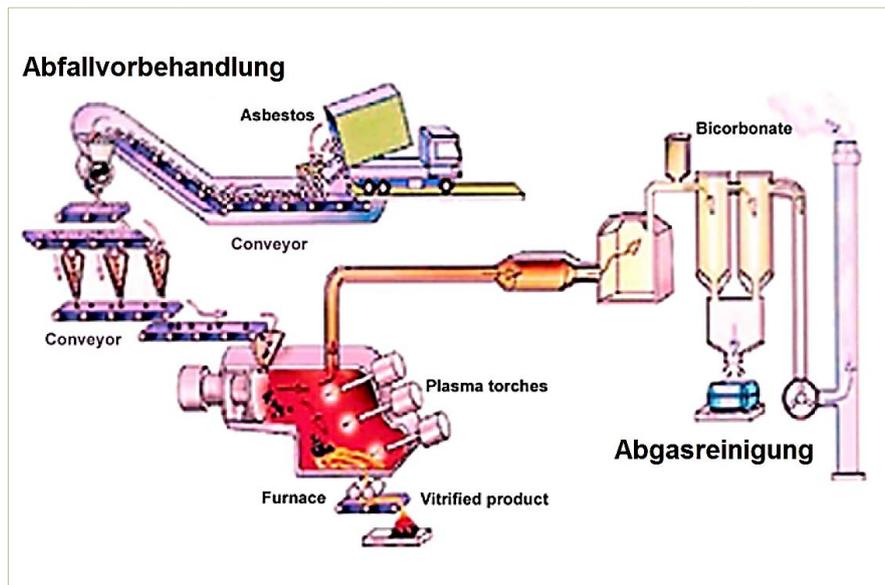


Figure 3.78: Melting reactor offered by Europlasma [Heberlein 2008].

### INERTAM Asbestos Vitrification

In Morcenx (France), INERTAM operates a plant to vitrify waste containing asbestos. According to the operator, this is the only installation of this kind. [Inertam 2014].



Energy is supplied to the melting chamber by three plasma burners installed at different heights (see figure on the left). The process is fed continuously with a maximum of 20 Mg input material per day. One of the plasma burners has a power of 0.5 MW, two have 2 MW each. The specific energy demand per Mg of waste containing asbestos is 1,300 kWh. Vitrified slag is discharged continuously and used in road construction. Process gases are converted in a downstream combustion chamber.

Figure 3.79: Asbestos melting reactor operated by Inertam [Heberlein 2008].

### C.H.O.-Power Municipal Waste Gasification

C.H.O.-Power is currently constructing a plant to gasify waste and biomass in Morcenx. It is designed for 37,000 Mg industrial waste and 15,000 Mg woodchips per year [CHO 2014]. The two-stage process (see figure below) is based on autothermal gasification with post-treatment of gasification products with plasma [Drechsler 2014].

### Technology

In the first stage, pre-sorted and shredded waste is gasified in a fixed bed on the grate. As shown in the figure below, the grate is divided into a drying and a gasification zone (idealized). Exhaust vapors from the drying zone are heated up in a waste heat boiler and returned to the grate. In a second treatment stage, synthesis gas and solid residue undergo separate post-treatment. Using thermal plasma, the synthesis gas is heated and cracked at temperatures of more than 1200 °C. Solid residue is molten in a second plasma chamber and discharged from the process.

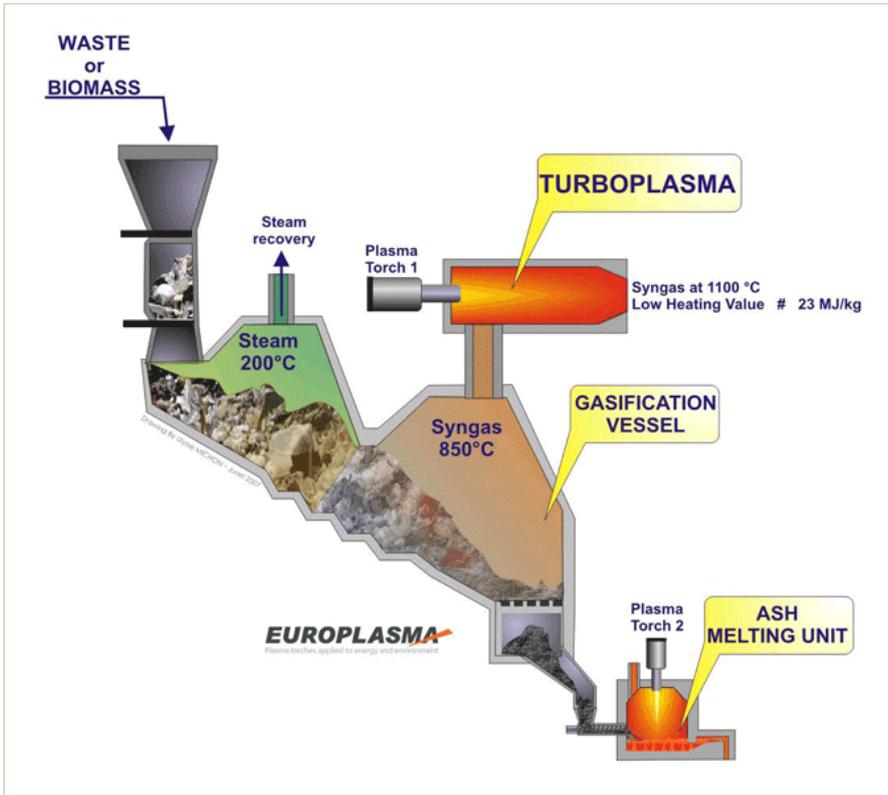


Figure 3.80: Two-stage gasification process as offered by C.H.O.-Power [CHO 2008]

Decomposition of complex carbohydrates using plasma is supposed to allow utilization of the gas in a gas turbine. With this cracking process called Turboplasma, a process which has been under development since 2009 is implemented at industrial scale. A waste heat boiler follows the Turboplasma-stage. Part of the heat recovered from synthesis gas is used to preheat the gasification air. This is supposed to allow quasi-autothermal operation of the complete process. Excess heat is available as useful heat [CHO 2014].

is used to preheat the gasification air. This is supposed to allow quasi-autothermal operation of the complete process. Excess heat is available as useful heat [CHO 2014].

### Operating Data

There have been no details published on the plant in Morcenx . Available literature to evaluate the process is based on data from a study by Credit Suisse for a planned site in New Jersey. This information refers to an industrial size plant with a yearly capacity of 122,400 Mg. Instead of biomass as used in Morcenx, in this plant 3 wt.-% waste tires are added to the waste feedstock. [Ducharme 2010] An energy balance derived from this data is shown in table 3.37. A mass balance is not available. An energy loss of 400 kWh per Mg of treated waste is calculated in the energy balance. It must be stated that the data given below has been collected for an economic analysis by a third party and has not been verified by the supplier itself.

Table 3.37: Energy balance of the C.H.O. gasification process according to [Ducharme 2008], [CHO 2014]

Input	[kWh/Mg Waste]	Output	[kWh/Mg Waste]
Municipal Solid Waste	2,800	Synthesis Gas (sensible)	400
Waste Tires	291	Synthesis Gas (chemical)	1,825
Electrical Energy Plasma	240	Process Heat	720
		Loss*	386
<b>Sum</b>	<b>3,331</b>	<b>Sum</b>	<b>3,331</b>

\*calculated as difference

In the survey commissioned by Credit Suisse, treatment costs of the process were projected to amount to about 149 US-\$/Mg waste (ca. 110 €/Mg).

Table 3.38: Average treatment costs of C.H.O. gasification process [Ducharme 2008].

Costs	US-\$/Mg
Personnel	10
Other Operating Costs	53
Capital Expenditures and Other Costs	86
<b>Sum</b>	<b>149</b>

### Development Status

Except for the testing plant to develop the Turboplasma process which was constructed in 2009, no other reference plant is known.

### 3.3.3 Advanced Plasma Power (Tetronics)

The British company Tetronics is represented on the market with plasma processes to treat respectively vitrify hazardous waste mono-fractions. Since 2005, Tetronics has been offering a plasma gasification technology under the name of Gasplasma via the company Advanced Plasma Power. This process is meant to gasify waste derived fuels from mixed waste. It is designed as two-stage process with a “conventional” gasification stage followed by a plasma converter used for post-treatment of synthesis gas, in order to crack organic compounds and tars contained in the gas. A pilot plant with a throughput of 100 kg/h has been operated in Swindon (United Kingdom) since 2008. [Tetronics 2014, Chapman 2013]

### Technology

The Gasplasma-process is shown schematically in figure 3.81. Waste derived fuel is converted with steam and oxygen as gasification agents in a stationary fluidized bed at temperatures of 750-850 °C. The air ratio of the gasification process is 0.3. In a downstream second gasification stage designed as plasma converter, complex organic compounds and tars are cracked at temperatures of more than 5,000 °C. The gas then leaves the converter at 1,000 to 1,200 °C and is cooled down to 200 °C. A gas purification to remove dust and acid gases follows. [Chapman 2013, Morrin 2012].

According to the provider, purified gas can be utilized either in a power plant or in a gas motor or - provided sufficient purification - in fuel cells. The pilot plant is equipped with a gas motor.

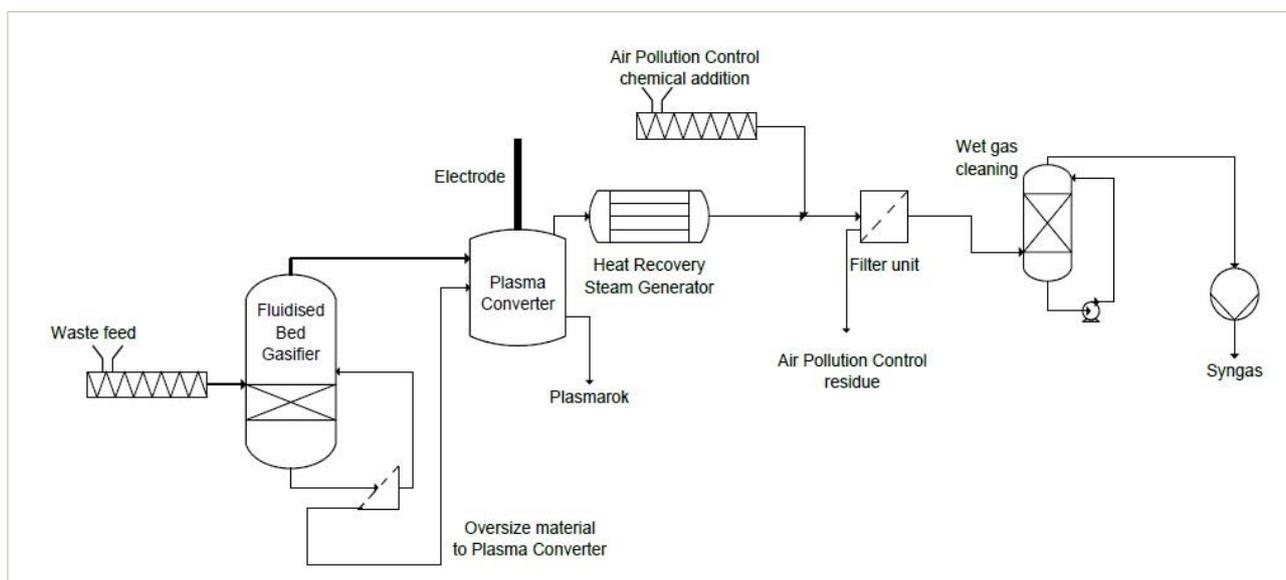


Figure 3.81: Process diagram of the two-stage APP Gasplasma Process [Taylor 2013].

The plasma converter resembles a cyclone. A large part of flue ash from the fluidized bed is separated here and molten by plasma. Gasification residue discharged at the bottom of the fluidized bed is also led to the plasma converter for post-treatment. Vitrified process residue called “Plasmarok” is supposed to be marketed.

### Operating Data

Operating data from the pilot plant is summarized in table 3.39. High shares of carbon monoxide and hydrogen from fuel gases are noticeable. This goes back to the use of pure oxygen respectively steam as gasification agents.

Table 3.39: Operating data of Gasplasma pilot plant.

Operating Parameter		Gas Composition	
Throughput	100 kg/h	CO	40%
Gasification Agent	O <sub>2</sub> /H <sub>2</sub> O	H <sub>2</sub>	37.5 %
Stoichiometry	0.3	CO <sub>2</sub>	15%
Gasification Temperature	750–850 °C	CH <sub>4</sub>	< 1 %
Gas Temperature in Plasma Converter	1,000–1,200 °C	H <sub>2</sub> O	3.2 %
Gas Temperature After Heat Exchanger	200 °C	N <sub>2</sub>	3.3 %
Carbon-Conversion Efficiency	93–97 %		

A rough mass- and energy balance was prepared by the process provider for an industrial size plant to treat 150,000 Mg/a residual waste [APP 2008]. These balances give an impression, yet they are only fragmentary. It is not possible to assess the reliability of this data.

There is no information available on process costs.

Table 3.40: Mass and energy flows for an industrial size APP Gasplasma plant [APP 2008]

Mass Balance [kg/Mg Waste]				Energy Balance [%]			
Input		Output		Input	%	Output	%
Municipal Waste	1000	Water (Drying)	200	Municipal Waste	100	Electrical Energy	37
		Oversize Material	65			Internal consumption	14
		Metals	65			Electrical Energy (net)	23
		Inert Material	65			Heat	47
		Slag	75			Heat Loss	30
		Flue Gas Cleaning Residue	10				
<b>Sum</b>	<b>1000</b>	<b>Sum</b>	<b>480</b>	<b>Sum</b>	<b>100</b>	<b>Sum</b>	<b>100</b>

Concerning the mass balance it has to be stated that municipal solid waste used in the process is conditioned as refuse derived fuel prior to the process. During conditioning, water, oversized material, metals and inert materials are already removed from the waste stream. Since there is no data available on gasification agents and operating resources, it is not possible to conclude the balance. The energy balance shows a comparably high electric efficiency concurrent with high heat loss.

### Development Status

Except for the pilot plant in Swindon, no further plant is known. According to the supplier, there are several projects under development aiming to implement the process on industrial scale. [APP 2014]

### 3.3.4 Plasco Energy (Phoenix Solutions Company)

The Canadian company Plasco Energy developed a two-stage process to generate synthesis gas out of pre-treated municipal solid waste. The process consists of a „classic“ gasification of waste in a fixed bed followed by one plasma stage intended for post-treatment of synthesis gas and one for post-treatment of gasification residue. The arrangement of process steps resembles the C.H.O.-process described above. Plasco Energy cooperates with the Phoenix Solution Company (PCS), one of the leading providers of thermal plasma systems. [Fabry 2013, PSC 2014].

### Technology

Prior to being used in the Plasco process, municipal waste must be conditioned (separation of inert material, shredding). Conditioned material is fed to the first gasification stage, a conversion chamber with sloping floor. Air is used as gasification agent and flows through the floor from below. [Ademe 2009, Plasco 2011]. To provide the necessary energy for gasification, the air is heated up in a heat exchanger located within synthesis gas conditioning. Hence, process temperatures are higher than 800 °C. In the second stage, synthesis gas and gasification residue are separated for post-treatment. Using thermal plasma, the gas is heated up to more than 1,200 °C and complex carbohydrates contained in the gas are cracked. Solid residues are molten in a second plasma chamber and discharged from the process. Organic compounds from the first process step are converted completely. Mineral waste components are molten and vitrified. Gas purification is located downstream the plasma stage. Purification includes dust removal, removal of heavy metals, cooling and scrubbing. Purified synthesis gas is used to generate electricity in a combustion motor. [Ademe 2009, Plasco 2014] The gasification process is shown in figure 3.82.

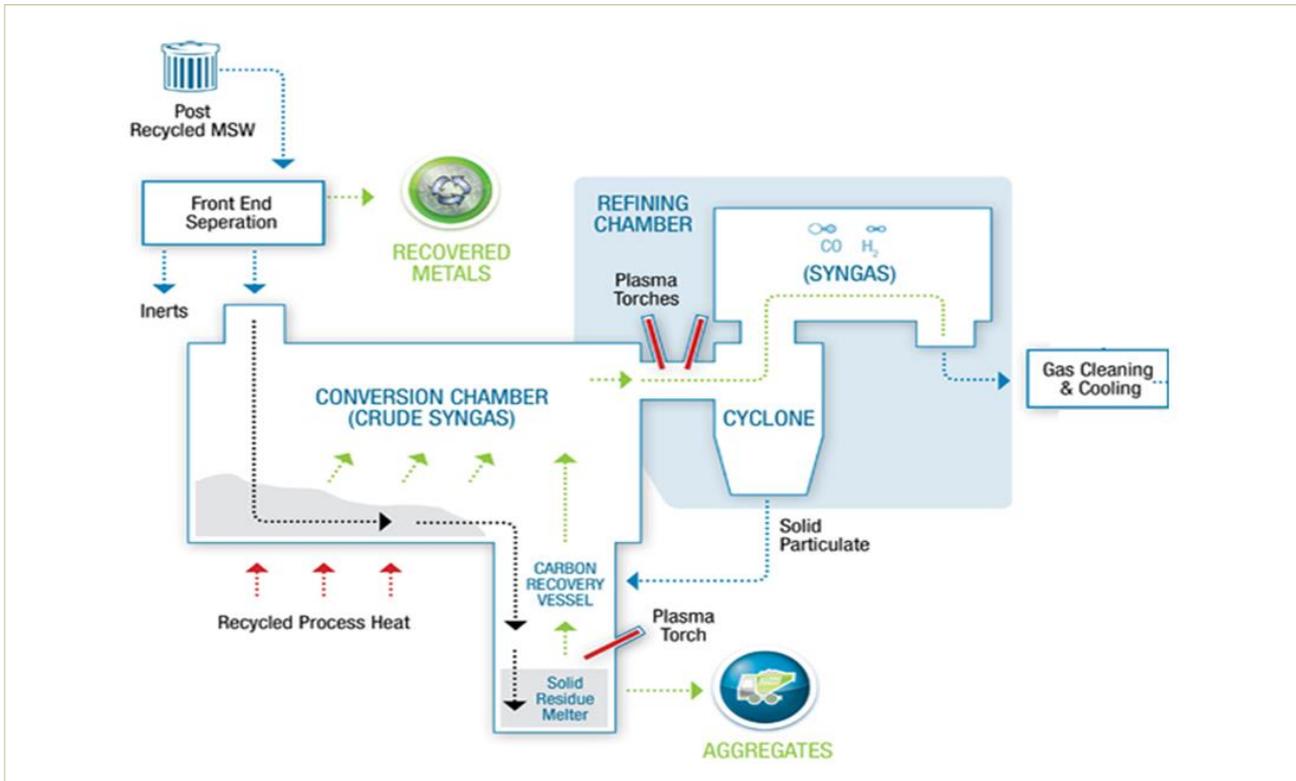


Figure 3.82: Schematic view of Plasco conversion process [Plasco 2014].

**Operating Data**

So far, the Plasco process has not been implemented on commercial scale. Concerning energy output, data on chemical energy in the gaseous phase and on electrical energy in case of conversion into electricity is available. Possibilities of energy conversion are not known in detail.

Information given in table 3.41 has been derived from company documents referring to a demonstration plant with a nominal capacity of 85 Mg/d. A brief description of this installation can be found further below under “Development Status”. Due to incomplete data available from the provider, materials and energy could not be balanced. This accounts especially for the required amount of both gasification agent and process energy.

Table 3.41: Mass and energy flows Plasco-process [Aitkin 2008, Plasco 2008]

Mass Balance [kg/Mg waste]				Energy Balance [kWh/Mg input]			
Input	kg	Output	kg	Input	kWh	Output	kWh
RDF	1.000	Synthesis Gas	n/a	RDF	4.583	Synthesis Gas (chem.)	3,502
		Slag	150			alternatively: Electricity	1,400
		Condensate (Water)	300				
		Residue Flue Gas Purification	13				

Independent studies show that the net energy output is significantly lower than claimed by the process provider [Best 2008]. Treatment costs listed in table 3.42 are based on the demonstration plant described below. Predicted costs of 149 US-\$/Mg treated waste are on the same level at those published by the competitor Europlasma.

Table 3.42: Average treatment costs Plasco process [Ducharme 2008].

Costs	US-\$/Mg
Personnel	10
Other Operating Costs	43
Capital Expenditures and Other Costs	86
<b>Sum</b>	<b>149</b>

### Development Status

The Plasco process has been operated at the „Trail Road“ site in Ottawa since 2006 on a landfill site and in cooperation with public authorities. The facility was designed for a nominal throughput of 85 Mg/d refuse derived fuel with a net electricity generation of 1.4 MWh/Mg RDF. After start-up, the average throughput was 4.5 Mg/d and therefore clearly below the intended throughput. Electricity generation (0.06 kWh/Mg waste) clearly missed the target as well. Another plant with a nominal throughput of 5 Mg/d has been operated in the Spanish Castell Galli since 2003. This installation served inter alia for the design of the Trail Road facility.

## 3.4 Liquefaction Processes

Liquefaction processes are designed to generate a product oil comparable to fuel oil or diesel. Industrial size plants to produce fuel oil or diesel in permanent operation do not exist so far. Statements concerning economic figures are therefore solely based on planning data. Besides economic feasibility, especially smooth permanent operation for weeks or months still has to be proved.

Hydrocarbons should be the predominant component of the product oil. Compared to other waste treatment processes, the range of possible input materials is very limited. Extensive processing of input materials is essential. Suitable input materials can be polyolefins (e.g. PE, PP, PF) respectively waste fractions with a high share of these plastic materials or compounds containing oil (e.g. waste oils). Some of the processes claim to allow a wider spectrum of input materials (e.g. biomass). Yet, this is doubted in literature [Behrendt 2006, Willner 2009]. Acceptance criteria for input materials are low water and ash contents (in the lower single-digit range at the most) as well as defined particle size.

Pilot plants to obtain oil from waste fractions have mainly been using tube reactors in recent years. At comparably low temperatures ranging from circa 250 to 420 °C, input material is converted at low underpressure. Uniform temperature distribution is highly important to prevent coke generation. Inside the reactor, an oily phase promotes mixability of input materials, a high heat-up rate and uniform temperature distribution within the reactor. Processes considered in this report vary mainly in the type of heat input, mixing of the oily phase and application of catalysts.

In the Alphakat-process, heat is generated in the plastic-oil-mixture by friction caused by turbines. At the same time, these turbines provide for uniform temperature distribution. A catalyst is supposed to increase oil yield. The effectiveness of catalysts could not be proved on laboratory scale [Willner 2009]. Nevertheless, the operators claim to see a positive effect of catalysts in pilot plant operation. Installations are offered by Recenso GmbH (formerly Alphakat Engineering GmbH) and Alphakat GmbH. A visitation of the Dieselwest plant (Recenso) in Ennigerloh (Germany) took place in February 2014.

The Logoil-process is intended for integrated treatment solutions of biologically contaminated waste, for example from the health care sector. In this process, too, catalysts are used. A

planned visitation could not be carried out since the company had to move on short notice because of official requirements.

The Clyvia process, operated between 2006 and 2009, uses a stirring reactor with external heating. Inside the reactor, a mixer is located which is equipped with scrapers to prevent deposition of coke. Since Clyvia proved the ineffectiveness of catalysts in laboratory tests, there are no catalysts used in this process. Ever since the insolvency of the Clyvia Technology GmbH, there has been no further activity by the current owner DEPO Anlagenbau UG. [Franz 2008]

Based on the Plastoil-plant constructed by Nill Tech GmbH in 2006, two similar processes are currently being offered under the name Plastoil respectively Synthrol. The system is made up of three stirring reactors connected in series. They are heated using pipes filled with heat transfer oil. Catalysts are not used. It was not possible to visit a functioning facility.

To date, no industrial size plant for high pressure hydrogenation of waste fractions is operated. High-pressure hydrogenation goes back to processes for liquefaction of oil started in the twenties of the last century with process design according to Bergius and Pier. A further development of this process started to operate in Bottrop (Germany) in 1981. From 1993 to 1999, plastic waste from the Duales System Deutschland (DSD, also known as Green Dot) was successfully hydrogenated in this plant (capacity 80,000 Mg/a). Treated material had a PVC content of up to 4 %. In the first process step, waste was depolymerized and HCl originating from PVC-rich fractions was separated. In the following VCC reactor (Veba Combi Cracker), hydration was carried out at 400 to 450 °C and a pressure of about 100 bar. Process products were synthetic crude oil, HCl, solid residue (for coke production) and gaseous hydrocarbon. Since economic operation was not possible, the plant was closed down in 1999. According to [Tukker et al. 1999], an acceptance price of 250 € was assumed for further calculations.

### 3.4.1 Dieselwest

The Dieselwest process is a catalytic depolymerization process. The plant is based on a demonstration plant which was operated with electrical and electronic waste recycling in Barrie (Canada) between 2007 and 2012 and constructed by Recenso GmbH. The Dieselwest plant in Ennigerloh (Germany) has been operated since 2012. This test plant is used to research suitability of diverse input fractions as well as to advance technology development. According to the operator, the aim is to prove cost effectiveness for liquefaction of refuse derived fuel produced on site.

#### Technology

Figure 3.83 shows a view of the plant and a process flow chart. According to the operator, refuse derived fuel, mixed plastics, sunflower husk, wood-plastic composites (WPC) and rapeseed meal have been tested successfully as input material. Prior to the reactor, a catalyst based on aluminum-silicate and iron oxide for sulfur fixation are added to the input material. Input material with a grain size of less than 30 mm and free of ferrous and non-ferrous metals is conveyed with a screw. To prevent oxygen intake, the reactor is separated from the surrounding atmosphere by a lock system purged with nitrogen. The reactor operates according to the principle heavy oil sump phase at a temperature of circa 320 °C. Before start-up a “start-up oil” has to be filled into the reactor. This oil is supposed to be consumed only at the same ratio that new oil is generated from the input material.

The process is powered by electrically driven turbines (figure 3.84) which keep the sump phase in rotation in order to provide for a uniform temperature distribution. In order to prevent destruction of the turbines, reliable complete removal of metals from the input material is of particular importance. At operating temperatures, the reaction product is in the gaseous phase. It passes a column. Currently, only the overhead is discharged. It is then condensed and dewatered. Small amounts of non-condensables are burned in a regenerative thermal oxidizer. A

mixture of solid material and catalyst is discharged regularly using a pumping system located at the reactor sump. In a settling tank, separated from the reactor by a lock, the solid-catalyst mixture is separated from the oily phase, which is then recirculated.

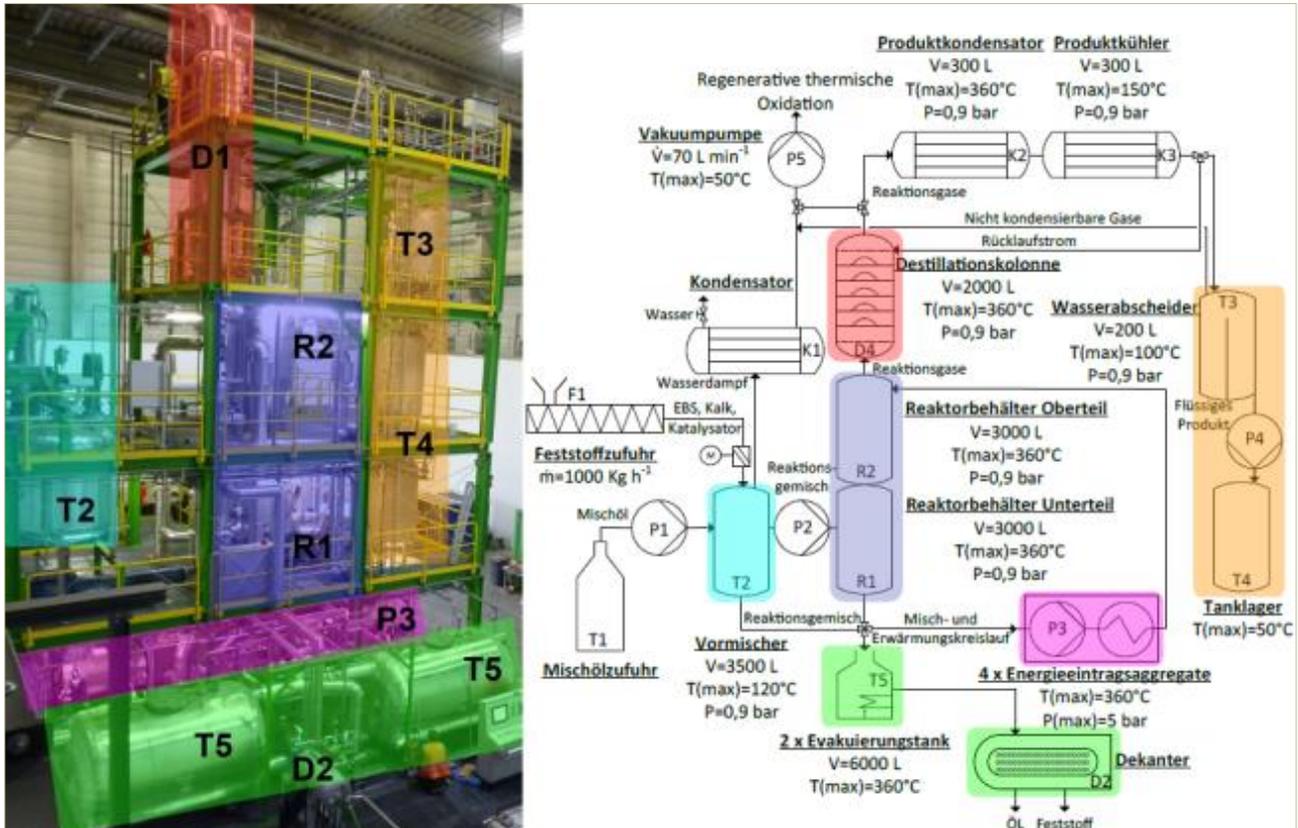


Figure 3.83: Dieselwest plant (left) and flow chart [Wiezorkowski 2012].

### Operating Parameters

The intended production output of the installation is at least 375 l/h. Currently, an oil production of 100 to 200 l/h is achieved in the development plant. The longest period of uninterrupted operation was a 23-day test campaign. Yet, the intended oil yield as given in table 3.43 could not be achieved. The operator specifies an energy demand of 2.5 kW<sub>el</sub> per liter oil produced. According to the operator, a complete mass balance is not yet available. The high amount of start-up oil involved in the thermochemical processes or even dominating these makes it difficult to determine the mass balance. Operating data of the plant can be seen in table 3.43.

Table 3.43: Operating data of the Dieselwest plant

Reactor Parameters		Products	
Filling Level	50 %	Gas	not recorded
Temperature	320 °C	Liquid	400 l/Mg
Residence Time	3 min	Solid	10-15 %
Underpressure	50 – 100 mbar (rel.)		
Additive	Fe <sub>2</sub> O <sub>3</sub> (Sulfur Fixation)		
Catalyst Quantity	3 % of Input		
Oil yield	100-200 l/h		

## Product Properties

Product oil mainly consists of the distillable fraction of the gasoil. Specifications are not according to EN 590 for diesel fuels. For example, sulfur and water contents significantly exceed the limits, depending on input material. During our visitation, a sample was taken and analyzed. Selected results are listed in table 3.44. The product oil sample segregated into three different liquid phases, which could be separated in the separatory funnel: an oily light fraction (12 wt.-%), a hydrous medium phase (81 wt.-%) and an oily heavy fraction (7 wt.-%). Figure 3.85 shows the three segregated phases. The sulfur content of the oily light fraction and the heavy fraction is significantly higher than values given in EN 590. High nitrogen content of all oil fractions, especially the heavy fraction, is striking. Low values from input analysis (see table 3.44) make clear that this nitrogen cannot originate from the starting material. It is assumed that nitrogen is introduced with the starting oil which is filled into the reactor before start-up.



Figure 3.84: Left: reactor of the Dieselwest plant with feeding screw which conveys feedstock beneath the surface of the reactor filling, a mixture of oil and solids; right: turbines for energy supply

Table 3.44: Laboratory analysis of Dieselwest samples

Parameter	Unit	Educt (WPC)	Light Fraction	Medium Fraction*	Heavy Fraction
Mass Fraction	wt.-%	-	12	81	7
Density	kg/m <sup>3</sup>	-	0.83	1.01	1.04
Net Calorific Value	kJ/kg	29,710	43,150	6,580*	27,900
Sulfur	wt.-%	< 0.05	0.25	< 0.05	0.26
Nitrogen	wt.-%	< 0.1	0.2	0.65	1.86

\*Determination of the net calorific value of the medium fraction was problematic due to high water content. After tenfold determination, the given value is considered as realistic.

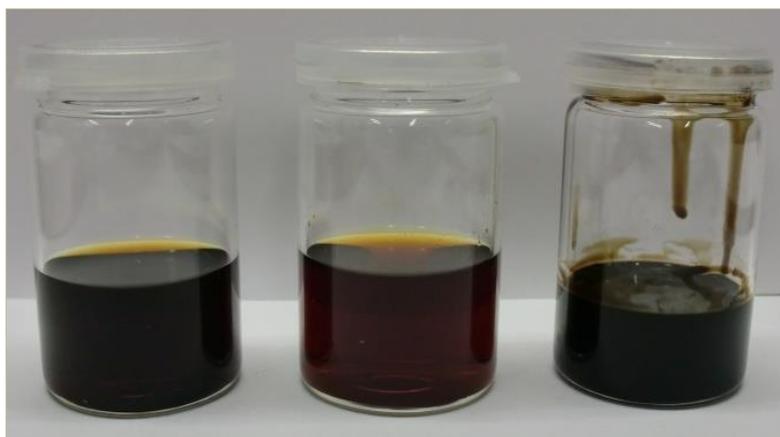


Figure 3.85: Liquid products from Dieselwest plant. Left: light oil, middle: aqueous phase, right: heavy oil (own pictures)

### Costs and Development Status

The plant in operation serves for further development and maturing of the process. Cumulated run time sums up to circa 4,000 hours with a throughput of more than 1,000 Mg input material. To achieve profitably operation, throughput respectively oil yield would have to be increased. In permanent operation mode, the operator projects production costs of 0.5 €/l liquid product. Assuming an oil production of 400 l per Mg of input material, this implies treatment costs of around

200 €/Mg. Whether functionality of the plant is given in long-term operation and with which input material this can be achieved has yet to be proved.

Surveys on KDV, the technology on which the Dieselwest process is based, assume that the process can only be operated with plastic fractions. Operation with biomass is only considered to be possible as long as start-up oil is available as reacting agent [Willner 2009].

Intended application for the oil are cement kilns, heating plants, utilization in combustion plants in the public or farm sector or in combined heat and power plants. In addition, conditioning of product oil in order to blend it with other liquid fuels is planned.

According to the operator, internal and external tests have proved conversion of biomass.

### 3.4.2 Logoil

The Logoil technology is a catalytic depolymerization of plastic fractions. Until the end of 2013, a demonstration plant with a capacity of 600 Mg/a was operated in Halle, Germany. It is intended to operate the process again after reconstruction at a different site.

#### Technology

Logoil plants are offered in container design. These small-scale plants are meant for decentral applications. Plastic waste materials rich of polyolefins are used as input material. It can be combined with a “Logmed-Plant” to condition of input material and is then supposed to be applicable for highly infectious waste (e.g. hospital waste).

Pre-treatment of input material requires:

- Shredding
- Thermal disinfection with saturated steam at 110 °C if necessary
- Density separation by float/sink separation to remove disturbing materials like non-convertible plastics or metals
- Drying

Processed polyolefins have a grain size of 30 to 60 mm, a water content of less than 10 %. They are converted using a zeolite catalyst at temperatures of circa 360 to 380 °C.

## Operating Parameters

Table 3.45 shows operating parameters of the Logoil plant. Product oils and gaseous hydrocarbons pass through a distillation column and are separated into several fractions. Waxes and solid residues are discharged at the bottom of the reactor. The reactor is heated with electrically driven turbines.

Table 3.45: Operating data Logoil plant

Reactor Parameters		Products	
Temperature	360-380 °C	Gas	10-15 %
Residence Time	ca. 7 to 9 min	Light, Medium, Heavy Oils	50-75 %
Pressure	atmospheric	Wax	10-40 %
Additives	zeolite catalysts	Solid (Sump/Sand)	3-5 %

## Costs and Development Status

The Logoil demonstration plant serves to evaluate input materials and to adapt and optimize the process. According to the manufacturer, cumulated operating time amounts to 5,000 hours with an overall throughput of 160 Mg. Treatment costs range from 25 to 39 €/Mg waste. Depending on input material, the main product share is a product that lies in the boiling range of gasoil (more than 50 %), followed by smaller amounts of low-boiling liquid hydrocarbons (up to 15 %) and gaseous hydrocarbons (up to 15 %). A complete analysis of the product oil according to EN 590 is not available. Single analysis shows that sulfur contents exceed limits given by the standard.

## 3.5 HTC Process

HTC-processes are only suitable for biogenic waste like sewage sludge or biowaste. Treatment of municipal solid waste with these processes is not reasonable. Therefore, offered process concepts are not explained in further detail. Instead, the general stage of development is described. Table 3.46 shows a list of all suppliers active in the market.

Table 3.46: Suppliers of hydrothermal waste treatment processes (list is not exhaustive).

Supplier	Internet Address
Artec Biotechnologie GmbH	<a href="http://www.artec-biotechnologie.com">www.artec-biotechnologie.com</a>
AVA-CO2 Schweiz AG	<a href="http://www.ava-co2.com">www.ava-co2.com</a>
CS carbonSolutions Deutschland GmbH	<a href="http://www.cs-carbonsolutions.de">www.cs-carbonsolutions.de</a>
Grenol GmbH	<a href="http://www.grenol.de">www.grenol.de</a>
Ingelia	<a href="http://www.ingeliahtc.com">www.ingeliahtc.com</a>
KWT Rosenkranz GmbH	<a href="http://htc-anlagenbau.de">htc-anlagenbau.de</a> , <a href="http://www.dampfturbinenkraftwerk.de">www.dampfturbinenkraftwerk.de</a>
SmartCarbon AG	<a href="http://www.smartcarbon.eu">www.smartcarbon.eu</a>
SunCoal Industries GmbH	<a href="http://www.suncoal.de">www.suncoal.de</a>
TerraNova Energy GmbH	<a href="http://www.terranova-energy.com">www.terranova-energy.com</a>

Figure 3.86 shows fundamentals of the HTC process with main products and residues. Besides the main product “HTC coal”, a significant amount of waste water, which is highly polluted with organics, is generated and has to be treated. Also, generated permanent gases and exhaust air from dewatering and potentially dispensable drying must be purified (see chapter 2.3.3).

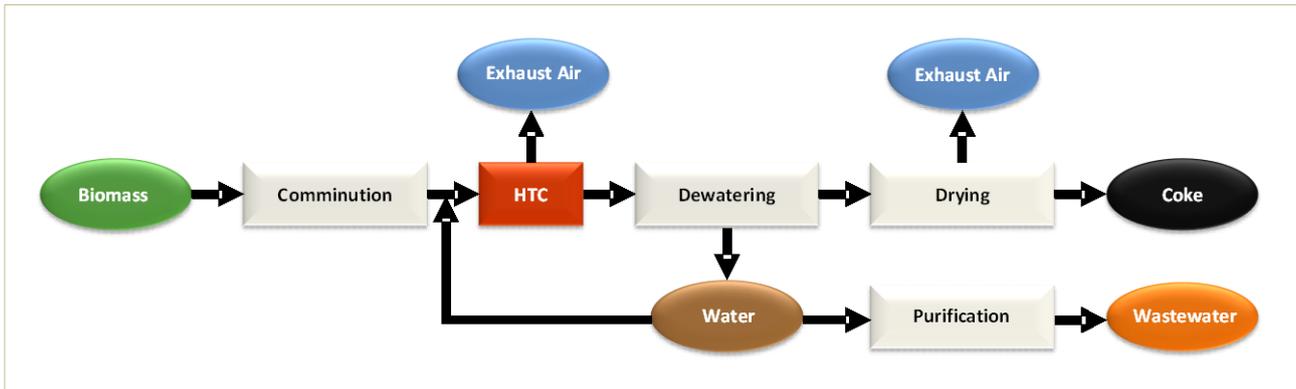


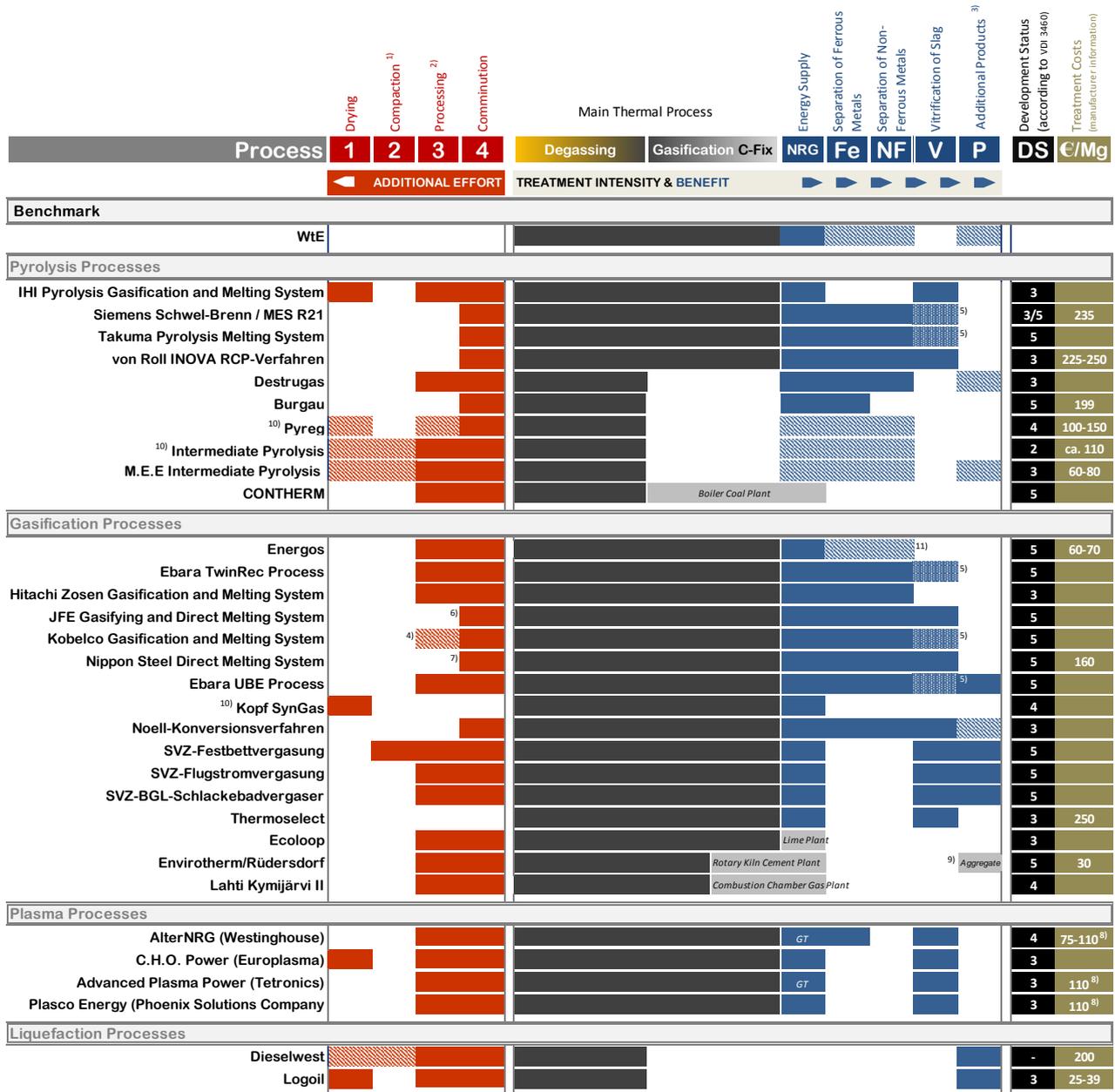
Figure 3.86: Basic scheme of hydrothermal carbonization, adapted from [Clemens 2011], translated.

One positive effect of hydrothermal treatment is the improved dewaterability of treated materials. Dry matter contents of more than 60 % have been reported [Buttmann 2011, Ramke 2011]. The process could therefore be suitable as alternative pre-treatment process prior to thermal utilization, especially for sewage sludge and wet bio-waste. In the end, comparing the energy efficiency of both pathways would be the crucial point here. Buttmann (2011) gives an energy demand of 1,700 MWh (of which 324 MWh are electrical energy), or 212 kWh/Mg input material. This is specified for operation of a HTC plant applying partially stabilized sewage sludge (DM content 23 %) with 7,200 operating hours per year and a carbonization product with a dry matter content of 90 %. In this case, the energy demand amounts to 23 % of the generated carbonization product (7,260 MWh/a). The energy demand for a purely thermal drying from 23 to 90 % dry matter content would be more than twice as high [Buttmann 2011].

At present, there is no HTC-process in permanent operation on industrial scale. A number of semi-industrial scale test plants exist, yet they are only operated in campaigns in order to test input materials or to improve process technology. Generally, facilities are only made up of the process core: a carbonization unit, usually connected to a dewatering stage. A complete process chain including treatment of all material flows (waste water, exhaust air) is usually not implemented.

### 3.6 Summarized Process Overview

Table 3.47: Intensity of treatment, costs and development status of considered processes.



- LEGEND**
- Takes place within the thermal process
  - Pre-treatment optional (depending on educt properties)
  - Optional benefit (e.g. by conditioning and combustion of pyrolysis coke, upgradable with metal separation)
  - In subsequent installation
- <sup>1)</sup> usually briquetting / pelletization
  - <sup>2)</sup> separation of metals and inert materials; fractionation
  - <sup>3)</sup> e.g. liquid fuels
  - <sup>4)</sup> processing necessary for commercial waste; MSW only requires comminution
  - <sup>5)</sup> only vitrification of fly ash
  - <sup>6)</sup> maximum edge length of 600 mm, no other pre-treatment necessary
  - <sup>7)</sup> maximum edge length of 800 mm required
  - <sup>8)</sup> conversion of US-\$ in €, Kurs vom 10.04.2014: 1 €= 1,3858 US-\$, rounded
  - <sup>9)</sup> mineral fraction embedded in cement clinker
  - <sup>10)</sup> only for special fraction
  - <sup>11)</sup> realized by external service provider in Minden

## 4 Evaluation and Discussion

In the introductory part of this chapter, country specific and regional frameworks under both political and social aspects are discussed. These conditions have major influence on waste management including the implementation of processes. Without knowledge of these conditions, it is not comprehensible why certain processes can be operated successfully over long periods of time in some regions while - under different conditions - the same process fail in other regions.

### 4.1 Political and Societal Framework of Waste Treatment

When looking at waste management all over the world, considerable differences occur not only concerning the stage of development but also in both administrative and organizational framework. First, it has to be stated that the distribution of thermal treatment processes is limited to only a few regions. According to Lamers (2013), four geographic regions can be identified:

- Europe, especially Germany, Scandinavia (Norway, Sweden, Denmark), the Netherlands, Italy, France, Great Britain  
→ approximately 500 plants
- United States of America  
→ approximately 75 plants
- Japan  
→ more than 1,000 plants
- China and South Korea  
→ approximately 120 plants, number growing strongly

According to [Döring 2014], circa 2,200 installations for thermal treatment of about 255 million Mg of waste per year exist worldwide.

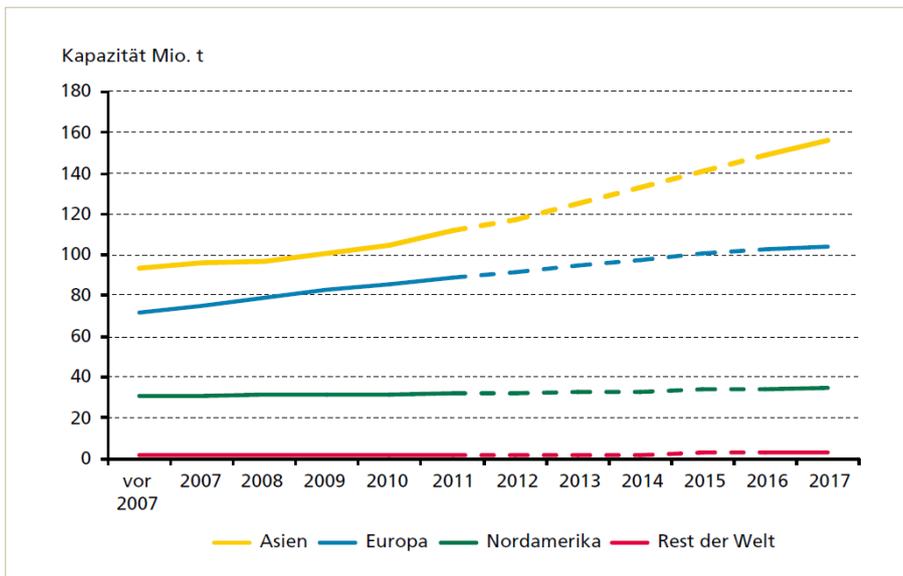


Figure 4.1: Worldwide development of capacities for thermal waste treatment [Döring 2014].

So far, alternative processes have only been implemented and permanently operated in larger numbers in South East Asia, especially in Japan. In other regions, long-term operation of facilities of this kind is the exception, despite a high level of interest.

The adjacent figure shows the development of worldwide capacities in recent years and a forecast of future capacity development, listed separately for Asia, Europe, North America and the rest of the world. The expected capacity increase in Asia is clearly visible. Europe, too, will see significant growth, when Southern and Eastern European countries adapt to Central European standards in waste management in the course of further implementation of the European Landfill Directive. In the other regions, little increase in capacity is expected at the moment [Döring 2014].

capacity increase in Asia is clearly visible. Europe, too, will see significant growth, when Southern and Eastern European countries adapt to Central European standards in waste management in the course of further implementation of the European Landfill Directive. In the other regions, little increase in capacity is expected at the moment [Döring 2014].

### 4.1.1 Europe

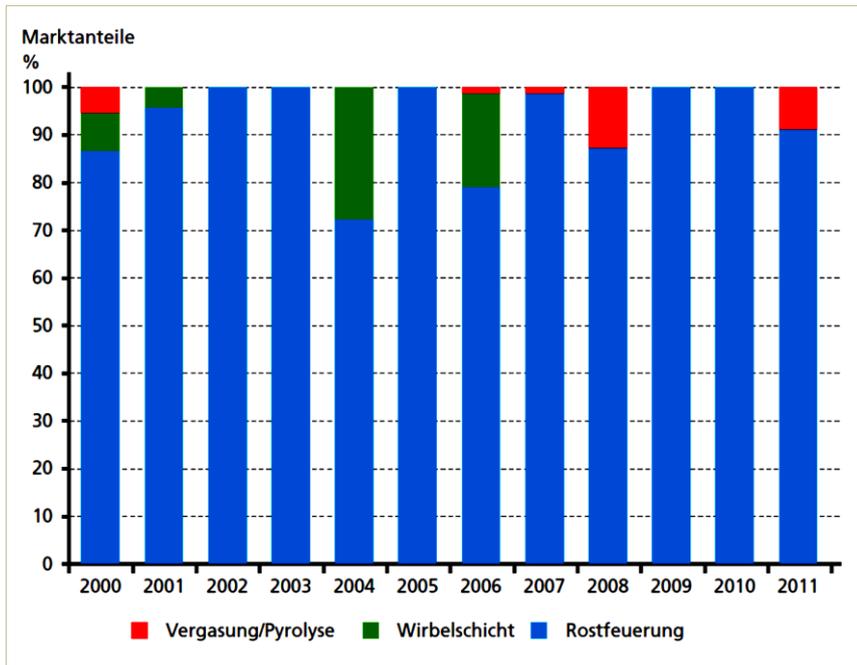


Figure 4.2: Market share of processes in newly built thermal waste treatment systems in Europe in recent years, according to [Martin 2013].

Thermal waste treatment in Europe usually refers to incineration with very few exceptions (see adjacent figure). Yet, incineration technology and - industry have a negative image in Europe. Obviously, this goes back to environmental scandals in the last century.

Waste incineration is widely accepted in Northern and Central Europe (i.a. Scandinavia, Benelux, Germany, Austria and Switzerland) despite many doubts and public protest. On these grounds, nationwide treatment capacities have been created. Yet in other European regions, waste incineration is considered old-fashioned and out of

date. Social desire and the political pressure driven hereby are sometimes so strong, that technologies are rigorously implemented even though they have not been tested to any great extent and may even be questionable considering objective criteria. A large number of abandoned projects, unfinished buildings and failed investments in Germany and other nations support this statement.

Nevertheless, the official policy of the European Union favors alternative processes. In a press release by the European Commission in February 2014 on the occasion of granting European investment aid of 15 million € for the project Lahti II (see chapter 3.2.4.4), it is stated that (regarding gasification): „Its commercialization would provide a more efficient option for waste-to-energy plants in the EU“ (Joaquín Almunia, vice president of the commission and commissioner responsible for competition), and elsewhere in the text: „The Commission [...] found that gasification allows for a cleaner and more efficient recovery of energy from waste than traditional techniques. In particular, it allows for a more efficient generation of energy and a better power-to-heat ratio.“ [Colombani 2014]

These citations, which are worthy of scientific discussion, prove that a new wave of investments for alternative treatments can be expected at least in some European regions. However, these processes have to compete against incineration costs of between 25 €/Mg waste on the open Scandinavian market and 100 €/Mg on the state-protected Belgian market before they can be successfully placed on the market [Lamers 2013]. The same applies for operating periods of partly more than 7,500 h/a as requested in Europe.

#### 4.1.1.1 Germany

Efforts to introduce alternative processes for thermal treatment in Germany, preferably with higher efficiency and optimized product properties, go back to the 1970s and are associated with the emerging environmental awareness and the energy crisis. A large number of pyrolysis projects goes back to these efforts, so that in the beginning of the 1980s more than 10 industrial

scale pilot plants with a throughput of several Mg per hour were operated in Germany [Pruckner 2008] (see figure 4.3). Of these sites, only the Burgau plant is still in operation today.



Figure 4.3: Industrial scale pilot plants for waste pyrolysis in Germany at the beginning of the 1980s Goldshöfe, Ulm-Wiblingen, Bernau (top, from left to right), Eilenburg and Salzgitter (bottom, from left to right) [Pruckner 2008].

The further development of alternative thermal processes in Germany is marked by the failure of the Siemens Schwel-Brenn process and the Thermoselect process. Besides the RCP process, these were the only processes that were implemented on industrial scale in Germany (see figure 4.4). Both processes promised significant benefits in comparison to waste incineration. This is exemplified by the front page of the journal “Umweltpraxis” dating from 2003 that is shown below. The Thermoselect process - which was already being discussed among experts at that time - is displayed as quasi all-embracing waste treatment technology, underlining the fascination processes of this kind brought on in public and media.



Figure 4.4: Industrial size plants for alternative thermal waste treatment in Germany left to right: Siemens Schwel-Brenn plant in Fürth (operated 1997-1999), Thermoselect plant in Karlsruhe (1999-2003), RCP plant in Bemerhaven (1998-2005) [Vaccani 2014].

Looking back it must be stated that discussed process advantages could not be verified in industrial application. On the contrary: contracted performance targets were not met and thus plants were shut down.

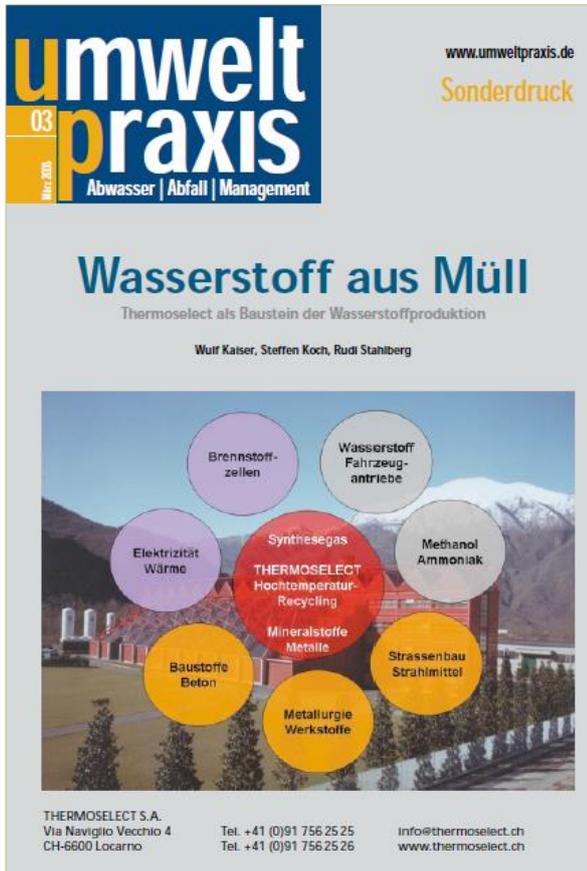


Figure 4.5: Front Page of the Journal „Umweltpraxis“ praising the ThermoSelect process, March 2003.

Even technologically successful processes like waste gasification in the Secondary Recycling Center Schwarze Pumpe (SVZ; see chapter 3.2.3) could not prevent failure of alternative thermal waste treatment technologies in Germany. Here, former lignite gasification facilities, which could only be built and operated under the conditions of the planned economy in the German Democratic Republic, had been retrofitted at the beginning of the 1990s and were successfully operated for several years with conditioned waste as feedstock. Despite the high-quality product methanol, economic production could not be achieved and after two insolvencies, the plant was closed down in 2004.

Despite current overcapacities, time and again new alternative thermal processes are developed, offered and implemented in Germany. Fascination is unbroken so that investors again and again sponsor new projects. However, and partly because of certain overcapacities, there is no significant market effect to be expected.

#### 4.1.1.2 Great Britain

The situation in Great Britain is very different to that in Germany. Even though waste incineration was developed in this country and more than 200 waste incineration facilities existed around 1900 [de Fodor 1911], nowadays this technology is widely criticized. While, experiences with alternative thermal waste treatment described above have led to realistic assessment of the actual potential at least among experts in Germany, a certain affinity for alternative technologies can be stated in Great Britain among scientists and many experts.

Current information on new constructions in England proves that Great Britain offers a favorable market environment for alternative thermal waste treatment. In the last seven years, alternative processes have been object to targeted funding with research funding followed by so-called Renewable Energy Obligation Credits (ROCs). This led to a large number of projects in the development stage. At the moment, several Energos projects (Glasgow, Milton Keynes) and two plants from Alter NRG (Tees valley) are being implemented. [Vaccani 2014].

#### 4.1.1.3 Italy – France – Spain

A strong opposition to waste incineration exists in some regions of these three countries. Therefore projects based on gasification, pyrolysis or melting processes were driven forward. Realiza-

tion of most projects is still uncertain. Many projects are inhibited or prevented by local opposition. [Vaccani 2014]

#### **4.1.1.4 Poland**

Poland is an active market for thermal waste treatment technologies in Europe. Accordingly, several suppliers of alternative processes including Japanese companies are present in Poland.

A number of projects is currently in development with alternative thermal process variations being closely examined. Alternative processes have been approved several times in recent years. In 2014, at last two invitations to tender for alternative thermal processes are expected.

#### **4.1.1.5 North America**

„Waste-to-Energy“, i.e. waste incineration processes, develops slowly in the United States of America. Even though incineration plants have been in operation for decades in metropolitan areas, cheap mega-landfills inhibit economic capacity build-up of waste incineration.

Were projects are developed, increasing interest in alternative thermal treatment process can be stated. Advertised process characteristics like eco-friendliness, energy efficiency and modernity seem to find strong interest. Accordingly, several projects are in the tendering phase with alternative thermal technologies involved (Los Angeles, New York).

The situation in Canada is similar. Two of ten processes invited for a project in Vancouver are gasification processes. In Ottawa, Plasco built a plant with a capacity of 100,000 Mg/a in an operator model. [Martin 2012, Vaccani 2014]

Due to low prices for landfilling as mentioned above, marketable gate fees in the USA are significantly lower than in Europe. 20 to 40 US-\$/Mg (14-20 €/Mg) are common. Without changes in legislation (e.g. landfill tax or imperative pre-treatment like in Europe, requirements concerning slag quality like in Japan) it cannot be expected that complex and therefore expensive alternative treatment methods will play a significant role in the North American market.

### **4.1.2 Asia**

Within Asia, the Japanese market stands out. Several alternative thermal technologies for waste treatment are established in Japan because of the prevailing general conditions.

#### **4.1.2.1 Japan**

Several factors have significant influence on waste management in Japan. This led to a specific development of thermal waste treatment including building of large capacities in alternative thermal treatment processes.

Crucial factors for the distinctive Japanese development are:

- Legal requirements
  - Requirements regarding molten slag
  - Requirement of municipal self-sufficient treatment
- Short operation times (caused by the high number of installations)
- High level of treatment costs (intransparent funding)
- Focus on disposal, so far little interest in energetic utilization
- Waste quality

### Requirements for Molten Slag

Going back to dioxin scandals in fluidized bed incineration of waste in the 1990s, the rule was adopted that slag from thermal waste treatment must be molten. This rule was a major impulse to establish different alternative thermal processes with integrated slag melting at the beginning of the current century.

After regulations were relaxed in 2008, the number of newly built alternative thermal processes dropped significantly (see figure 4.7). [Vaccani 2014]

Further reasons to melt residues from waste treatment to generate usable products are scarcity of space and high costs of landfilling. [California 2007, Döring 2014]

### Requirement Regional Self-Sufficiency

The Japanese „Waste Management and Public Cleansing Law” dating from 1970 stipulates that waste must be collected and disposed within the municipality where it was generated, i.e. municipalities must organize their waste management independently. As a result, all municipalities in Japan created treatment capacities and hold them available. Accordingly, the capacity of most facilities is significantly below 100,000 Mg/a. [Eysen 2011, Shinagawa 2013, Lamers 2013]

Figure 4.6 shows the size distribution of Japanese facilities for thermal waste treatment. Compared to 168 waste treatment plants in Germany [DESTATIS 2014] it is mainly the large number of plants that is particularly striking.

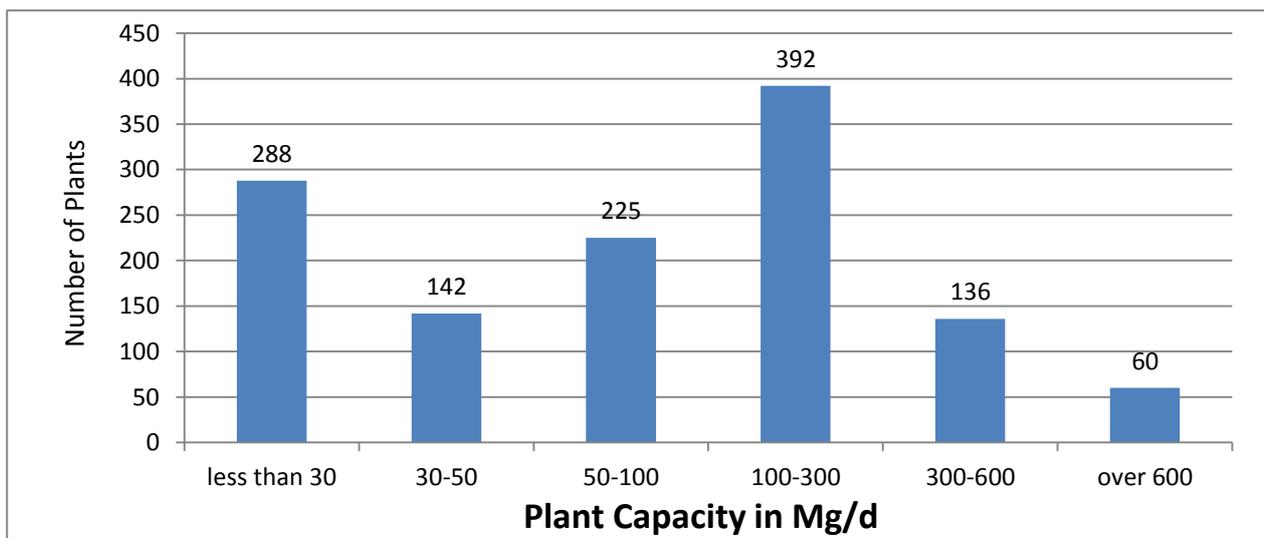


Figure 4.6: Distribution of treatment capacities for thermal waste treatment in Japan [HZI 2011].

### Operating Time

Despite seemingly rather low capacities of Japanese plants, they have been over-dimensioned in the past in order to anticipate future growth. In order to guarantee safety of disposal, generous maintenance and repair periods were set. [Shinagawa 2013]. Scheduled operating periods are mainly between 6,500 and 7,500 h/a.

This is why thermal treatment plants in Japan often operate only on 240-280 days per year (see e.g. figure 3.43).

Hence, much time is available for maintenance and repairs. Of course, this is helpful when complex and maintenance intensive technologies are applied.

## Treatment Costs

Treatment Costs in Japan are considerably higher than in Europe. According to Lamers [2013], gate fees are about 300 €/Mg waste. The waste report for „Tokyo 23“, an alliance of 23 municipalities in the Tokyo metropolitan area, gives average waste treatment costs of 56,975 yen/Mg waste in 2013 [Tokyo 2013], corresponding to 400 €/Mg waste. Experts assume even higher costs. Landfilling costs, too, are very high in Japan.

More details on waste treatment costs are not available because expenses are not reported separately as waste treatment fees. Instead, they are covered - more or less transparently - by tax-financed municipal budgets.

Treatment costs as high as described above certainly allow for operation of far more costly processes that could not be operated under the economic conditions of Europe or the USA.

## Energy Efficiency

For a long time, energy efficiency of waste treatment was no issue in Japan. Instead, waste management aimed at processes without residual waste materials and failure-free operation of treatment plants. Lower energy efficiency for the benefit of improved environmental characteristics (e.g. elution values of slag) and uninterrupted operation (e.g. less corrosion due to lower steam parameters) were gladly accepted. [Shinagawa 2013]

This is another factor that supported the establishment of alternative thermal processes with a high energy demand.

It was not until electricity from nuclear power plants was questioned in the course of the nuclear accident in Fukushima that energy efficiency became an issue in waste treatment. It can be expected that greater focus will be put on aspects of energy recovery in future. [Martin 2011, Lamers 2013]

## Waste Quality

Besides the regulatory framework described above, it is also the quality of municipal solid waste that is often mentioned as success factor for the operation of alternative thermal processes in Japan. It is reported that waste is pre-sorted to a large extent and shows an ash content of only 10-15 wt.-%. Hence, processing for utilization in complex thermal processes is simplified. It is obvious that the low ash content significantly reduces the energy demand for ash melting.

As a consequence of the described general conditions, between 1997 and 2011 more than 100 alternative thermal waste treatment plants with an overall capacity of 5.5 million Mg/a were erected [Vaccani 2014] of which 44 gasification plants were built between 2000 and 2001. Therefore many of the gasification plants in Japan have more than 10 years operating experience. [Eyssen 2011]

Figure 4.7 shows the yearly increase of thermal treatment capacities by process type. It can easily be seen that especially at the beginning of the millennium, the Japanese market was dominated by alternative processes. At the moment, processes with grate firing prevail, making up 7 of 11 new plants commissioned from April 2009 to March 2010. Three projects are based on gasification technology, one is realized as fluidized bed. The average capacity of new gasification facilities is 75,000 Mg/a, slightly exceeding the overall average of new plants which lies at nearly 70,000 Mg/a. [Eyssen 2011]

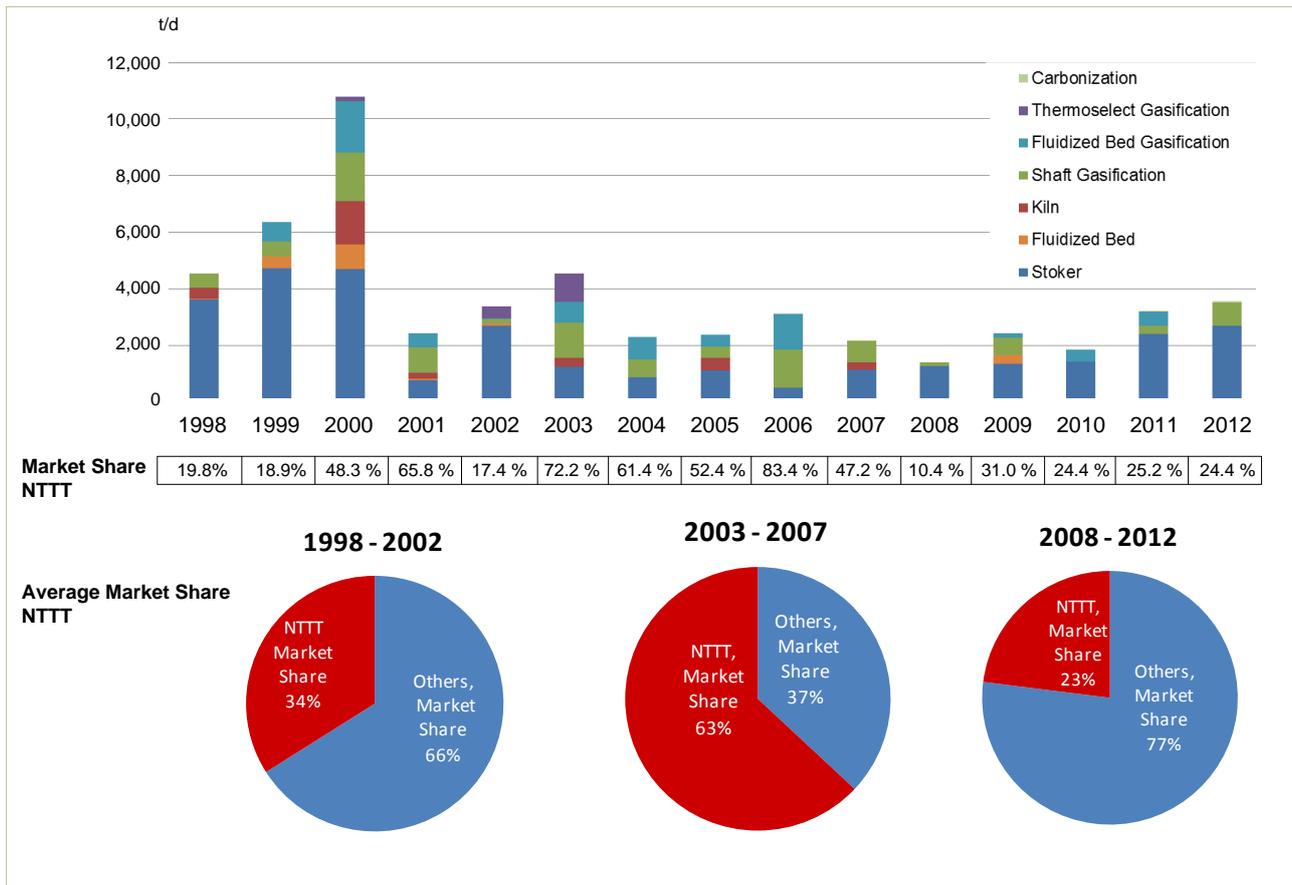


Figure 4.7: Development of newly built thermal waste treatment plants in Japan by process [Vaccani 2014].

#### 4.1.2.2 China

At the moment, China is the fastest growing market for thermal waste treatment plants. Since 2008, 78 new waste incineration plants have started operation [Döring 2014]. A government decree (2010 (30)) published by the Chinese State Council, named 600 other cities which shall be provided with WtE-plants [Martin 2011]. Additional capacities of 40 million Mg/a are supposed to be installed every year.

Most facilities are built by Chinese companies which also offer services on markets outside of China. [Döring 2014]

Market prices for the installation of incineration plants are about 150 €/Mg/a which is about two thirds lower than in Europe [Martin 2011].

This could be an important reason why alternative thermal processes are not relevant in China.

#### 4.1.2.3 Other Asian Countries

Of the other Asian countries, mainly South Korea is active in the field of thermal waste treatment. Between 2008 and 2012, seven gasification plants with an overall capacities of 325,000 Mg/a were built. Two plants are based on the Ebara fluidized bed process, two on the Nippon DMS process. [Vaccani 2014]

The Korean market is currently saturated. [Martin 2011]

First projects for thermal waste treatment have been prepared in India and Vietnam. Due to very low calorific values and marginal revenue (landfilling is virtually free of charge), application

of alternative thermal waste treatment processes is currently not to be expected in these countries.

## **4.2 Assessment of Classical Alternative Thermal Waste Treatment Processes**

The following chapter gives a summary and assessment of generalizable characteristics of alternative processes. Processes are classified according to the structure of chapter 3.

### **4.2.1 Pyrolysis**

A general and inherent challenge for pyrolysis processes is the problem of condensable gas contents, which require either heating of those plant components conveying product gas or systematic separation of condensate (e.g. quenching with water) immediately behind the reactor.

Another characteristic that is considered critical by experienced operators but which can be solved with according efforts is sealing - especially of rotary kilns - in order to prevent explosive mixtures in the reactor respectively toxic contamination of ambient air.

#### **4.2.1.1 Pyrolysis as Sub-Step of Combustion/Melting-Processes**

The process principle of this process type is pyrolytic degassing of volatile waste components in a first process stage, immediately followed by combustion of pyrolysis gases together with remaining coke. This two-stage combustion usually achieves higher oxidation temperatures causing inorganic waste components to melt.

The advantage of these high-temperature processes lies in the obtainable slag qualities. Excellent leachate values (comparable to "lead crystal") are achieved which allow high-value follow-up utilization of the slag product.

Unfavorable aspects are the usually high energetic effort and complexity of equipment. Due to high costs, it is not possible to achieve economic operation of these processes under European respectively German conditions. Only a legal framework similar to that of Japan could establish this process type outside of Japan.

#### **4.2.1.2 Stand-Alone Pyrolysis**

This process type is characterized by the fact that the product gas is usually used to provide the internal energy demand of pyrolysis, but the carbonization product is utilized neither internally nor externally.

Hence, these processes generate a solid residue material with significant energy content which can only be deposited with special permission. The technological effort of waste treatment does not include additional benefits, instead extra efforts are necessary to find options for worthwhile disposal of the generated pyrolysis coke.

One of the few statements on alternative methods found in the BREF document on waste incineration refers to stand-alone pyrolysis. Best available technology in the field of pyrolysis or gasification as named in chapter 5.1 (No. 24) are only processes which a) "combine the gasification or pyrolysis stage with a subsequent combustion stage with energy recovery and flue-gas treatment [...]" and/or b) "recover or supply for use of the substances (solid, liquid or gaseous) that are not combusted".

Landfilling of pyrolysis coke is therefore not best available technique as defined in the BREF document on waste incineration [BREF 2005] and this will most likely also be the case in the revised version of the document. Hence, landfilling of this material will face enormous problems considering approval procedures.

### **4.2.1.3 Pyrolysis as Upstream Process**

When pyrolysis is used as upstream / pre-treatment process, generated gaseous and coke fraction are directly utilized in a consecutive process (e.g. cement- or lime kilns or power plants). Thus, organic content of waste can be exploited completely and, provided an appropriate concept, metal resources can be recovered in high quality. The effort for complex purification of pyrolysis gas is avoided when the gas is used in a consecutive industrial combustion process.

„Homogenization“ by conversion to coke and gas usually allows a more effective utilization in the following process than the use of untreated waste as fuel. Thermochemical treatment might even be crucial for the substitution of fossil energy carriers. Therefore, this approach can be an interesting option to access the energy content of waste for industrial applications. Accordingly, future potential can be attributed to this process type.

## **4.2.2 Gasification**

In gasification processes, too, the purification of generated gas is the main challenge as long as product gas is not directly combusted.

### **4.2.2.1 Gasification as Sub-Step of Staged Combustion**

Under this heading, processes are summarized which include thermal treatment as first process step that is immediately connected to combustion. In these cases, gasification is an integral part of a staged and overall overstoichiometric combustion and not a “real” gasification process.

Often, this process type is referred to as gasification. This relabeling serves marketing purposes. In some countries funding is granted for alternative thermal waste treatment facilities and the assumed higher public acceptance of “alternative” processes also plays a role.

Besides these assets, some technological advantages are being discussed. These are mainly lower investment costs because of simpler technology in comparison to waste incineration, the possibility to reduce nitrogen oxides by staged combustion and less heat loss through waste gas because of a reduced waste gas volume flow.

However, the simpler technology leads to unavoidable limitations in flexibility and operational management.

Facilities in which gasification is only the first stage of a staged combustion are to be classified as combustion processes. Therefore, these concepts must be measured against classical waste incineration concerning quality, operations and availability.

### **4.2.2.2 Gasification as Sub-Step of Combustion/Melting Processes**

This process type is characterized by the fact that initial gasification is followed by a high-temperature combustion zone, either in the same or a subsequent reactor, in which either the complete inorganic waste content or only fly ash is molten and vitrified.

In principle, the same statements apply as for melting processes with an initial pyrolysis stage prior to high-temperature combustion (see chapter 4.2.1.1). The advantage respectively additional benefit is in the achievable slag quality. Disadvantages lie in the usually high energy demand and complexity of equipment.

Melting processes with gasification as first step of thermochemical treatment are costly and can only be operated under special (legal) conditions. As long as these do not exist in Europe, implementation of these processes will fail due to economic reasons.

#### **4.2.2.3 Gasification for Syngas Production**

Processes of this kind have been and still are in the center of interest of developers and experts. The aim is to generate a high-value fuel gas from waste which is to be utilized energetically in motors, turbines, for waste-derived fuels or even in fuel cells.

Since waste is a most heterogeneous and complex input material, these processes can only be operated with elaborate systems engineering. In addition, the ambition to generate fuel gases with a high calorific value often involves using oxygen or steam as gasification agent instead of air, resulting in even higher process expenditures. The major challenge generally is gas purification. Dust and tars must be removed from the product gas prior to the intended high-value utilization. This requires multi-stage gas purification processes which again generate both waste and waste water. Utilization of gases in internal combustion engines also causes a) problems like high emissions of stable gas components (CO, CH<sub>4</sub>, benzol) that are not completely oxidized in the motor or b) new formation of pollutants like formaldehyde (HC=OH) [Bauer 2009].

Experiences for example made in Japan or SVZ Schwarze Pumpe show that the generation, conditioning and high-value utilization of product gases from gasification of waste is in general technically feasible and can be operated steadily over a long period of time.

Nevertheless, general conditions as discussed above cause high efforts in investment, operation, maintenance and repair of these processes. Therefore, this process concept cannot be operated economically in Germany under current conditions.

#### **4.2.2.4 Gasification as Upstream Process**

Gasification processes, too, can be used to transfer the energy content of waste by thermochemical conversion to generate a process output (product gas, gasification coke) that is easier to handle in industrial processes than heterogeneous solid waste and therefore suitable to substitute fossil fuels.

Combining gasification with an industrial follow-up process allows implementing process concepts that are far simpler and therefore more robust than processes intended to generate a high-value product gas. In particular, complex gas purification is rendered unnecessary.

Just as stated for pyrolysis, upstream processes based on gasification are an interesting option. Especially utilization of special fractions for example with low calorific value or high ash or chlorine contents seems to be a promising option for this process type.

Since this process requires intensive pre-treatment in order to maintain the necessary properties of the process input, this process is not suitable for mixed municipal solid waste.

### **4.3 Evaluation of Recent Developments in Thermal Waste Treatment**

#### **4.3.1 Plasma Processes**

Plasma processes in the waste sector have been developed to vitrify especially critical waste fractions (e.g. asbestos). A number of companies is currently trying to establish plasma processes for the treatment of residual waste. Process concepts include both plasma treatment of the whole waste as well as thermal treatment of critical fractions like fly ash, filter dust or generated product gas ("polishing").

These processes are characterized by high costs for investment, operation and maintenance. The technology is comparably prone to failure. Electrodes have a short lifetime, the electronic system for plasma generation is susceptible.

So far, no plasma process has proved technical maturity in permanent industrial operation. In case these processes reach the necessary degree of technical maturity, plasma treatment might be interesting to treat certain problematic fractions. Yet, this will only be the case when for example legal regulations dictate such treatment. Otherwise, high expenditures will prevent establishment in the market.

It is unlikely that plasma processes will be applied for industrial scale treatment of municipal solid waste and because of high energy demand, technical vulnerability and high process costs this is also not considered to be desirable.

### 4.3.2 Liquefaction Processes

Liquefaction processes aim to generate a liquid product fraction rich of carbohydrates that is usable as fuel. Operating temperatures of these processes are between 300 and 400 °C. The use of catalysts in the oily phase is supposed to enhance conversion rate and product quality.

As shown in table 4.1, the decomposition temperature of most plastics lies in the range of operating temperatures of liquefaction processes. Therefore, decomposition of plastic fractions by liquefaction in principle appears to be possible.

Table 4.1: Decomposition temperatures of important polymers. [Roth 1990, Troitzsch 1981, Ortner 1995].

Polymer	Decomposition Temperature [°C]
Polyethylene (PE)	340-440
Polypropylene (PP)	330-410
Polyvinylchloride (PVC)	200-280
Polyamide (PA)	300-350
Polymethylmethacrylate (PMMA)	170-300
Polycarbonate (PC)	350-400
Polyurethane (PU)	200-220
Phenolic Resins (Thermoset, PF)	270-400
Polyethylene Terephthalate (PETP, PET)	255-305
Polystyrene (PS)	300-400
Epoxy Resins (EP)	250-450
Polyimides (PI)	260-320 (short-term stability up to 500 °C)
Urea Resin Foams	250-300

Many experts believe that conversion of other waste derived fractions to high-value product oils is not possible. Especially biogenic materials are problematic because of their high oxygen content.

Questions concerning effectiveness and function of catalysts and their stability in continuous operation are unanswered as well as it is still unknown which product qualities can be achieved in liquefaction processes. Already simple balancing of processes is a challenge because of the use of start-up oils.

Several pilot plants have produced product oils in campaign operation. Yet the quality of these oils is insufficient for direct marketing as fuel. To achieve necessary product properties, post-treatment, for example hydrogenation, is required.

Even if liquefaction processes would prove technical feasibility in future, for example in combination with suitable post-treatment processes, direct liquefaction of municipal solid waste is out

of the question. Only treatment of intensely processed mono-material plastic fractions seems possible. It remains to be seen whether the rather low product quality is worth this effort.

### 4.3.3 Hydrothermal processes

As described above, hydrothermal processes can only be applied for biogenic input materials. Therefore, this process type is generally not applicable for municipal solid waste.

HTC could be an interesting treatment process for sewage sludge and other wet waste materials, since hydrothermal processes improve dewatering and could therefore play a role in optimized dewatering and drying of this kind of waste materials.

However, further development is necessary. Especially the following aspects must be considered:

- Treatment of secondary material flows  
(water with refractory COD, organically contaminated exhaust air)
- Effectiveness and necessity of used catalysts  
(citric acid is often used but consumed within the process and is therefore no catalyst)
- Energy balance of the whole process

At present, none of the processes listed in table 3.46 would be classified as development stage higher than 3 (according to VDI guideline 3460, see table 1.1).

## 5 Conclusion

Attempts to recover reusable material from waste are as old as waste management itself. Especially the idea to generate energy carriers of higher value and quality, if possible even fuels conforming to standards, seem to exert particular fascination.

The fact remains, however, that so far in the history of waste management - starting with first attempts at the beginning of the 19th century until now - so-called alternative thermal processes as singular waste treatment process could only be operated permanently when this was enabled by the particular political or societal framework as is the case in Japan for high-temperature processes (legal requirements) or the pyrolysis plant in Burgau (funded pilot project).

Of the many variations of alternative thermal waste treatment processes considered in this report, only upstream pre-treatment processes operated in a plant network with other thermal processes (power plants, cement or lime plants) that allow for direct utilization of generated products (gas, eventually coke) under optimized conditions (e.g. higher electrical efficiency of power plant) can be considered as potentially reasonable and in part as actual economic alternative for thermal waste treatment under European conditions.

Of further interest are also those processes that allow treatment of special fractions like for example highly toxic or chlorine contaminated substances or materials of low calorific values not allowing auto-thermal combustion, e.g. contaminated soil. The ecological necessity of a high quality treatment of such problematic waste materials justifies costly treatment processes, including energy-intensive plasma processes in specific cases. Here, legal requirements are vital.

Stand-alone processes that do not achieve complete inertization of products are problematic. Generation of not marketable pyrolysis coke for example leads to additional follow-up costs for product disposal. Economic operation hardly seems possible under such conditions. What is more, according to the currently valid Reference Document on Best Available Techniques in waste incineration, processes are only best available technique when they are equipped "with a subsequent combustion stage with energy recovery" or when they "recover or supply for use of the substances that are not combusted" [BREF 2005, chapter 5.1, No. 24a/b].

Especially when processes are designed in a rather simple way (e.g. low temperature pyrolysis or direct liquefaction), the conditioning of products requires significant effort, be it gas conditioning following pyrolysis/gasification or fuel refining following liquefaction. The alleged advantage of a simple main process is at the expense of higher complexity in product treatment. Accordingly, post-treatment often is the weak point of these processes, in some cases it is even ignored during development.

It has to be pointed out that all alternative thermal processes considered require higher treatment efforts than classical waste incineration. Generally, in-depth processing of input materials is mandatory. At least crushing of waste is necessary, often also comminution of waste and removal of metals and inert materials. Some processes even require pre-drying or pelletizing of input materials. Those few Japanese melting processes which may be operated without waste conditioning (still, piece-size is restricted) are intricate in operation. Addition of coke and oxygen is common in these processes.

As can be learned from examples in Japan or the SVZ Schwarze Pumpe, even operating experience of several years does not lead to a significant reduction in the extensive effort to operate complex alternative processes. With this background, the argument that is sometimes brought on in Europe that alternative technologies for thermal waste treatment are not on par with clas-

sic waste incineration only because of a lack of operating experience and the necessity for further optimization seems untenable.

In conclusion, it must be stated that waste incineration is state of the art for the treatment of residual waste. None of the so-called alternative processes has proved comparable performance and flexibility under comparable conditions.

Alternative thermal processes can only be economically successful under specific circumstances respectively requirements which are:

- Compliance with legal requirements  
(e.g. melting processes in Japan)
- Achievement of specific product properties  
(e.g. vitrified slag, low contaminant content)
- Treatment of special fractions  
(e.g. highly toxic materials, materials containing chloride, fractions with very low calorific value like contaminated soils)
- Upstream processes  
(e.g. in power plants, cement or lime plants) to substitute fossil fuels

There are currently no alternative thermal processes available that can be used to treat mixed municipal solid waste under comparable economic and ecological conditions as is the case for waste incineration. Due to the higher complexity of alternative processes, this can also not be expected in future. Therefore, treatment of mixed municipal solid waste should generally be reserved to incineration processes that have been developed and approved for this application.

## 6 Process Fact Sheets

### 6.1 Pyrolysis

#### 6.1.1 Pyrolysis as Sub-Step of Combustion/Melting Processes

Process	IHI Pyrolysis Gasification and Melting System	Development Status	<b>3</b>	
Manufacturer / Provider	IHI Corporation	Number of Reference Plants	1	
		Cumulated Operating hours		
Internet	<a href="http://www.ihico.jp">http://www.ihico.jp</a>	Cumulated Fuel Throughput		
Contact		Operated Since		
E-Mail Address		Patent granted?		
Telephone		Sites	Chita, Japan	
Fax				
Process / Reactor	Rotary drum pyrolysis with combustion of coke and gas in a surface melting furnace (Kobelco Furnace) with downstream horizontal combustion chamber			
Aim	Pyrolysis of municipal solid waste with combustion of products with energy recovery			
Special Features	Complex combustion stage			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing	Thermochemical Process		
	Grain Size		Reactant	
	Water Content		Temperature	
	Ash Content		Pressure	
	Homogenization		Throughput	2 x 65 Mg/d
	Calorific Value		Residence Time	
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Separated inert material from pyrolysis, molten slag from combustion			
Liquid				
Gaseous	Flue Gas			
<b>Product Gas Utilization</b>				
Actual	Combustion			
Planned				

Process	<b>Siemens Schwel-Brenn</b>		Development Status	<b>3</b>
Manufacturer / Provider	Siemens-KWU		Number of Reference Plants	In Germany: 2 (no regular operation)
			Cum. Operating hours	
Internet			Cumulated Fuel Throughput	
Contact			Operated Since	
E-Mail Address			Patent granted?	
Telephone			Sites	Ulm-Wiblingen (demonstration plant), Fürth (industrial scale, trial operation)
Fax				
Process / Reactor	Pyrolysis (internally heated rotary drum), high-temperature combustion (combustion chamber)			
Aim	Nearly residue-free conversion of waste into secondary raw materials and energy			
Special Features				
Treatment Costs	Ca. 235 DM/Mg (assumptions: capacity 160,000 tons municipal solid waste per year, $H_u = 10,000$ kJ/kg)			
Process Disturbances and Their Causes	Difficulties in transport of residual materials (formation of conglomerates of iron- and steel wire on cooling trough and in treatment of residual materials (low quality of coke discharged from the low temperature carbonization drum because of coke adhesion); refractory lining had to be fundamentally revised and renewed; emission of low temperature carbonization gas from pyrolysis drum after destruction of a mechanical seal			
Service Intervals	N/A			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, household-like commercial waste, refuse, bulky waste, optionally sewage sludge (dewatered or dried)	Grain Size	< 150 mm	Reactant	Combustion: air
	Water Content		Temperature	Pyrolysis: ca. 450 °C Combustion: 1,300 °C
	Ash Content		Pressure	atmospheric
	Homogenization		Throughput	
	Calorific Value		Residence Time	Pyrolysis: ca. one hour Combustion: > 2 s (gas)
			Additives	No specific additives
			Power, thermal	Fürth: 51.3 MW (gross)
		Power, electric	Fürth: ca. 12 MW (gross)	
<b>Output</b>				
Solid	Fe-metal scrap, NF-metals scrap, glass/stone/ceramics, melting granulate, AGR-products			
Liquid	Process is free of waste water			
Gaseous	Purified waste gas (from combustion of pyrolysis gas & pyrolysis gas containing carbon)			
<b>Product Gas Utilization</b>				
Actual	Combustion of pyrolysis gas in high-temperature combustion chamber; generation of electricity, district heat, process steam			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>MES R21</b>	Development Status	<b>5</b>
Manufacturer / Provider	Mitsui Engineering & Shipbuilding Company	Number of Reference Plants	25
		Cumulated Operating hours	
Internet	<a href="http://www.mes.co.jp">http://www.mes.co.jp</a>	Cumulated Fuel Throughput	Yame (2000-2002) ca. 120,000 t >> 1,000,000 Mg
Contact	Mitsui Zosen Europe Limited	Operated since	2000
E-Mail Address		Patent granted?	
Telephone	+44-20-7256-7171	Sites	Japan
Fax	+44-20-7256-7272		
Process / Reactor	Pyrolysis rotary drum with subsequent combustion of pyrolysis gases and coke freed of metals		
Aim	Inertization of waste fractions; metal recovery energy conversion using steam power process		
Special Features			
Treatment Costs	20-24 €/Mg average costs for operating materials 2000-2002 (note: not treatment costs!); investment costs 2009 ca. 1,300 €/(Mg/a)		
Process Disturbances	widely free of disturbances		
Cause of Disturbances			
Service Intervals			
<b>Process Description</b>			
Input	Processing	Thermochemical Process	
	Grain Size		Reactant
	Water Content		Temperature
	Ash Content		Pressure
	Homogenization		Throughput
	Calorific Value		Residence Time
		Additives	
		Power, thermal	
		Power, electric	
<b>Output</b>			
Solid			
Liquid			
Gaseous			
<b>Product Gas Utilization</b>			
Actual			
Planned			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Takuma Pyrolysis Melting System</b>		Development Status	5
Manufacturer / Provider	Takuma Co. Ltd. Osaka, Japan		Number of Reference Plants	5
			Cumulated Operating Hours	
Internet	http://www.takuma.co.jp		Cumulated Fuel Throughput	776 Mg/d
Contact	KAB Takuma GmbH		Operated Since	
E-Mail Address	contact@kab-takuma.com		Patent granted?	
Telephone	+49-30 5465 0		Sites	Japan
Fax	+49-30 5465-2113			
Process / Reactor	Pyrolysis in rotary drum with subsequent combustion of pyrolysis gases and pyrolysis coke (metals removed)			
Aim	Pyrolysis of municipal solid waste with combustion of products, recovery of metals, energy recovery with steam boiler			
Special Features				
Treatment Costs				
Process Disturbances	Seemingly trouble-free operation in Japan			
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
	Grain Size	< 200 mm	Reactant	
	Water Content		Temperature	Pyrolysis: 250 - 470 °C combustion: 1,250 – 1,400 °C
	Ash Content	10 – 12 %	Pressure	Pyrolysis at low under-pressure
	Homogenization		Throughput	258 Mg/d (Moriya)
	Calorific Value	4.2 – 10.5 MJ/kg	Residence Time	ca. 1 h
			Additives	
			Power, thermal	
			Power, electric	2 MW
<b>Output</b>				
Solid	Inert residual materials from pyrolysis, metals, liquid slag from combustion chamber			
Liquid				
Gaseous	Flue gas			
<b>Product Gas Utilization</b>				
Actual	Combustion			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Von Roll INOVA RCP-Process</b>		Development Status	<b>3</b>
Manufacturer / Provider	Hitachi Zosen INOVA AG, Zürich, Schweiz		Number of Reference Plants	1
			Cumulated Operating Hours	
Internet	http://www.hz-inova.com		Cumulated Fuel Throughput	
Contact			Operated Since	
E-Mail Address	info@hz-inova.com		Patent granted?	
Telephone	+41-442771111		Sites	Bremerhaven, Germany
Fax	+41-442771313			
Process / Reactor	Pyrolysis, partial gasification on grate, followed by slag melting furnace with HSR-plant and circulating fluidized bed for gas combustion, flue gas transferred to waste incineration plant			
Aim	Treatment of municipal solid waste and slag from waste incineration			
Special Features	Complex slag melting and gas combustion			
Treatment Costs				
Process Disturbances	Frequent; especially in slag melting device heated with oxygen			
Cause of Disturbances	Control of gas feed, spatial proximity of oxygen storage			
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
	Grain Size	No pre-treatment	Reactant	Oxygen for partial gasification
	Water Content		Temperature	Pyrolysis 900 °C, melting furnace 1,400 °C, fluidized bed 1,000 °C
	Ash Content		Pressure	
	Homogenization	none	Throughput	6 Mg/h
	Calorific Value	MSW	Residence Time	
			Additives	Oxygen
			Power, thermal	17.5 MW
			Power, electric	
<b>Output</b>				
Solid	Molten slag, Fe-Cu-alloys			
Liquid				
Gaseous	Flue gas (to waste incineration)			
<b>Product Gas Utilization</b>				
Actual	Direct combustion			
Planned	Process abandoned			

### 6.1.2 Pyrolysis as Stand-Alone Process

Process	<b>Destrugas</b>	Development Status	<b>3</b>
Manufacturer / Provider	Inventor: Karl Kroyer Manufacturer Denmark: Pollution Control Manufacturer Japan: Hitachi Engineering & Construction Provider Germany: Wifos GmbH & Co. KG, Gelnhausen (no longer offered)	Number of Reference Plants	3 (all shut down)
		Cumulated Operating Hours	> 10,000 h
Internet		Fuel Throughput	
Contact	Wifos: Hans Müller	Operated Since	
E-Mail Address		Patent granted?	yes
Telephone		Sites	Kalundborg, Kolding, Hitachi City, pilot plant in MVA Berlin-Ruhleben
Fax			
Process / Reactor	Pyrolysis shaft reactor, indirect heating		
Aim	Production of gas with a quality similar to town gas		
Special Features	Low processing intensity of input		
Treatment Costs	Not determined		
Process Disturbances	Blockages of gas pipes, partial slagging when temperatures are too high in lower part of retort		
Cause of Disturbances	Condensation of product gas and dust		
Service Intervals	N/A		
<b>Process Description</b>			
Input	Processing	Thermochemical Process	
Household waste, commercial waste similar to household waste, bulky waste, waste oil, sewage sludge,	Grain Size	< 100 mm	Reactant
	Water Content	e.g. 30 %	Temperature
	Ash Content	e.g. 28 %	Pressure
	Homogenization	yes	Throughput
	Calorific Value	e.g. 7,500 kJ/kg	Residence Time
			200-800 °C, bottom area of retort max. 1,050 °C atmospheric 5 Mg/d per retort ca. 4 h
<b>Output</b>			
Solid	Pyrolysis coke, iron scrap		
Liquid	Water from wet deslagger and gas processing		
Gaseous	Pyrolysis gas		
<b>Product Gas Utilization</b>			
Actual			
Planned	Generation of town gas and electricity		

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Burgau (Babcock)</b>		Development Status	<b>5</b>
Manufacturer / Provider			Number of Reference Plants	1
			Cumulated Operating Hours	ca. 200,000
Internet			Cumulated Fuel Throughput	ca. 800,000 Mg
Contact			Operated Since	1983
E-Mail Address			Patent granted?	
Telephone			Sites	Burgau (Germany)
Fax				
Process / Reactor	Pyrolysis in rotary drum; utilization of pyrolysis gas to provide process energy			
Aim	Pyrolysis of municipal solid waste			
Special Features	Only pyrolysis plant for MSW in Germany in normal operation			
Treatment Costs	199 €/Mg without revenue from electricity and heat and expenses for landfilling of coke			
Process Disturbances	Blockage of feeding screws, tail formation in rotary drum sealings at face sides of rotary drum, formation of deposits			
Cause of Disturbances	Spiral springs (mattresses) and bands contained in the waste, leakages			
Service Intervals	12 months			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Municipal solid waste, commercial waste, sewage sludge	Grain Size	< 300 mm	Reactant	(Air in combustion chamber)
	Water Content	20 %	Temperature	470-500 °C
	Ash Content	ca. 30 %	Pressure	atmospheric
	Homogenization	Comminution	Throughput	4 Mg/h
	Calorific Value	9 MJ/kg	Residence Time	60 minutes
			Additives	CaO to bind acid components
			Power, thermal	
			Power, electric	2.2 MW
<b>Output</b>				
Solid	Pyrolysis coke (Fe-metals removed)			
Liquid				
Gaseous	Pyrolysis gas			
<b>Product Gas Utilization</b>				
Actual	Generation of electricity (steam turbine)			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Pyreg</b>	Development Status	<b>4</b>	
Manufacturer / Provider	PYREG GmbH	Number of Reference Plants	7	
		Cumulated Operating Hours	> 25,000 h	
Internet	<a href="http://www.pyreg.de">http://www.pyreg.de</a>	Cumulated Fuel Throughput		
Contact	Dipl. Ing. Helmut Gerber	Operated Since		
E-Mail Address	<a href="mailto:info@pyreg.de">info@pyreg.de</a>	Patent granted?	yes	
Telephone	+49-6747-95388-0	Sites	CH, AUT, D	
Fax	+49-6747-95388-19			
Process / Reactor	Twin-screw reactor and combustion chamber			
Aim	Decentral conversion of residual biomass to generate heat staged combustion or production of bio char			
Special Features	Immediate combustion of synthesis gases, no synthesis oils			
Treatment Costs	100-150 €/Mg DM			
Process Disturbances	Co-firing necessary			
Cause of Disturbances	Inhomogeneous material not conforming to specifications			
Service Intervals	2 weeks			
<b>Process Description</b>				
Input	Processing	Thermochemical Process		
Humid residual biomass (e.g. sewage sludge, green cuttings, biowaste etc.)	Grain Size	< 30 mm	Reactant	Air
	Water Content	< 50 %	Temperature	500 - 800 °C
	Ash Content	< 35 %	Pressure	> 0.5 mbar underpressure
	Homogenization		Throughput	max. 180 kg DM / h
	Calorific Value	> 10 MJ/kg TS	Residence Time	15-30 min
		Additives		
		Power, thermal	up to 150 kW; from 2015 on: 250 kW	
		Power, electric		
<b>Output</b>				
Solid	Ash, biochar			
Liquid				
Gaseous	Flue gas from staged combustion			
<b>Product Gas Utilization</b>				
Actual	Combustion of product gas with FLOX-burner in combustion chamber – process heating; energy generation			
Planned	Electricity generation			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Intermediate Pyrolysis</b>		Development Status	<b>2</b>
Manufacturer / Provider	Susteen GmbH Aston University (Pyroformer) Fraunhofer UMSICHT (TCR)		Number of Reference Plants	1
			Cumulated Operating Hours	500
Internet	www.umsicht.suro.fraunhofer.de		Cumulated Fuel Throughput	600 Mg
Contact	Thorsten Hornung		Operated Since	2013
E-Mail Address	thorsten.hornung@umsicht.fraunhofer.de		Patent granted?	Pyroformer: yes; TCR: applied
Telephone	+49-9661-908-407		Sites	Birmingham
Fax	+49-9661-908-469			
Process / Reactor	Thermocatalytic reforming; coaxial screw reactor			
Aim	Production of gas and oil applicable in combustion engines			
Special Features	Low share of particles and tar in pyrolysis gas by process-integrated reforming (reaction of recirculated pyrolysis coke with pyrolysis gas)			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals	90 days (to be proved in long-term testing)			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Sewage Sludge, biogenic residues e.g. digestate, wood, paper sludge, draff	Grain Size	Pellets	Reactant	
	Water Content	< 30 %	Temperature	450-500 °C
	Ash Content	< 50 %	Pressure	200 mbar
	Homogenization		Throughput	100 kg/h
	Calorific Value	10-18 MJ/kg	Residence Time	5-30 min (mean)
			Additives	
			Power, thermal	90 kW (scrubbing with biodiesel in a share oil/biodiesel of 1/1)
			Power, electric	75 kW
<b>Output</b>				
Solid	Coke			
Liquid	Oil (mixable with RME), aqueous phase			
Gaseous	Syngas			
<b>Product Gas Utilization</b>				
Actual	Combustion engines (Dual Fuel Common Rail, Cummings Motor, 500h)			
Planned	Reduction of ratio product oil / RME			

## Status of Alternative Techniques for Thermal Waste Treatment

Process	M.E.E. GmbH	Development Status	<b>3</b>	
Manufacturer / Provider	M.E.E. GmbH Werkstrasse 206, 19061 Schwerin	Number of Reference Plants	1	
		Cumulated Operating Hours	4,000	
Internet	www.m-e-e.biz	Cumulated Fuel Throughput	500 Mg	
Contact	Philipp Hagemann	Operated Since		
E-Mail Address	info@m-e-e.biz	Patent granted?	yes	
Telephone	+49-385-6380-294	Sites	Schwerin, Germany	
Fax	+49-385-6380-201			
Process / Reactor	Low temperature pyrolysis in screw reactor			
Aim	Thermal treatment of waste and residual materials, including biomass, with utilization of the energetic potential			
Special Features	Downstream reformer (partial gasification with water); low tar content in coke; working temperature significantly below ash melting temperature			
Treatment Costs	59-81 €/Mg			
Costs Energy Generation	10-60 €/MWh			
Process Disturbances	none			
Cause of Disturbances	none			
Service Intervals	Annually (planned)			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Sewage sludge, waste tires, shredder fraction, bones, chicken dung, digestate, rejects,...	Grain Size	< 40 mm	Reactant	
	Water Content	< 15 %	Temperature	350-550 °C
	Ash Content	< 70 %	Pressure	300 mbar
	Homogenization		Throughput	up to 750 kg/h
	Calorific Value	not restricted	Residence Time	0.1-0.2 h
		Additives	none	
		Power, thermal	up to 20 MW	
		Power, electric	up to 5 MW (planned)	
<b>Output</b>				
Solid	Coke (40-50 %)			
Liquid	Pyrolysis Oil (40-50 %)			
Gaseous	Permanent Gas (5-10 %)			
<b>Product Gas Utilization</b>				
Actual	Flare			
Planned	Steam / ORC Process			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Pyrum</b>	Development Status	<b>2</b>	
Manufacturer / Provider	Pyrum Innovations ESC GmbH Dieselstraße 8, 66763 Dillingen/Saar	Number of Reference Plants	1 (industrial scale plant under construction)	
		Cumulated Operating Hours	Campaign operation max. 1 week	
Internet	www.pyrum.net	Cumulated Fuel Throughput		
Contact		Operated Since	2008	
E-Mail Address	contact@pyrum.net	Patent granted?		
Telephone	+49-68319788227	Sites	Dillingen/Saar	
Fax	+49-6831978229			
Process / Reactor	Pyrolysis / tube reactor			
Aim	Thermal decomposition of organic substances			
Special Features	Electric heating of tube reactor (planned: heating by combustion of product gas in CHP)			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Rubber, waste tires (shredded and granulated)	Grain Size	3 – 12 mm	Reactant	
	Water Content	Dry, conveyable	Temperature	up to 750 °C
	Ash Content		Pressure	
	Homogenization		Throughput	10-30 kg/h under construction: 0.5 - 1 Mg/h
	Calorific Value		Residence Time	ca. 1 h
		Additives		
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Coke, rubber meal, soot, activated carbon			
Liquid	Crude oils (intended utilization: refining, CHP)			
Gaseous	Pyrolysis gas			
<b>Product Gas Utilization</b>				
Actual	Flare			
Planned	Supply of heating power			

### 6.1.3 Pyrolysis as Upstream Process

Process	Contherm		Development Status	5
Manufacturer / Provider	Technip Germany GmbH Theodorstrasse 90 40472 Düsseldorf		Number of Reference Plants	1
			Cumulated Operating Hours	> 50,000
Internet	www.technip.com		Cumulated Fuel Throughput	> 500,000 Mg
Contact	A. Goorse, M. Mladenovic		Operated	2001-2010
E-Mail Address	ales-tpgy@technip.com		Patent granted?	
Telephone	+49 211 659 2314		Sites	Hamm, Germany
Fax	+49 211 659 2912			
Process / Reactor	Pyrolysis rotary drum			
Aim	Co-combustion of generated pyrolysis gas and processed coke in hard coal power plant, metal recovery (external)			
Special Features	Rotary drum fired with natural gas			
Treatment Costs				
Process Disturbances	Sealing and pressure regulation in rotary drum; pyrolysis gas heating rotary drum too small			
Cause of Disturbances	design			
Service Intervals				
Process Description				
Input	Processing		Thermochemical Process	
RDF	Grain Size		Reactant	
	Water Content		Temperature	500 °C
	Ash Content		Pressure	low underpressure
	Homogenization	Pre-treatment	Throughput	Realized: 70,000 Mg/a Design: 100,000 Mg/a
	Calorific Value		Residence Time	1.5 h
			Additives	
			Power, thermal	72.5 MW (design)
			Power, electric	
Output				
Solid	Coke (with metals and inorganic substances)			
Liquid				
Gaseous	Pyrolysis gas (hot, including condensable components)			
Product Gas Utilization				
Actual	Installation has been shut down; previously co-combustion in hard coal power plant			
Planned	No further operation planned because of sharp price drop of RDF			

## 6.2 Gasification

### 6.2.1 Gasification as Sub-Step of Staged Combustion Processes

Process	Energos	Development Status	5	
Manufacturer / Provider	Energos <a href="http://www.energ-group.com">http://www.energ-group.com</a>	Number of Reference Plants	8 (1 shut down)	
		Cumulated Operating Hours	> 500,000	
Internet		Cumulated Fuel Throughput	> 1,000,000 Mg	
Contact	info@energos.com	Operated Since	2002 (Minden)	
E-Mail Address		Patent granted?		
Telephone		Sites	Minden, Norway, Isle of Wright, UK	
Fax				
Process / Reactor	Gasification / grate (fixed grate section cooled with external thermal oil circuit), fuel transport on grate by water cooled duplex conveyor, gas combusted in combustion chamber (two-stage combustion)			
Aim	Thermal treatment of municipal solid waste in small facilities with energy utilization			
Special Features	Compliance with NO <sub>x</sub> , CO and PCDD/F emission limits due to two-stage combustion			
Treatment Costs	60-70 €/Mg (data published by operator for Minden facility)			
Process Disturbances	Uptime Minden 2010: 86.4 %; 2009: 77.4 %; 2008: 86.5 %			
Cause of Disturbances	Specific causes unknown			
Service Intervals	2 x per year (Minden)			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Processed Municipal Solid Waste (RDF)	Grain Size	< 300 mm (Minden) manufacturer: - max. vol. 300 cm <sup>3</sup> - 100 % < 200 mm - 90% < 150 mm	Reactant	Air
	Water Content	max. 40 %	Temperature	850-950 °C gasification 900-1,100 °C combustion
	Ash Content	max. 30 %	Pressure	
	Homogenization		Throughput	40,000 Mg/a
	Calorific Value	10-14 MJ/kg 7-25 MJ/kg possible	Residence Time	
			Additives	
			Power, thermal	20 Mg/h steam (13 bar, 240 °C) (Minden)
			Power, electric	
<b>Output</b>				
Solid	Slag, metals, fly dust			
Liquid				
Gaseous	Flue gas			
<b>Product Gas Utilization</b>				
Actual	Immediate combustion of synthesis gas			

## 6.2.2 Gasification as Sub-Step of Combustion/Melting Processes

Process	Ebara TwinRec / TIFG		Development Status	5
Manufacturer / Provider	Ebara Corporation <a href="https://www.ebara.co.jp/en">https://www.ebara.co.jp/en</a>		Number of Reference Plants	12
			Cumulated Operating Hours	> 100,000 ca. 6,000 h/(a, plant)
Internet	Ebara Corporation Thurgauerstrasse 40 8050 Zürich, CH		Cumulated Fuel Throughput	>> 1,000,000 Mg
Contact			Operated Since	2000
E-Mail Address	+41-44 307 35 20		Patent granted?	yes
Telephone			Sites	i.a. Japan (Aomori)
Fax				
Process / Reactor	Circulating fluidized bed with subsequent swirl combustion chamber			
Aim	Inertization of waste fractions, metal recovery energy conversion using steam process			
Special Features	Separation of heavy inert components from non-combustible components and dust in the gasifier			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
Process Description				
Input	Processing		Thermochemical Process	
Shredder residue, fly ash, sewage sludge, plastics, liquid and hospital waste, household waste	Grain Size		Reactant	Air
	Water Content		Temperature	Gasification: 500-600 °C combustion: 1,350-1,450 °C
	Ash Content		Pressure	atmospheric
	Homogenization		Throughput	100-300 Mg/d per line
	Calorific Value		Residence Time	
			Additives	
			Power, thermal	e.g. 40 MW per line (Aomori)
			Power, electric	
Output				
Solid	Metals, bed ash, vitrified fly ash			
Liquid				
Gaseous	Synthesis gas (after gasifier); flue gas (after combustion chamber)			
Product Gas Utilization				
Actual	Combustion to melt fly ash and energy recovery with steam boiler			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Hitachi Zosen Gasification and Melting System</b>		Development Status	<b>5</b>
Manufacturer / Provider	Hitachi Zosen Corporation, Osaka, Japan www.hitachizosen.co.jp/english/		Number of Reference Plants	10
			Cumulated Operating Hours	> 400,000
Internet	Hitachi Zosen Inova AG Hardturmstrasse 127 8037 Zürich, Switzerland		Cumulated Fuel Throughput	> 1,000,000 Mg
Contact	info@hz-inova.com		Operated Since	2003
E-Mail Address	+41 44 277 11 11		Patent granted?	
Telephone	+41 44 277 13 13		Sites	9 Japan, 1 South Korea
Fax				
Process / Reactor	Gasification and combustion / fluidized bed and melting furnace + combustion chamber			
Aim	Treatment of household waste, metal recovery (Fe, Al), utilization of inert fraction			
Special Features	Combustion of synthesis gas in melting chamber with downstream post-combustion			
Treatment Costs				
Process Disturbances				
Cause of Disturbances	Weak point: refractory lining			
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, commercial waste, shredder residue	Grain Size		Reactant	Air
	Water Content		Temperature	Gasification: 500 – 600 °C, combustion melting chamber: 1,200 – 1,400 °C, post-combustion: > 850 °C
	Ash Content		Pressure	
	Homogenization		Throughput	15,000 – 121,500 Mg/a
	Calorific Value		Residence Time	
			Additives	Sand for fluidized bed
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Slag, metals, fly ash / gas purification residue			
Liquid				
Gaseous	Flue gas			
<b>Product Gas Utilization</b>				
Actual	Combustion in melting furnace + combustion chamber			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>JFE Gasifying and Direct Melting System</b>		Development Status	<b>5</b>
Manufacturer / Provider	JFE Engineering Corporation		Number of Reference Plants	10 & 2 under construction
			Cumulated Operating Hours	
Internet	www.jfe-eng.co.jp		Cumulated Fuel Throughput	> 3,000,000 Mg
Contact	Takehiko Aoki		Operated Since	2003
E-Mail Address	aoki-takehiko@eu.jfe-eng.com		Patent granted?	yes
Telephone	+49-69-2980-2870		Sites	Japan
Fax	+49-69-2980-28769			
Process / Reactor	Fixed bed gasifier with fluidization of fuels in upper part of reactor			
Aim	Inertization of waste fractions, metals recovery, energy conversion using steam power process			
Special Features	Combined fixed-bed and fluidized bed process for gasification and melting of waste fractions in one reactor			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals	Uptime usually 250 to 280 days per year			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, RDF, sewage sludge, shredder residue, hazardous waste fractions (i.a. hospital waste)	Grain Size	< 600 mm	Reactant	Enriched air with 30-35 % O <sub>2</sub> , air, water
	Water Content	No limit	Temperature	Oxide zone 2,000 °C reduction zone: 700-850 °C
	Ash Content		Pressure	underpressure
	Homogenization		Throughput	1-13 Mg/h per line
	Calorific Value	< 20 MJ/kg	Residence Time	
			Additives	5 % coke, 3 % lime
			Power, thermal	
			Power, electric	1.6-20 MW
<b>Output</b>				
Solid	Slag, metals, fly ash			
Liquid				
Gaseous	Product gas			
<b>Product Gas Utilization</b>				
Actual	Combustion of product gas in secondary combustion chamber			
Planned				

Process	<b>Kobelco Gasification and Melting Process</b>		Development Status	<b>5</b>
Manufacturer / Provider	Kobelco Eco-Solutions		Number of Reference Plants	17
			Cumulated Operating Hours	>> 100,000
Internet	www.kobelco-eco.co.jp		Cumulated Fuel Throughput	Overall 2,789 Mg/d
Contact	Kazuaki Sakata (Düsseldorf) Tsuyoshi Aimoto (Kobe)		Operated since	2000
E-Mail Address	k.sakata@kobelco-eco.co.jp t.aimoto@kobelco-eco.co.jp		Patent granted?	
Telephone	+49-211-779-204-30 +81-78-232-8014		Sites	Japan 14, South Korea 2
Fax	+49-211-779-204-50 +81-78-232-8086			
Process / Reactor	Fluidized bed gasification and melting process			
Aim	Inertization of waste fraction, metal recovery, energy conversion using steam power process			
Special Features				
Treatment Costs	6-12 €/Mg average costs for operating materials ( <b>consumables</b> ) in 2005			
Process Disturbances	No disturbances in standard operation			
Cause of Disturbances	Inadmissible waste fractions (e.g. bulky waste, special waste fractions)			
Service Intervals	3 times per year: 2 x 7 days, 1 x 18 days			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, processed commercial waste	Grain Size	Household waste: comminuted	Reactant	Air
	Water Content		Temperature	Gasifier: 500-600 °C Melting: 1,200-1,300 °C
	Ash Content		Pressure	Underpressure
	Homogenization		Throughput	up to 100,000 Mg/a
	Calorific Value	8-12 MJ/kg	Residence Time	ca. 30-40 s (Gas RT up to chimney)
			Additives	none
			Power, thermal	
			Power, electric	0.9-10 MW
<b>Output</b>				
Solid	Iron, aluminum, slag, fly ash			
Liquid				
Gaseous	Product gas			
<b>Product Gas Utilization</b>				
Actual	Combustion of product gas in secondary combustion chamber			
Planned				
Process	<b>Nippon Steel</b>		Development Status	<b>5</b>

Status of Alternative Techniques for Thermal Waste Treatment

Direct Melting System				
Manufacturer / Provider	Nippon Steel & Sumikin Engineering Ltd.	Number of Reference Plants	37 & 5 under construction	
		Operating Hours	ca. 7,500-8,000 per installation and year	
Internet	<a href="http://www.env.go.jp/recycle/circul/venous_industry/en/skill_pdf/t036.pdf">http://www.env.go.jp/recycle/circul/venous_industry/en/skill_pdf/t036.pdf</a>	Cumulated Fuel Throughput	Overall 9,214 Mg/d	
Contact	Nobuhiro Tanigaki MSc.	Operated since	1979	
E-Mail Address	tanigaki.nobuhiro@eng.nssmc.com	Patent granted?	several	
Telephone	+49-211-528095-0	Sites	Japan; South Korea	
Fax	+49-211-528095-69			
Process / Reactor	Fixed bed gasifier			
Aim	Inertization of waste fractions, metal recovery, energy conversion using steam power process			
Special Features	High flexibility regarding input material, no processing of input material (but: grain size < 800), no heavy metals in slag			
Treatment Costs	160 €/Mg (basis of calculation unclear)			
Process Disturbances	none			
Cause of Disturbances	none			
Service Intervals	1 x per year			
Process Description				
Input	Processing		Thermochemical Process	
Household waste, hospital waste, sewage sludge, ashes, bed ash, asbestos etc.	Grain Size	< 800 mm	Reactant	Air enriched to 36 % O <sub>2</sub> , air
	Water Content	20-60 %	Temperature	1,800-300 °C
	Ash Content	5-30 %	Pressure	Atmospheric
	Homogenization	none	Throughput	1-12 Mg/(h, line)
	Calorific Value	5-16 MJ/kg	Residence Time	4 h
		Additives	5-10 % coke, lime	
		Power, thermal		
		Power, electric	up to 23.5 MW	
Output				
Solid	Slag, metals, fly ash			
Liquid				
Gaseous	Synthesis gas			
Product Gas Utilization				
Actual	Combustion of synthesis gas in downstream combustion chamber			
Planned				

### 6.2.3 Gasification for Syngas Production

Process	<b>Ebara UBE Process (EUP)</b>		Development Status	<b>5</b>
Manufacturer / Provider	EUP Co. Ltd. (Ebara Corporation & Ube Industries Ltd.) ab 2008 Ube Co. Ltd.		Number of Reference Plants	3
			Operating Hours	
Internet	http://www.ebara.co.jp/ http://www.ube-ind.co.jp		Cumulated Fuel Throughput	
Contact			Operated	2001-2008
E-Mail Address			Patent granted?	
Telephone			Sites	Japan (Ube City)
Fax				
Process / Reactor	Two-staged pressurized gasification 1. Stage: rotating fluidized bed, 2. Stage: high-temperature gasifier			
Aim	Generation of hydrogen for ammonia synthesis			
Special Features				
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Packaging waste containing plastics, high-calorific wastes	Grain Size		Reactant	O <sub>2</sub> , H <sub>2</sub> O
	Water Content		Temperature	1. stage: 600-800 °C 2. stage: 1,300-1,500 °C
	Ash Content		Pressure	5-16 bar
	Homogenization	Removal of metals and coarse inert materials	Throughput	30-98 Mg/d
	Calorific Value	27-37 MJ/kg	Residence Time	
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Unburnt material, sand, slag			
Liquid				
Gaseous	Hydrogen, heating gas			
<b>Product Gas Utilization</b>				
Actual	Ammonium synthesis until 2008			
Planned	Currently not in operation			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Kopf SynGas</b>	Development Status	<b>4</b>	
Manufacturer / Provider	Kopf SynGas GmbH & Co.KG Stützenstraße 6 72172 Sulz Bergfelden	Number of Reference Plants	2	
		Cumulated Operating Hours		
Internet	www.kopf-verw.de	Cumulated Fuel Throughput		
Contact	Michael Gaiffi	Operated Since	2002 Balingen 2011 Mannheim	
E-Mail Address	m.gaiffi@kopf-syngas.de	Patent granted?		
Telephone	+ 49-7071-54954-51	Sites	Balingen, Mannheim	
Fax	+ 49-7071-54954-60			
Process / Reactor	Stationary fluidized bed gasifier			
Aim	Inertization of sewage sludge with energy recovery			
Special Features	Product gas cleaning in packed bed of input material			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Sewage sludge	Grain Size	2-10 mm	Reactant	Air
	Water Content	96 % DM	Temperature	Up to 900 °C
	Ash Content		Pressure	
	Homogenization		Throughput	2,200 Mg/a (Balingen) 5,000 Mg/a (Mannheim)
	Calorific Value	ca. 11.4 MJ/kg	Residence Time	ca. 30 min
			Additives	
			Power, thermal	140 kW (pilot plant)
			Power, electric	70 kW (pilot plant)
<b>Output</b>				
Solid	Ash, granulate			
Liquid	condensate			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	CHP			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Noell-Conversion Process</b>		Development Status	<b>3</b>
Manufacturer / Provider	Noell KRC GmbH		Number of Reference Plants	1
			Cumulated Operating Hours	
Internet			Cumulated Fuel Throughput	
Contact			Operated Since	
E-Mail Address			Patent granted?	yes
Telephone			Sites	Pyrolysis stage: Salzgitter
Fax				
Process / Reactor	Pyrolysis (rotary drum indirectly heated), gasification (entrained flow gasification reactor)			
Aim	Conversion of waste into secondary resources and synthesis gas with very little process residues			
Special Features	Co-treatment of liquid wastes			
Treatment Costs	Process could not be operated economically			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Solid and liquid wastes	Grain Size	comminution	Reactant	Pyrolysis: - Gasification: Oxygen
	Water Content		Temperature	Pyrolysis: up to 650 °C Gasification: 1,400 – 1,700 °C
	Ash Content		Pressure	Gasification: 2-25 bar
	Homogenization		Throughput	
	Calorific Value		Residence Time	Pyrolysis: ca. 2 h
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Iron scrap, non-iron scrap, melting granulate, sulfur from desulfurization of synthesis gas, salt/heavy metal concentrate from waste water treatment			
Liquid	Purified waste water			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual				
Planned	Methanol synthesis, feeding to municipal gas grid (after conditioning), gas turbine, gas motor, generation of low pressure for industrial applications, heating of drying installations			

Process	<b>SVZ Fixed-Bed Pressure Gasification</b>		Development Status	<b>5</b>
Manufacturer / Provider	Retrofitting of fixed-bed gasification of lignite to generate town gas in former GDR		Number of Reference Plants	1, with 7 fixed bed pressurized gasifiers
			Cumulated Operating Hours	
Internet			Cumulated Fuel Throughput	Until July 2001: 1 Mio. Mg solid waste
Contact			Operated Since	
E-Mail Address			Patent granted?	Yes (fixed-bed pressure gasification of lignite)
Telephone			Sites	Schwarze Pumpe
Fax				
Process / Reactor	Gasification (shaft reactor with rotating grate)			
Aim	Generation of synthesis gas for methanol production and of electricity			
Special Features	Retrofitting of reactors designed for lignite for use with pelletized waste			
Treatment Costs	Process could not be operated economically.			
Process Disturbances	Blockage of pellet presses in waste processing plant, channeling in shaft reactor, damages of refractory lining			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
RDF-pellets from household waste and commercial waste similar to household-waste, mixed plastics, wood chips, sewage sludge briquettes, tar sludge pellets, shredder light fraction (mixed with coal)	Grain Size	Min. 16x16x16 mm, Max. 80x80x120 mm, Ø RDF-pellets: 16 mm	Reactant	Oxygen and steam (27 bar)
	Water Content	< 20 %; RDF-pellets: ca. 10 %	Temperature	Oxidizing area: 1,200-1,300 °C; raw gas discharge: 450 °C
	Ash Content	< 20 %	Pressure	25 bar
	Homogenization		Throughput	12.5 Mg/h per pressure gasifier
	Calorific Value		Residence Time	
<b>Output</b>				
Solid	Iron and non-iron scarp, inert materials (glass, stones, ceramics, ash) from mechanical processing, sintered gasifier slag, FGD gypsum			
Liquid	Methanol grade AA			
Gaseous	Synthesis gas (partial flow)			
<b>Product Gas Utilization</b>				
Actual	Processed synthesis gas was transferred to a methanol production plant and to a gas and steam power plant to generate steam, a part was marketed.			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>SVZ Entrained Flow Gasification</b>	Development Status	<b>5</b>	
Manufacturer / Provider	Retrofitting of town gas generation from lignite in former GDR	Number of Reference Plants	1, with 2 gasifiers	
		Cumulated Operating Hours		
Internet		Cumulated Fuel Throughput		
Contact		Operated Since		
E-Mail Address		Patent granted?	yes	
Telephone		Sites	Schwarze Pumpe	
Fax				
Process / Reactor	Gasification (entrained flow reactor)			
Aim	Generation of synthesis gas to produce methanol and electricity			
Special Features	Retrofitting of splitting plants constructed in the former GDR intended to generate town gas into entrained flow gasifiers to treat liquid and paste-like waste			
Treatment Costs	Process could not be operated economically			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Liquid and pasty waste (oil, liquids containing hydrocarbons, slurries, tars,...)	Grain Size	-	Reactant	Oxygen and steam
	Water Content	≤ 1,0 wt.-%	Temperature	ca. 1,500 °C
	Solids Content	≤ 10,0 wt.-%	Pressure	
	Homogenization		Throughput	15 Mg/h (capacity)
	Calorific Value		Residence Time	
			Additives	no specific additives
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Slag			
Liquid	Methanol Grade AA			
Gaseous	Synthesis gas (partial flow)			
<b>Product Gas Utilization</b>				
Actual	Processed synthesis gas was transferred to a methanol production plant and to a gas and steam power plant to generate steam, a part was marketed.			

## Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>BGL British Gas Lurgi</b>		Development Status	<b>5</b>
Manufacturer / Provider	Envirotherm GmbH Ruhrallee 185, 45136 Essen		Number of Reference Plants	5 with 14 gasifiers
			Cumulated Operating Hours	> 100,000 (different fuels)
Internet	www.envirotherm.de		Cumulated Fuel Throughput	> 0.7 Mio. Mg (SVZ)
Contact	Hansjobst Hirschfelder		Operated Since	
E-Mail Address	info@envirotherm.de		Patent granted?	yes
Telephone	+49-201-6346-400		Sites	Treatment of waste only at SVZ and pilot plant Westfield
Fax	+49-201-6346-500			
Process / Reactor	Slag bath gasifier (pressurized fixed bed gasifier)			
Aim	Synthesis gas as raw material for chemical, petrochemical fertilizer industry, electricity generation, town gas			
Special Features	Applicable as raw material for chemical industry or substitute for natural gas due to high content of CH <sub>4</sub>			
Treatment Costs				
Process Disturbances	Problems with slag flow			
Cause of Disturbances	Amount of troubling materials too high			
Service Intervals	2-3 years			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Coal and up to 80 % waste, ash-containing coal, lignite, sewage sludge	Grain Size	Min.16x16x16 Max 80x80x120	Reactant	Oxygen, steam
	Water Content	< 30 %	Temperature	Up to 1,600 °C
	Ash Content	< 20 %	Pressure	30-40 bar
	Homogenization	conditional	Throughput	> 1,000 Mg/d
	Calorific Value	> 10 MJ/kg	Residence Time	Several hours
			Additives	Fluxing agent depending on slag quality
			Power, thermal	
			Power, electric	120 - 150 MW <sub>el</sub> per gasifier depending on heat utilization concept and utilization of synthesis gas
<b>Output</b>				
Solid	Slag			
Liquid	Depending on raw gas purification			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Chemical and petrochemical industry, refineries, energy and gas supply			
Planned				

Process	<b>Thermoselect</b>	Development Status	<b>3</b>	
Manufacturer / Provider	Thermoselect S.A. Lizenznehmer: Kawasaki Steel Erfinder: Günter Kiss	Number of Reference Plants	3	
		Cumulated Operating Hours		
Internet		Cumulated Fuel Throughput		
Contact		Operated	Karlsruhe 1999- 2004	
E-Mail Address		Patent granted?	ja	
Telephone		Sites	Verbania (Italy) Karlsruhe (Germany) Chiba (Japan)	
Fax				
Process / Reactor	Degassing canal with subsequent high-temperature gasification (direct melting of inorganic components)			
Aim	Generation of synthesis gas, vitrified mineral materials with positive eluate behavior			
Special Features	Shut down of degassing canal in Karlsruhe (pyrolysis abandoned)			
Treatment Costs	Not determined, originally calculated by supplier: 250 DM/Mg			
Process Disturbances	Insufficient operation of degassing canal and gasification reactor, untimely erosion of internal reactor lining, problems slag discharge, pump explosion in cooling water system, gas leakage due to material embrittlement, blocking of gas discharge of high temperature reactor with mineral slag (particle discharge due to too short residence time in reactor)			
Service Intervals	Unknown; the planned lifetime of high temperature reactor lining was not achieved due to strong wear			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, household-like commercial waste, bulky waste, sewage sludge	Grain Size	N/A	Reactant	Oxygen for gasification
	Water Content	Sewage sludge: max 65-70 %	Temperature	Degassing: up to 600-800 °C, gasification: up to 2,000 °C
	Ash Content	N/A	Pressure	200 mbar
	Homogenization	press	Throughput	10 Mg/h, working load Karlsruhe 50-70 %
	Calorific Value	7,000-16,000 kJ/kg	Residence Time	Degassing: 1-2 h Gasification: 2 s (Gases)
		Additives		
		Power, thermal	Karlsruhe: 100 MW; steam generator: 63.1 MW	
		Power, electric	Karlsruhe: 12.7 MW (gross), 2.7 MW net	
<b>Output</b>				
Solid	Vitreous mineral materials, metal granulate, metal precipitate and mixed salts from process water purification, sulfur from gas cleaning			
Liquid	Purified process waster (utilization as cooling water) → process free of waste water			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Heating degassing channel, high temperature reactor and homogenizing reactor, eventually also sewage sludge drying; further energetic utilization			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>BASURAgas</b>		Development Status	<b>4</b>
Manufacturer / Provider	ProCone GmbH CH-4800 Zofingen AG		Number of Reference Plants	4
			Cumulated Operating Hours	64,000 (four plants)
Internet	www.procone.org		Cumulated Fuel Throughput	64,000 Mg
Contact	Adrian FÜRST		Operated Since	1990-2006
E-Mail Address	Adrian.fuerst@procone.org		Patent granted?	yes
Telephone	+41-62 216 80 80		Sites	Switzerland & Germany
Fax	+41-62 216 80 81			
Process / Reactor	Fixed bed gasifier (autothermal)			
Aim	Generation of synthesis gas			
Special Features	Application of a movable counter-cone instead of a grate to regulate material flow, stabilize firebed and prevent bridging			
Treatment Costs	105 €/Mg waste			
Process Disturbances	Failures in slag discharge due to insufficient fuel processing			
Cause of Disturbances				
Service Intervals	Gas purification 1,800 h / gas generator 7,200 h			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Waste wood, sewage sludge, RDF	Grain Size	80 mm	Reactant	Air enriched with O <sub>2</sub> , air
	Water Content	12 %	Temperature	1,200 °C
	Ash Content	45 %	Pressure	max -150 mbar rel.
	Homogenization	none	Throughput	4,500 Mg/a
	Calorific Value	> 14.4 MJ/kg	Residence Time	1 h
			Additives	
			Power, thermal	up to 6 MW, up to 50 MW planned
			Power, electric	up to 3 MW, up to 15 MW planned
<b>Output</b>				
Solid	Vitrified slag			
Liquid	Purified water			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Generation of electricity and heat (e.g. gas motor, hot gas turbine, steam turbine)			
Planned	Gas fermentation to produce ethanol and butanol			

## 6.2.4 Gasification as Upstream Process

Process	Ecoloop		Development Status	<b>3</b>
Manufacturer / Provider	ecolooop GmbH Xella Group		Number of Reference Plants	1
			Cumulated Operating Hours	600
Internet	www.ecolooop.eu		Cumulated Fuel Throughput	800 Mg
Contact	Roland Möller		Operated Since	2013
E-Mail Address	roland.moeller@ecolooop.eu		Patent granted?	Yes (ca. 20 patents)
Telephone	+49-39454-58-301		Sites	Elbingerode
Fax	+49- 39454-58-433			
Process / Reactor	Gasification in caustic lime moving bed			
Aim	Generation of chlorine- and sulfur-free synthesis gas for thermal processes, electricity generation and material utilizations			
Special Features	Fixation of contaminants in lime matrix, sealing of reactor by lime-fuel column (14 m), no movable parts in hot areas, homogenization of filling by rotating chute			
Treatment Costs				
Process Disturbances	Stoichiometric distribution at reaction front is currently being optimized to ensure maximum stable thermal performance			
Cause of Disturbances				
Service Intervals	Once per year (planned)			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Commercial waste, shredder waste (heavy & light fraction) waste wood, sewage sludge (planned), waste containing bitumen, lignite, high-salt lignite, plastic waste, oil shale, contaminated soils	Grain Size		Reactant	Air, water (optional), CO <sub>2</sub> -rich off-gas from limestone burning or from gas motors
	Water Content		Temperature	< 1,300 °C
	Ash Content		Pressure	200-500 mbar
	Homogenization		Throughput	Ca. 40,000 Mg/a (depending on H <sub>U</sub> )
	Calorific Value		Residence Time	Ca. 12 h (full load)
			Additives	
			Power, thermal	32 MW, expansion to 45 MW planned
		Power, electric	11 MW (at 32 MW <sub>th</sub> )	
<b>Output</b>				
Solid	Fine lime (ca. 50 %), CaCl <sub>2</sub> and ash, ca. 25 % of fuel input; utilization of fine lime in industrial applications planned			
Liquid				
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Fuel gas for lime kiln to substitute natural gas			
Planned	Generation of electricity (CHP or gas turbine), CHP operated with oxygen → recirculation of hot off-gas (H <sub>2</sub> O and CO <sub>2</sub> ) as gasification agent, „Closed Recycling Loops“ in industry using synthesis gas, enrichment of reusable materials in the lime circle			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>ZWS Gasification (Rüdersdorf)</b>		Development Status	<b>5</b>
Manufacturer / Provider	Envirotherm GmbH Ruhrallee 185, 45136 Essen		Number of Reference Plants	4
			Cumulated Operating Hours	> 200,000
Internet	www.envirotherm.de		Cumulated Fuel Throughput	> Mio. Mg (Rüdersdorf)
Contact	Dr. Andreas Brors		Operated Since	1996
E-Mail Address	info@envirotherm.de		Patent granted?	
Telephone	+49-201-6346-400		Sites	4
Fax	+49-201-6346-500			
Process / Reactor	Circulating fluidized bed gasification			
Aim	Generation of synthesis gas, utilization of low-calorific waste and substitution of high-value fuels by low-priced waste and residual materials			
Special Features	Comparably high requirements regarding processing and composition of fuels, very low calorific values possible			
Treatment Costs	Rüdersdorf: ca. 30 €			
Process Disturbances	Agglomeration at nozzle floor and gasifier discharge, caking, temperatures below dew point, material flux in ash cooler			
Cause of Disturbances	Troubling materials in fuel (metals), caking due to low ash melting temperatures of fuels			
Service Intervals	yearly			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Sewage sludge, waste wood, plastic waste, oil sludges, RDF, paper sludge, coal, etc.	Grain Size	< 100x100x30 mm (95 %)	Reactant	Air, Oxygen, steam
	Water Content	< 50 %	Temperature	850-950 °C
	Ash Content		Pressure	atmospherics
	Homogenization	beneficial	Throughput	15,000 Mg/a (depending on plant capacity)
	Calorific Value	1-35 MJ/kg	Residence Time	minutes
			Additives	
			Power, thermal	100 MW
			Power, electric	Depending on plant concept
<b>Output</b>				
Solid	Bed- and filter ash			
Liquid	Depending on raw gas cleaning			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Cement-, paper-, steel- and chemical industry			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	Lahti Kymijärvi I		Development Status	4
Manufacturer / Provider	Foster Wheeler		Number of Reference Plants	1
			Cumulated Operating Hours	> 20,000
Internet			Cumulated Fuel Throughput	> 500,000 Mg (15-34% RDF)
Contact	Matti Nieminen, VTT		In Operation	1998-2008
E-Mail Address	matti.nieminen@vtt.fi		Patent granted?	
Telephone	+358-207226587		Sites	Lahti, Finland
Fax				
Process / Reactor	Gasification of plastic waste (separate collection) (RDF) with biomass / circulating fluidized bed, combustion of synthesis gas in coal power plant			
Aim	Waste management / disposal of municipal solid waste			
Special Features				
Treatment Costs	Investment costs 12 million €			
Process Disturbances				
Cause of Disturbances	Availability > 90 %			
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
	Grain Size		Reactant	Air
	Water Content		Temperature	850-1,000 °C
	Ash Content		Pressure	
	Homogenization		Throughput	
	Calorific Value		Residence Time	
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Small amounts of slag from gasification			
Liquid				
Gaseous	Synthesis gas with 2-3.5 MJ/kg			
<b>Product Gas Utilization</b>				
Actual	Combustion in coal power plant			
Planned	Plant shut down since not approvable for waste treatment; replaced by Lahti Kymijärvi II			

## Status of Alternative Techniques for Thermal Waste Treatment

Process	Lahti Kymijärvi II		Development Status	4
Manufacturer / Provider	Metso Oyj, Finland		Number of Reference Plants	1, 2 lines
			Cumulated Operating Hours	
Internet	http://www.metso.com		Cumulated Fuel Throughput	
Contact	Matti Nieminen, VTT		Operated Since	2012 (demonstration), since 2013 standard operation
E-Mail Address	matti.nieminen@vtt.fi		Patent granted?	
Telephone	+358-207226587		Sites	Lahti, Finland
Fax				
Process / Reactor	Gasification of RDF (from commercial and household waste) / circulating fluidized bed, synthesis gas is dedusted and used in gas power plant (power plant equipped with NaHCO <sub>3</sub> gas purification)			
Aim	Waste management / disposal of municipal solid waste			
Special Features				
Treatment Costs	Investment costs 160 million €			
Process Disturbances				
Cause of Disturbances	In starting phase blockages of RDF-infeed			
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
	Grain Size		Reactant	Air
	Water Content		Temperature	850-900 °C
	Ash Content		Pressure	
	Homogenization		Throughput	250,000 mg/a
	Calorific Value		Residence Time	
			Additives	
			Power, thermal	90 MW
			Power, electric	50 MW
<b>Output</b>				
Solid	Small amounts of slag from gasification, filter dust			
Liquid				
Gaseous	Synthesis gas with 2-3.5 MJ/kg			
<b>Product Gas Utilization</b>				
Actual	Combustion in coal power plant			
Planned				

### 6.3 Plasma Processes

Process	<b>Westinghouse, AlterNRG</b>		Development Status	<b>4</b>
Manufacturer / Provider	Alter NRG 215, 4000 - 4zh Street SE Calgary, Alberta T2G 2W3		Number of Reference Plants	4
			Cumulated Operating Hours	
Internet	http://www.alternrg.com		Cumulated Fuel Throughput	
Contact	Danny Hay		Operated Since	
E-Mail Address	info@alternrg.ca		Patent granted?	
Telephone	+1 403 806 3875		Sites	Japan, India, USA
Fax	+1 403 806 3721			
Process / Reactor	Plasma-heated countercurrent gasifier in shaft furnace with liquid slag discharge			
Aim	Generation of synthesis gas (with high calorific value and low in pollutants) and vitrified slag from processed municipal solid waste			
Special Features	Admixture of furnace coke and waste tires as energy carriers optionally gasification with oxygen			
Treatment Costs	105 US-\$/Mg - 152 US-\$/Mg (estimation)			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Processed MSW, hazardous waste, furnace coke, waste tires, shredder light fraction	Grain Size	< 25 cm	Reactant	Air, steam, Oxygen
	Water Content	not restricted	Temperature	1,500-5,500 °C
	Ash Content	N/A	Pressure	atmospheric
	Homogenization	Processing	Throughput	40-620 Mg/d MSW (max 1,000 Mg/d in case of oxygen gasification)
	Calorific Value		Residence Time	
			Additives	Coke, CaCO <sub>3</sub>
			Power, thermal	77.5 MW (max.)
			Power, electric	25 MW (max.)
<b>Output</b>				
Solid	Slag			
Liquid				
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Electricity generation steam power process			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Eurolasma (CHO Power)</b>	Development Status	<b>3</b>	
Manufacturer / Provider	CHO-Power 21 rue Daugère 33 520 Bruges, France	Number of Reference Plants	1	
		Cumulated Operating Hours		
Internet		Cumulated Fuel Throughput		
Contact		Operated Since		
E-Mail Address	contact@cho-power.com	Patent granted?		
Telephone	+ 33 (0)5 56 49 70 00	Sites	Moncenx (France)	
Fax	+ 33 (0)5 56 49 70 19			
Process / Reactor	Autothermal air gasification on grate with post-treatment of gasification product by plasma in 2 <sup>nd</sup> stage, derived from IMG Bellwether			
Aim	Generation of synthesis gas low in pollutants and vitrified slag from processes MSW and biomass			
Special Features	Tars and gasification residues from 1 <sup>st</sup> stage are converted in 2 <sup>nd</sup> stage; preheating of air prior to 1 <sup>st</sup> stage			
Treatment Costs	149 US-\$/Mg (estimation)			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Processed MSW together with biomass	Grain Size	6 cm	Reactant	air
	Water Content		Temperature	850/1,200 (1 <sup>st</sup> /2 <sup>nd</sup> stage)
	Ash Content		Pressure	
	Homogenization	processing	Throughput	
	Calorific Value		Residence Time	
		Additives	Air	
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Vitrified slag			
Liquid	Condensate			
Gaseous	Syngas			
<b>Product Gas Utilization</b>				
Actual	Gas motor			
Planned	Gas motor, turbine			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Advanced Plasma Power</b>		Development Status	<b>3</b>
Manufacturer / Provider	Advanced Plasma Power Ltd Marston Gate Business Park Stirling Road Swindon SN3 4DE, UK		Number of Reference Plants	1
			Cumulated Operating Hours	
Internet	www.advancedplasmapower.com		Cumulated Fuel Throughput	
Contact			Operated Since	2008
E-Mail Address			Patent granted?	
Telephone	+44-1793-238550		Sites	Swindon, UK
Fax				
Process / Reactor	Two-stage process with stationary fluidized bed gasifier and subsequent plasma conversion of synthesis gas and slag			
Aim	Generation of synthesis gas (with calorific value and low in pollutants) and vitrified slag from processed MSW			
Special Features	Tars and gasification residue from first stage are completely converted to synthesis gas			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
RDF, shredder light fraction, MSW, wood, biomass	Grain Size	15-80 mm	Reactant	Oxygen, steam
	Water Content	10-14 %	Temperature	700-850 °C Plasma > 5,000 °C
	Ash Content	14-18 %	Pressure	5-10 mbar underpressure
	Homogenization	processing	Throughput	2.5 Mg/d
	Calorific Value	12-16 MJ/kg	Residence Time	
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Vitrified slag			
Liquid				
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Gas motor			
Planned	Fuel cell			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>IMG - Integrated Multifuel Gasification</b>		Development Status	<b>3</b>
Manufacturer / Provider	Bellwether Gasification Technologies Ltd.		Number of Reference Plants	2
			Cumulated Operating Hours	3,000
Internet	www.bgt-online.de		Cumulated Fuel Throughput	15,000 Mg
Contact	Daniel Drechsler		Operated Since	
E-Mail Address	daniel.drechsler@bgt-online.de		Patent granted?	
Telephone	+49-176-78768079		Sites	France, Romania
Fax				
Process / Reactor	Fixed bed gasifier with plasma conditioning			
Aim	Inertization of waste fractions, generation of electricity and heat			
Special Features	1 <sup>st</sup> stage fixed bed reactor: generation of synthesis gas 2 <sup>nd</sup> stage plasma conditioning: decomposition of tars and toxic nano-particles			
Treatment Costs	30 € Mg/waste			
Process Disturbances	Fluctuating operating temperatures			
Cause of Disturbances	Fluctuations of calorific values of input material			
Service Intervals	2 years			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Household waste, hazardous waste, sewage sludge, mixed waste, bio-waste, peat, lignite	Grain Size	0-100 mm	Reactant	Air
	Water Content	< 50 %	Temperature	1,300 °C
	Ash Content	< 50 %	Pressure	
	Homogenization	none	Throughput	8-10 Mg/h
	Calorific Value	> 5 MJ/kg	Residence Time	
			Additives	
			Power, thermal	50 MW
			Power, electric	16 MW
<b>Output</b>				
Solid	Slag			
Liquid	Waste water			
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Boiler			
Planned	CHP, Gas motor			

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Plasco Energy Phoenix Solutions Company</b>		Development Status	<b>3</b>
Manufacturer / Provider	Plasco Energy Group Inc. 1000 Innovation Drive, Suite 400, Ottawa		Number of Reference Plants	2
			Cumulated Operating Hours	> 3,000 (Ottawa)
Internet	www.plascoenergygroup.com		Cumulated Fuel Throughput	> 7,000 Mg
Contact	Sharilyn McNaughton		Operating Hours by Years	
E-Mail Address			Patent granted?	yes
Telephone	+1 (613) 591-9438		Sites	Castel Galli, Spain Ottawa, Canada
Fax				
Process / Reactor	Autothermal gasification on slanted floor with post-treatment of gasification products by plasma in 2 <sup>nd</sup> stage			
Aim	Generation of syngas low in pollutants and vitrified slag from municipal solid waste			
Special Features	Tars and gasification residue from 1 <sup>st</sup> stage are converted to synthesis gas in 2 <sup>nd</sup> stage; pre-heating of air before 1 <sup>st</sup> stage			
Treatment Costs	149 US-\$ / Mg (estimated)			
Process Disturbances				
Cause of Disturb- ances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Processed municipi- pal solid waste (removal of inert materials)	Grain Size		Reactant	Air
	Water Content		Temperature	850/1,200 °C (1 <sup>st</sup> /2 <sup>nd</sup> stage)
	Ash Content		Pressure	
	Homogenization	processing	Throughput	85 Mg/d
	Calorific Value		Residence Time	
			Additives	
			Power, thermal	12 MW
			Power, electric	4,2 MW
<b>Output</b>				
Solid	Vitrified slag			
Liquid	Condensate			
Gaseous	Syngas			
<b>Product Gas Utilization</b>				
Actual	Gas motor			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Shark Industries</b>	Development Status	-	
Manufacturer / Provider	Shark Industries Summerstrasse 31, Herrsching, DE 82211	Number of Reference Plants	1	
		Cumulated Operating Hours	< 100 h	
Internet		Cumulated Fuel Throughput		
Contact		Operated Since		
E-Mail Address	info@s-i.ag	Patent granted?		
Telephone	+49 8152 396 42 00	Sites		
Fax	+49 8152 396 21 98			
Process / Reactor	Sublimation with plasma reactor			
Aim	Sublimation of waste and energy conversion to generate heat and electricity			
Special Features				
Treatment Costs				
Process Disturbances	No complete sublimation, problems with residual materials, frequent cleaning of reactor necessary			
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing	Thermochemical Process		
Mixed and household waste, hospital waste, hazardous waste, biogenic waste	Grain Size		Reactant	
	Water Content		Temperature	5,000 °C
	Ash Content		Pressure	1-5 bar
	Homogenization		Throughput	150 kg/h
	Calorific Value		Residence Time	< 10 s
		Additives		
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Slag			
Liquid				
Gaseous	Synthesis gas			
<b>Product Gas Utilization</b>				
Actual	Turbine			
Planned				

## 6.4 Liquefaction Processes

Process	<b>Dieselwest</b>	Development Status	-	
Manufacturer / Provider	Recenso GmbH Greuel 20 42897 Remscheid	Number of Reference Plants	1	
		Cumulated Operating Hours	4,000 h	
Internet	www.recenso.eu	Cumulated Fuel Throughput	6,000 Mg	
Contact	Christian Haupts	Operated Since	2012	
E-Mail Address	chaupts@recenso.eu	Patent granted?		
Telephone	+49-2191-42275-14	Sites	Ennigerloh	
Fax	+49-2191-42275-16			
Process / Reactor	Catalytic unpressurized liquefaction			
Aim	Production of fuels (Diesel/heating oil)			
Special Features	Single-stage process generation of heat by friction (circulation of reaction mass by turbines)			
Treatment Costs	200 €/Mg (planning figures, including investment and capital costs)			
Process Disturbances	Input and discharge of residual material need to be optimized			
Cause of Disturbances	Input volume too high			
Service Intervals	Pilot plant in campaign operation			
<b>Process Description</b>				
Input	Processing	Thermochemical Process		
RDF, plastic, sewage sludge, biomass (e.g. waste wood, wood-plastic composites, sunflower husks, rapeseed meal)	Grain Size	< 30 mm	Reactant	
	Water Content	< 5 %	Temperature	ca. 320 °C
	Ash Content	< 10 %	Pressure	50-100 mbar under-pressure
	Homogenization	yes	Throughput	6,000 Mg/a (per line; planned)
	Calorific Value	> 20 MJ/kg	Residence Time	3 min
		Additives	Lime, catalyst, Fe <sub>2</sub> O <sub>3</sub>	
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Inorganic substances, crystals, salts, 10 to 15 % of input as solid and ash residue			
Liquid	Middle distillate, ca. 400 l per Mg input			
Gaseous	Only small amounts (not balanced)			
<b>Product Gas Utilization</b>				
Actual				
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Logoil</b>	Development Status	<b>3</b>	
Manufacturer / Provider	Logmed Cooperation GmbH	Number of Reference Plants	1	
		Cumulated Operating Hours	5,000 h	
Internet	www.logmed-coop.de	Cumulated Fuel Throughput	160 Mg	
Contact	Helmut Göldner	Operated Since		
E-Mail Address	logmed@t-online.de	Patent granted?		
Telephone	+49-345-4780230	Sites	Halle	
Fax	+49-345-4780233			
Process / Reactor	Catalytic unpressurized liquefaction			
Aim	Generation of synthetic oils by depolymerization of plastic waste			
Special Features	Single-stage process			
Treatment Costs	25-39 €/Mg			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Processed plastic waste rich of polyolefins (e.g. from health sector)	Grain Size	30 - 60 mm	Reactant	
	Water Content	< 10 %	Temperature	360 - 380 °C
	Ash Content	< 1 %	Pressure	atmospheric
	Homogenization		Throughput	600 Mg/a
	Calorific Value		Residence Time	7-9 min
		Additives	Zeolite catalyst	
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Solids (sump, sand 3-5 %), wax (10-40 %)			
Liquid	Light-, heavy oils, aqueous phase (50-75 %)			
Gaseous	10-15 %			
<b>Product Gas Utilization</b>				
Actual	Used to dry input materials and for internal consumption			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>KDV</b>	Development Status	-	
Manufacturer / Provider	Alphakat GmbH Schulstraße 8 96155 Buttenheim	Number of Reference Plants	9	
		Cumulated Operating Hours		
Internet		Cumulated Fuel Throughput		
Contact	Dr. Christian Koch	Operated Since		
E-Mail Address	mail@alphakat.de	Patent granted?	DE10049377 A1	
Telephone	+49-9545-208	Sites	i.a. Eppendorf	
Fax	+49-9545-950325			
Process / Reactor	Direct liquefaction; catalytic unpressurized liquefaction			
Aim	Production of fuels (diesel/heating oil)			
Special Features	Generation of heat by circulation of reaction mass in turbine			
Treatment Costs	0.23-0.25 €/l [KDV 2014]			
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing	Thermochemical Process		
Renewable raw materials, plastic, rubber, waste tires, waste oils, waxes and fats, agricultural waste, animal waste, crude oil	Grain Size		Reactant	
	Water Content		Temperature	270 - 350 °C
	Ash Content		Pressure	0.9 bar
	Homogenization		Throughput	0.1-0.25 Mg/h
	Calorific Value		Residence Time	
		Additives	Soda, catalyst (Na-Al-silicate)	
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid	Salts, inorganic material			
Liquid	Liquid fuels			
Gaseous				
<b>Product Gas Utilization</b>				
Actual				
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Clyvia</b>	Development Status	<b>3</b>	
Manufacturer / Provider	Clyvia Technology GmbH Friedrich-List-Allee 10; 41844 Wegberg-Wildenrath	Number of Reference Plants	1	
		Cumulated Operating Hours		
Internet	www.clyviatec.de	Cumulated Fuel Throughput		
Contact		In Operation	2006-2009	
E-Mail Address	technical@clyviatec.de	Patent granted?	DE102005010151 B3	
Telephone	+49 - 2432 - 893626	Sites	Wegberg-Wildenrath, Germany	
Fax	+49 - 2432 - 893625			
Process / Reactor	Fractionated depolymerization in stirring reactor			
Aim	Conversion of plastic and oily waste to generate products similar to diesel/heating oil			
Special Features	Ineffectiveness of catalyst proved in laboratory tests			
Treatment Costs				
Process Disturbances				
Cause of Disturbances				
Service Intervals				
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Oil (waste oil, transformer oil, oil sludges, bilge oil), plastic (PE, PP, PVC max. 10 %), PS)	Grain Size	< 10 mm	Reactant	
	Water Content		Temperature	380-420°C
	Ash Content		Pressure	200-300 mbar under-pressure
	Homogenization		Throughput	600 l/h Produkt 10 Mg/d Input
	Calorific Value		Residence Time	
		Additives	Hydrated lime, soda (fixation of F and Cl)	
		Power, thermal		
		Power, electric		
<b>Output</b>				
Solid				
Liquid	90 % Diesel and heating oil, 5 % bitumous by-products			
Gaseous	5 % short-chained hydrocarbons			
<b>Product Gas Utilization</b>				
Actual	Process heating			
Planned				

Status of Alternative Techniques for Thermal Waste Treatment

Process	<b>Syntrol</b>		Development Status	<b>3</b>
Manufacturer / Provider	NILL-TECH GmbH Max Eythstr. 23, D-71088 Holzgerlingen		Number of Reference Plants	1
			Cumulated Operating Hours	8,000
Internet	www.nill-tech.de		Cumulated Fuel Throughput	
Contact	Wolf Eberhard Nill		Operated Since	
E-Mail Address	info@nill-tech.de		Patent granted?	3 patents
Telephone	+49-7031-43745-0		Sites	Siehlbrugg
Fax	+49-7031-43745-19			
Process / Reactor	Thermolysis in three-stage-reactor			
Aim	Gasoil and kerosene, raw materials for chemical industry			
Special Features				
Treatment Costs	150-200 €/Mg waste			
Process Disturbances				
Cause of Disturbances	Amount of impurities too high			
Service Intervals	Twice per year			
<b>Process Description</b>				
Input	Processing		Thermochemical Process	
Assorted plastic waste (PE, PP, PS, PB): PE/PP/PB 75 - 100 %, PS/EPS 0 - 20 % PET/PA/PUR 0 - 5 %	Grain Size	30-40 mm	Reactant	
	Water Content	< 1 %	Temperature	200-400 °C
	Ash Content	Not specified	Pressure	unpressurized
	Homogenization		Throughput	5,000 Mg/a
	Calorific Value	> 30 MJ/kg	Residence Time	
			Additives	
			Power, thermal	
			Power, electric	
<b>Output</b>				
Solid	Coke including disturbing materials (e.g. aluminum, glass, sand etc.)			
Liquid	Gasoil (major fraction), kerosene/gasoline fraction			
Gaseous	Non-condensable gases			
<b>Product Gas Utilization</b>				
Actual	Product gas mainly used to generate process heat			
Planned				

## Literature

- ADEME 2009 AGENCE DE L'ENVIRONNEMENT ET DE LA MAÎTRISE DE L'ENERGIE  
TECHNICAL, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF PLASCOENERGY GROUP GASIFICATION  
PROCESS USING PLASMA TORCHES, 2009
- ADEME 2012 C. DELAVELLE/AJI-EUROPE  
ETAT DE L'ART DE LA PRODUCTION DE LIQUIDES OU DE GAZ À PARTIR DE DÉCHETS AUTRES QUE LES DÉCHETS  
DE BIOMASSE PROPRE, 2012APP 2008 ADVANCED PLASMA POWER AND ITS GASPLASMA PROCESS  
ADVANCED PLASMA POWER LTD  
2008
- APP 2014 ADVANCED PLASMA POWER LTD  
ULR: [HTTP://WWW.ADVANCEDPLASMAPOWER.COM/REFERENCES-AND-PARTNERS/](http://www.advancedplasmaenergy.com/references-and-partners/)  
STAND 26.03.2014
- AYUKAWA 2002 A. AYUKAWA, S. UNO S  
UTILIZATION OF PYROLYSIS CHAR FROM MSW  
2. I-CIPEC, JEJU, KOREA, SEPTEMBER 5-7, 2002, PROCEEDINGS ON CD
- BAUER 2009 M. BAUER, G. WACHTMEISTER  
ENTSTEHUNG VON FORMALDEHYD IN MAGER-GASMOTOREN  
MTZ - MOTORTECHNISCHE ZEITSCHRIFT, JULY 2009, VOLUME 70, ISSUE 7-8, PP 580-587
- BEHRENDT 2006 F. BEHRENDT, Y. NEUBAUER, K. SCHULZ-TÖNNIES, B. WILMES, N. ZOBEL  
DIREKTVERFLÜSSIGUNG VON BIOMASSE - REAKTIONSMCHANISMEN UND PRODUKTVERTEILUNGEN  
STUDIE DER TU BERLIN FÜR DIE BUNDESANSTALT FÜR LANDWIRTSCHAFT UND ERNÄHRUNG, BERLIN 2006
- BERWEIN 1988 H.J. BERWEIN  
WEITERENTWICKELT: SCHWELBRENNVERFAHREN  
ENTSORGUNGSPRAXIS 6, 1988, S. 242-245
- BERWEIN 1990 H.J. BERWEIN, J. ERLECKE  
EINSATZMÖGLICHKEITEN DER VERSCHWELUNG ALS HOMOGENISIERUNGSSTUFE IN DER THERMISCHEN ABFALL-  
VERWERTUNG, IN: K.J. THOMÉ-KOZMIENSKY (HRSG.): MÜLLVERBRENNUNG UND UMWELT 4  
EF-VERLAG, BERLIN 1990, S. 225-245
- BEST 2008 J. BEST  
EXAMINING THE WASTE-TO-ENERGY OPTION: BACKGROUND PAPER  
RECYCLING COUNCIL OF BRITISH COLUMBIA  
VANCOUVER, 2008
- BINDER 2014 S. BINDER  
FRAUNHOFER-INSTITUT UMSICHT  
PERSONAL COMMUNICATION, 11.04.2014
- BISCHOFBERGER W. BISCHOFBERGER, R. BORN  
VERFAHRENS- UND UMWELTTECHNISCHE ANALYSE NEUER THERMISCHER PROZESSE IN DER ABFALLWIRT-  
SCHAFT, PHASE I: PYROLYSE, BERICHTE AUS WASSERGÜTEWIRTSCHAFT UND GESUNDHEITSINGENIEURWESEN  
TECHNISCHE UNIVERSITÄT MÜNCHEN, 1989, S. 62-73
- BONIZZONI 2002 G. BONIZZONI, E. VASALLO  
PLASMA PHYSICS AND TECHNOLOGY  
INDUSTRIAL APPLICATIONS. VACUUM. 64. JG. 2002, NR. 3-4, S. 327-336
- BREF 2005 N.N.  
INTEGRATED POLLUTION PREVENTION AND CONTROLL  
REFERENCE DOCUMENT ON THE BEST AVAILABLE TECHNIQUES FOR WASTE INCINERATION

## Status of Alternative Techniques for Thermal Waste Treatment

- BUTTMANN 2011 M. BUTTMANN  
KLIMAFREUNDLICHE KOHLE DURCH HYDROTHERMALE KARBONISIERUNG VON BIOMASSE  
CHEMIE INGENIEUR TECHNIK 2011, 83, No. 11, 1890-1896
- CALIFORNIA 2007 CALIFORNIA INTEGRATED WASTE MANAGEMENT BOARD  
NEW AND EMERGING CONVERSION TECHNOLOGIES REPORT TO THE LEGISLATURE  
CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY, SACRAMENTO, 2007
- CEMEX 2013 CEMEX OSTZEMENT GMBH  
ZIRKULIERENDE WIRBELSCHICHT - ZENTRALER TEIL DES SEKUNDÄRSTOFFKONZEPTEES BEI COZ  
FIRMENPRÄSENTATION, RÜDERSDORF, 2013
- CHO 2008 PROJET CHO-POWER - MORCENX. PRODUCTION D'ÉLECTRICITÉ PAR GAZÉFICATION  
C.H.O. POWER, PROJEKTPRÄSENTATION, 2008
- CHO 2014 C.H.O. POWER, EUROPLASMA GROUP  
URL: [HTTP://WWW.CHO-POWER.COM/EN/CHO-POWER-IN-MORCENX-FRANCE-A-FIRST-IN-EUROPE.HTML](http://www.cho-power.com/en/cho-power-in-morcenx-france-a-first-in-europe.html)  
STAND 26.03.2014
- CLEMENS 2011 A. CLEMENS  
HYDROTHERMALE CARBONISIERUNG - KONVERSIONSPROZESS ZUR BEREITSTELLUNG VON FESTBRENNSTOFFEN  
AUS BIOGENEN RESTSTOFFEN  
DBFZ-FACHGESPRÄCH „FESTE BIOMASSE“, LEIPZIG, 12. OKTOBER 2011
- CHAPMANN 2012 C. CHAPMAN, R. TAYLOR, R. RAY  
THE GASPLASMA<sup>TM</sup> PROCESS: ITS APPLICATION IN ENHANCED LANDFILL MINING  
[HTTP://ELFM.EU/UPLOADS/ELFM/FILE\\_DC1E4BF9-56DD-447C-827B-4312698BA59E.PDF](http://elfm.eu/uploads/elfm/file_dc1e4bf9-56dd-447c-827b-4312698ba59e.pdf)
- CHAPMAN 2013 C. CHAPMANN  
TRANSFORMATION OF SYNGAS DERIVED FROM LANDFILLED WASTE USING INNOVATIVE ADVANCED CONVERSION TECHNOLOGY  
INTERNATIONAL ACADEMIC SYMPOSIUM ON ENHANCED LANDFILL MINING, 14.-16.10.2013, HOUTHALEN-HELCHTEREN
- COLOMBANI 2014 A. COLOMBANI, M.G. IGLESIAS  
STATE AID: COMMISSION AUTHORISES INVESTMENT AID FOR "ENERGY FROM WASTE" GASIFICATION PLANT IN LAHTI, FINLAND, PRESSEMITTEILUNG DER EUROPÄISCHEN KOMMISSION, BRÜSSEL, 4. FEBRUAR 2014
- CON THERM 2004 N.N.  
CON THERM - POWER PLANT WESTFALEN. HAMM, WEST GERMANY  
POWER GEN INTERNATIONAL 2004, MAY 27, 2004, BARCELONA, SPANIEN
- CON THERM 2010 N.N.  
CON THERM-ANLAGE IN HAMM WIRD NICHT WEITER BETRIEBEN  
WESTFÄLISCHER ANZEIGER, HAMM, 11.MÄRZ 2010
- DGE 2010 N.N.  
PYROLYSE-DREHROHRANLAGEN IN DER MÜLLENTSORGUNG  
FIRMENSCHRIFT DGENGINEERING, MAI 2010
- DE FODOR 1911 E. DE FODOR  
ELEKTRIZITÄT AUS KEHRICHT  
NACHDRUCK DER MABEG GESELLSCHAFT FÜR ABFALLWIRTSCHAFT UND ENTSORGUNGSTECHNIK  
ORIGINALVERÖFFENTLICHUNG IN BUDAPEST 1911
- DEL ALAMO G. DEL ALAMO, A. HART, A. GRIMSHAW  
CHARACTERIZATION OF SYNGAS PRODUCED FROM MSW GASIFICATION AT COMMERCIAL-SCALE ENERGOS PLANTS. WASTE MANAGEMENT (32) 2012, 1835-1842

- DELAVELLE 2012 C. DELAVELLE  
 ETAT DE L'ART DE LA PRODUCTION DE LIQUIDES OU DE GAZ À PARTIR DE DÉCHETS AUTRES QUE LES DÉCHETS DE BIOMASSE PROPRE  
 STUDIE DER AJI EUROPE FÜR DIE ADEME (AGENCE DE L'ENVIRONNEMENT ET DE LA MAÎTRISE DE L'ENERGIE), 2012
- DIEPENSEIFEN 2011 K. DIEPENSEIFEN, R. KARPf  
 BRENNSTOFF DAMPF RAUCHGAS  
 LÜHRS & RÖVER GMBH & Co. KG 2011
- DÖRING 2014 M. DÖRING  
 DER WELTMARKT FÜR ABFALLVERBRENNUNGSANLAGEN, IN: K. THOMÉ-KOZMIENSKY (HRSG.):  
 STRATEGIE - PLANUNG - UMWELTRECHT, BAND 8  
 NEURUPPIN, TK VERLAG KARL THOMÉ-KOZMIENSKY, 2014, S.141
- DOUGLAS N.D. DOUGLAS, E.; WEBB, M.; DABORN, G.R.: THE PYROLYSIS OF WASTE AND PRODUCT ASSESSMENT  
 WARREN SPRING LABORATORY, STEVENAGE, HERB, NO DATE.
- DRECHSLER 2014 D. DRECHSLER  
 BELLWETHER GASIFICATION LTD.  
 PERSÖNLICHES GESPRÄCH AM 03.04.2014
- DUCHARME 2010 C. DUCHARME  
 TECHNICAL AND ECONOMIC ANALYSIS OF PLASMA-ASSISTED WASTE-TO-ENERGY PROCESSES  
 ABSCHLUSSARBEIT, COLUMBIA UNIVERSITY, 2010
- EBARA 1999 N.N.  
 PROSPECTS OF WASTE TREATMENT TECHNOLOGY IN THE 21ST CENTURY - FLUIDIZED-BED GASIFICATION  
 COMBUSTION AND ASH MELTING SYSTEM.  
 EBARA CORPORATION 1999
- EEK 2011 N.N.  
 DAS VTC-VERFAHREN  
 ERDÖL ERDGAS KOHLE, 127. JG. 2011, HEFT 12, S.477
- ENERGOS N.N.  
 ENERGY FROM WASTE - COMMERCIALY PROVEN ENERGY RECOVERY  
 FIRMENBROSCHÜRE ENERGOS HOLDING LTD., ST. HELIER, JERSEY
- ENERGOS 2013 N.N.  
 ENERGY FROM WASTE - A PROVEN SOLUTION  
[HTTP://WWW.ENERG-GROUP.COM/MEDIA/291848/H2810\\_ENERGOS\\_BROCHURE\\_2012\\_1.PDF](http://www.energ-group.com/media/291848/h2810_energос_brochure_2012_1.pdf)
- ENERGOS 2014 [HTTP://WWW.ENERG-GROUP.COM/ENERGY-FROM-WASTE/THE-PROCESS/](http://www.energ-group.com/energy-from-waste/the-process/)  
 ABGERUFEN AM 20.03. 2014
- ENTECH 2014 [HTTP://WWW.ENTECH-RES.COM/WTGAS/](http://www.entech-res.com/wtgas/)  
 ABGERUFEN AM 20.03. 2014
- ENVIROTHERM 2013 ENVIROTHERM GMBH  
 REFERENCE LIST GASIFICATION TECHNOLOGIES - FIRMENSCHRIFT  
 ESSEN, 2013
- ENVIROTHERM 2014 ENVIROTHERM GMBH  
[HTTP://WWW.ENVIROTHERM.DE](http://www.envirotherm.de)  
 ABGERUFEN AM 08.04.2014
- EYSSEN 2011 R. EYSSEN  
 ABFALLVERWERTUNG AUF JAPANISCH  
 UMWELTMAGAZIN, 1-2 (2011), S.64-66

- FABRY 2013 F. FABRY, C. REHMET, V. ROHANI, L. FULCHERI  
WASTE GASIFICATION BY THERMAL PLASMA: A REVIEW  
WASTE AND BIOMASS VALORIZATION, JG. 2013, AUSGABE 3, S. 421-439
- FREDE 1996 M. FREDE, W. RUCKDESCHEL  
PYROLYSEVERFAHREN ZUR RESTMÜLLBEHANDLUNG IN BAYERN  
ZEITSCHRIFT FÜR UMWELTCHEMIE UND ÖKOTOXIKOLOGIE (UWSF), 1996, 9, No. 4, S. 207-212
- FRANZ 2008 M. FRANZ  
TREIBSTOFFHERSTELLUNG AUS KUNSTSTOFFABFÄLLEN  
MÜLL UND ABFALL, BAND 40 (2008) NR. 12, S. 609-616
- GBB 2013 GBB SOLID WASTE MANAGEMENT CONSULTANTS  
GASIFICATION OF NON-RECYCLED PLASTICS FROM MUNICIPAL SOLID WASTE IN THE UNITED STATES  
GERSHMAN, BRICKNER & BRATTON, INC., FAIRFAX 2013
- GERDES 2001 C. GERDES  
PYROLYSE VON BIOMASSE-ABFALL: THERMOCHEMISCHE KONVERSION MIT DEM HAMBURGER-  
WIRBELSCHICHTVERFAHREN  
DISSERTATION, UNIVERSITÄT HAMBURG 2001
- GLASNER 2011 C. GLASNER, G. DEERBERG, H. LYKO  
HYDROTHERMALE CARBONISIERUNG: EIN ÜBERBLICK  
CHEMIE INGENIEUR TECHNIK 2011, 83, No. 11, S.1-13
- GOMEZ 2009 E. GOMEZ, D. AMUTHA RANI, C.R. CHEESEMAN, D. DEEGAN, M. WISE, A.R. BOCCACCINI  
THERMAL PLASMA TECHNOLOGY FOR THE TREATMENT OF WASTES: A CRITICAL REVIEW  
JOURNAL OF HAZARDOUS MATERIALS. 161 Jd., 2009, Nr. 2-3, S. 614-626
- GRANATSTEIN 2002 D.L. GRANATSTEIN,  
CASE STUDY ON LAHDEN LAMPOW OIMA GASIFICATION PROJECT KYMIJÄRVI POWER STATION LAHTI  
NATURAL RESOURCES CANADA/CANMET ENERGY TECHNOLOGY CENTRE (CETC) 2002
- HÄBLER 1995 G. HÄBLER (HRSG.)  
THERMOSELCT - DER NEUE WEG, RESTMÜLL UMWELTGERECHT ZU BEHANDELN  
2. AUFLAGE, VERLAG KARL GOERNER, KARLSRUHE 1995
- HEBERLEIN 2008 J. HEBERLEIN, A. MURPHY  
THERMAL PLASMA WASTE TREATMENT. TOPICAL REVIEW.  
JOURNAL OF PHYSICS: APPLIED PHYSICS. 053001. JG., 2008, NR. 41
- HEIL 1990 J. HEIL  
STAND DER HAUSMÜLL-ENTGASUNGSTECHNIKEN (PYROLYSE) IN DER BUNDESREPUBLIK  
IN: THOMÉ-KOZMIENSKY, K. J. (HRSG.): MÜLLVERBRENNUNG UND UMWELT, 4  
EF-VERLAG FÜR ENERGIE- UND UMWELTECHNIK, BERLIN 1990
- HELSEN 2010 L. HELSEN, A. BOSMANS  
WASTE-TO-ENERGY THROUGH THERMOCHEMICAL PROCESSES: MATCHING WASTE WITH PROCESS  
1<sup>ST</sup> INT. SYMPOSIUM ON ENHANCED LANDFILL MINING. HOUTHALLEN-HELCHTEREN, 2010
- HESSSELING 2002 W.M.M. HESSELING  
CASE STUDY RCP BREMERHAVEN FACILITY  
TNO-REPORT R 2002/125
- HONKOLA 2013 T. HONKOLA  
FINNISH-SWEDISH FLAME DAYS, APRIL 17, 2013, JYVÄSKYLÄ, FINNLAND
- HORNUNG 2014 A. HORNUNG  
ENERGETISCHE VERWERTUNG DER RÜCKSTÄNDE AUS BIOGASANLAGEN UND KOMPOSTIERWERKEN ZUR GE-

- STEHUNG VON STROM, WÄRME UND BIOKOHLE  
 VORTRAG BEI DER BERLINER ABFALLWIRTSCHAFTS- UND ENERGIEKONFERENZ, 27.-28. JANUAR 2014
- HUANG 2007 H. HUANG, L. TANG  
 TREATMENT OF ORGANIC WASTE USING THERMAL PLASMA PYROLYSIS TECHNOLOGY  
 ENERGY CONVERSION AND MANAGEMENT. 48 JG. (2007) NR. 4., S. 1331-1337
- HZI 2011 N.N.  
 IMPROVEMENT OF EFW IN JAPAN  
 ISWA BEACON CONFERENCE, NOVEMBER 4, 2011  
[HTTP://WWW.BEACON-WTE.NET/FILEADMIN/AVFALLSVERIGE/DOCUMENTATION\\_2011/4-3.\\_SHIMODA.PDF](http://www.beacon-wte.net/fileadmin/avfallsverige/documentation_2011/4-3._SHIMODA.PDF)
- IEA 2009 N.N.  
 INTEGRATING ENERGY RECOVERY INTO SOLID WASTE MANAGEMENT SYSTEMS (2007-2009)  
 IEA BIOENERGY TASK 36 (2009) ACCOMPLISHMENTS FROM IEA BIOENERGY TASK 36  
[HTTP://WWW.IEABIOENERGYTASK36.ORG/PUBLICATIONS\\_2007\\_2009.HTM](http://www.ieabioenergytask36.org/publications_2007_2009.htm)
- INERTAM 2014 INERTAM, EUROPLASMA GROUP  
[HTTP://WWW.INERTAM.COM](http://www.inertam.com)  
 STAND 26.03.2014
- ISAKSSON 2012 J. ISAKSSON  
 KYMIJÄRVI II WASTE GASIFICATION PLANT  
 ADVANCED WTE TECHNOLOGIES, LAHTI, FINNLAND , MAY 8-9 2012
- ITO 2006 T. ITO, H. HOSODA, K. SAKATA  
 OPERATION DATA OF GASIFICATION AND MELTING PLANT  
 4TH I-CIPEC, KYOTO, 26-29 SEPTEMBER 2006, PROCEEDINGS AUF CD-ROM
- JUNIPER 2008 JUNIPER CONSULTANCY  
 THE ALTER NRG / WESTINGHOUSE PLASMA GASIFICATION PROCESS  
 INDEPENDENT WASTE TECHNOLOGY REPORT, STANCOMBE, 2008
- KALTSCHMITT 2009 M. KALTSCHMITT, H. HARTMANN, H. HOFBAUER  
 ENERGIE AUS BIOMASSE - GRUNDLAGEN, TECHNIKEN, VERFAHREN  
 2. AUFLAGE, SPRINGER-VERLAG, BERLIN HEIDELBERG 2009
- KDV 2014 [HTTP://WWW.INNOVA-ENERGIE.COM/TECHNOLOGIEN/KDV?SHOWALL=1](http://www.innova-energie.com/technologien/kdv?showall=1)  
 ABGERUFEN AM 17.06.2014
- KIV 2014 [HTTP://WWW.KIV.SI/ATTACHMENTS/018\\_KIV\\_WTE\\_PLANT.PDF](http://www.kiv.si/attachments/018_KIV_WTE_PLANT.PDF)  
 ABGERUFEN AM 20.03.2014
- KIVELA 2006 M. KIVELA  
 LAHTI ENERGIA OY 2006  
[HTTP://WWW.PALMENIA.HELSINKI.FI/REPLASTFINEST/WS3/MATTI%20KIVEL%C3%A43GASIFIER\\_IN\\_ENGLISH\\_SHORT%200906.PDF](http://www.palmenia.helsinki.fi/replastfinest/ws3/MATTI%20KIVEL%C3%A43GASIFIER_IN_ENGLISH_SHORT%200906.PDF)
- KLEMM 2009 M. KLEMM, M. KALTSCHMITT, D. THRÄN, C. VIEHMANN  
 HYDROTHERMALE CARBONISIERUNG IM VERGLEICH ZU ANDEREN VERFAHREN ZUR ENERGETISCHEN NUTZUNG  
 NASSER BIOMASSE  
 FACHTAGUNG „ENERGIE UND ROHSTOFFE AUS LANDWIRTSCHAFTLICHEN RESTSTOFFEN - HYDROTHERMALE  
 CARBONISIERUNG EIN GEEIGNETES VERFAHREN?“  
 JOHANN HEINRICH VON THÜNEN-INSTITUT (VTI), BERLIN, 5.MÄRZ 2009
- KNOEF 2012 H.A.M. KNOEF (ED.)  
 HANDBOOK OF BIOMASS GASIFICATION  
 BTG BIOMASS TECHNOLOGY GROUP BV, ENSCHEDE 2012

- KOBELCO 2013 N.N.  
WASTE TREATMENT - FLUIDIZED BED GASIFICATION AND MELTING FURNACE  
[HTTP://WWW.KOBELCO-ECO.CO.JP/ENGLISH/PRODUCT/HAIKIBUTUSHORI/RYUDO\\_Q3.HTML](http://www.kobelco-eco.co.jp/english/product/haikibutushori/ryudo_q3.html)
- KOPF 2014 [HTTP://WWW.KOPF-VERW.DE/SYNGAS.HTML](http://www.kopf-verw.de/syngas.html)  
ABGERUFEN AM 25.03.2014
- KRÄMER 2010 P.KRÄMER, G.WALTER, DR.T.MAMIYA, PROF.DR.S.FLAMME  
ABFALLWIRTSCHAFT IN JAPAN - INTENSIVE RECYCLINGAKTIVITÄTEN TROTZ HOHER VERBRENNUNGSKJAPAZITÄTEN  
MÜLL UND ABFALL (4) 2010
- LAMERS 2013 F. LAMERS, E. FLECK, L. PELLONI, B. KAMUK  
ISWA WHITE PAPER ON ALTERNATIVE WASTE CONVERSION TECHNOLOGIES  
ISWA WORKING GROUP ON ENERGY RECOVERY 2013
- MARTIN 2012 J. MARTIN  
MÄRKTE FÜR ABFALLVERBRENNUNGSANLAGEN, , IN: K. THOMÉ-KOZMIENSKY (HRSG.): STRATEGIE - PLANUNG - UMWELTRECHT, BAND 6, NEURUPPIN, TK VERLAG KARL THOMÉ-KOZMIENSKY, 2012, S. 21
- MARTIN 2013 J. MARTIN  
ABFALLVERBRENNUNG IM 21. JAHRHUNDERT: ENERGIEEFFIZIENTE UND KLIMAFREUNDLICHE RECYCLINGANLAGE UND SCHADSTOFFSENKE, IN: K. THOMÉ-KOZMIENSKY (HRSG.): STRATEGIE - PLANUNG - UMWELTRECHT, BAND 7, NEURUPPIN, TK VERLAG KARL THOMÉ-KOZMIENSKY, 2013, S. 84
- MEIER 2014 M. MEIER, K. SCHMID, S. HEGER  
PYROLYSEVERFAHREN IN BURG AU - EINE BETRACHTUNG AUS SICHT DER ÜBERWACHUNGSBEHÖRDE ENERGIE AUS ABFALL, TK VERLAG, NEURUPPIN, 2014
- MITSUI 2004 N.N.  
MITSUI RECYCLING 21 - PYROLYSIS GASIFICATION & MELTING PROCESS (TOYOHASHI R21 PLANT)  
BESUCHERINFORMATION-SCHRIFT 2004
- MCINTYRE 1974 A.D. MCINTYRE, M.M. PAPIĆ  
PYROLYSIS OF MUNICIPAL SOLID WASTE  
CAN. J. CHEM. ENG., VOL. 52, NO. 4 (1974) P. 263
- MÖLLER 2011 R. MÖLLER  
ECOLOOP: VERGASUNG - BRENNGASHERSTELLUNG UND VERWERTUNG VON PROBLEMSOFFEN  
VORTRAG INTERNATIONALE FACHMESSE & KONFERENZ WASTE-TO-ENERGY, BREMEN, 18.-19. MAI 2011
- MORRIN 2012 S. MORRIN, P. LETTIERI, C. CHAPMAN, L. MAZZEI  
TWO-STAGE FLUID BED-PLASMA GASIFICATION PROSESS FOR SOLID WASTE VALORISATIO: TECHNICAL REVIEW AND PRELIMINARY THERMODYNAMIC MODELLING OF SULFUR EMISSIONS  
WASTE MANAGEMENT, 32 (2012) 676 - 684
- NAGAYAMA 2010 S. NAGAYAMA  
HIGH ENERGY EFFICIENT THERMAL WTE PLANT FOR MSW RECYCLING  
ISWA WORLD CONGRESS, HAMBURG, NOVEMBER 2010  
[HTTP://WWW.ISWA.ORG/UPLOADS/TX\\_ISWAKNOWLEDGEBASE/NAGAYAMA.PDF](http://www.iswa.org/uploads/tx_iswaknowledgebase/nagayama.pdf)
- NISHINO 2009 M. NISHINO, S. NISHIMURA, M. KATAFUCHI  
WASTE MELTING SYSTEMS OFFERED BY JFE ENGINEERING  
JFE TECHNICAL REPORT NO. 13, MAY 2009
- OBERMEIER 2001 T. OBERMEIER  
EIGNUNG DER SVZ-TECHNOLOGIE FÜR DIE VERWERTUNG VON KOMMUNALEN RESTABFÄLLEN

IN: THOMÉ-KOZMIENSKY, K. J. (HRSG.): REFORMBEDARF IN DER ABFALLWIRTSCHAFT  
TK VERLAG KARL THOMÉ-KOZMIENSKY, NEURUPPIN, 2001, S. 775-786

- ORTNER 1995 J. ORTNER, G. HENSLER  
BEURTEILUNG VON KUNSTSTOFFBRÄNDEN. BEI EINER STÖRUNG DES BESTIMMUNGSGEMÄßEN BETRIEBS ENT-  
STEHENDE STOFFE NACH DEN ANHÄNGEN II-IV DER 12. BImSchV  
BAYERISCHES LANDESAMT FÜR UMWELTSCHUTZ, LFU. Az: 1/7-1515-21294, 1995
- OUTOTEC 2014 [HTTP://WWW.OUTOTEC.COM/EN/ABOUT-US/OUR-TECHNOLOGIES/FLUIDIZED-BED-FOR-ENERGY1/](http://www.outotec.com/en/about-us/our-technologies/fluidized-bed-for-energy1/)  
ABGERUFEN AM 20.03.2014
- PALONEN 1998 J. PALONEN, M. NIEMINEN, E. BERG  
THERMIE DEMONSTRATES BIOMASS CFB GASIFIER AT LAHTI  
MODERN POWER SYSTEMS, **18** (1998), 37 - 42
- PLASCO 2008 PLASCO ENERGY GROUP  
WTERT BI-ANNUAL MEETING  
COLUMBIA UNIVERSITY, 2008
- PLASCO 2011 PLASCO ENERGY GROUP  
FINAL ASSESSMENT REPORT  
2011
- PLASCO 2014 PLASCO ENERGY GROUP  
[HTTP://WWW.PLASCOENERGYGROUP.COM/OUR-TECHNOLOGY/THE-PLASCO-PROCESS/](http://www.plascoenergygroup.com/our-technology/the-plasco-process/)  
ABGERUFEN AM 26.03.2014
- PRUCKNER 2008 E. PRUCKNER  
PYROLYSE - URSACHEN FÜR ERFOLG UND SCHEITERN, IN: M. FAULSTICH, P. QUICKER [HRSG.]: VERFAH-  
REN & WERKSTOFFE FÜR DIE ENERGIETECHNIK: BAND 4, BIOMASSE & ABFALL - REGIONALE BRENNSTOFFE  
RICHTIG NUTZEN, DORNER PRINTCONCEPT, SULZBACH-ROSENBERG, 2008
- PSC 2014 PHOENIX SOLUTIONS COMPANY  
[HTTP://WWW.PHOENIXSOLUTIONSCO.COM/ENERGYPRODUCTION.HTML](http://www.phoenixsolutionsco.com/energyproduction.html)  
STAND 26.03.2014
- PYREG N.N.  
PYREG 500 - KARBONISIERUNGSANLAGE  
FIRMENPROSPEKT DER PYREG GMBH, DÖRTH
- RAMKE 2011 H.-G. RAMKE  
HTC-BIOKOHLE AUS ORGANISCHEN ABFÄLLEN  
BIOKOHLE - KLIMARETTER/MOGELPACKUNG - 72. SYMPOSIUM DES ANS  
BERLIN, 05.-06. OKTOBER 2011
- REIMANN 1991 D.O. REIMANN (HRSG.)  
ROSTFEUERUNGEN ZUR ABFALLVERBRENNUNG  
EF-VERLAG FÜR ENERGIE- UND UMWELTTECHNIK, BERLIN 1991
- RICHERS 1996 U. RICHERS, B. BERGFELDT  
DAS SIEMENS SCHWEL-BRENN-VERFAHREN, WISSENSCHAFTLICHE BERICHTE FZKA 5826  
FORSCHUNGSZENTRUM KARLSRUHE GMBH, KARLSRUHE 1996
- RÖTHLEIN 2006 B. RÖTHLEIN  
ZAUBERKOHLE AUS DEM DAMPFKOCHTOPF  
MAXPLANCKFORSCHUNG 2/2006, S. 20
- ROTH 1990 L. ROTH, U. WELLER  
CHEMIEBRÄNDE - BRANDTABELLEN, FALLBEISPIELE, RISIKEN UND VORSORGEABNAHMEN  
ECOMED VERLAGSGESELLSCHAFT MBH, LANDSBERG, 1990

- RYMSA 1977 K. -H. RYMSA  
MÜLLPYROLYSE NACH DEM DESTRUGAS-VERFAHREN, IN: THOMÉ-KOZMIENSKY, K. J. (HRSG.): ABFALL-  
WIRTSCHAFT IN FORSCHUNG UND PRAXIS - NEUE TECHNOLOGIEN ZUR ABFALLBESEITIGUNG, BAND 2  
ERICH SCHMIDT VERLAG, BERLIN, 1977, S. 87-111
- SANDQUIST 2011 J. SANDQUIST  
SMALL-SCALE WASTE GASIFICATION. SINTEF  
[HTTP://WWW.IEATASK33.ORG/APP/WEBROOT/FILES/FILE/2011/NORWAY.PDF](http://www.ieatask33.org/app/webroot/files/file/2011/norway.pdf)
- SCHINGNITZ 1993 M. SCHINGNITZ, H. LORSON, P. GÖHLER  
DIE VERWERTUNG VON REST- UND ABFALLSTOFFEN DURCH DRUCKVERGASUNG IN DER FLUGWOLKE  
ABFALLWIRTSCHAFTS-JOURNAL 5 (1993) 10
- SCHINGNITZ 1994 M. SCHINGNITZ  
DARSTELLUNG DES NOELL-KONVERSIONSVERFAHRENS  
IN: J. CARL, P. FRITZ: NOELL-KONVERSIONSVERFAHREN ZUR VERWERTUNG UND ENTSORGUNG VON ABFÄL-  
LEN. BERLIN: EF-VERLAG FÜR ENERGIE- UND UMWELTTECHNIK GMBH, 1994, S. 24-53
- SCHOLZ 2001 R. SCHOLZ, M. BECKMANN, F. SCHULENBURG  
ABFALLBEHANDLUNG IN THERMISCHEN VERFAHREN - VERBRENNUNG, VERGASUNG, PYROLYSE, VERFAHRENS-  
UND ANLAGENKONZEPTE  
B.G. TEUBNER VERLAG STUTTGART 2011
- SCUR 2005 P. SCUR  
HERSTELLUNG EINES KOSTENGÜNSTIGEN BRENNSTOFFS FÜR DIE ZEMENTHERSTELLUNG DURCH DIE VERGA-  
SUNG VON ABFÄLLEN IN EINER ZWS  
CEMEX DEUTSCHLAND AG, KONFERENZBEITRAG, 2005
- SCUR 2014 P. SCUR  
PERSÖNLICHER SCHRIFTVERKEHR IM RAHMEN DER DATENRECHERCHE ZUR STUDIE  
CEMEX DEUTSCHLAND AG, 2014
- SEIFERT 2001 H. SEIFERT  
VERGASUNGSTECHNOLOGIEN FÜR ABFALL  
IN: THOMÉ-KOZMIENSKY, K. J. (HRSG.): REFORMBEDARF IN DER ABFALLWIRTSCHAFT  
TK VERLAG KARL THOMÉ-KOZMIENSKY, NEURUPPIN, 2001, S. 767
- SERFASS 2014 K. SERFASS  
EMISSIONSDATEN VON HTC - ANLAGEN  
VORTRAG BEIM ARBEITSGRUPPENTREFFEN ZUR RICHTLINIE VDI 3933, BERLIN, 13. FEBRUAR 2014
- SIEMENS AG 1996 N.N.  
EIN GANG DURCH DIE SCHWEL-BRENN-ANLAGE FÜRTH  
INFORMATIONSBROSCHÜRE DER SIEMENS AG, 1996
- SIEMENS AG 1997 N.N.  
DIE SCHWEL-BRENN-ANLAGE - EINE VERFAHRENSBESCHREIBUNG  
INFORMATIONSBROSCHÜRE DER SIEMENS AG, 1997
- SHINAGAWA 2013 T. SHINAGAWA  
PERSÖNLICHE MITTEILUNG, NOVEMBER 2013
- SPANTIG 2010 A. SPANTIG  
PRÄSENTATION DER VERSUCHSERGEBNISSE AUS DER VTC-BEHANDLUNG VON GRÜNSCHNITT  
FA. HYDROCARB GMBH 2010
- SPINDELDREHER 2004 O. SPINDELDREHER, N. USDROWSKI, R. HAUKE  
CON THERM - THERMISCHE ABFALLVERWERTUNG IM KRAFTWERK, IN: M. FAULSTICH, B. BILITEWSKI, A. I.

- URBAN (HRSG.): TAGUNGSBAND ZUR 9. FACHTAGUNG THERMISCHE ABFALLBEHANDLUNG  
SCHRIFTENREIHE DES FACHGEBIETES ABFALLTECHNIK DER UNIVERSITÄT KASSEL, KASSEL 2004
- STAMMBACH 1999 M.R. STAMMBACH  
RCP - STAND DER ERKENNTNISSE AUS DER ANLAGE BREMERHAVEN  
FACHTAGUNG ZUM 25-JÄHRIGEN JUBILÄUM DES VBSA BASEL, 28.-29. 10. 1999
- STEINER 2002 C. STEINER, O. KAMEDA, T. OSHITA , T. SATO  
FLUIDIZED BED GASIFICATION: ATMOSPHERIC 2 X 225 T/D FOR SHREDDING RESIDUES RECYCLING AND  
TWO-STAGE PRESSURIZED 30 T/D FOR AMMONIA SYNTHESIS FOR WASTE PLASICS  
THE 2ND INTERNATIONAL SYMPOSIUM ON FEEDSTOCK RECYCLING OF PLASTICS, OOSTENDE, 9. SEPT. 2002
- SUZUKI 2011 A.SUZUKI, S.NAGAYAMA  
HIGH EFFICIENCY WTE POWER PLANT USING HIGH-TEMPERATURE GASIFYING AND DIRECT MELTING FURNACE  
PROCEEDINGS SARDINA 2011, THIRTEENTH INTERNATIONAL WASTE MANAGEMENT AND LANDFILL SYMPOSIUM,  
CAGLIARI/ITALY, 2011
- SVZ 2003 N.N.  
SVZ SEKUNDÄRROHSTOFF-VERWERTUNGSZENTRUM SCHWARZE PUMPE GMBH - ABFALLVERWERTUNG  
HTTP//: WWW.SVZ-GMBH.DE  
ABGERUFEN AM 12.06.2003
- TABASARAN 1977 O. TABASARAN, G. BESEMER, E.THOMANETZ  
PYROLYSE ORGANISCHER ABFÄLLE ALS BEHANDLUNGSMETHODE UND ALS MÖGLICHKEIT ZUR GEWINNUNG VON  
ENERGIE UND ROHSTOFFEN  
MÜLL UND ABFALL **10** (1977), S. 293
- TABATA 2013 T.TABATA  
WASTE-TO-ENERGY INCINERATION PLANTS AS GREENHOUSE GAS REDUCERS: A CASE STUDY OF SEVEN JAPANESE  
METROPOLISES  
WASTE MANAGEMENT & RESEARCH **31** (11) 1110-1117
- TAKUMA 2014 JAPANISCHES UMWELTMINISTERIUM  
WWW.ENV.GO.JP/RECYCLE/CIRCUL/VENOUS\_INDUSTRY/EN/SKILL\_PDF/T052.PDF  
STAND: 06.07.2014
- TANAGAKI 2012 N. TANAGAKI, K. MANAKO, M. OSADA  
CO-GASIFICATION OF MUNICIPAL SOLID WASTE AND MATERIAL RECOVERY IN A LARGE-SCALE GASIFICATION  
AND MELTING SYSTEM,  
WASTE MANAGEMENT **32** (2012), 667 - 675
- TANIGAKI 2013 N. TANIGAKI, Y.FUJINAGA, H.KAJIYAMA, Y.ISHIDA  
OPERATING AND ENVIRONMENTAL PERFORMANCES OF COMMERCIAL-SCALE WASTE GASIFICATION AND MELTING  
TECHNOLOGY  
WASTE MANAGEMENT & RESEARCH **31** (11) 1118-1124
- TAYLOR 2013 R. TAYLOR, C. CHAPMAN, A. FARAZ  
TRANSFORMATIONS OF SYNGAS DERIVED FROM LANDFILLED WASTES USING THE GASPLASMA PROCESS  
2ND INTERNATIONAL ACADEMIC SYMPOSIUM ON ENHANCED LANDFILL MINING •  
HOUTHALEN-HELCHTEREN , 2013
- TETRONICS 2014 TETRONICS INTERNATIONAL  
URL: HTTP://WWW.TETRONICS.COM/WASTE-ENERGY.ASPX  
STAND 26.03.2014
- THOMÉ 1979 K. THOMÉ -KOZMIENSKY, J. HEIL, K.L. LINK, J. SEGBRECHT  
PROZESSGESTALTUNG ABFALLPYROLYSE - UNTERSUCHUNGEN ÜBER DIE ENTGASUNG VON  
ABFÄLLEN IN EINEM KONTINUIERLICH BETRIEBENEN SCHACHTREAKTOR  
UMWELTFORSCHUNGSPLAN DES BUNDESMINISTERIUM DES INNERN, BERLIN, 1979

- THOMÉ 1985 K. THOMÉ -KOZMIENSKY (HRSG.)  
PYROLYSE VON ABFÄLLEN  
EF-VERLAG, BERLIN, 1985
- THOMÉ 1994 K. THOMÉ -KOZMIENSKY (HRSG.)  
THERMISCHE ABFALLBEHANDLUNG  
EF-VERLAG, BERLIN, 1994
- THOMÉ 1998 K.J. THOMÉ-KOZMIENSKY  
KLÄRSCHLAMMENTSORGUNG  
TK VERLAG KARL THOMÉ-KOZMIENSKY, NEURUPPIN, 1998, S. 560-563
- TOKYO 2013 N.N.  
WASTE REPORT 2013  
CLEAN ASSOCIATION OF TOKYO 23
- TORCHPROCESS 2014 TORCH&PROCESS, EUROPLASMA GROUP  
URL: [HTTP://WWW.TORCHPROCESS.COM/EN/SERVICES-A-SUPPORT/PLASMA-SYSTEMS.HTML](http://www.torchprocess.com/en/services-a-support/plasma-systems.html)  
STAND 26.03.2014
- TROITZSCH 1981 J. TROITZSCH, H.-D. BEENKEN, H.-J. BÖNOLD, M. RIEBER  
BRANDVERHALTEN VON KUNSTSTOFFEN - GRUNDLAGEN, VORSCHRIFTEN, PRÜFVERFAHREN  
CARL HANSER VERLAG, MÜNCHEN, 1981
- TUKKER 1999 TUKKER, DE GROOT, SIMONS, WIEGERSMA  
CHEMICAL RECYCLING OF PLASTIC WASTE (PVC AND OTHER RESINS) TNO-REPORT STB-99-55 FINAL-  
NETHERLANDS ORGANISATION FOR APPLIED SCIENTIFIC RESEARCH, DELFT 1999, S. 19-22
- VACCANI 2014 A.C. VACCANI  
INTERNATIONALE MÄRKTE FÜR ALTERNATIVE VERFAHREN UND STRATEGIEN DER WICHTIGSTEN MARKTTEIL-  
NEHMER, VORTRAG BERLINER ABFALLWIRTSCHAFTS- UND ENERGIEKONFERENZ, 28. JANUAR 2014
- VDI 3460 KOMMISSION REINHALTUNG DER LUFT IM VDI UND DIN - NORMENAUSSCHUSS KRDL (HRSG.)  
VDI 3460 - EMISSIONSMINDERUNG - THERMISCHE ABFALLBEHANDLUNG  
BEUTH VERLAG, BERLIN 2014
- VON ROLL 1999 N.N.  
VON ROLL RCP-VERFAHREN MIT HSR ALS OPTION,  
FIRMENSCHRIFT, ZÜRICH, 1999
- WALLMANN 2011 R. WALLMANN, C. AHLBORN  
STABILITÄT UNTERSCHIEDLICH AUFBEREITETER BIOMASSE  
BIOKOHLE - KLIMARETTER/MOGELPACKUNG - 72. SYMPOSIUM DES ANS  
BERLIN, 05.-06. OKTOBER 2011
- WARNECKE 1991 R. WARNECKE, M. ERZ  
PYROLYSEATLAS - ÜBERBLICK ÜBER VERFAHREN ZUR PYROLYTISCHEN ABFALLBEHANDLUNG  
UNIVERSITÄT DUISBURG, FACHBEREICH MASCHINENBAU, FACHGEBIET THERMODYNAMIK, DUISBURG 1991
- WEINSTEIN 1976 J. WEINSTEIN, F. TORO  
THERMAL PROCESSING OF MUNICIPAL SOLID WASTE FOR RESOURCE AND ENERGY RECOVERY  
ANN ARBOR SCIENCE PUBLISHERS, 1976
- WESTINGHOUSE 2014 WESTINGHOUSE PLASMA: GASIFIERS MODELS.  
URL: [WWW.WESTINGHOUSE-PLASMA.COM](http://www.westinghouse-plasma.com)  
STAND: 26.03.2014
- WIEZORKOWSKI 2012 S. WIEZORKOWSKI  
UNTERSUCHUNG DER KATALYTISCHEN DRUCKLOSEN VERÖLUNG VON RESTSTOFFSTRÖMEN  
MASTERARBEIT AN DER RWTH AACHEN, AACHEN 2012

Status of Alternative Techniques for Thermal Waste Treatment

- WILLNER 2009 T. WILLNER  
GUTACHTEN ZUR KATALYTISCHEN DRUCKLOSEN VERÖLUNG (KDV-VERFAHREN) DER FIRMA ALPHAKAT  
GUTACHTEN DER HAW HAMBURG FÜR DIE FREIE HANSESTADT HAMBURG, HAMBURG 2009
- WOOD 2013 S. WOOD, M. FANNING, M. VENN, K. WHITING  
REVIEW OF STATE-OF-THE-ART WASTE-TO-ENERGY TECHNOLOGIES, STAGE TWO - CASE STUDIES  
WSP HOUSE, LONDON 2013
- SUZUKI 2011 A. ZUZUKI, S. NAGAYAMA  
HIGH EFFICIENCY WTE POWER PLANT USING HIGH-TEMPERATURE GASIFYING AND DIRECT MELTING FURNACE  
13TH INTERNATIONAL WASTE MANAGEMENT AND LANDFILL SYMPOSIUM  
S. MARGHERITA DI PULA, CAGLIARI, OCTOBER 3 - 7, 2011

## Abbreviations

ASR	AUTO SHREDDER RESIDUE
BAT	BEST AVAILABLE TECHNIQUE
BOD	BIOLOGICAL OXYGEN DEMAND
BREF	BAT-REFERENCE DOCUMENT
BSNG	BIO SUBSTITUTE NATURAL GAS
BTL	BIOMASS TO LIQUID
CHP	COMBINED HEAT AND POWER PLANT
COD	CHEMICAL OXYGEN DEMAND
DM	DRY MATTER
DMS	DIRECT MELTING SYSTEM
FE-METALLS	FERROUS METALS
FGD	FLUE GAS DESULFURIZATION
GT	GASTURBINE
HSR-PROCESS	HIGH-TEMPERATURE MELT-REDOX-PROCESS
HTC	HYDROTHERMAL CARBONIZATION
HTP	HIGH-TEMPERATURE PYROLYSIS
HTU	HYDROTHERMALE LIQUEFACTION („HYDROTHERMAL UPGRADING“)
HTV	HYDROTHERMAL GASIFICATION
MSW	MUNICIPAL SOLID WASTE
MTP	MIDDLE-TEMPERATURE-PYROLYSIS
NF-METALS	NON-FERROUS METALS
NTK	LOW-TEMPERATURE CONVERSION (GERMAN: NIEDERTEMPERATURKONVERTIERUNG)
NTP	LOW-TEMPERATURE PYROLYSIS (GERMAN: NIEDERTEMPERATUR-PYROLYSE)
NTTT	NEW THERMAL TREATMENT TECHNOLOGIES (ALTERNATIVE THERMISCHE VERFAHREN)
PB	POLYBUTYLENE/POLYBUTEN
PE	POLYETHYLENE/POLYETHEN
PP	POLYPROPYLENE/POLYPROPEN
PVC	POLYVINYLCHLORIDE
RCP	RECYCLED CLEAN PRODUCTS
RDF	REFUSE DERIVED FUEL
RME	RAPSEED OIL METHYL ESTER („BIODIESEL“)
SCR	SELECTIVE CATALYTIC REDUCTION
SNCR	SELECTIVE NON-CATALYTIC REDUCTION
SVZ	GERMAN: SEKUNDÄRROHSTOFF-VERWERTUNGSZENTRUM (SCHWARZE PUMPE) (SECONDARY RAW MATERIAL UTILIZATION CENTER)
TCR	THERMO-KATALYTIC REFORMING
TDF	TIRE DERIVED FUEL
TDH	THERMO-DRUCK-HYDROLYSE
VTC	VAPOTHERMAL CARBONIZATION
VTT	TECHNICAL RESEARCH CENTRE OF FINLAND (VALTION TEKNILLINEN TUTKIMUSKESKUS)
WTE	WASTE-TO-ENERGY (WASTE INCINERATION)

## List of Figures

FIGURE 2.1:	OVERVIEW THERMOCHEMICAL PROCESSES .....	13
FIGURE 2.2:	PYROLYSIS AND GASIFICATION IN A SIMPLIFIED OVERVIEW .....	14
FIGURE 2.3:	PYROLYSIS OF WOOD: PRODUCT RANGE AS A FUNCTION OF TEMPERATURE AND RESIDENCE TIME .....	15
FIGURE 2.4:	PROCESSES AND TEMPERATURE DEPENDANCY OF PYROLYTIC DECOMPOSITION OF CELLULOSE .....	16
FIGURE 2.5:	TEMPERATURE AND PRESSURE DEPENDENCY HYDRATING GASIFICATION REACTION AND WATER-GAS-REACTION ...	17
FIGURE 2.6:	PLASMA GENERATION WITH NON-TRANSFERRED ARC AND TRANSFERRED ARC .....	18
FIGURE 2.7:	HYDROTHERMAL CARBONIZATION - STARTING MATERIAL AND PRODUCTS .....	22
FIGURE 3.1:	SCHEMATIC DIAGRAM OF THE IHI PYROLYSIS GASIFICATION AND MELTING SYSTEM .....	25
FIGURE 3.2:	PROCESS DIAGRAM SCHWEL-BRENN-PROCESS BY THE EXAMPLE OF THE FÜRTH PLANT. ....	26
FIGURE 3.3:	PROCESS PRINCIPLE SCHWEL-BRENN-PROCESS SIEMENS AG .....	27
FIGURE 3.4:	CONVERSION DRUM SCHWEL-BRENN PLANT IN FÜRTH. ....	28
FIGURE 3.5:	CONVERSION DRUM SCHWEL-BRENN PROCESS WITH ARRANGEMENT OF HEATING PIPES .....	28
FIGURE 3.6:	GRANULATE FROM SIEMENS SCHWEL-BRENN-PROCESS .....	30
FIGURE 3.7:	SCHWEL-BRENN PLANT IN FÜRTH .....	31
FIGURE 3.8:	EXTERNAL VIEW OF PYROLYSIS DRUM AND ARRANGEMENT OF STEAM-HEATED PIPES INSIDE THE DRUM MES R21 PLANT TOYAHASHI .....	32
FIGURE 3.9:	PROCESS DIAGRAM WITH PROCESS EXPLANATIONS OF THE MES R21 INSTALLATION IN TOYAHASHI .....	33
FIGURE 3.10:	ILLUSTRATION OF MES R21 INSTALLATION TOYAHASHI .....	33
FIGURE 3.11:	VIEW OF MES R21 INSTALLATION KOGA AND TOYAHASHI .....	35
FIGURE 3.12:	PROCESS DIAGRAM TAKUMA PYROLYSIS MELTING SYSTEM .....	35
FIGURE 3.13:	PICTURE OF TAKUMA PYROLYSIS GAS MELTING SYSTEM .....	36
FIGURE 3.14:	PROCESS DIAGRAM RCP-PROCESS .....	37
FIGURE 3.15:	PROCESS DIAGRAM DESTRUGAS PROCESS .....	39
FIGURE 3.16:	DESTRUGAS-PROCESS; DETAIL SHOWING TWO INDIRECTLY HEATED RETORTS WITHIN A BATTERY OF RETORTS .....	40
FIGURE 3.17:	PROCESS SCHEMA DESTRUGAS PLANT KALUNDBORG .....	41
FIGURE 3.18:	DETAILS PILOT PLANT DESTRUGAS PROCESS .....	42
FIGURE 3.19:	WASTE PYROLYSIS PLANT BURGAU .....	43
FIGURE 3.20:	RAW WASTE, SHREDDED WASTE, SEPARATED UPHOLSTERY AT MPA BURGAU .....	43
FIGURE 3.21:	PROCESS DIAGRAM MPA BURGAU .....	44
FIGURE 3.22:	OVERBELT MAGNETIC SEPARATOR, FE-PRODUCT AND RESIDUAL COKE LANDFILL WITH VISIBLE AMOUNTS OF NON-FERROUS METALS, MPA BURGAU .....	45
FIGURE 3.23:	PYROLYSIS ROTARY KILN MPA BURGAU .....	45
FIGURE 3.24:	PROXIMATE ANALYSIS OF PYROLYSIS COKE MPA BURGAU .....	46
FIGURE 3.25:	DETAILS MPA BURGAU .....	46
FIGURE 3.26:	PROCESS SCHEMA PYREG PROCESS .....	47
FIGURE 3.27:	PYROFORMER. SCHEMA; ON SITE AT HARPER ADAMS UNIVERSITY .....	48
FIGURE 3.28:	MEE-PLANT SCHWERIN .....	50
FIGURE 3.29:	IMMEDIATE AND ELEMENTARY ANALYSIS OF INPUT MATERIAL AND CARBONIZED PIG MANURE FROM MEE-PLANT SCHWERIN .....	51
FIGURE 3.30:	SCHEMATIC VIEW CONTHERM PROCESS .....	52
FIGURE 3.31:	CONTHERM-PROCESS - ROTARY DRUMS AND GENERATED PYROLYSIS COKE AFTER POST-TREATMENT .....	52

FIGURE 3.32:	CONTERM PROCESS - PYROLYSIS GAS PIPES BLOCKED BY DEPOSITIONS. ....	54
FIGURE 3.33:	ENERGOS PROCESS - SCHEMATIC DIAGRAM OF GASIFICATION AND POST-COMBUSTION CHAMBER .....	56
FIGURE 3.34:	ENERGOS PROCESS: THREE-DIMENSIONAL SECTIONAL VIEW.....	57
FIGURE 3.35:	EXTERNAL VIEW OF THE ENERGOS PLANT IN MINDEN .....	58
FIGURE 3.36:	INFEED OF WASTE AT THE ENERGOS PLANT IN MINDEN.....	59
FIGURE 3.37:	SCHEMATIC DIAGRAM EBARA PROCESS .....	59
FIGURE 3.38:	FLOW CHART AOMORI TWINREC PLANT WITH RESIDUAL MATERIALS AND RECYCLING PATHWAYS RESPECTIVELY DISPOSAL MEASURES .....	60
FIGURE 3.39:	HITACHI ZOSEN GASIFICATION AND MELTING SYSTEM. ....	61
FIGURE 3.40:	GASIFICATION REACTOR JFE HIGH-TEMPERATURE GASIFYING AND DIRECT MELTING FURNACE SYSTEM .....	62
FIGURE 3.41:	PROCESS SCHEMA JFE HIGH-TEMPERATURE GASIFYING AND DIRECT MELTING FURNACE SYSTEM IN FUKUYAMA .....	63
FIGURE 3.42:	PROCESS SCHEMA KOBELCO PLANT IN ISHINOMAKI .....	65
FIGURE 3.43:	OPERATION AND SHUT-DOWN PERIODS OF THE KOBELCO PLANT IN ISHINOMAKI	66
FIGURE 3.44:	SHAFT FURNACE NIPPON STEEL DMS PROCESS WITH DISPLAY OF REACTION ZONES.....	67
FIGURE 3.45:	PROCESS SCHEMA NIPPON STEEL DMS PROCESS. ....	68
FIGURE 3.46:	PROCESS DIAGRAM EBARA UBE-PROZESSES. ....	70
FIGURE 3.47:	SEWAGE SLUDGE GASIFICATION PLANT IN BALINGEN.....	71
FIGURE 3.48:	KOPF PROCESS: PROCESS DIAGRAM FOR GASIFICATION OF SEWAGE SLUDGE .....	72
FIGURE 3.49:	PROCESS DIAGRAM NOELL CONVERSION PROCESS.....	73
FIGURE 3.50:	NOELL CONVERSION PROCESS - PYROLYSIS STAGE .....	73
FIGURE 3.51:	NOELL CONVERSION PROCESS: GASIFICATION STAGE WITH ENTRAINED-FLOW GASIFIER .....	74
FIGURE 3.52:	SCHEMATIC DIAGRAM OF AN ENTRAINED-FLOW GASIFIER .....	75
FIGURE 3.53:	INPUT MATERIALS FIXED BED PRESSURE GASIFIER IN SCHWARZE PUMPE.....	77
FIGURE 3.54:	PLANT OVERVIEW OF GASIFICATION AND SECONDARY INSTALLATIONS AT SVZ SCHWARZE PUMPE.....	78
FIGURE 3.55:	CONDITIONING OF HOUSEHOLD WASTE AND COMMERCIAL WASTE SIMILAR TO HOUSEHOLD WASTE AT SVZ.....	79
FIGURE 3.56:	FIXED BED PRESSURE GASIFICATION UNIT WITH SURROUNDINGS AT SCHWARZE PUMPE.....	80
FIGURE 3.57:	FIXED BED REACTOR WITH ROTARY GRATE FOR GASIFICATION OF SOLIDS & TAR AT SVZ SCHWARZE PUMPE .....	81
FIGURE 3.58:	PROCESS DIAGRAM OF FIXED BED GASIFICATION AT SVZ SCHWARZE PUMPE. ....	82
FIGURE 3.59:	SVZ SCHWARZE PUMPE WITH GAS AND STEAM TURBINE POWER STATION AND METHANOL PLANT .....	82
FIGURE 3.60:	GASIFICATION AND GAS UTILIZATION AT SVZ SCHWARZE PUMPE .....	83
FIGURE 3.61:	FIXED BED REACTOR WITH ROTARY GRATE TO GASIFY SOLID MATERIALS AND TAR AT SVZ SCHWARZE PUMPE.....	85
FIGURE 3.62:	ENTRAINED FLOW GASIFIER AT SVZ SCHWARZE PUMPE .....	86
FIGURE 3.63:	PROCESS PRINCIPLE ENTRAINED FLOW GASIFICATION AT SVZ SCHWARZE PUMPE. ....	87
FIGURE 3.64:	BRITISH-GAS-LURGI (BGL)-REACTOR FOR GASIFICATION OF SOLID MATERIALS AT SVZ SCHWARZE PUMPE.....	88
FIGURE 3.65:	PROCESS CONCEPT THERMOSELECT PROCESS.....	90
FIGURE 3.66:	OVERVIEW THERMOSELECT PROCESS.....	91
FIGURE 3.67:	GRANULATED MELT FROM THERMOSELECT PROCESS .....	92
FIGURE 3.68:	THERMOSELECT PLANT IN KARLSRUHE AFTER SEVERAL YEARS OF DOWNTIME.....	94
FIGURE 3.69:	SCHEMATIC VIEW ECOLOOP GASIFICATION REACTOR.....	94

FIGURE 3.70:	ECOLOOP PLANT - GENERAL VIEW AND GASIFICATION REACTOR .....	95
FIGURE 3.71:	INTEGRATION OF ZWS-GASIFIER INTO PRODUCTION OF CEMENT AT RÜDERSDORF SITE .....	97
FIGURE 3.72:	ZWS GASIFIER IN RÜDERSDORF.....	98
FIGURE 3.73:	PROCESS DIAGRAM KYMIJÄRVI PLANT INCLUDING PERFORMANCE DATA.....	99
FIGURE 3.74:	PLANT LAYOUT KYMIJÄRVI II.....	102
FIGURE 3.75:	PROCESS DIAGRAM KYMIJÄRVI II (GAS CLEANING NOT INCLUDED).....	102
FIGURE 3.76:	INDUSTRIAL SIZE PLANTS FOR PLASMA GASIFICATION OF WASTE BUILT AND PLANNED .....	104
FIGURE 3.77:	ALTER NRG GASIFICATION REACTOR.....	105
FIGURE 3.78:	MELTING REACTOR OFFERED BY EUROPLASMA.....	108
FIGURE 3.79:	ASBESTOS MELTING REACTOR OPERATED BY INERTAM .....	108
FIGURE 3.80:	TWO-STAGE GASIFICATION PROCESS AS OFFERED BY C.H.O.-POWER.....	109
FIGURE 3.81:	PROCESS DIAGRAM TWO-STAGE APP GASPLASMA PROCESS .....	111
FIGURE 3.82:	SCHEMATIC VIEW OF PLASCO CONVERSION PROCESS .....	113
FIGURE 3.83:	DIESELWEST PLANT AND FLOW CHART.....	116
FIGURE 3.84:	REACTOR DIESELWEST PLANT WITH FEEDING SCREW; TURBINES FOR ENERGY SUPPLY .....	117
FIGURE 3.85:	LIQUID PRODUCTS FROM DIESELWEST PLANT.....	118
FIGURE 3.86:	BASIC SCHEME HYDROTHERMAL CARBONIZATION.....	120
FIGURE 4.1:	WORLDWIDE DEVELOPMENT OF CAPACITIES FOR THERMAL WASTE TREATMENT .....	122
FIGURE 4.2:	MARKET SHARE OF PROCESSES IN NEWLY BUILT THERMAL WASTE TREATMENT SYSTEMS IN EUROPE IN RECENT YEARS. ....	123
FIGURE 4.3:	INDUSTRIAL SCALE PILOT PLANTS FOR WASTE PYROLYSIS IN GERMANY AT THE BEGINNING OF THE 1980s.....	124
FIGURE 4.4:	INDUSTRIAL SIZE PLANTS FOR ALTERNATIVE THERMAL WASTE TREATMENT IN GERMANY.....	124
FIGURE 4.5:	FRONT PAGE OF THE JOURNAL „UMWELTPRAXIS“ PRAISING THE THERMOSELECT PROCESS.....	125
FIGURE 4.6:	DISTRIBUTION OF TREATMENT CAPACITIES FOR THERMAL WASTE TREATMENT IN JAPAN .....	127
FIGURE 4.7:	DEVELOPMENT OF NEWLY BUILT THERMAL WASTE TREATMENT PLANTS IN JAPAN BY PROCESS .....	129

## List of Tables

TABLE 1.1:	DEVELOPMENT STATUS OF THERMAL WASTE TREATMENT PROCESSES ACCORDING TO [VDI 3460] (SIMPLIFIED).....	11
TABLE 2.1:	BASIC PROCESS PARAMETERS OF HYDROTHERMAL PROCESSES, .....	23
TABLE 3.1:	TECHNICAL DATA AND OPERATING PARAMETERS OF SIEMENS SCHWEL-BRENN PLANT FÜRTH.....	29
TABLE 3.2:	BASIC PARAMETERS OF FORMER SCHWEL-BRENN PROJECTS.....	30
TABLE 3.3:	OPERATING PARAMETERS MES R21 PLANT KOGA.....	34
TABLE 3.4:	OPERATING DATA RCP PLANT BREMERHAVEN. ....	37
TABLE 3.5	TRIAL OPERATION RCP PLANT BREMERHAVEN -INPUT AND AUXILIARY MATERIALS .....	38
TABLE 3.6:	DESTRUGAS PROCESS - COMPOSITION OF PURIFIED SYNGAS.....	41
TABLE 3.7:	INPUT PROPERTIES AND PROCESS PARAMETERS OF MPA BURGAU .....	44
TABLE 3.8:	MASS- AND ENERGY BALANCE MPA BURGAU .....	46
TABLE 3.9:	PROCESS PARAMETERS PYREG PLANT AND MASS BALANCE FOR FEEDSTOCK PIG SLURRY .....	48
TABLE 3.10:	PRODUCTS AND SUPPLY OF ENERGY FROM INTERMEDIATE PYROLYSIS.....	49
TABLE 3.11:	OPERATING PARAMETERS ANA MASS BALANCE M.E.E. PLANT .....	51
TABLE 3.12:	OPERATING PARAMETERS CONTHERM FACILITY. ....	53
TABLE 3.13:	ENERGY BALANCE CONTHERM FACILITY .....	53
TABLE 3.14:	OPERATING PARAMETERS ENERGOS PROCESS .....	57
TABLE 3.15:	COMPOSITION AND GROSS CALORIFIC VALUE OF GAS FROM FIRST STAGE OF ENERGOS PROCESS .....	58
TABLE 3.16:	OPERATING PARAMETERS EBARA TWINREC .....	60
TABLE 3.17:	CHARACTERISTIC FUEL PARAMETERS OF RDF TREATED IN JFE PLANT.....	63
TABLE 3.18	OPERATING PARAMETERS JFE PLANT FUKUYAMA.....	64
TABLE 3.19:	AUTHORIZED LIMITS AND MEASURED EMISSIONS JFE PLANT FUKUYAMA .....	64
TABLE 3.20:	OPERATING PARAMETERS KOBELCO PLANT ISHINOMAKI.....	66
TABLE 3.21:	OPERATING PARAMETERS NIPPON STEEL DMS FACILITY MUKATA ECO PARK, KIUSHU .....	69
TABLE 3.22:	EMISSIONS NIPPON STEEL DMS FACILITY MUKATA ECO PARK, KIUSHU.....	69
TABLE 3.23:	TECHNICAL DATA AND OPERATING PARAMETERS NOELL CONVERSION PROCESS.....	76
TABLE 3.24:	TECHNICAL DATA, OPERATING PARAMATERS AND RDF REQUIREMENTS FIXED BAD PRESSURE GASIFICATION SVZ SCHWARZE PUMPE.....	83
TABLE 3.25:	TECHNICAL DATA AND OPERATING PARAMETERS ENTRAINED FLOW GASIFIERS SVZ SCHWARZE PUMPE .....	87
TABLE 3.26:	TECHNICAL DATA AND OPERATING PARAMETERS FIXED BED SLAGGING GASIFIER (BGL) SVZ SCHWARZE PUMPE.....	89
TABLE 3.27:	OPERATING PARAMETERS THERMOSELECT PLANT KARLSRUHE .....	93
TABLE 3.28:	DESIGN DATA ECOLOOP REFERENCE PLANT.....	95
TABLE 3.29:	ZWS-GASIFIER RÜDERSDORF: PROCESS CHARACTERISTICS AND PROPERTIES OF INPUT MATERIAL .....	98
TABLE 3.30:	AVERAGE TREATMENT COSTS OF ZWS GASIFICATION RÜDERSDORF.....	99
TABLE 3.31:	OPERATING DATA LAHTI KYMIJÄRVI I PLANT .....	100
TABLE 3.32:	SYNTHESIS GAS COMPOSITION LAHTI KYMIJÄRVI I.....	100
TABLE 3.33:	ALTERATIONS IN EMISSIONS FROM LAHTI KYMIJÄRVI I CAUSED BY UTILIZATION OF PRODUCT GAS FROM GASIFICATION .....	101
TABLE 3.34:	COMPOSITION SYNTHESIS GAS LAHTI KYMIJÄRVI I .....	103
TABLE 3.35:	MASS- AND ENERGY BALANCE ALTER NRG PLASMA GASIFICATION PROCESS. ....	106

Status of Alternative Techniques for Thermal Waste Treatment

TABLE 3.36:	AVERAGE TREATMENT COSTS ALTER NRG PLASMA GASIFICATION .....	106
TABLE 3.37:	ENERGY BALANCE C.H.O. GASIFICATION PROCESS .....	110
TABLE 3.38:	AVERAGE TREATMENT COSTS C.H.O. GASIFICATION PROCESS.....	110
TABLE 3.39:	OPERATING DATA GASPLASMA PILOT PLANT .....	111
TABLE 3.40:	MASS AND ENERGY FLOWS FOR INDUSTRIAL SIZE APP GASPLASMA PLANT.....	112
TABLE 3.41:	MASS AND ENERGY FLOWS PLASCO PROCESS.....	113
TABLE 3.42:	AVERAGE TREATMENT COSTS PLASCO PROCESS.....	114
TABLE 3.43:	OPERATING DATA DIESELWEST PLANT .....	116
TABLE 3.44:	LABARATORY ANALYSIS OF DIESELWEST SAMPLES .....	117
TABLE 3.45:	OPERATING DATA LOGOIL PLANT .....	119
TABLE 3.46:	SUPPLIERS OF HYDROTHERMAL WASTE TREATMENT PROCESSES.....	119
TABLE 3.47:	TREATMENT INTENSITY, COSTS AND DEVELOPMENT STATUS OF CONSIDERED PROCESSES. ....	121
TABLE 4.1:	DECOMPOSITION TEMPERATURES OF IMPORTANT POLYMERS .....	133