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IEA Biomass Agreement

TASK X. BIOMASS UTILIZATION
BIOMASS THERMAL GASIFICATION AND GAS TURBINES ACTIVITY

Sub-task 6 - Gasification of Waste

Summary and Conclusions of Twenty-five Years of Development

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Abstract

An overview of nearly thirty years' development of waste gasification and pyrolysis technology is given, and some major general conclusions are drawn.

The aim has been to give new developers an overview of earlier major attempts to treat MSW/RDF with thermochemical processes, gasification or pyrolysis. Research work in general is not covered, only R&D efforts that have led to substantial testing in pilot scale or demonstration.

For further details, especially related to ongoing R&D, readers are referred to other recent reviews.

The authors' view is that gasification of RDF with appropriate gas cleaning can play an important role in the future, for environmentally acceptable and efficient energy production. A prerequisite is that some of the major mistakes can be avoided, such as:

1) too rapid scale-up without experimental base
2) unsuitable pretreatment of MSW to RDF and poor integration with material recycling
3) too limited gas/flue gas cleaning.

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Gasification of Waste
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1. Summary and Conclusions

The gasification - including pyrolysis - of different types of waste has been carried out at the development stage for at least twenty-five years. Occasionally, regular production units have been installed more or less as demonstration plants. The total number of pyrolysis/gasification processes for waste during these twenty-five years exceeds forty, out of which some twenty have been demonstrated at capacities of more than 1 ton per hour.

In some countries, second to deposition in disposal areas, incineration or combustion techniques have been ”conventional” treatments for waste since the sixties. With the increasing environmental consciousness, these incineration units have been subjected to tightening emission limits and steadily increasing costs for the waste treatment. The reason for this is of course the complex nature of the waste, and one could say in principle, that a responsible caretaking of waste must include the separation of the various components at some stage in the process.

The nature of these separations will depend on their location, from a flue gas cleaning after incineration/combustion, to some kind of mechanical pre-treatment/separation of the waste.

Basically this evaluation of thermal treatment of waste is to some extent an examination of where the separation is advantageous, and what type of separation is appropriate. Moreover, there are fundamental differences between various gasification and pyrolysis processes which have a principle impact on the process performance - especially in the material handling aspect. A key question is thus the fuel considered (Municipal Solid Waste) MSW, or untreated RDF (Refuse Derived Fuels) of different qualities. In general, MSW-incinerations in grate-fired boilers have been favoured due to the low pre-treatment cost. In many countries today pre-treatment is mandatory due to material recovery aspects including metals, glass and paper. Such schemes yield an RDF-type of waste, both when source separation before collection or mechanical separation after collection, is employed.

During the past two or three decades, there has also been an increasing concern about other types of waste. Today, hazardous waste (from the medical and veterinary sides, as well as from chemicals) are restricted in handling and tied to special incineration units. Special techniques have been investigated for plastic waste, where there is increasing attention to scrap from cars, boats, computers etc. The problems with spent rubber tyres and other forms of rubber, are well-known.

With the mentioned philosophy of recycling and separation at source, these waste streams are likely to become more and more separate. This enables a more effective treatment of them, whilst at the same time the specific streams may be smaller in volume. Consequently, there is a parameter of flexibility and scale introduced in treatment technologies.

Products and Markets
Gasification and pyrolysis have a wider range of possibilities with regard to products, by-products and markets, compared with conventional mass burn burners. The main products are gas of different types and qualities, and liquids also of different qualities.

Gases are usually considered to have potential markets for instance in:

- ovens, limekilns, brick kilns, metallurgical furnaces, etc.
- dryers
- boilers

and for advanced gasification with gas cleaning, also in:

- power generation in engines and gas turbines (combined cycles)
- power generation in fuel cells
- synthesis of SNG
  Methanol
  Ammonia
  Hydrocarbons (gasoline, diesel).

There is no requirement for high gas temperatures in gasification, enabling for instance counter-current flows (up-flow reactors). A high temperature may in turn be maintained in the bottom, providing a melted ash outlet (in contrast to ”dry” ashes coming out of the combustion units).

Regarding the ”markets”, a melted ash is superior to the common ”dry” ash. It still cannot be attributed any value, but the costs are considerably lower for deposition as a result of less volume, as well as that melted ash is usually considered a non-leaching material.

Further, several gasification processes have a potential advantage regarding the bottom ash quality not containing fermentable products. Due to the composition of waste, there are temperature limitations in incineration. Chlorine and other compounds may induce severe corrosion on the superheaters etc., if the material temperatures are higher than 480^{o}C in the superheater.

A gas cleaning in between the gasification and the gas combustion in a combined unit should be less costly than the corresponding flue gas cleaning after the combustion, since the gas flow may be less than half the flow of flue gas. For oxygen-blown gasifiers the gas volume is even lower and that gives further possibilities for low emissions after gas cleaning.

Assuming that gas cleaning between the gasification and the combustion is cheaper - or at any rate not more expensive than flue gas cleaning - the effects of a combined system on the combustion are considerable. With a clean fuel, and especially with a gaseous fuel, the investments will be lower and the energy efficiency of the combustion may be considerably increased. There is no longer a restriction on the temperatures on the superheaters.

Early Efforts in Waste Gasification
In the opening remarks it was stated that the gasification of waste started almost thirty years ago. These efforts were by no means negligible. More than 20 processes were suggested and developed to some extent during the seventies, 13 of these were run at capacities of more than 10 tons a day, and five were tested at between one and ten tons per day.

Several of the early developments in the USA were later demonstrated/tested in Europe and/or Japan (ANDCO-TORRAX, PUROX, Twin-bed pyrolysis/Bailie).

The most striking point from the earlier developments of waste gasification is of course the fact that hardly any one of the processes remains today as a commercial product. The only exception may be the Andco-Torrax process which has had a certain success, with five plants being erected. However only one, outside Paris, seems to be still in operation.

Behind the disappointing experiences with early waste gasification processes, several factors can be identified:

1. Most of the processes intended to gasify or pyrolyse the raw MSW, i.e. no separation was envisioned. In combination with the proposed techniques, this often led to a more or less endless number of mechanical problems, shut-downs, sintering and so on.

2. The basic knowledge about waste and gasification/pyrolysis was poor. In several cases not even an acceptable analysis of the waste was at hand, and the heterogeneity of the raw material was underestimated. Both short-term (hours, day-to-day, and long-term (seasonal) variations have to be considered.

3. Scaling-up in the capacities of the units was too fast. Today we know that there is a vast difference between pre-treated material in laboratory reactors and smaller units (where a shredding is necessary due to the dimensions), and the real waste going into a full-scale reactor.

4. The fact that pyrolysis/gasification is a complex chemical conversion was seriously under-estimated. Several of the processes were ”inventions” treating the process as a ”thermal process”.

5. Most of these process efforts included a fixed bed reactor, the ideas coming from coal gasification and old-time biomass gasification or metallurgical processes. The most common equipment is a shaft reactor with a bottom temperature of about

1000°C. The overall experiences are transport problems from feeding, over to inbed problems in the shaft to the ash outlet (sinterings, etc.).

6. Most of the systems were pyrolysis/gasification producing tar or a mixture of tar and gas. Only a few of the processes included gas cleaning. The tar-rich gas caused problems on the gas side as well as condensations, cloggings etc. in the pipes to the combustor. The Garrett/Occidental process, with advanced recycling and thermal treatment on the other hand, probably was before its time, and included many new technologies.

Later Developments

With regard to gasification and pyrolysis techniques, it is obvious that development during the eighties and the nineties has focused to a considerable extent on specific waste streams including RDF.

In some cases, e.g. Thermoselect, the further development has been trying to use untreated MSW, but with excellent environmental performance, melted slag and low gaseous emission.

The more recent developments try to give solutions superior to incineration for:

- emission problems (e.g. dioxins)
- inert solid residues
- higher efficiency to power
- better product flexibility.

To achieve these goals, two stage processes e.g. Siemens-Kiener, TPS, and/or high temperature processes are tested, e.g. Thermo select and Plasma Waste (Scan Arc). Several processes have been tested on pilot scale, but very few are erected on demonstration scale. Both fuel gas cleaning (LURGI, TPS, DANECO) and flue gas cleaning (Siemens-Kiener, ScanArc), are under development.

Conclusions

Judging from estimated investment costs and energy efficiencies, combinations between gasification and gas combustion units may be feasible, in comparison with incinerators for heat production. For power generation, the gasification processes with gas cleaning hold a potential advantage due to lack of high temperature corrosion on steam superheaters.

Pyrolysis processes producing liquid product, in combination with combustion, do not provide an advantage since a cleaning of the liquid is far more complicated than cleaning of the gas, and the energy efficiencies are markedly lower. Pyrolysis techniques yielding both char and liquids from contaminated waste fuels have very low or negative product value.

High temperature processes have a strong advantage in the solid residue (slag) but are hampered by a lower energy efficiency.

The final choice of process will depend on local circumstances such as recycling policy, MSW/RDF availability, heat and power price, emission limits to air and disposal costs for different types of residues.

The later developments, and particularlynew attempts, should seriously examine the vast experience from the past, and try to find new solutions to the identified problems.

2. Scope and Limitations

Gasification - including pyrolysis - of different types of wastes has been performed on a development stage since at least twenty-five years. Occasionally, regular production processes have been installed more or less as demonstration units. The total number of pyrolysis/gasification processes during these twenty years exceeds forty, out of which some twenty have been demonstrated at capacities more than 1 ton per hour.

The specific processes for rubber and plastics, back to monomer pyrolys and others, are not covered in this overview. An overview is a Novem report 9305 ”Studie Hoge Temperatuur Vergassing (HVT) van kunststofafval” (In Dutch) by Aarssen and Temmink.

This survey aims primarily at drawing conclusions from the past and present development for the future. For that reason, the report focuses on principal and fundamental points rather than economic terms. Operational costs always reflect the the principles of the process but investments are often subjected to specific circumstances. In consequence, the total production costs - including financial costs for the investment - are difficult to compare and very site-specific.

This is emphasized when gasification techniques under development are compared with fully commercialized incineration or combustion processes - even if the gasification process has been demonstrated on a larger scale. A new process cannot possibly have acquired the effects of a more mature technique when it comes to equipment costs, engineering, etc.

In addition, there are always business considerations in offers for a specific unit. They may be market motivated or raw material induced, but they could affect the investment by tenths of a per cent on the investment.

Thus**,** in our opinion the investment is a tricky instrument for evaluations of different techniques. If investments are collected from installed plants, the above comments are applicable. If, on the contrary they are estimated on a uniform basis, they tend to be somewhat theoretical and they suffer from discrepancies between new equipment and established pieces. Feasibility studies based on a uniform base for a wide range of processes are very expensive, and far outside the limitations of this study.

In our approach the review and the evaluation of the processes do not omit the economics of them, but handle the economy as a result of the the technique rather than judging from reported investments.

Second to deposition of wastes in disposal areas, incineration or combustion techniques have been ”conventional” treatment since the seventies - at least in some countries like Sweden. With the increasing environmental awareness, these incineration units have been subjected to greater measures for environmental protection, steadily increasing the costs for the treatment. The reason for this is of course the complex nature of the wastes, and in principle a responsible care-taking of wastes must include separation of various components somewhere in the process.

The following table shows where the separation steps can be installed. The nature of these separations will depend on the location of them; from a flue gas cleaning after incineration/combustion to some kind of pretreatment/separation of the wastes.

A.										
WASTES	-	-	-	-	-	-	-	Incineration	-	Flue gas cleaning
B.										
WASTES	-	Separation	-	-	-	-	-	Incineration	-	Flue gas cleaning
C.										
WASTES	-	-	-	Gasification	-	-	-	Combustion	-	Flue gas cleaning
D.										
WASTES	-		-	Gasification	-	Gas cleaning	-	Combustion	-	-
E.										
WASTES	-	Separation	-	Gasification	-	-	-	Combustion	-	Flue gas cleaning
F.										
WASTES	-	Separation	-	Gasification	-	Gas cleaning	-	Combustion	-	-

Taking this into consideration, the present evaluation of thermal treatment of wastes is to some extent an examination of where the separation is advantageous and what type of separation is appropriate. Moreover, there are fundamental differences between various gasification and pyrolysis processes which have a principle impact on the process performance - especially in the material handling aspect.

Technically, the comparisons are made primarily with reference to incineration processes. Methane extraction from deposits and other techniques are not forgotten, but considered less comparable.

Most of the basic material for the evaluations is extracted from reported experiences with gasification and pyrolysis of wastes on a larger scale during the past twenty years. Chapter 5.1 reviews some recent overviews. Language barriers tend to affect review papers, and our report does not properly cover the Japanese development. Japan has specifically tested and demonstrated dual fluidized bed systems (gasification/combustion); the units however seem to be closed down.

3. Wastes and Trends in Waste Composition

The concept ”waste” incorporates a number of streams in a modern society. Relevant to gasification and pyrolysis (and incineration) are streams such as chemical waste, medical waste, waste from autoshredder, industrial wastes and municipal wastes. Like other raw materials for industrial processing these different materials require different processes for optimal operation.

”Municipal Wastes” is not a clear-cut definition either. In Europe an average composition would be approximately:

Paper	25%
Plastics	7%
Green waste	30%
Textiles	10%
Metals	8%
Glass	10%
Other	10%

From this compilation it is obvious that ”Municipal Wastes” requires special measures if processed. In effect, several or most of the gasification and pyrolysis processes today dictate RDF - a treated fraction of the municipal waste.

In Europe and other places the recycle philosophy is gaining, leading to a markedly increased waste separation in industry as well as in the households. The result of this separation at source is a gradually changing municipal waste and in some respects a ”refined” mixture.

Estimates on the future municipal waste in Sweden and test results from one Swedish city have given the following compositions:

	Estimated	**Test**
Paper	35-45%	67%
Plastics	6-9%	13%
Green wastes	25-35%	10%
Textiles	-	-
Metals	2-4%	6%
Glass	-	6-8%
Other	6-8%	1%

Judging from this, a future trend in composition of the municipal waste may be something that is more like RDF, even if it seems unlikely that for instance the metal and glass content will reach present standards for RDF. Some specifications on RDF require virtually no iron and glass in the product. It should also have less than 10 % moisture and a heating value of >16 MJ/kg. The last requirements may be encountered in future separations, but are unlikely in the first ones.

During the past two or three decades there has also been an increasing concern about the other types of wastes. Hazardous wastes (from the medical and veterinary sides as well as from chemicals) are restricted in handling and tied to special incineration units today. Special techniques have been investigated for plastic wastes where there is an increasing attention to

scrap from cars, boats, computers, etc. The problems with spent rubber tyres and other rubbers are well known.

With the mentioned philosophy of recycling and separation at source, these waste streams are likely to become more and more separate. This enables a more effective treatment of them at the same time as the specific streams may be smaller in volume. In consequence, there is a parameter of flexibilty and scale introduced in the treatment technologies.

Recycling will limit the total amount of waste in the future, and can locally, in countries with a large installed capacity for mass burning of waste, lead to lack of fuel and competition to get the available MSW/RDF. This is the local situation in Holland and Sweden.

Regarding the gasification and pyrolysis techniques, it is obvious that the development during the eighties and the nineties have focused to a considerable extent on these specific waste streams.

4. Markets and Products

The recycle concept includes more than separations at the source. In the idea also lies the perception of making as much use of the materials as possible and of minimizing what has to be deposited. This touches on the present subject in two respects, firstly, incineration is often not regarded as a production process if ”only” heat is gained - power production has to be incorporated. Secondly, the ashes or the solid residue after the process, have to be minimized and made safe in their disposal. Environmentally acceptable MSW destruction including melted solid residues and a limited heat (hot water) or power production, have been the major goal for waste processing. This has led to limitations on incineration as a ”recycling” technology.

Future more efficient power process from RDF, including gasification, will put away those obstacles and place also the thermal treatment as a part of the recycling concept.

Incineration or combustion of wastes has the option of two main products - heat and power - and results in at least two by-products or residues, ash coming out of the furnace and fly ash coming from the filters. In addition, the flue gas cleaning produces solids or water-borne contaminants that are washed out of the gas. Despite great efforts, none of these by-products have found a market where actual contributions to the economy are obtained. The nearest market is gypsum board manufacture from dry flue gas cleaning (SO_x) but this has not been applied with waste incineration. (In the future, gypsum boards will also be recycled which decreases this potential market). The melted bottom ash and probably also solidified fly ash, will be a strong requirement on future RDF technologies.

The gasification processes have a potential advantage regarding the ashes coming out of the bottoms. In gasification there is no requirement on high gas temperatures, enabling for instance countercurrent flows (up-flow reactors). In turn a high temperature may be maintained in the bottom, providing a melted ash outlet (in contrast to ”dry” ashes coming out of the combustion units).

Regarding the ”markets”, a melted ash is superior to the common ”dry” ash. It can still not be attributed any value but the costs are considerably lower for deposition, as a result of smaller volumes as well as the melted ash usually being considered to be a non-leaching material.

Gasification and pyrolysis have a wider range of possibilities when it comes to products, by-products and markets. The main products are gas of different types and qualities and liquids - also of different qualities.

Usually, gases are stated to have potential markets in for instance:

- ovens, limekilns, brick kilns, metallurgical furnaces, etc
- dryers
- boilers
- power generation in engines and gasturbines (combined cycles)
- power generation in fuel cells
- synthesis of SNG

Methanol
Ammonia
Hydrocarbons (gasoline, diesel)

Of these potential markets close coupling to industrial furnaces with an 8000h per year operation is of course a very suitable application. Short-term, the other major option seems to be power production and cogeneration when possible.

Liquid products from pyrolysis (primarily), are suggested for use as fuels for heat and power generation and as chemical raw materials. In these cases more conventional markets are referred to, covering multiple customers at greater distances. This type of application seems to be appropriate for ”clean wastes” such as forest wood waste, but hardly for contaminated fuels.

5. Overview Papers and Reports

5.1 EEC report 1984

An excellent detailed review of the early developments in waste gasification/pyrolysis were made in 1977 and updated in 1984:

”Thermal Methods in Waste Disposal - pyrolysis, gasification, incinceration, RDF-firing” by A. Buekens and J. Schoeters, EEC Contract number ECI 1011/B7210/83/B, Final Report 1984. Detailed process overviews and causes for failure of demonstration projects in Japan, USA and Europe are reported.

5.2 Aston University/DK Teknik 1993

The most extensive report covering gasification and pyrolysis processes currently being developed or commercialized is prepared by AV Bridgewater and GD Evans: **An Assessment of Thermochemical Conversion Systems for Processing Biomass and Refuse**. Contracted from the Aston University and DK Teknik (Denmark) it is published in 1993 and it includes a detailed description of 24 processes**:**

Designation	**Gasification/ /Pyrolysis**	**Reactor technology**	**Waste fuel (tested or intended for (?))**	**Product; gas/ /liquid**	**Operation**
Ansaldo/ /Aerimpianti TPS	Gasification	Atmospheric Fast fluidized	RDF	Gas LHV	Demo
Ahlström, atm	Gasification	Atmospheric Fast fluidized	RDF? (not marketed for RDF)	Gas LHV	Commercial
Ahlström, Bioflow	Gasification	Pressurized Fast fluidized	RDF?	Gas LHV	Demo
Arizona State University	Gasification	Atmospheric Fluidized, bubbling	MSW	Liquid	Pilot plant
ASCAB/Stein Industrie	Gasification	Pressurized ”Fast fluidized”	-	Gas LHV	abandoned
Batelle Columbus	Gasificstion	Atmospheric Fluidized, bubbling	RDF	Gas MHV	Pilot plant
Egemin	Pyrolysis	Atmospheric Entrained	RDF?	Liquid	Pilot plant ?
Ensyn (RTP III)	Pyrolysis	Atmospheric Fast fluidized	RDF?	Liquid	Commercial
IGT Renugas	Gasification	Pressurized Fluidized, bubbling	RDF?	Gas MHV	Demo
Interchem	Pyrolysis	Atmospheric ”Vortex”	-	Liquid	Pilot plant ?
JWP Energy Products	Gasification	Atmospheric Fluidized, bubbling	RDF?	Gas LHV	Commercial - closed down
Lurgi	Gasification	Atmospheric Fast fluidized	RDF, MSW (shredded for metals)	Gas LHV	Commercial
MTCI	Gasification	Atmospheric Fluidized, bubbling	RDF?	Gas MHV	Demo
SEI	Gasification	Atmospheric Fluidized, bubbling	RDF?	Gas LHV	Commercial

Designation	**Gasification/ /Pyrolysis**	**Reactor technology**	**Waste fuel (tested or intended for (?))**	**Product; gas/ /liquid**	**Operation**
Sofresid/ /Caliqua	Gasification	Atmospheric Updraft - fixed bed	RDF, MSW	Gas LHV	Commercial
TPS	Gasification	Atmospheric Fast fluidized + CFB cracker	RDF	Gas LHV	Pilot plant (Demo gasifier Gréve Ansaldo)
Tampella/ /Enviropower	Gasification	Pressurized Fast fluidized	RDF?	Gas LHV	Pilot plant
Union Electric Fenosa	Pyrolysis	Atmospheric Fast fluidized (initially bubbl.?)	RDF?	Liquid	Pilot plant
University of Hamburg	Pyrolysis	Atmospheric Fluidized, bubbling	RDF?	Liquid	Commercial - closed down
Université Laval	Pyrolysis	Vacuum Moving bed	RDF, MSW	Liquid	Commercial - closed down
University of Sherbrooke	Gasification	Atmospheric Fluidized, bubbling	RDF	Gas LHV	Pilot plant
Voest Alpine	Gasification	Atmospheric Fixed bed	RDF	Gas LHV	abandoned
Völund	Gasification	Atmospheric Fixed bed	RDF?	Gas LHV	Pilot plant
Wastewater Tech. Centre	Pyrolysis	Atmospheric Fixed bed	RDF?, MSW?	Liquid	Pilot plant

As is seen, only 4 of the 24 processes have been run on municipal waste (MSW). Another 6 processes have tested refuse derived fuel (RDF) of fluff type and pellets. (Still 2 more processes (IGT and JWP) have tested what is called ”urban waste” which is not described more closely)

Most of the processes are, however, regarded as suitable for RDF in different forms.

For MSW only the 3 processes that have tested the fuel are considered feasible for it and out of these one is a high temperature process (Sofrecid/Caliqua), one is a special vacuum process (Université Laval) and one is a semi-pyrolysis process with a special product synthesis (Arizona State University).

Regarding the above table and in addition to it the following short comments can be made:

Reactor Technique
Most of the process concepts are based on fluidized beds; 8 with bubbling beds and 9 with fast fluidization. Four reactors are using fixed beds and three are designed with specific features (entrained, ”vortex” and moving bed).

A few of the processes are pressurized, use oxygen or indirect heating and produce medium Btu gas. In most cases these processes are not tested with MSW or RDF.

Gasification/Pyrolysis and Product Cleaning
Seven processes are pyrolysis processes with liquids as main products. None of these include a product cleaning from contaminants that eventually will be discharged from a combustion without flue gas treatment.

From the gasification processes, a gas scrubbing is envisioned in 8 cases. For 2 processes a tar cracker is included as well. In the rest of the processes only a (hot) gas filter is used or no gas cleaning is proposed.

The gas scrubbing creates a waste water problem. From the filters another solid waste is added to the ash. The only process with an advantageous solid residue is the Sofrecid/Caliqua process which produces a molten slag.

Investments
From the survey the authors conclude that ”There is no perceptible difference in capital cost between atmospheric gasification and pyrolysis systems. Pressure gasification systems are more costly by themselves but offer a potential cost saving at the power generation stage due to the lack of gas compression required and higher system efficiency.”

5.3 Novem BGT/TNO 1994
In a Novem report, Gasification of waste. Evaluation of the waste processing facilities of the Thermoselect and TPS/Gréve, these two gasification treatment processes are compared to an incineration technique for wastes. The study was conducted for (Novem) Netherlands Organisation for Energy and Environment and it was published in April 1994.

The Thermoselect process is a combined pyrolysis/high temperature (oxygen blown) gasification process. The MSW is fed into a pyrolysis chamber at a temperature of some 600 ^{o}C. It is further pushed through this reactor into a fixed bed, oxygen blown gasifier which has a bottom temperature of 2000 ^{o}C. At this temperature a molten slag is obtained as a solid waste.

The gas from the gasifier (and the preceding pyrolysis) is cleaned in three steps; acid scrubbing, alkaline scrubbing and activated carbon filtration. After that the gas is fed to a gas engine for power production. Extensive processing is required for the scrubbing liquids.

In the TPS/Gréve process MSW is subjected to a separation and a conversion into RDF. The RDF is gasified in a combined bubbling and fast fluidized bed. After a mechanical gas cleaning (cyclone) the gas is fired in a boiler with flue gas cleaning. The steam from the boiler is used for power production.

The waste to the incineration technique is 63% MSW, some coarse minicipal waste and some industrial waste. The material is combusted on a moving bed and the flue gases are conventionally treated in an electro-static precipitator and a wet scrubber. The steam (43 psig) is fed to a turbine to generate power.

The net energy efficiencies of the three processes are calculated at (power produced/energy content MSW):

TPS/Gréve	7%
Thermoselect	12%
Incineration	22%

with the comments that the TPS/Gréve and the Thermoselect figures are based on pilot units and not full scale, commercial plants and that the TPS/Gréve process is operating the turbine at 50% part-load.

As for the gaseous emissions the data for Thermoselect and the incineration comply with the BLA standard in the Netherlands. In general, the emissions from the Thermoselect are lower. The gaseous emissions from the TPS/Gréve unit are higher and do not completely agree with the BLA standard.

When costs are compared, the TPS/Gr• ve unit comes out with the lowest costs per ton of processed waste. However, it has to be born in mind that this process only handles a part of the MSW and that disposal costs for the rest has to be added.

With this comment all three processes lie within +/- 15 % in costs per ton of waste processed.

5.4 R. Hauk and J. Poller; Kraftwerkstechnik, 1994

In an article in VGB Kraftwerkstechnik 74 (1994), Heft 9, p790 ff, five processes for pyrolysis and gasification of MSW are described and disussed under the heading:
Vergasungsverfahren für Abfälle (Gasification Technique for Wastes).

In two cases a pyrolysis of the wastes is carried out with direct combustion of the pyrolysis gas without intermediate cleaning. In the third case there is a mechanical cleaning of the gas in a cyclone followed by a catalytic conversion in a ”coal reactor” before power production in a gas engine.

The last two systems are the Thermoselect process and the Lurgi fast fluidized gasification already covered in the first over-views.

Another seven processes for other types of wastes are also listed in the article. However, the authors do not draw any decisive conclusions from the material, due to lack of large scale data.

5.5 The NREL/CDM Report, June 1996

The most up-to-date review of waste gasification technologies is the NREL Report, Sub-Contract No.YAR-5-15116-01 **”Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste”.** The study is undertaken by **Camp Dresser and McKee Inc.** Out of 40 possible processes, first 20 and then seven processes were chosen for final evaluation including site visits. These seven processes are:

- EPI (Energy Products of Idaho)
- TPS (Termiska Processer AB)
- Proler International Corporation
- Thermoselect Inc.
- Batelle (High Throughput Gasifier)
- Pedco Inc. (Combustion MSW)
- ThermoChem Inc. (MCTI)

A draft final report was prepared in January 1996, and the final report is expected in June 1996.

6. Survey of Waste Gasification and Pyrolysis Processes

6.1 Early Developments in Waste Gasification (Prior to 1980)

In the opening it was stated that gasification of wastes started almost thirty years ago. These efforts were by no means negligible. More than 20 processes were suggested and developed to some extent during the seventies. Thirteen of these were run at capacities of more than 10 tons a day and five were tested between 1 and 10 tons per day.

(The source for this table is in-house information and data)

Designation	Gasification/ /Pyrolysis	Reactor technology	Waste fuel (tested or intended for (?))	Product; gas/ /liquid	Operation
Andco-Torrax	Gasification	Fixed bed	MSW	Gas	Commercial
Purox	Gasification	Fixed bed	MSW	Gas	Demo
Pyrogas	Gasification	Fixed bed	MSW	Gas + Liquid	Demo
Destrugas	Pyrolysis	Fixed bed	MSW	Char	Pilot plant
Landgard	Gasification	Moving bed	MSW	Gas	Demo
Batelle	Gasification	Fixed bed	Shredded	Gas	Abandoned
Sodetag	Pyrolysis	Multiple beds	?	Char	Abandoned?
Garret Occidental	Pyrolysis	Fixed bed	Shredded	Liquid	Demo
Hercules	Pyrolysis	Fluidized, bubbling	Shredded	Char	Lab.
Lantz	Pyrolysis	Moving bed	Shredded	Char	Abandoned
West Virginia Univ.	Gasification	Multiple fluidized beds	Shredded	Gas	Lab.
Cities Serv. Oil	Pyrolysis	Moving bed	Shredded	Liquid, char, gas	Lab.
URDC	Gasification	Fixed bed	MSW	Gas	Pilot Plant
Devco	Pyrolysis	Moving bed	Shredded	Char	Pilot Plant
Fink's ”Müllhütte”	Gasification	Molten bath	MSW	Gas	Lab.

(Comment: In most cases ”Moving bed” refers to a rotary kiln)

Surprisingly many projects during the seventies did reach a Pilot Plant or Demo stage. Most of them were, however, abandoned during the last years of the decade or during the early eighties.

The following processes are covered in the Appendices:

Waste gasification before 1980
ANDCO-TORRAX

MOTALA PYROGAS
PUROX
LANDGAARD
DESTRU GAS
ERCO (see below 1980-1990 ”Power Recovery Systems”)
ECO-FUEL (later OMNIFUEL)
EBARA
GARRETT/OCCIDENTAL

6.2 Waste Gasification 1980-90

Whilst solid wastes were somewhat in focus for the gasification and pyrolysis activities around 1970, biomass gasification took over the central role when the oil prices went up after 1973. This is reflected in the following table where most of the processes are designed for wood - or rather wood waste. Since some of these processes have also been proposed for RDF handling they are listed without further comments than that they were more adapted to the commercialization trend during the eighties e.g. biomass gasification and pyrolysis.

The sources for this table are mainly two:

1. Biomass Conversion, Activity 4 in the IEA Bioenergy Agreement Task VII: Thermal Gasification, 1990

2. Report to the IGU Sub-Committee B-II for the World Gas Conference in Berlin, 1991

Designation	**Gasification/ /Pyrolysis**	**Reactor technology**	**Waste fuel (tested or intended for (?))**	**Product; gas/ /liquid**	**Operation**
Applied Eng. Company	Gasification	Fixed bed	Wood Waste	Gas	Commercial
Batelle Pacific Northwest Lab.	Gasification	Fixed bed	MSW, wood waste	Gas	Lab. Abandoned ?
Bio-Solar	Gasification	Fixed bed	Wood pellets	Gas	Lab. Abandoned ?
C.H.H. Technology Inc.	Gasification	Fixed bed	Wood waste	Gas	Commercial
Century Research Inc.	Gasification	Fixed bed	Agircultural waste	Gas	Commercial
D.M. International Inc.	Gasification	Fixed bed	Wastes	Gas	Commercial
EZ Manufacturin g Company	Gasification	Fixed bed (co-current, upwards)	Wood waste	Gas	Commercial
Forest Fuels Manufacturin g Inc.	Gasification	Moving bed	Wood waste	Gas	Commercial
Halcyon Associates Inc.	Gasification	Fixed bed	Wood waste	Gas	Commercial
Maschinenfab rik A. Lambion	Gasification	Fixed bed	Wood waste	Gas	Commercial
Maschinenfab rik Augsburg-Nürnberg AG	Gasification	Fixed bed	Wood waste	Gas	Commercial
Westwood Polygas Ltd	Gasification	Fixed bed	Wood waste	Gas	Demo
National Synfuels Inc.	Pyrolysis/Gasi fication	Moving bed	Wood waste	Gas	Dev. unit
Alberta Industrial Development	Gasification	Fluidized, bubbling	Wood waste	Gas	Dev. unit

Designation	**Gasification/ /Pyrolysis**	**Reactor technology**	**Waste fuel (tested or intended for (?))**	**Product; gas/ /liquid**	**Operation**
Batelle Columbus	Gasification	Fluidized, dual bubbling bed	Wood waste RDF	Gas	Dev. unit
Energy Product of Idaho	Gasification	Fluidized, bubbling	Wastes	Gas	Demo
Omnifuel	Gasification	Fluidized, atmos. bubbl. pressurized	Wood waste RDF?	Gas	Demo Plant Demo Plant
Sur-Lite Corporation	Gasification	Fluidized, bubbling	Wastes	Gas	Commercial
Universal Energy Internat. Inc.	Pyrolysis	Moving bed	MSW	Char	Commercial
Energy Resources Company Inc.	Pyrolysis	Fluidized, bubbling	Wood waste	Char	Demo
VynckeWarm te-techniek	Gasification	Moving bed/ /fluidized bed	Wood waste	Gas	Commercial
Thermoquip	Gasification	Fixed bed	Wood waste	Gas	Commercial
Dansk Termo Industri	Pyrolysis	Fixed bed?	Agricultural waste	Gas?	Demo
ABB	Gasification	Fluidized bed	Plastic Waste	Gas	Dev.
Fritz Werner	Gasification	Fixed bed	Wood waste	Gas	Commercial
Imbert	Gasification	Fixed bed	Wood waste	Gas	Commercial
KHD-Humboldt Wedag	Gasification	Fixed bed	Wood waste	Gas	Commercial
Rotopyr	Pyrolysis	Moving bed	Plastic and rubber waste	Liquid?	Demo
Deutsche Babcock	Pyrolysis	Moving bed	MSW	Liquid?	Demo
EFEU GmBH	Gasification	Fixed bed	Wood waste	Gas	Demo
Chevet	Gasification	Fixed bed	Wood waste	Gas	Dev.
Touillet	Gasification	Fixed bed	Wood waste	Gas	Dev.
Creuzot-Loire/ /Frama	Gasification	Fluidized bed	Wood waste	Gas	Demo
TNEE	Gasification	Fluidized bed	Wood waste	Gas	Demo

Designation	Gasification/ /Pyrolysis	Reactor technology	Waste fuel (tested or intended for (?))	Product; gas/ /liquid	Operation
CEMAGREF Carbonizer	Gasification	Fixed bed	Wood waste	Gas	Dev.
GA-10 (20) (Duvant)	Gasification	Fixed bed	Wood waste	Gas	Commercial
Pillard	Gasification	Fixed bed	Wood waste	Gas	Commercial
Entropie SA	Gasification	Fixed bed	Wood waste	Gas	Commercial
BECE	Gasification	Fixed bed	Wood waste	Gas	Demo
Götaverken Energy System	Gasification	Fast fluidized	Wood waste	Gas	Commercial
Thalapnat AG	Gasification	Fixed bed	Wood waste	Gas	Commercial
Century Research Inc	Gasification	Fixed bed	Wood waste	Gas	Commercial
Rolla, Univ of Missouri	Gasification	Fluidized bed	Wood waste, agricultural wastes	Gas	Dev.
Biosyn	Gasification	Fluidized bed	Wood waste	Gas	?
EPI	Gasification	Fluidized bed	Wood waste	Gas	Commercial
Pyrenco	Gasification	Fixed bed	Wood waste	Gas	Commercial
SYNGAS	Gasification	Fixed bed	Wood waste	Gas	Demo
Biotherm	Gasification	Fixed bed	Wood waste	Gas	Commercial
Cross Cut	Gasification	Fixed bed	Wood waste	Gas	Commercial
Dekalb Agriresearch	Gasification	Fixed bed	Agricultural waste	Gas	Commercial
HalyconAss.I	Gasification	Fixed bed	Wood waste	Gas	Commercial
Pendu Gas	Gasification	Fixed bed	Wood waste	Gas	Commercial
PRM	Gasification	Moving bed	Agricultural waste	Gas	Commercial

The comments about operation in the above tables refer to the time in question and it is notable thatmost of the technologies are not being commercially avilable today. From the seventies, there seem to be none for MSW/RDF beside the Andco-Torrax process. Some other processes have developed from early attempts like Kiener and Batelle Columbus.

Most of the fixed bed reactors have capacities less than 10 MW (updraft) or less than 1 MW (downdraft) and for most of the technologies gas cleaning is not incorporated. This reflects the local energy situation where small scale utilization of - primarily - wood waste is beneficial. Regarding MSW and RDF it can be argued whether the small scale (fixed bed) gasification is a reasonable technique in relation to society's handling of (waste) material. This, however, touches on a more system or political question - whether wastes should be handled locally or in large scale, centralized units.

In the Appendix, the following processes are further described:

Waste gasification 1980-90
ANDCO-TORRAX (CALIGULA) (see before 1980)
ELAJO/KOMAKO
VOEST ALPINE
KIENER (see below after 1990)
POWER RECOVERY SYSTEMS

Basically, the choice of these processes is to reflect different features in the techniques in relation to the main questions in this report as stated in the introduction. As earlier, these processes have also been run on actual MSW or RDF - not solely on wood or agricultural wastes as many of the other processes even if at least RDF has been proposed for them.

6.3 Topical Processes in the Current Development

Regarding the purpose of this report, only some of the processes mentioned are being described more in detail. A selection is made covering on one hand processes that are actually being run on MSW and RDF (at least in pilot scale) and in addition, processes reflecting different techniques. Processes with similar technologies are not described repeatedly. The authors are aware that there are other attempts in pilot scale e.g. fixed bed updraft, downdraft, and rotary kilns, that have not been covered. We believe that the experiences are well in line with what we report for the selected processes.

In the attachments, the following is covered:

Waste gasification development (still active) 1990-95
SKF PLASMA/SCANARC
BATELLE COLUMBUS
TERMOSELECT
LURGI (with and without gas cleaning)
TPS/ANSALDO
TPS/Cracker (gas cleaning)
SIEMENS KIENER
DANECO
BIOTHERMIA INT.INC. (University of Sherbrooke – See OMNIFUEL/ECOFUEL abovebefore 1980)

6.4 Summary and Conclusions From the Earlier Development

The most striking fact from the earlier developments of waste gasification of course is that very few of the processes remain today as a commercial product. In fact, in most cases even the erected units do not exist in operation.

The only exceptions may be the Andco-Torrax process - which has had a certain success with more than five plants being erected (only one, however, seems to still be in operation).

Behind these disappointing experiences regarding MSW (and RDF?) at least six factors can be identified:

1. Most of the processes intended to gasify or pyrolyse the raw MSW, i.e. no separation was envisioned. In combination with the proposed techniques, this often led to a more or less endless number of mechanical problems, shut-downs, sintering and so on.

2. The basic knowledge about waste and gasification/pyrolysis was poor. In several cases not even an acceptable analysis of the waste was at hand, and the heterogeneity of the raw material was underestimated. Both short-term (hours, day-to-day, and long-term (seasonal) variations have to be considered.

3. Scaling-up in the capacities of the units was too fast. Today we know that there is a vast difference between pre-treated material in laboratory reactors and smaller units (where a shredding is necessary due to the dimensions), and the real waste going into a full-scale reactor.

4. The fact that pyrolysis/gasification is a complex chemical conversion was seriously under-estimated. Several of the processes were ”inventions” treating the process as a ”thermal process”.

5. Most of these process efforts included a fixed bed reactor, the ideas coming from coal gasification and old-time biomass gasification or metallurgical processes. The most common equipment is a shaft reactor with a bottom temperature of about 1000^{o}C. The overall experiences are transport problems from feeding, over to inbed problems in the shaft to the ash outlet (sinterings, etc.).

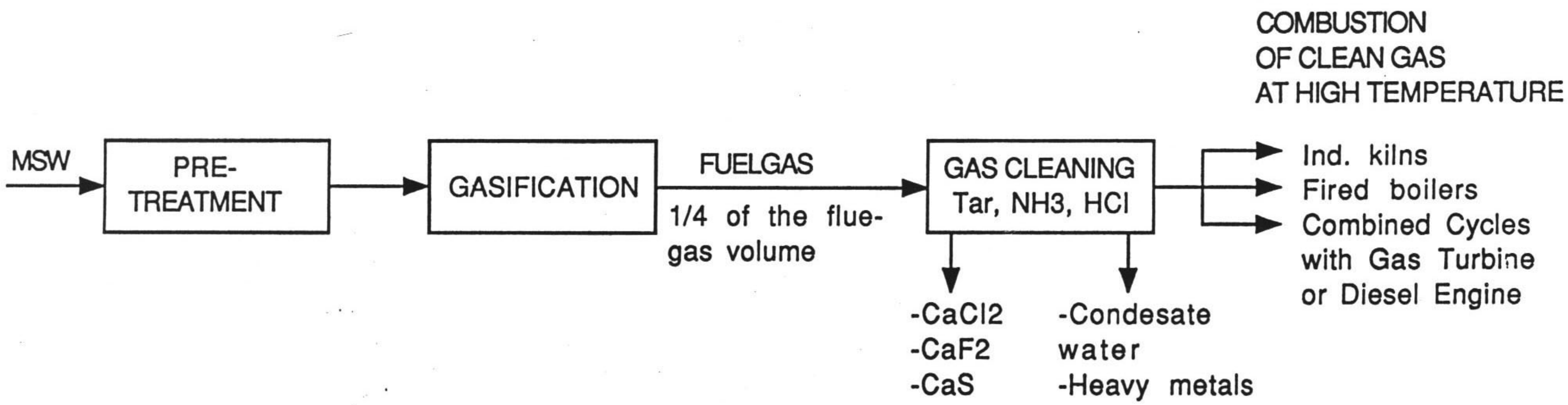
6. Most of the systems were pyrolysis/gasification producing tar or a mixture of tar and gas. Only a few of the processes included gas cleaning. The tar-rich gas caused problems on the gas side as well as condensations, cloggings etc. in the pipes to the combustor. The Garrett/Occidental process, with advanced recycling and thermal treatment on the other hand, probably was before its time, and included many new technologies.

The conclusions from these early process designs for gasification/pyrolysis of wastes are quite unambiguous: MSW is a complicated material to handle in a thermochemical process. On one hand the process produces tar and other sticky materials at fairly low temperatures. On the other hand metals, glas and inorganic materials may sinter and melt at higher temperatures. In addition MSW contains several enviromentally sensitive components and is of a very heterogenous composition.

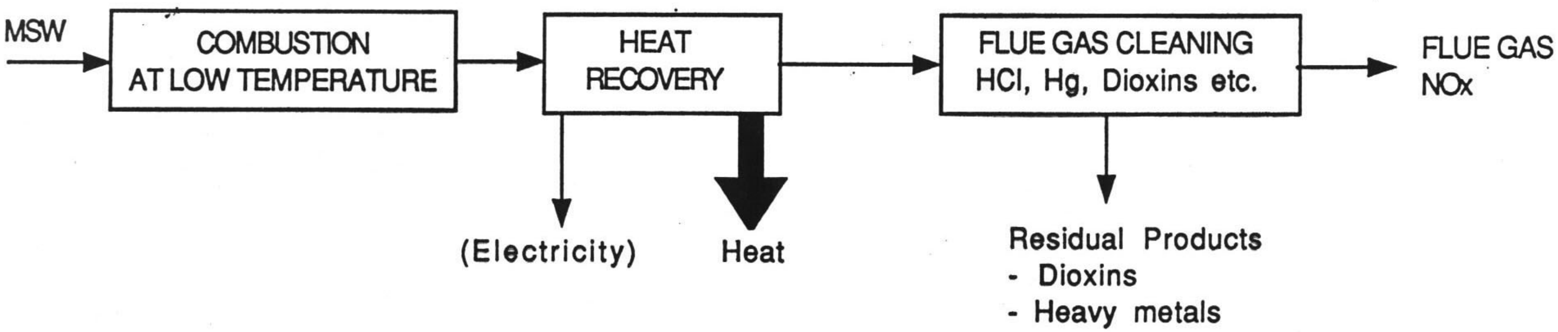
This can be compared to the rather succesful development of wood waste gasification where tenths of processes were commercialized. Beside initial technical problems - that should not be underestimated - the main draw-back for these processes has been the development of energy prices (oil and gas).

GASIFICATION OF WASTE

- Volume Reduction
- Energy Recovery
- Minimum of Pretreatment



CONVENTIONAL COMBUSTION OF WASTE



Judging from the experiences with MSW, a shaft reactor seems feasible only if the temperature is high enough to outmaneuver all the material problems at lower temperatures or if the MSW is pretreated into a more homogeneous raw material; e.g. a RDF-pellet.

Since the earlier efforts in development, the environmental concern has grown considerably. Today a simple combustion of tar and gas/tar is hardly feasible without a flue gas treatment. In this respect most of the (omitted) processes would be obsolete unless a gas treatment is installed.

7. Conclusions

7.1 Conclusions Regarding Function and Environmental Effects

From the numerous attempts with gasification and pyrolysis of wastes in different techniques and at various scales, some principal conclusions may be drawn. Below, they are structured according to reaction and reactor parameters. The basic conditions then are that the wastes have to be handled and treated according to forthcoming (or in some places existing) practice and rules; e.g. separation of wastes and environmental protection at the treatment of it.

It should be noted that the parameters below are interacting and that the separation of them is made for practical text reasons.

Reaction Temperatures

Regarding the heterogeneous composition of wastes, it is obvious that the mechanical transportation of it through the reactor is severely hampered at some temperatures. If unsorted material is used, melting and sintering is occurring at medium range of temperatures; approxiamtely 700-1.000 ^{o}C. At lower temperatures tar is formed. Both these effects result in potential risk for clogging in the reactor.

At higher temperatures - over 1.000 ^{o}C and preferrably above 1.200 ^{o}C - the ashes melt and require a special configuration in the bottom of the reactor. The intermediate temperatures 900 - 1200^{o}C should preferably be avoided.

From environmental point of view, low temperature processes forming tar, create a problem since the tar will contain several risk components. If the tar is incinerated or combusted <u>without</u> flue gas teatment, these contaminants will be let to the atmosphere. Tar separation is an akward operation where definitely energy is lost due to condensations, etc. For low temperature operation (<900^{o}C) some kind of secondary tar treatment is necessary.

High temperature processes, on the other hand, result in a potential NO_x formation, and reduced efficiency.

Bed Configurations

Fixed beds are evidently more apt to problems than rotary kilns and even fluidized beds.

Unless a real high temperature (>1200 ^{o}C) is used most of the earlier efforts failed in this respect. This is also evident from the numerous small (and simpler) constructions that work well with more suitable raw materials such as wood chips and charcoal. A close connection between fuel quality (particle size) and bed pressure drop, gas distribution and so on gives inherent problems with MSW and even RDF fluff. RDF pellets might work better.

With MSW as feed, there has evolved a number of sophisticated devices for the transportation of the material through the reactor and for contacting hot medias to the material. Screw transportations, rotating walls, piston forces and pneumatic devices are examples. Some of the have been successful but the investments tend to increase considerably.

With fluidized beds the same problems are present but a little less restrictive. A coarser type of feed is accepted in these reactors but not as far as MSW. Fast fluidized beds are more tolerant to particle size than bubbling beds, to a large fraction of fines mixed with courser particles.

The most advantageous reactor from this point of view seem to be the high temperature, melted ash reactors. In principle they are fixed bed reactors but the extremely high temperature sets aside the material problems providing the bed is not too high.

Environmentally, this parameter does seem to have direct implications on the effluents. Indirectly though, for instance a mechanical device gives a restriction on the reactor temperatures and thus effects are obtained. However, no principle conclusions can be drawn in this respect.

Co-current or Counter-current, Updraft or Down-draft
Beside the obvious effect that counter-current (up-draft) reactors create large amounts of tar in the gas, the general experience from the reviewed processes is that co-current and down-draft reactor is limited to very small sizes (1 MW).

Regarding environmental effects, co-current and down-draft reactors require less gas cleaning although it can not be omitted. It is unlikely that a small plant <1MW can take the cost of emission control equipment for MSW/RDF.

MSW and RDF as Feed
From what is commented earlier, it is obvious that MSW is far more difficult to process than sorted fractions from MSW; e.g. RDF. Broadly speaking, RDF fluff is suitable as feed in fluidized gasification/pyrolysis - at least in fast fluidized beds - whilst it is hardly suitable in a fixed bed without higher temperatures (very shallow bed). In the latter case special features are usually applied in the reactor to secure functioning. Alternatively, RDF pellets are produced to suit a fixed-bed gasifier.

Beside the heterogeneity of MSW, the improved heating value is another argument for upgrading to RDF. Very clean RDF-fractions (low Chlorine) might compete on the biomass fuel market.

7.3 Comparisons Between Flue Gas Cleaning and Fuel Gas Cleaning

The main conditions in making the comparison below include environmental restrictions concerning the emissions. As the final emissions from gasification and pyrolysis eventually will appear after a combustion, the presumed requirements are all given as emissions in flue gases in mg/m^3. The following comparisons are made assuming that the emissions are lower than the BLA standard quoted from the NOVEM report (see page 16).

Compound	**Maximum emission in flue gas (mg/m^3)**	
HCl	10	
HF	1	
SO_x	40	
NO_x	70	
C	10	
PCDD/PCDF	0.1	ng TEQ/m^3
dust	5	
Cd	0.05	
Hg	0.05	
Sb..Te	1	
CO	50	

If these restrictions are to be met in incineration (combustion) an advanced flue gas cleaning is required. A flue gas treatment to remove So_x, VOX, Dioxin etc., more than doubles the costs for incineration of the waste. The investments for the environmental protection technique almost equal the investment for the combustion unit (50-100 %).

A gascleaning in between the gasification and the gas combustion in a combined unit, may be less costly than the corresponding flue gas cleaning after the combustion, since the gas flow is less than, or much less (depending on the process 1/2 - 1/5), than the flow of flue gas. (See the attached figure on the next page.)

If only the equipment size is considered, the gas cleaning would cost less than two thirds of the corresponding flue gas cleaner in investment (with a scale-up factor of 0.65). However, the cleaning technique would not be the same since the compounds are in a reduced state after the gasification and in an oxidized state after the combustion. This induces different techniques - in some cases favourable to the gas, in others to the flue gas. SO_2 is easier to scrub or absorb than H_2S, NH_3 may be cracked whilst NO_x is preferrably chemically converted, HCl is easier to wash or absorb than Cl_2, etc.

No detailed evaluations seems to have been made on this subject or to have been reported. With reference to the contaminants listed above, it is estimated that the flow effect will have the largest impact on the costs.

Assuming that gas cleaning between the gasification and the combustion is cheaper - or at any rate not more expensive than flue gas cleaning - the effects of a combined system on the combustion are large. With a clean fuel, and especially a gaseous fuel, the investments will be lower and the power production efficiency of the combustion may be raised considerably. There is no longer a restriction on the temperatures on the superheaters. In addition the bottom design can be made differently since there are no limiting design factors from the solid material.

Comparisons between gasfired and coalfired furnaces in the range og 50-100 MW give an investment ratio of about 1:3 for smaller boilers and about 1.5 for larger power units.

These figures agree roughly with the data from the NOVEM report where the combination Thermoselect gasification + gas engine carries a smaller investment than a modern incineration + steam turbine. The corresponding cost for a TPS gasifier + gas combustion + steam turbine is also smaller. (The estimated investment for the latter is actually much smaller but the gas emissions are higher and as RDF is used instead of MSW as in the other cases. If these factors are compensated for, the investment still seems lower)

Regarding the ash, all mass burn units give a dry ash. In the future, secondary ash treatment will be installed in even more plants (vitrification). The bulk density is usually in the region of 500-1000 kg/m^3 and metals can leach when the ash is deposited. Even fermentable (unburned) solids are present. The same type of by-product is obtained from low temperature gasification, but usually without fermentable material. High temperature gasification gives a vitrified material directly. Gasification bottom ash and fly ash from fluid beds might have a lower leachability even withhout melting. The volume of the melted ash is decreased to some 10-20 % and the solid ash is non-leachable giving a considerably lower disposal cost. Even ash from gasifiers will probably be vitrified in the future in most countries.

7.3 Conclusions Regarding Products and Energy Efficiencies

In Chapter 4 the potential advantages of gasification and pyrolysis of wastes were sketched out regarding the products.

From the experiences of earlier efforts, it can be concluded that liquid products emanating from primarily pyrolysis processes, have a rather limited market. In certain locations and at certain times they have been sold at resonable prices. However, this type of business have not been sustainable when oil prices have gone down or other circumstances have changed.

Oil products from waste will be difficult to get clean enough to be sold at a price similar to oil or gas. Gas products has also had a limited market or use - up until now. In some lime furnaces and similar applications, gas has had a value. At present the situation seem to change in terms that power generation from biomass has been focused especially as part of ”recycle philosophies” and CO_2 abatement.

Power generation can be carried out also with conventional incineration. In consequence, a product discussion on this point has to be carried out as comparisons between gasification/pyrolysis + combustion/power generation and incineration with power production.

The energy efficiency for the incineration unit calculated as (energy in - losses in the combustion and in the flue gases and ash) / energy in is in the region of 80-85 % depending on technique. The flue gas cleaning may take an extra 5-10 % in flue gas cooling/reheating and electricity, giving an overall result to steam or heat of 70-80 % efficiency.

With a gas fired furnace and a clean fuel the corresponding efficiency could be about 90% without less loss in flue gas cleaning and ash. In addition the steam data could be raised, increasing the efficiency of a steam turbine.

For gasification efficiencies there is a number of alternatives, all collected from the above survey and calculated as energy in product divided by energy in the wastes:

a) a simple gasification at atmospheric pressure and with air - without gas cleaning - can provide a hot gas with 90-95 % efficiency.

b) a high temperature gasification with oxygen gives an efficiency of 80-90 % to hot gas.

c) a gas cleaning via a scrubbing or washing and reheat of the gas will take 5-10 off the efficiency.

d) a condensation of tar-rich gas and reheating of the gas will take 10-15 % off the efficiency.

e) pyrolysis to liquid product (condensed) gives an energy efficiency of 50-60 %.

a)-e) all have the conditon that the wastes have <15 % moisture. Drying the wastes from 50 to 15 % moisture content takes some (0)5-20 % of the efficiency, depending on technique and use of flue gases, etc for drying. This, however, is the same for incineration.

To compete with an incineration unit on efficiency basis, a gasification including gas cleaning has to accomplish at least 80 % efficiency which seems to be possible for an airblown, atmospheric gasifier.

High temperature gasification may be able to compete but it is close to the restriction.

Pyrolysis processes and gasifiers producing a tar-rich gas can hardly achieve efficiency factors in the range of incineration units.

All the above efficiencies are commented only regarding heat generation. If power production is focused, the results are about the same providing steam turbines. In advanced power generation, the gasification techniques hold advantage due to the higher efficiencies in the last step. Waste incineration integrated with for instance gas turbines still need development of efficient gas cleaning before entering the gas turbine combustor.

7.4 Comparisons Between Incineration and Gasification/Pyrolysis

Potential advantages with gasification and pyrolysis have been implicated in some of the earlier parts - as well as the draw-backs or problems that have been experienced. A comparison between incineration (with heat recovery or power generation) and gasification/pyrolysis based on fundamental aspects is shown below. The problem with economic effects of the fundamental differences - which was touched on in the introduction -

remains. However, this is may be handled in relative terms; regardless of what the absolute costs are, the ratio between them should be of a certain magnitude, etc.

QUALITATIVE COMPARISON BETWEEN GASIFICATION PROCESSES AND COMBUSTION PROCESSES FOR WASTE TREATMENT

Gasification processes	Combustion processes
Only certain processes can handle MSW	Can handle MSW (on grates)
Potentially higher energy efficiency in power generation via combined cycles and engines	In heat generation the energy efficiency may be somewhat (≈ 5 %) higher than in a combination gasification-gas combustion. In power generation there is a limit due to temperature/corrosion on the superheaters.
Gas cleaning induces a loss of energy corresponding to 100-200 ^{o}C in the gas (providing heat exchange) and more if a quench system is used.	The flue gas treatment induces a loss of energy that corresponds to some 100 ^{o}C in the flue gas (2-3 times the flow of fuel gas = gas after a gasification).
The design of the reactor is guided by the gas flow and the flow of wastes only.	The design of the combustion unit is guided by the waste material (usually on moving grates) and the flue gas flow in addition to the heat transfer areas.
In some processes molten slag is obtained. Adaptable to dry RDF and high heating values (plastic).	One ”reactor” unit in comparison to two in gasification + gas combustion

Judging from estimated investment costs and energy efficiencies, combinations between gasification and gas combustion units may be feasible in comparison with incinerators in heat production.

In power generation the gasification processes hold a potential advantage.

Pyrolysis processes - producing liquid product - in combination with combustion do not provide an advantage since cleaning the liquid is far more complicated than cleaning the gas, and the energy efficiencies are markedly lower.

High temperature processes have an advantage in the solid residue (ash) but are hampered by a lower energy efficiency.

7.5 Aspects on Gasification/Pyrolysis Regarding Present Experiences

Considering the information reported above, the following summarized aspects on gasification/-pyrolysis of Municipal Solid Waste can be given.

1. The material is extremely difficult to handle with high energy efficiencies in either incineration processes or with gasification/pyrolysis techniques.

2. The present trend or ambitions with separation of wastes at the source - or later in the chain - will improve the handling of the materials substantially.

   Gasification/pyrolysis will gain the most from such developments as these processes are more specialized and tentatively result in higher energy efficiencies - providing a suitable RDF-type fuel. The latter is given by separations as proven by several techniques. Until recently, the economics of these processes are however, ruined by the fact that the separation costs (and sometimes power consumption) are also included in the gasification processing.

   In the waste systems of the future, it is likely that the separations will be included in the handling costs in the total recycling concept. The incineration processes will gain less from this than gasification/pyrolysis. RDF combustion in fluidized bed is limited by the chlorine corrosion as well as MSW-mass burn.

3. The question whether an incineration + conventional power generation (steam turbines) is superior or inferior to a gasification + combustion + (advanced) power generation (combined cycle) remains unanswered.

   There are factors pointing in either direction and a definite answer will not be obtained until full-scale facilities are erected, and run for some time. It might even be that the answer depends on other peripheral factors, such as feed type and local markets.

4. Some conclusions can be drawn from previous experiences for the gasification/pyrolysis systems in question.

A simple or single pyrolysis reactor is not generally feasible. Untreated liquid product cannot be used in a gas turbine or in a combustion unit without flue gas cleaning, and then the costly treatment in a pyrolysis plant does not provide any advantage.

A special treatment of the liquid product will require condensation and a cumbersome process for liquid purification. This will also ruin the economy, unless a novel treatment of the liquid is proposed.

Gasification of MSW in fluidized beds is evidently not feasible. The technique requires a separated fraction of MSW; e.g. RDF. Under these circumstances however, the processes are economically as well as technically feasible, providing the costs for the separation are not all put on the gasification.

For an acceptable utilization of the gas, either a gas cleaning is required or a flue gas treatment after combustion. To effect the potential advantages with gasification, the gas cleaning is suggested, and an advanced power generation can be used. The gas cleaning should not generate new waste streams that are difficult to handle e.g. tar water. Tar conversion catalytically or at high temperature is then a major option.

Gasification of wastes at high temperatures offers several advantages. The main decisive disadvantages, are the lowered energy efficiencies and the investment costs.

On the one hand these costs are correlated to the fuel or oxygen to obtain the high temperature, and on the other hand to the costs for primary gas treatment or cleaning.

Interesting techniques to achieve the latter are for instance the ”coke gasifier” or ”filter” used in some techniques, and possibly the plasma process which, however, decreases the energy efficiency still further.

5. A conclusive suggestion concerning the principle results from previous efforts with gasification/pyrolysis may be as follows:

   As single techniques, all the gasification/pyrolysis processes are hampered by some factor(s). On the other hand, benefits from combinations of techniques are not ruled out. Using the simplicity of a pyrolysis reaction as a first step, the capability of a subsequent gasification unit as a gas treatment and a gasification unit for the remaining solids, might prove advantageous.

   This is analogical with some of the later developments where high temperature second steps are used however.

8. ENCLOSURE PROCESS DESCRIPTIONS

8.1 THE SOFRESID/CALIQUA PROCESS (ANDCO-TORRAX)

General
The gasification is carried out in a fixed bed, updraft reactor by means of air. The slagging conditions in the bottom of the shaft are achieved by the use of hot - preheated - air. The oxygen content of the air is lowered by combustion of smaller amounts of gas in the air.

Municipal Solid Waste (MSW) can be introduced without separation - even (hazardous) hospital waste can be handled. The solids are fed in the top of the reactor and the gas leaving the gasifier is directly burnt in a conventional combustion unit. Heat is collected as steam for power production and district heating. Some of the heat generated is recycled to the preheating of the gasification air.

The solids from the wastes are melted and quenched into slag in the gasifier and the combuster:

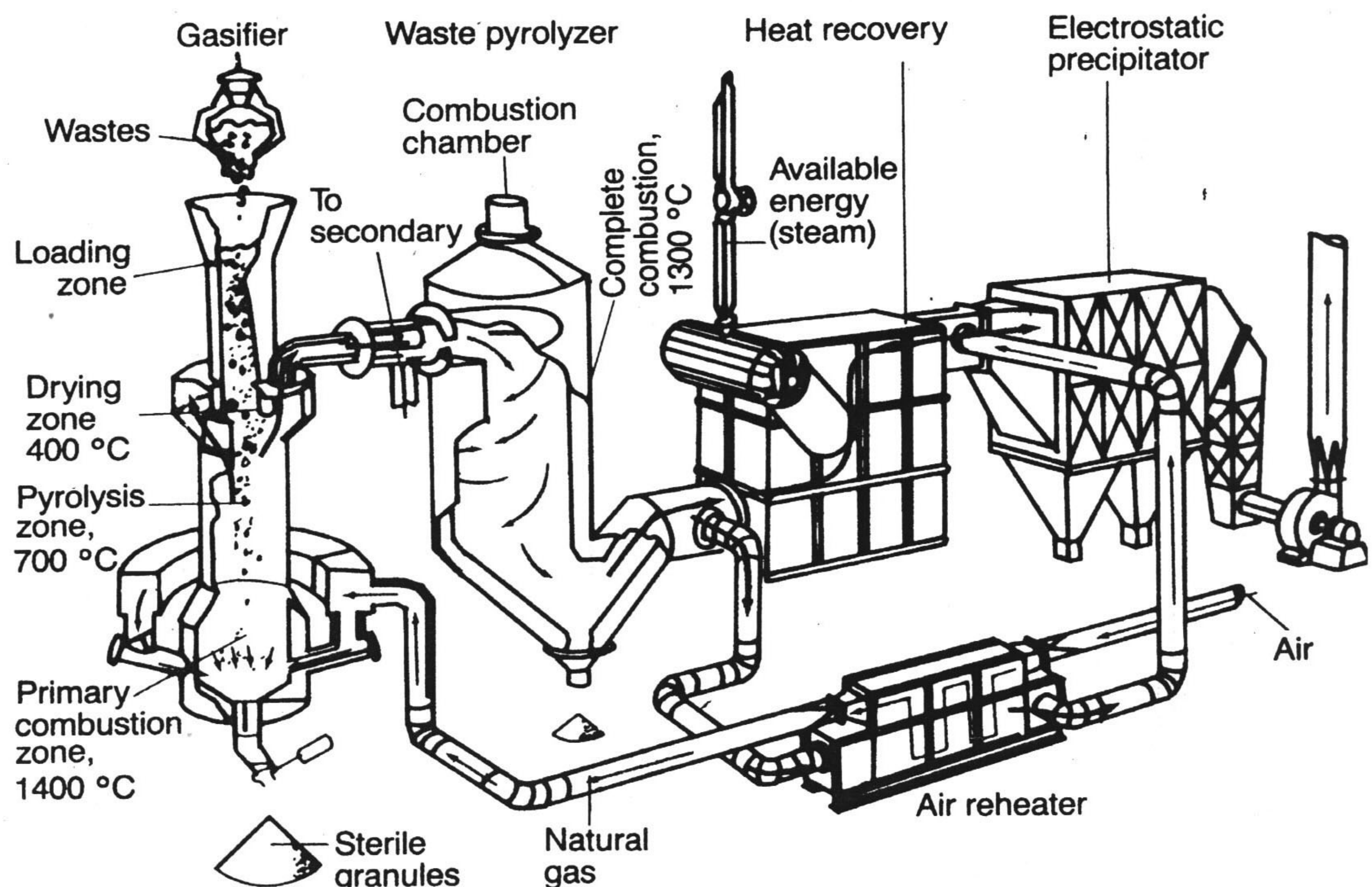
Process description
By preheating the air to some 1.000 ^oC, the gasification temperature can be maintained well above 1200 ^oC in the bottom of the shaft and the countercurrent gas can leave the reactor at high temperature. Combustion air is added before the combustion unit and the flue gases will have immediate temperature of - also - more than 1200 ^oC. Steam is produced in a conventional boiler and after an electrostatic precipitator the flue gases are discharged to the atmosphere.

The slag from the gasifier as well as from the combustor (gas-borne solids from the gasifier) is quenched by circulating water and collected as granules.

With a shaft size of a couple of meters the gasifier has a capacity of about 8 tons (daf) per hour, consuming 6.000 m^3 of air and an amount of natural gas as fuel for the preheating of the air. Adding the combustion air in the second stage, the flue gases amount to 30-45.000 m^3/h.

No fuel gas is collected as a product - only power and steam (hot water) for district heating. The secondary product is granulated slag for which uses have been sought for years. Beside minor uses as fillings, etc they are being deposited. Calculations by Bridgewater and Evans show an electricity production of about 1.8 MW from the 8 tons of fuel/h and some 12 MW of district heating. This is based on an energy efficiency of almost 70 %.

With only an electrostatic precipitator on the flue gases, all volatile - non-combustible - pollutants will be let to the atmosphere. From the Sofresid/Caliqua plant at Creteil almost 1 g



Source: CALIQUA

Andco Torrax (Caliqua)

of HCl per m^3, 5 mg of Hg and - for instance - 0.01 mg of Cd per m^3 is reported. (The feed rate then is a little more than 8 tons an hour.)

Status
The first, commercial Andco-Torrax process was erected in the beginning of the 70's and was based on a patent from 1968.

Since then, six units have been built but only one of them still running in 1993. This unit - in Creteil - suffered from some drawbacks and in 1987 some modifications were suggested; a filtering of the raw gas before the combustion to counteract fouling on the heat exchanger tubes and a recycle of particulates from the raw gas to the gasifier to reduce the fuel gas consumption. Since then no effiency data or availabilities of the unit have been reported.

Considering only the flexible costs, a revenue is obtained from the unit at "ordinary" incineration fees. If the fixed costs are added, however, a considerable subsidy is required . With the turn-key cost at Creteil (about 100 MFF in 1979-80), they amount to some 2 M$ per year at today's value (annuity = 15 %).

Present Situation and Future
With six erected plants the Andco-Torrax technique was comparatively successful on the market to start with. However, it seems that operational problems and the high costs for the gasification in comparison to incineration is hampering a further expansion. Further developments of gas cleaning could be an option. With an added flue gas cleaning - nowadays required - the costs will be still higher.

The basic reason for the costs seem to be the high temperature employed and the fact that a lot of heat is quenched.

The advantages with the process include the fact that almost any waste may be handled in theory. In practice in-bed problems in shaft gasifiers are frequent.

8.2 MOTALA PYROGAS, SWEDEN

General
Motala Pyrogas was an atmospheric air-blown updraft fixed bed gasifier coupled to a boiler in a rubber and tyre manufacturing plant. The fuel was waste rubber, MSW (not pretreated) and coal. The co-gasification with coal was to try to stabilize the lower char layer in the bed.

Process Description
To be able to feed the MSW stream a new robust lock hopper cell with 1m^3 volume was designed and installed. The shaft was 3,6m and a rotating grate fed out the ash through a water seal. The lower part of the reactor was cooled, and produced steam to moderate the ash temperature thus limiting clinkering.

A two-stage design was used to control the tar condensation in the gas pipeline to the boiler. A lower hot gas exit mixed with the cool top gas which had also passed through a electrostatic filter. The recovered tar was fired in a separate burner in the boiler.

After initial bed problems the upper part of the gasifier was separated from the lower part with another water seal. The upper part could then rotate and stir the fuel bed.

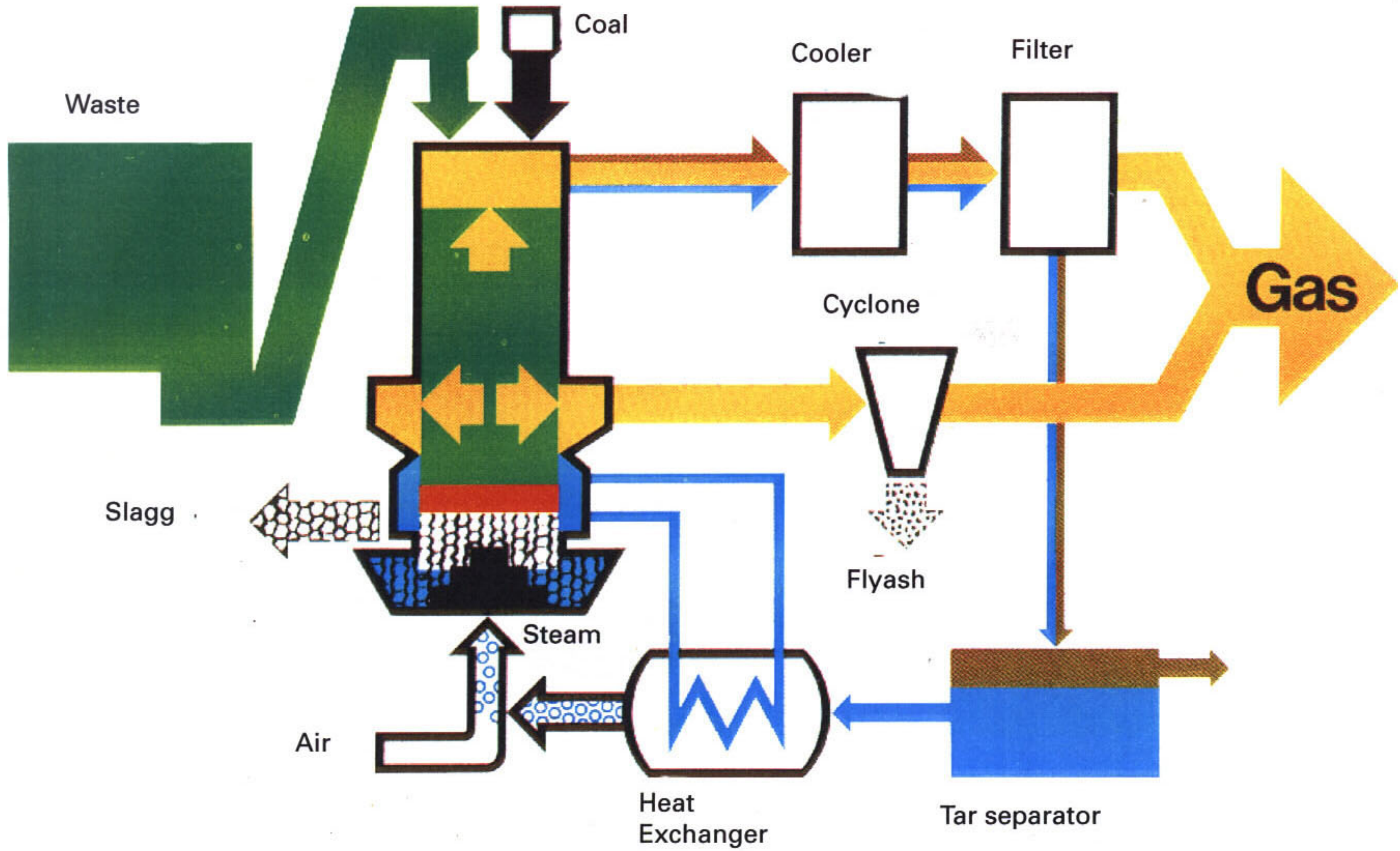
Status
A demonstration plant with a fuel capacity of 15MW was erected in1974 in Gislaved, Sweden. Due to the physical properties and the pyrolysis behaviour of MSW, several problems with channelling and ”rat holes” (up to m^3), and high pressure drops in the bed were encountered. The redesign (movable upper part) did not solve the problems, and the plant was shut down in 1977.

Present Situation and Future
The source of the technology was a conventional two-stage coal gasifier that Motala Verkstad delivered before the fifties. A few pilot tests with MSE were also run in a coal gasifier, still in operation in the early seventies. Despite very limited results, the positive conclusion was drawn that the technology was applicable. The company was in a ´down` period and needed a new major product.

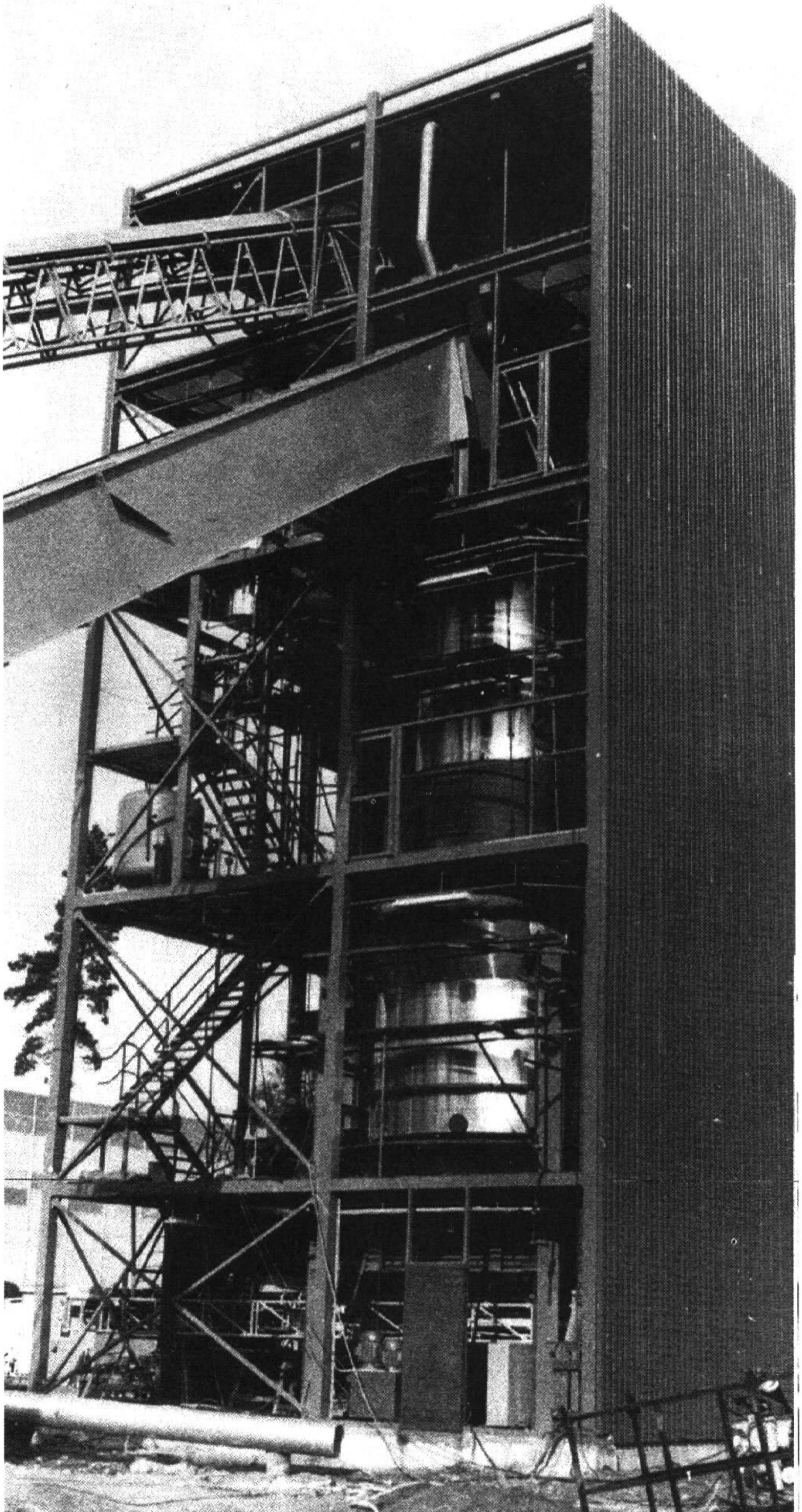
The channelling problems and bed distortion, led to that the temperature profiles could be almost inverted higher in the top than further down in the shaft. Even during rather stable bed performance there were hot spots and ”rat holes” with a volume of more than 1m^3. Despite major efforts to solve the fundamental problems in the bed, no major progress was made.

Several minor problems such as tar elimination and handling were solved during the development work.

The company reduced the number of employees, and was taken over by KMW. There is no activity in the field today.



Motala Pyrogas



Motala Pyrogas

8.3 THE PUROX PROCESS

General
The Purox process includes a high temperature gasification with oxygen. Molten slag is obtained and in the beginning untreated MSW (Municipal Solid Waste) was envisioned but this was altered into shredded waste.

A subsequent use of the product gas for ammonia or methanol production was proposed but such processes were never realized.

The development of the Purox process was carried out by Union Carbide completely as a commercial project without support from governments or other external funds. Despite two demonstration units and considerable marketing efforts no further commercialization was managed.

Process Description
The MSW is stored and shredded before fed to the top of the high temperature updraft shaft furnace which is blown with oxygen from the bottom. The reactor is similar to a shaft furnace sponge iron production in the steel industry.

Molten slag is quenched with water and constitutes a material that can easily be deposited.

The raw product gas is cleansed by conventional techniques from for instance the chemical industry. A small part of the product gas is fed to the reactor to ensure the high temperature and the rest is a ”clean fuel”. Tars and some of the contaminants in the water (from scrubbing) are returned to the reactor.

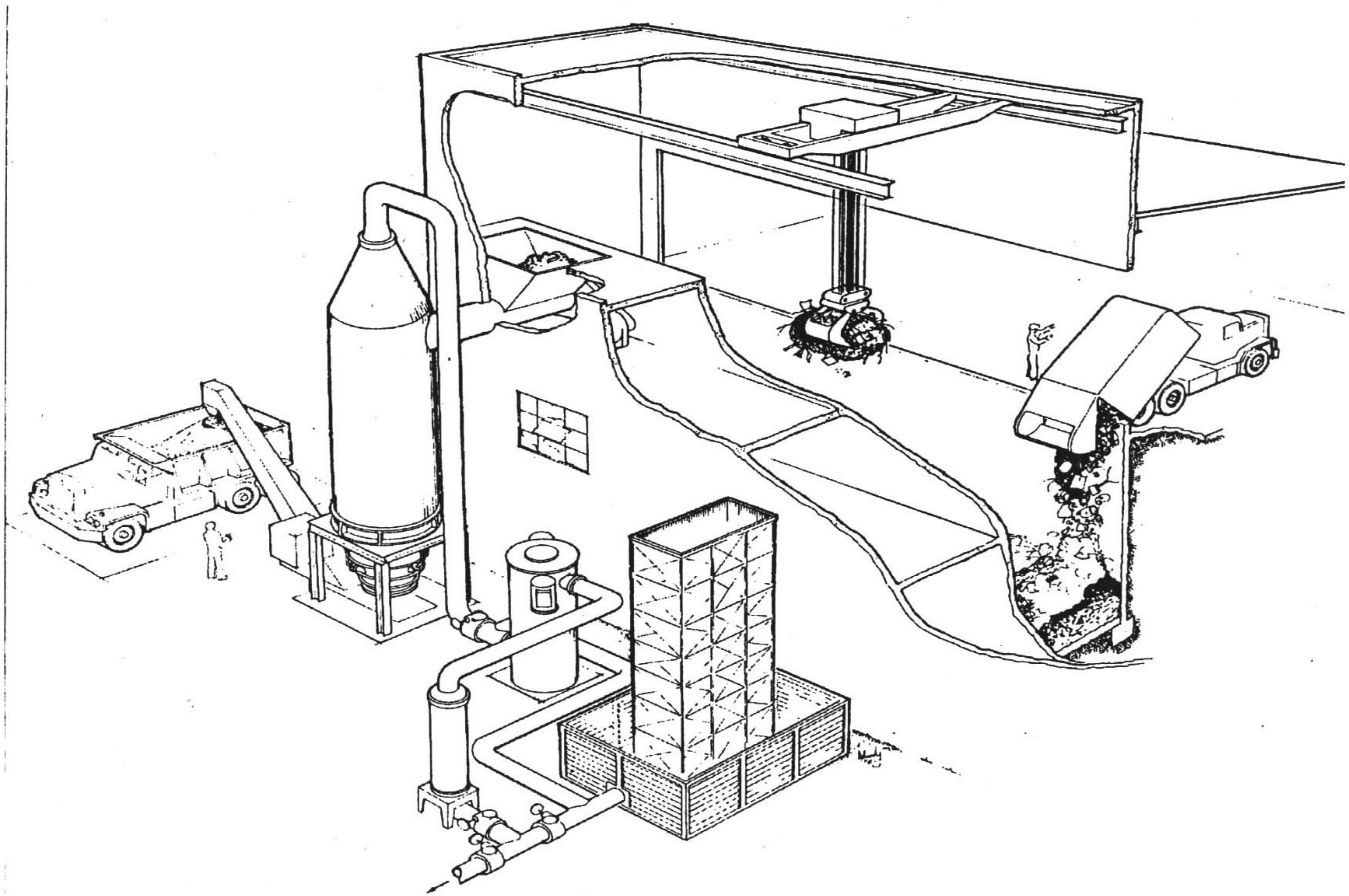
The total thermal efficiency is reported to be more than 60%.

Status
After the pilot unit at Union Carbide, two commecial (demonstration) units were erected; one in Charlestown, West Virginia (180 tons/d) and one in Japan (75 tons/d).

Since then, the mid-seventies, no further installations have been made.

Technical Situation and the Future
Using shredded material the Purox process has performed quite successfully. The high temperature secures a 100 % conversion which minimizes mechanical problems at least in the bottom of the reactor. The inert slag is a major advantage with the oxygen blown process. A drawback is the relatively high power consumption for oxygen production. Later developments try to reduce the oxygen consumption by preheating the waste indirectly (e.g. Thermoselect).

Although successfully demonstrated, no further commercial units were sold and Union Carbide turned the business down. The system seems to have perhaps been ahead of time and later on incinerations captured a substantial market share.



Purox

8.4 THE LANDGARD PROCESS (Monsanto)

General
The Landgard process is in effect not an energy producing technique. It is more or less based on assumed advantages with pyrolysis versus conventional incineration in the handling of solid waste where a decrease of volumes is one objective. As commented in the report smaller volumes for gas cleaning and better residues due to temperatures and reducing conditions are examples of potential advantages.

These factors were achieved in the Landgard where MSW (Municipal Solid Waste) was treated in rotary kiln heated by oil - much like a cement kiln.

The process was developed by Monsanto Enviro-Chem and already in the early seventies two pilot units of 30 tons/d were erected, one in the USA and one in Japan.

Process Description
Municipal Solid Waste (MSW) is shredded and fed to a rotary kiln where it meets hot gases from an oil burner. At a maximum temperature of 1000 ^{o}C a solid residue is collected in the lower part of the kiln while pyrolysis gases exit at the upper end (where the MSW is fed).

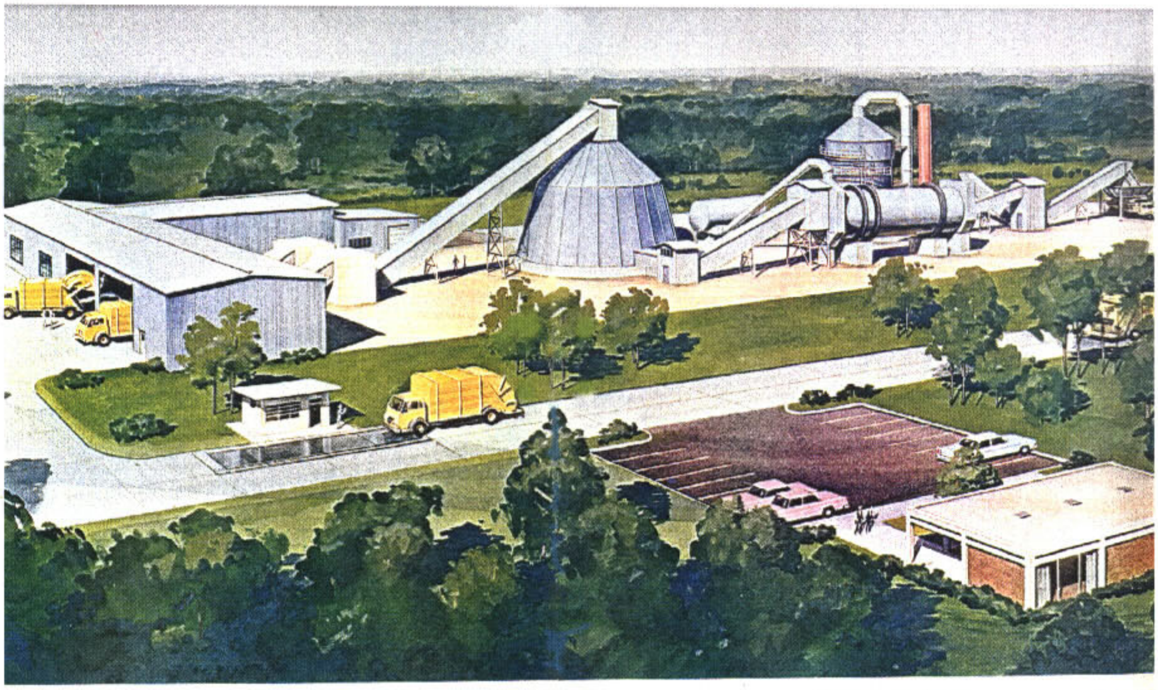
The gases are directly burned with steam production and the flue gases are scrubbed before let to the atmosphere. Although the steam represents a by-product little attention was drawn to this when the Landgard projects were focused in the 70's (before the so called "oil crisis")

In the beginning the total MSW was intended to be fed to the reactor. By experiences this had to be altered to a homogenized feed through shredding. See below.

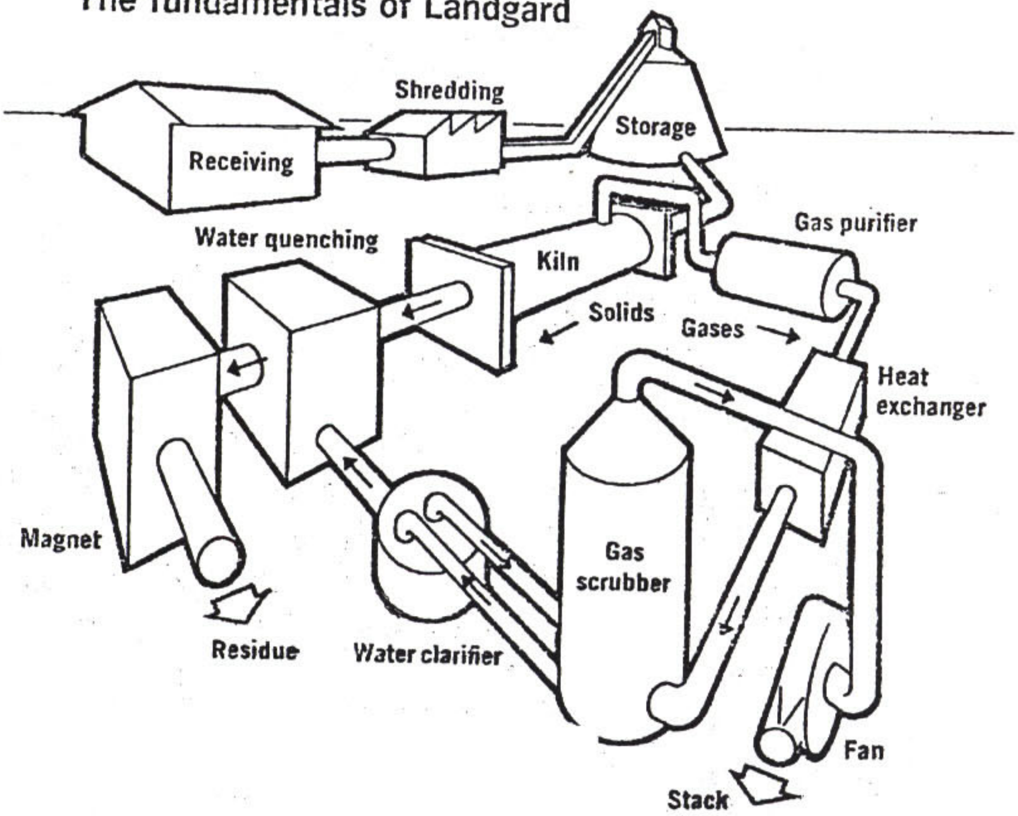
Status
After the two rather successful pilot plants installations of the Landgaard process, a giant scale-up to a 900 tpd in Baltimore was erected in the mid-seventies..

Technical Situation and the Future
The scale-up of the process was obviously too fast. A number of technical problems appeared in the units:

- the storage of MSW caused problems; packing and solidification
- material problems; for instance the ceramic lining was worn out
- the energy balance in the rotary kiln was not sufficiently investigated or known
- slag was formed in the reactor and the slagging temperatures were not known enough
- etc.



Landgard



Landgard

Attached is also a summary of all problems from Beukens and Schoeters (1984).

These factors in conjunction with the evolution of a number of competing combustion/incineration processes, led to the withdrawal of Monsanto from the Landgaard process and since then it has not reappeared.

The plant was then operated as a combustor, but then finally replaced by mass burn technology.

8.5 THE DESTRUGAS PROCESS

General
The Danish Destrugas process was developed partly on the basis of former coke technology. In a downdraft (concurrent) with indirect heating (retort) reactor shredded MSW (Municipal Solid Waste) is fed at the top.

The process was demonstrated in Kolding in Denmark as early as 1967 (pilot scale 0,5 tpd) and attracted attention during the early seventies. The only demonstration unit was erected in Kalundsborg, Denmark, 5 tpd (1970). Despite efforts in Germany as well as Japan it was not further commecialized.

After cleaning the excess gas was intented to be sold. Almost half of the produced gas was used as fuel in the process. With the attitudes today, neither the gas cleaning through washing nor the quality of the gas would be acceptable from environmental points of view.

Process Description
The shredded MSW flows downwards in the shaft while it is indirectly heated to about 1000 ^{o}C.The energy required to obtain 900-1050 ^{o}C in the shaft is supplied indirectly through the walls and is originally formed by combustion of some of the gas. With this configuration the reactor can be called a retort (see the attached figure).

With the downdraft technique the tar content in the gas is lower than with updraft reactors. The gas is further cleansed in a scrubber where the water - at that time - was considered no more polluted that it could be sent to the communal sewage treatment.

After the scrubber the gas was considered a fuel gas. Some char and tar follows the gas and is separated in the scrubber. Being a pyrolysis process a solid char containing residue was also produced and had to be landfilled.

About 50 % of the energy in the MSW is obtained as gas. If the entire energy demand is supplied by this gas, the overall thermal efficiency drops to some 20-30 %.

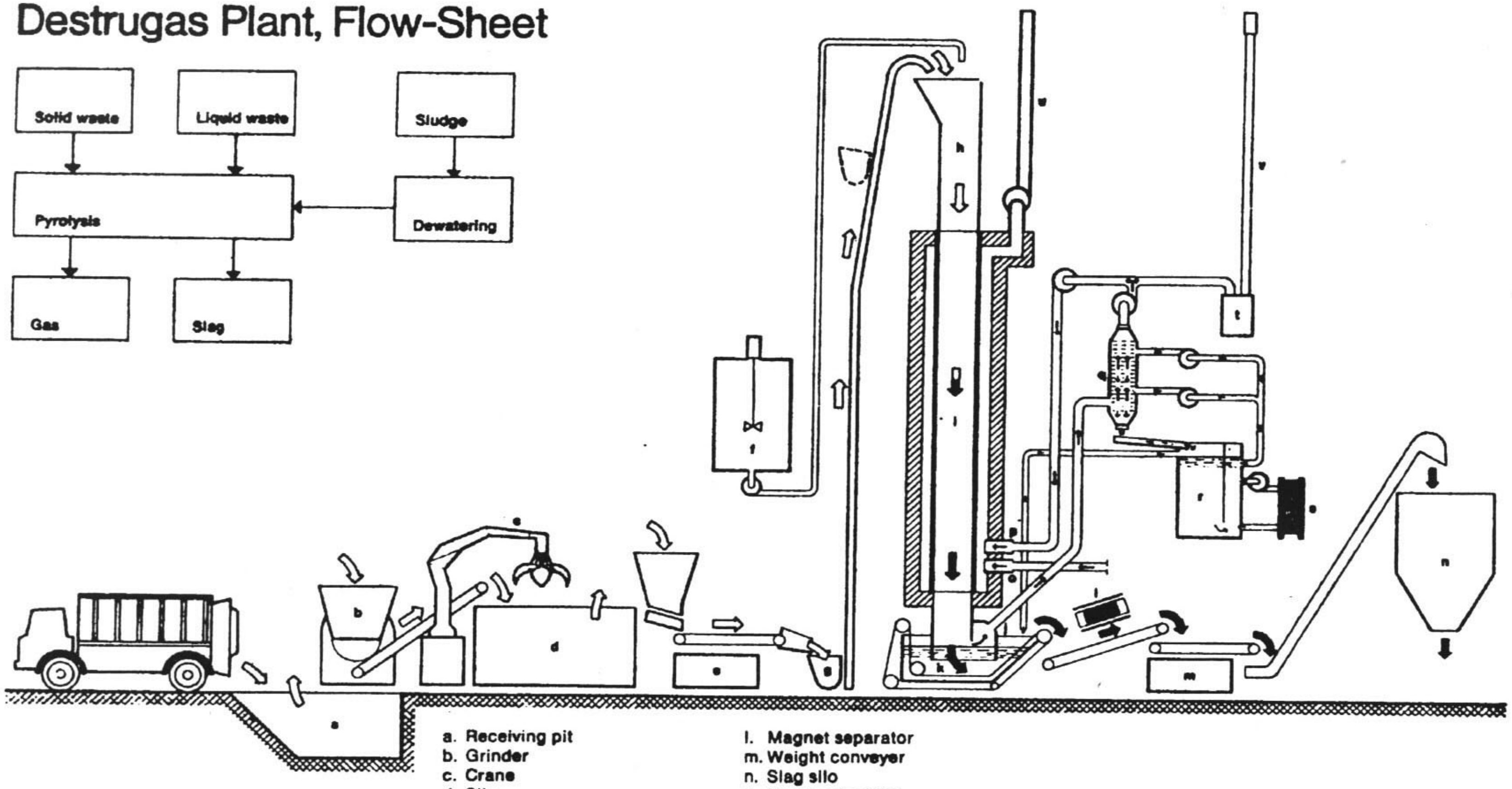
Status
In Kalundsborg in Denmark, two units were erected: one at 1 ton/d and one at 5 ton/d. A smaller test unit was built in Berlin in 1978 and a larger in Japan 1976 (5 tons/d).

Since then no further units have been built, and all those which had been erected were closed during the seventies.

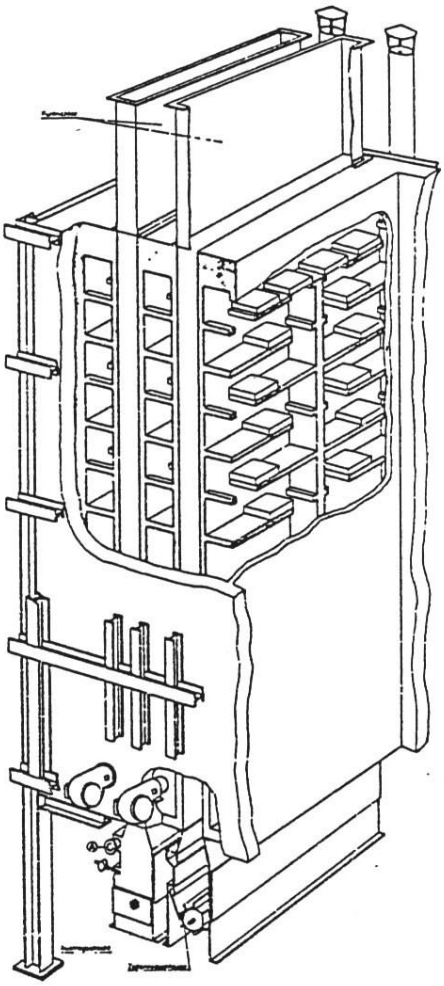
Present Situation and the Future
The downdraft reactors and retorts suffer from comparatively low capacities and low thermal effiencies. In addition the material transport in the Destrugas reactor turned out to be a problem requiring a uniform particle size and an even distribution of the material in the shaft. Thus, MSW could not be used as such but had to be pretreated to satisfy the pyrolysis reactor.

Apart from the marked problems in the seventies, the Destrugas would not be technically feasible today. The cleaning of gas and water would be necessary as well as a handling system for the char/slag. The products have no market value and as a destruction process, it is neither economic nor efficient.

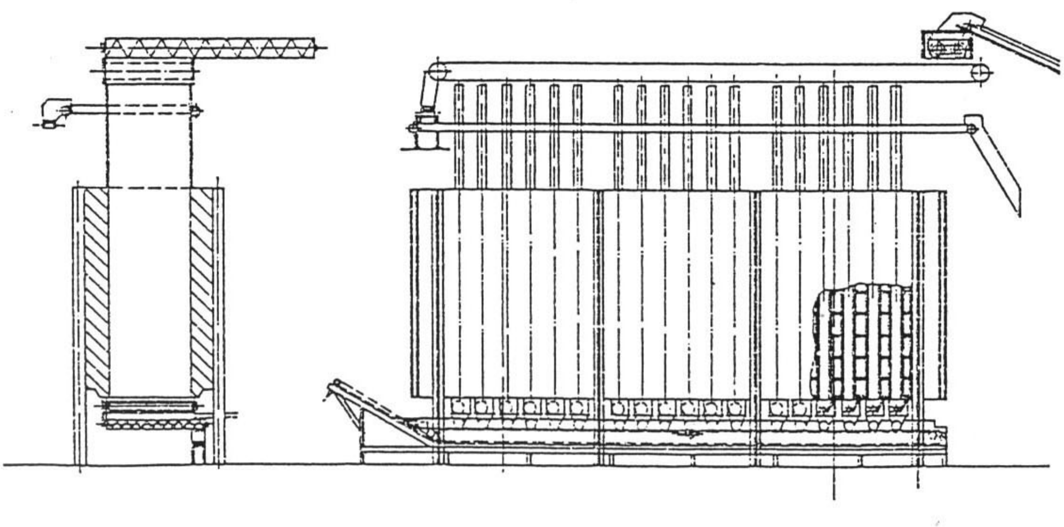
Destrugas Plant, Flow-Sheet



Destrugas



Destrugas reactor



Battery of pyrolysis furnaces (Destrugas)

8.6 THE OMNIFUEL PROCESS (ECO-FUEL, UNIVERSITY OF SHERBROOKE)

General
One of the first developments of a fluidized bed gasifier for RDF started at CIL Canadian Industry Limited (also called EcoResearch), Canada during the late-seventies. The CIL work with RDF preparation (see the attached figure) and RDF gasification, was pioneering work. The team who developed the process later formed a company of their own, OMNIFUEL, and built one of the first large-scale FB biomass gasifiers in Canada (in the early eighties). After reasonably good technical experiences, the gasifier was closed for commercial reasons.

By joining forces with other Canadian companies and the Canadian State, a large-scale pressurized demonstration gasifier was erected and operated (BIOSYN) during the mid-eighties. Some of the tests were devoted to fuel a dual fuel engine with low Btu gas.

Based on that experience, a pressurized biomass gasifier (O,7Mpa) and a dual fuel engine (6,8Mw_e) was installed in French Guyana. Due to mechanical (start-up) problems, the engine never operated on biomass gas, and the gasification plant was closed down.

The pressurized demonstration plant was dismantled because of lack of funding, and some equipment e.g. the gasifier, was taken over by THE UNIVERSITY OF SHERBROOKE. They have re-installed the plant and are operating it at atmospheric pressure for further developments aiming at waste gasification and gas cleaning.

Process Description
In the Sherbrooke project a sorted and shredded MSW has been tested which is similar to the common RDF (Refuse Derived Fuel).

The raw material is fed to the middle or the lower half of the reactor and the fluidized bed consists of inert material - in this case sand. Dolomite and similar "reactive" materials are suggested in the development. Gas and solids leave the reactor top where a cyclone separates the solids to be recycled to the reactor. The gas is further cleaned in another cyclone.

The arrangements of this process are common to most of the fast fluidized bed gasification processes. The main differences are usually in the gas cleaning and in detailed technical solutions at various points.

The CIL/Omnifuel/Biogas development worked very early with tar cracking and hot gas filtration, but that type of work was never scaled up to demo-scale.

The thermal efficiency is about 75 % calculated on cold gas. On hot gas the efficiency approaches 90%.

Status

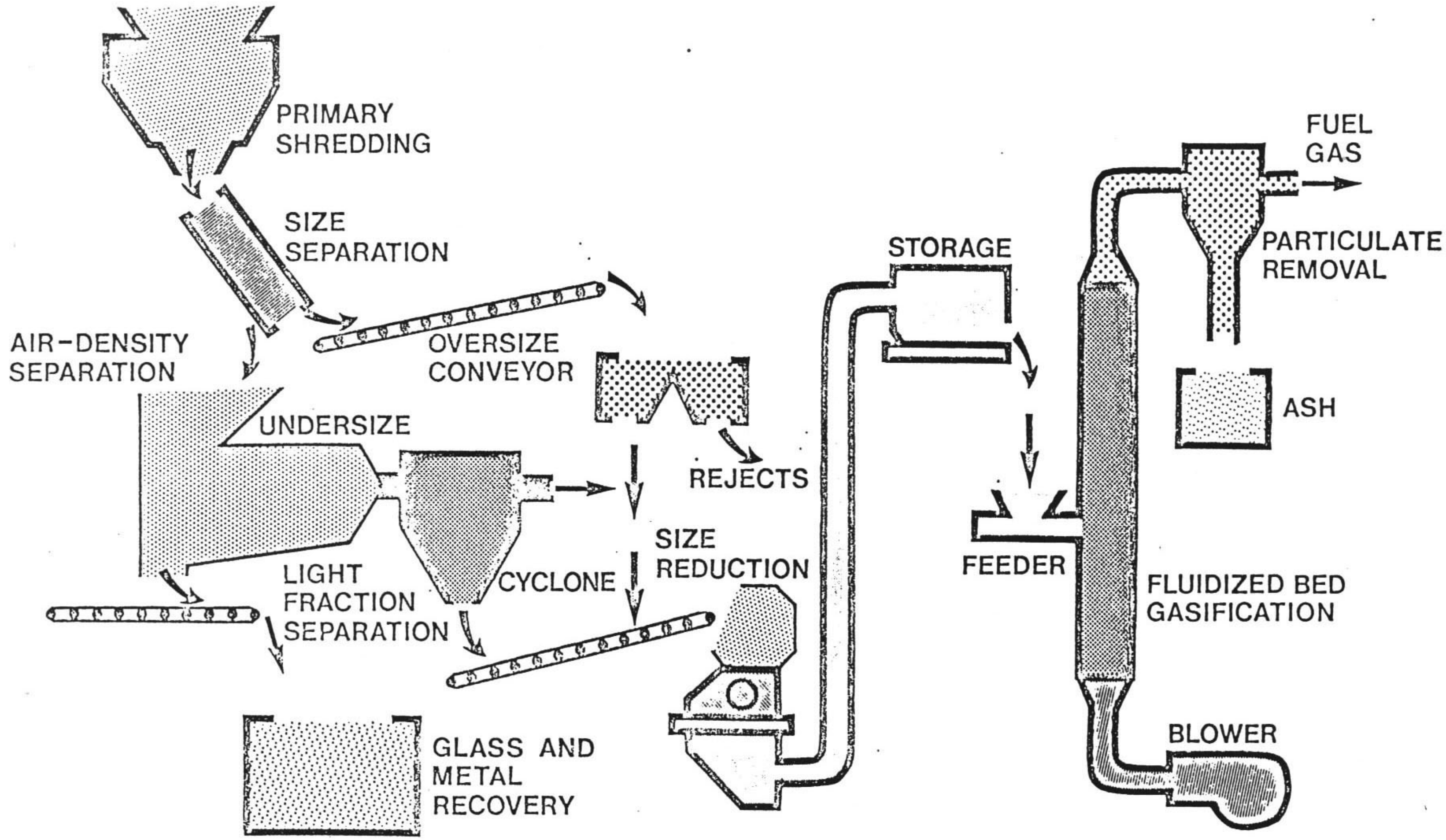
To larger (5-10 tons/h) units have been built using wood feed; one for fuel gas and one for the mentioned dual fuel engine (see above). No demo-plant for RDF.

Development for RDF feed which was the original development in 1978 is restarted and on-going at pilot level.

Present Situation and Future

The OMNIFUEL/BIOSYN process (biomass) has initially been rather successful commercially since two larger units have been established. This development and Canada as a country, had a leading role in the world in biomass gasification in 1980-85. From the technical point of view the units have experienced some difficulties but the main obstacle for further commecialization and scale probably lies in the domestic Canadian market. Wood fuel in this form is still more costly than oil gas fuel.

The renewed solid waste gasification activity has not yet led to any large scale commercial project.



THE CIL PROGRAM

8.7 THE EBARA PROCESS

General
Very early in the seventies, Bailie at West Virginia University developed the concept of two fluidized sand beds, one for combustion and one for steam gasification, with circulating sand as the heat carrier between the two beds. This principle is later further developed in Japan, and by Batelle Columbus, USA.

Process Description
The energy supply is carried out in the combustion reactor where residual char is burned. The heat is transferred to the pyrolysis reactor by means of the fluidized bed material (sand), which flows between the reactors. The energy balance requires some extra fuel to match deficiencies.

In the pyrolysis reactor RDF (Refuse Derived Fuel) is pyrolysed by means of the hot bed material at 650-750 ^{o}C. As in all these fluidized systems a certain homogeneity of the feed is vital.

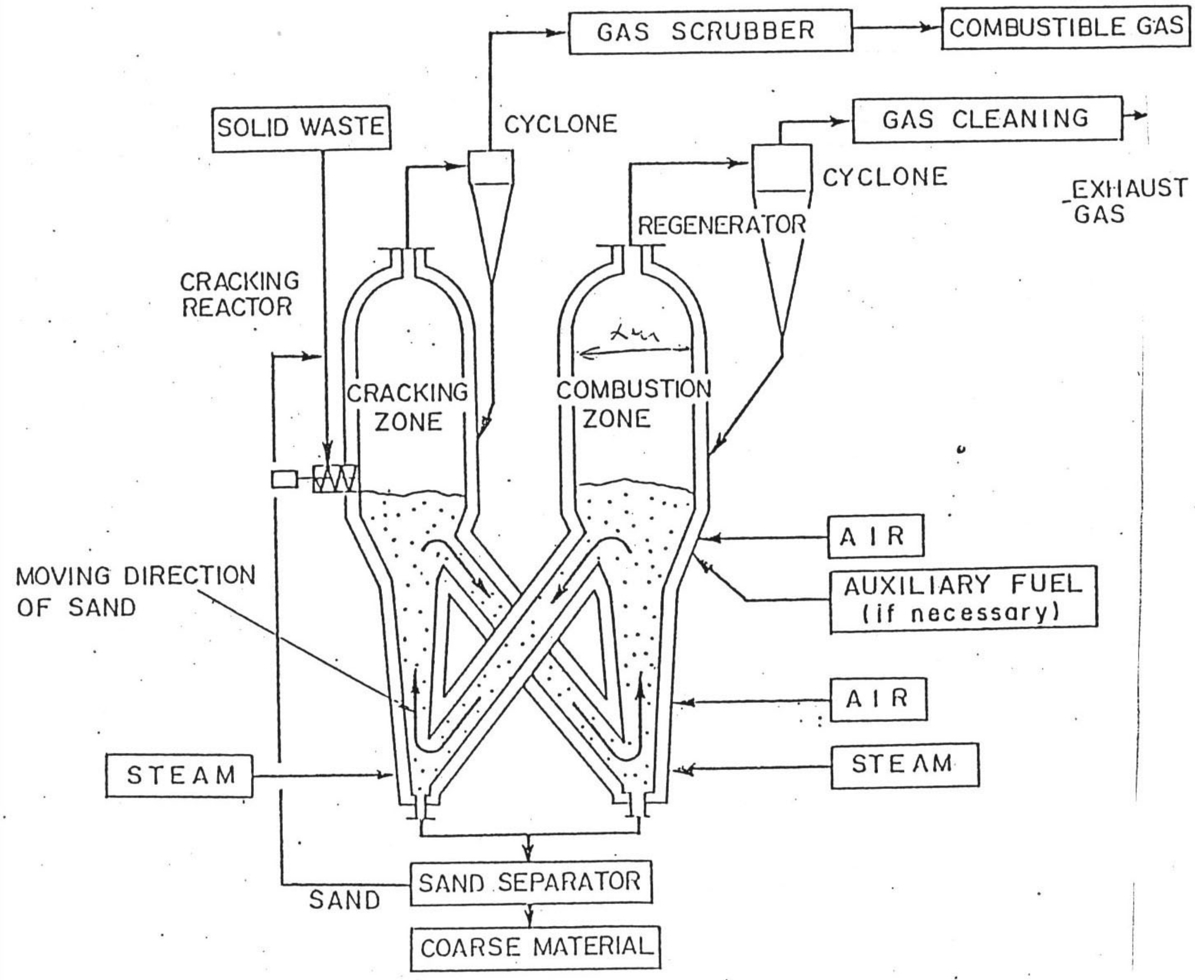
The outgoing raw gas from the pyrolysis unit contains tar and char and has to be cleaned. This is effected in a scrubber system where the upper tar layer is collected as fuel for the combustor. Char is also collected as fuel. The remaining water is sent to water treatment. The resulting gas has a high heating value and the overall thermal efficiency is reported 50 - 60 %. From both reactors an ash fraction is continuously withdrawn to be landfilled.

Status

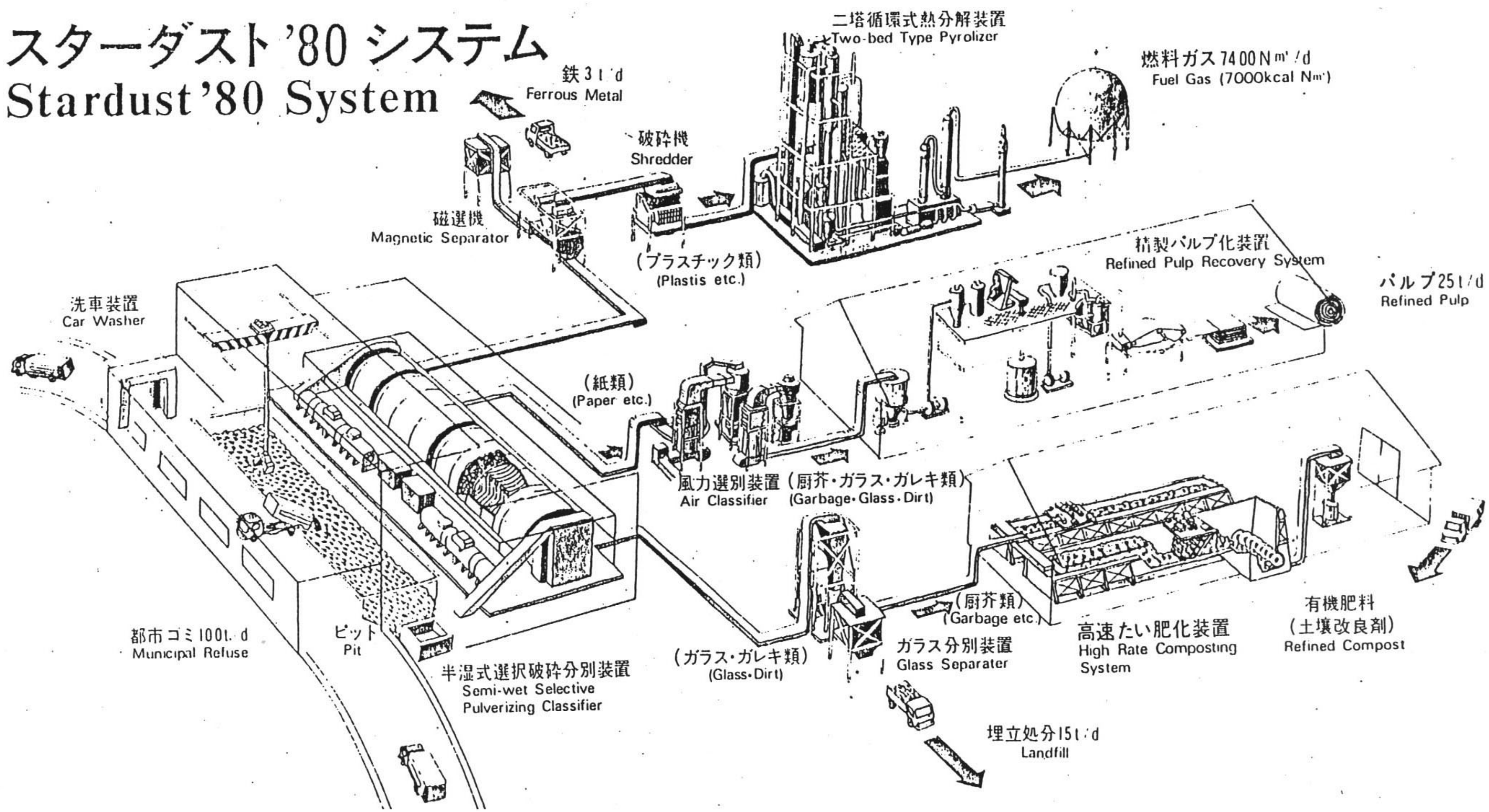
That technology was later scaled-up in Japan within a national programme ”Star Dust 80” 1979-1982 (EBARA 5 tpd to 100 tpd). In 1983 the Tsukisima Kikai company constructed a full-scale demonstration (PYROX) 450 tpd, 3 x 150 tpd of a similar process, but based on other Japanese technologies (cracking of crude oil). It was in operation until 1990, when it was closed for economic reasons. No active further development is known to the authors.

Technical Situation and Future
The information from the Ebara process indicates problems and development work in agreement with other developments of fluidized beds for pyrolysis and gasifications. It may possibly be noted that the bubbling beds seem to put even stronger restrictions on the feed than the fast fluidization beds do.

From earlier reports it seems that the developers of the Ebara process have overcome these problems and that a lack of further commercializations possibly is more connected to the lack of market in the eighties.



TWO FLUIDIZED BED REACTORS



Stardust '80 System

8.8 THE FLASH PYROLYSIS PROCESS (GARRETT - OCCIDENTAL)

General
The flash pyrolysis process was developed for coal, and also as part of a more general separation system for Municipal Solid Waste (MSW). (See the attached figure.) After separation of metals and other components in the wastes the combustible or carbon containing fraction was delivered to a pyrolysis unit where a liquid product was produced through flash pyrolysis. The reasoning for this was that a liquid product or fuel was easier to sell as an energy carrier than as gaseous or solid products.

Based on the basic idea that wastes ultimately had to be recycled and used in the society a full scale separation unit was established in San Diego in the mid-seventies. For the organic part of the wastes a flash pyrolysis system, developed by Garrett and later Occidental, was chosen. The process had been demonstrated in a smaller scale development unit before.

The object of the process was to produce as much tar - or liquid product - as possible from the organic fraction and the flash pyrolysis had demonstrated a superior capacity in this respect. The same reaction thermo-chemistry has been studied later and developed for the pyrolytic oil from wood production (ENSYN, SCOTT).

Process Description
After separation of metals, glas and minerals, the organic fraction of the wastes is milled and shredded into a fine material (RDF) - as homogeneous as possible (see the attached figure).

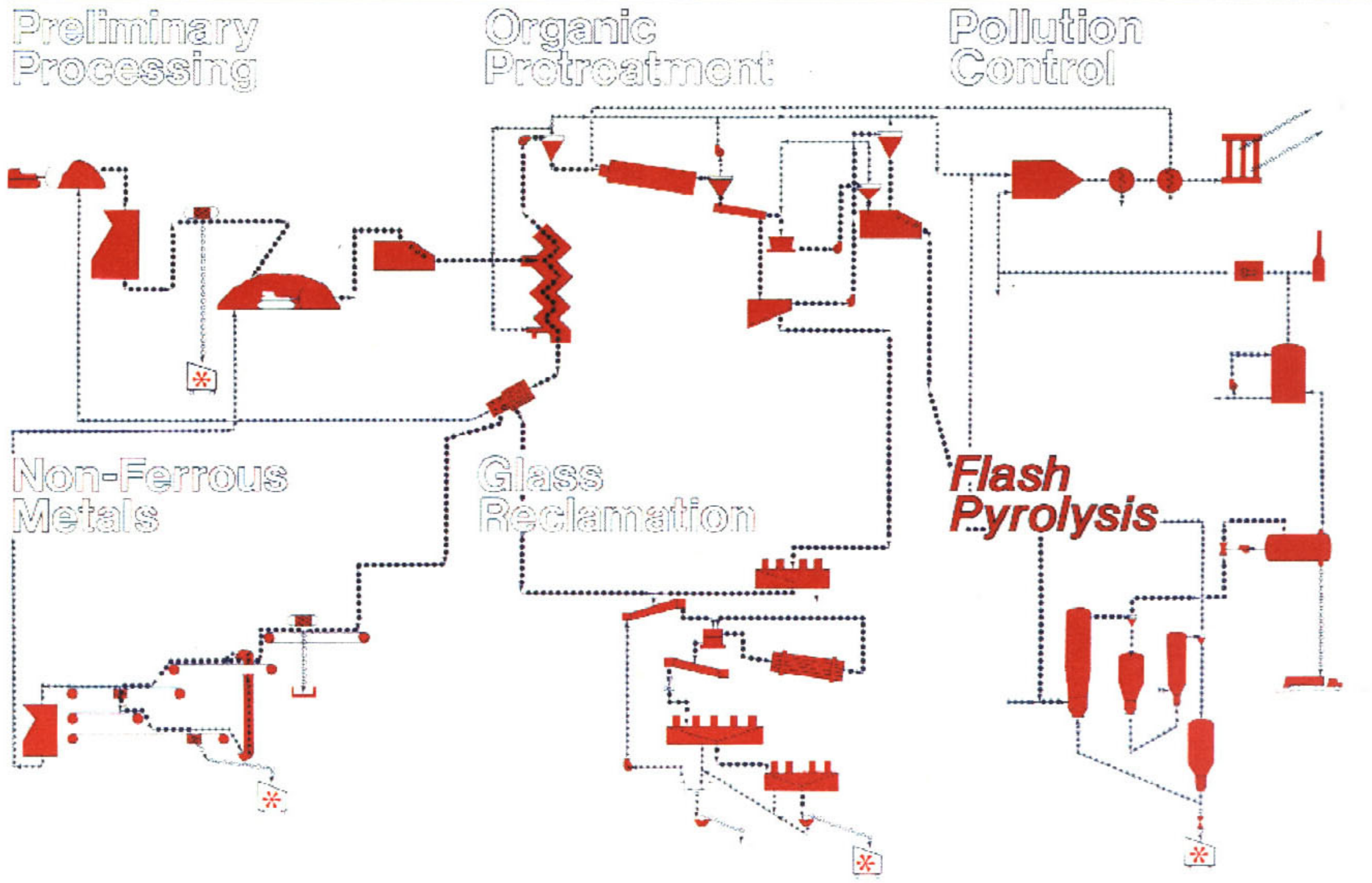
This raw material is fed to a reactor similar to a transport in a reactor. At a temperature of 450-500 ^oC and a short residence time (seconds) (and a slight over-pressure) some 40 % of pyrolytic oil (tar) is formed. The tar is in the vapor phase and the gases are separated from the char in a cyclone.

Upon cooling tar condensates and it is separated from the lighter gases.

The lighter gases are used as fuel together with the solid char to provide the necessary heating for the process. The ash/char fraction was also used as a heat carrier. The actual pyrolysis is slightly exothermic and the thermal efficiency of it is about 50 % (calculated on the oil). The energy losses were not attempted to be used in reality.

Status
The San Diego plant was closed after a few years due to technical problems and lack of customers for the fractions from wastes, not only the pyrolytic oil.

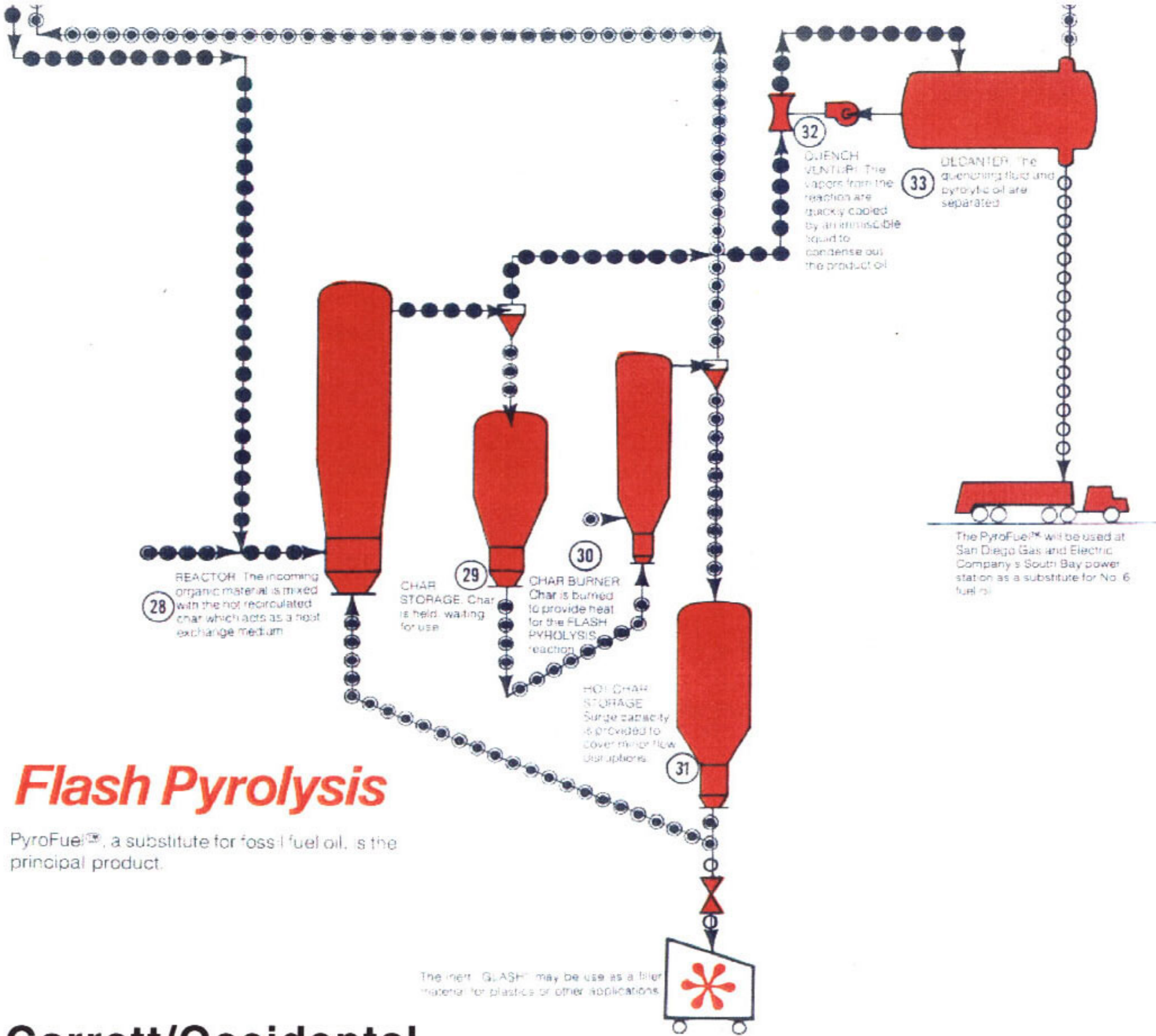
Similar attempts with fractionation and marketing of the fractions have been studied and tried elsewhere during the eighties, but none of them seem to have succeeded. Today, San Diego appears to have been a little ahead of time. The general impression is that the project tried to



Garrett/Occidental

Flash Pyrolysis

PyroFuel™, a substitute for fossil fuel oil, is the principal product.



Garrett/Occidental

put together a lot of new technology in RDF preparation, recycling and flash pyrolysis in one early plant. Twenty years later some of those technologies have still to be further developed.

Present Situation and Future

As commented, the flash pyrolysis technique has been studied further - mainly for biomass - since the seventies, with different designs.

Flash pyrolysis of wood has been studied extensively and in evaluations it has been shown one of the most economic ways of converting wood into a gaseous or liquid products. A similar application is being used commercially for pyrolysis of spent rubber tyres.

With strict emission limits, a relatively clean fuel or extensive secondary oil treatment is needed, to reach an oil product that can be used without extensive flue gas treatment.

8.9 THE ERCO/POWER RECOVERY SYSTEM PROCESS

General
This technology is an example of technology that has been marketed under different names over a long period of time. Originally developed as a directly heated pyrolysis in fluid bed (ERCO) for charcoal and tar liquid production in the seventies, Power Recovery Systems was an engineering company with a somewhat broader field of activities but with emphasis on fluidized beds and gasification, and they marketed and developed the technology in the eighties. This process is a complete process from MSW (Municipal Solid Waste) to power generation; e.g. considering all the subprocesses forming the entire system.

Beside the gasifications process, the Power Recovery Systems proposed technologies for the preparation of RDF (Refuse Derived Fuel), for gas cleanup, for combustion of the gas, etc.

The pyrolysis or gasifications reactor in the ERCO processes is a fluidized bed with sand as bed material. It has been installed in at least two commercial applications, one for charcoal production and one for energy (steam) production.

Process description
The ERCO processes in principle look very much alike other gasification/pyrolysis systems. The MSW is upgraded into RDF and fed to the fluidized bed where it is primarily gasified by air at temperatures of 760-820^{o}C. In waste gasifications a "reactive" bed material is used instead of the former sand. The "reactive" material is claimed to include an adsorbent for SO_2.

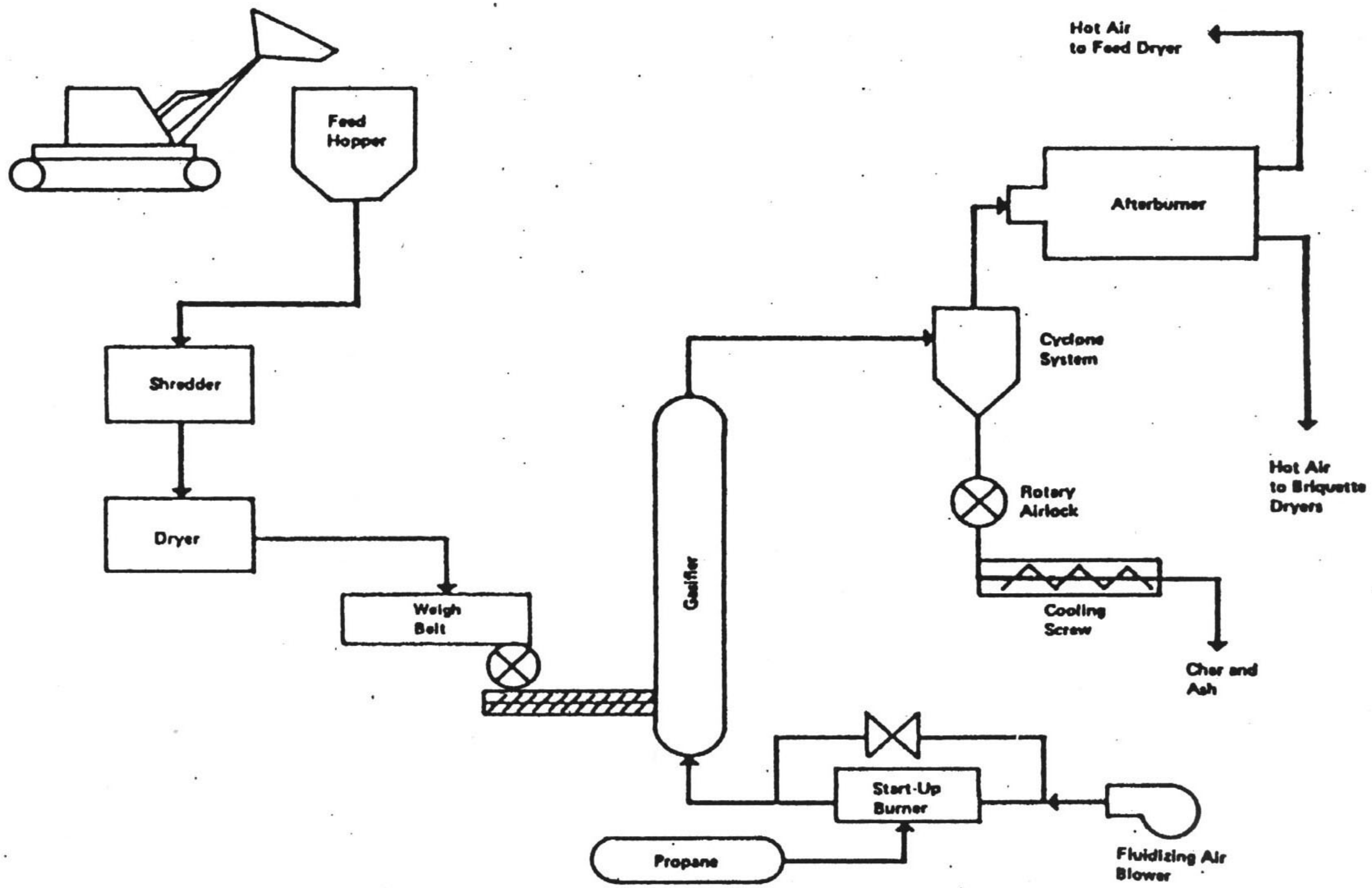
The solids are separated from the gas in one or two cyclones. Whether they are recycled to the reactor or not is not clear. In some process configurations an ash bin is shown but it seems likely that in practice at least some of the solids would be recycled. The gas is further cleansed in a multistage system including scrubbing and mist elimination. High-boiling - or solid - tars are returned to the gasification and the rest is treated in the water.

When the gas is to be used in an engine for power production a fabric filter is also used in the gas cleansing. The thermal efficiency is reported up to 75% calculated on the raw gas.

Status
The early attempts to market the pyrolysis process for RDF was not successful. The Power Recovery System pyrolysis and gasification process has been commercialized in a couple of occasions for biomass fuel (charcoal and steamboiler). Southern Electric International (SCEI) erected two fluid bed gasifiers for clay drying. By-product charcoal was sold to a charcoal briquette factory.

The development work evidently continued at least up til the late eighties. To achieve high carbon conversion char recycling to the bed is necessary in FB as well as CFB reactors.

As far as known, no new plants have been erected despite offers in waste treatment as well as biomass conversion.


Feed
Hopper
Shredder
Dryer
Weigh
Belt
Gasifier
Propane
Start-Up
Burner
Fluidizing Air
Blower
Cyclone
System
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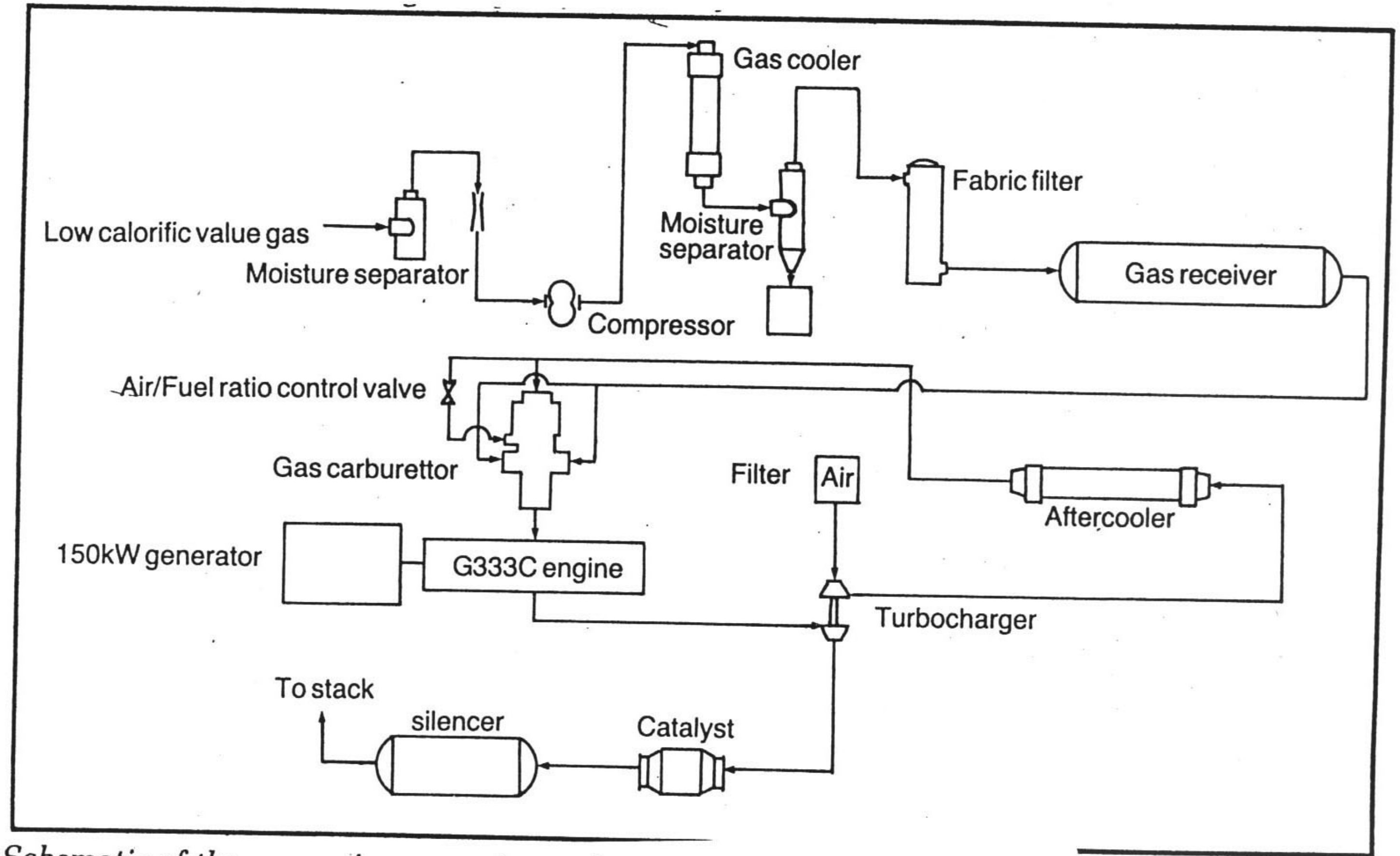
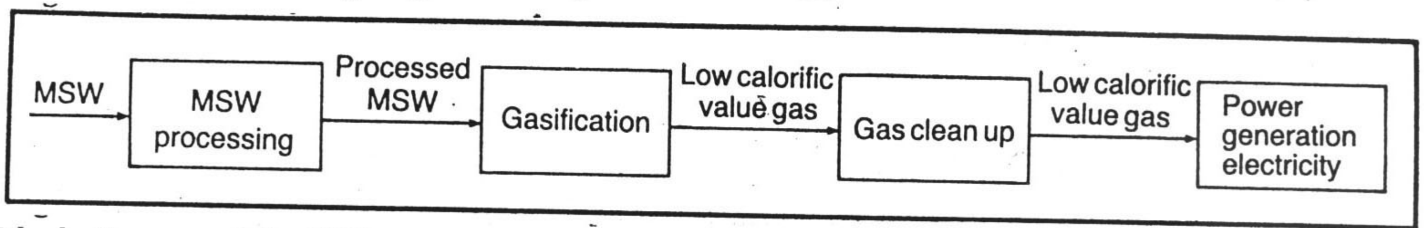
Airlock
Cooling
Screw
Char and
Ash
Afterburner
Hot Air
to Feed Dryer
Hot Air
to Briquette
Dryers

Erco



Schematic of the gas engine generator system



Block diagram of the PRS process

Technical situation and future

The informations from ERCO and Power Recovery Systems is quite scarce. Problems evidently have appeared but seem to have been successfully attended to. Comments have been made about the restrictions on the feed; moisture content, size distributions, etc.

In the mid-eighties pilot tests with RDF were performed for engine applications.

The companies are no longer in existence. The technology-rights, at least for biomass applications, are owned by the Bioenergy Development Corporation, New York.

8.10 ELAJO/TORNEGAARD/KOMAKO, Sweden

General
The Elajo gasifier is an airblown down-draft fixed bed gasifier. Based on experience with woodchips gasification, a test unit for waste was designed. The intention was to combust the gas and then apply wet/dry flue gas cleaning with a fabric filter. The raw material was initially RDF Fluff, and after testing only RDF pellets a small scale modular unit (2-5 MWth) was planned as standard. Power production with gas engine, steam engine or turbine was seen as a future development for small scale technology.

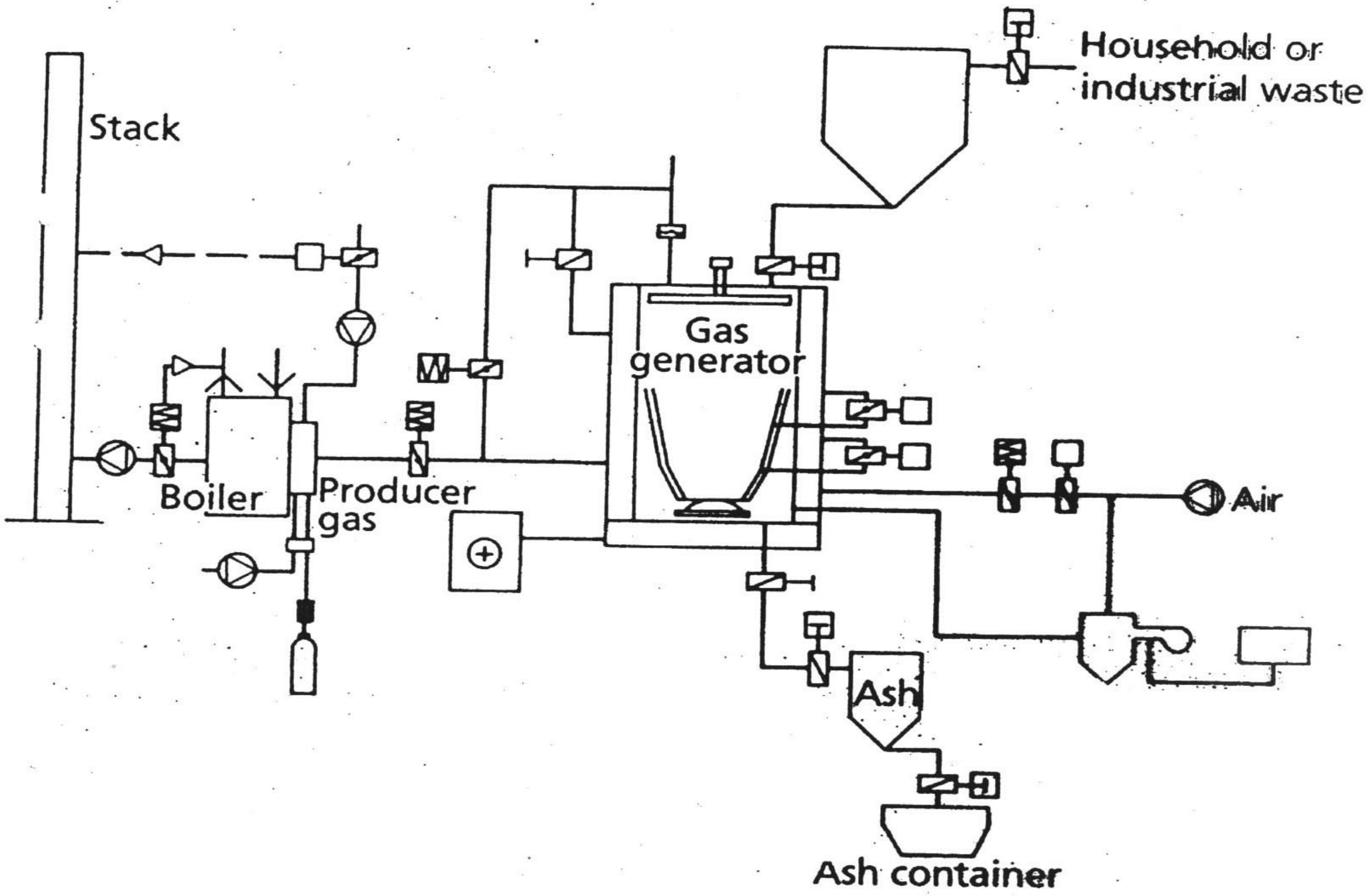
Process Description
The attached figure describes the gasifier. During earlier tests with the down-draft gasifier different air injection and grate types were tested by the same inventor (Tornegaard). In the presented design, a rotating movable grate should allow control of pressure drop and ash discharge.

The Figure describes the whole system (excluding RDF pretreatment). Gas cooling/heat exchanger down to 500^{o}C took place in the gasifier. The gasifier was directly coupled to a boiler without any cooling/cleaning. A bottom ash that could be partly treated and recycled was anticipated, heavy metals should be retained in the ash, and dioxin formation should be low. The turn down ratio was promised to be one to ten.

Demonstration
For woodchips a 2MWth gasifier was erected, close coupled to a boiler heating a hospital in Filipstad (1986). The fuel was green chips from whole tree harvesting. Several start-up problems with supplementary systems such as feeding, ash discharge, control system, delayed the operation of the unit, but all these problems were finally solved. The interesting problem of high bed pressure drop due to fuel characteristics (particle size and distribution) was however, never solved. The maximum capacity achieved was 0,8MW and with considerable amounts of tar. The unit is now shut down but still *in situ*. Despite these experiences, a second demonstration unit for RDF was erected in Kalmar. The operation was time limited, and after experiences similar to those in Filipstad, together with local problems such as odour, the unit was dismantled.

Technology Background and Future
The technology is a typical example of an inventor who in cooperation with different companies tries to commercialize a new technology. Based on Swedish Second World War experience, the inventor first operated a small pilot plant and then several demonstration units.

On the waste side, the same inventor together with VBB, tested a rotory drum pyrolyser in the early eighties in Söderham. Overheating and deformation of the drum ended the testing. The down-draft demonstrations was managed by an electrical engineering company (ELAJO). The activities were stopped due to the poor results, and the Filipstad unit is for sale.



Elajo/Komako

8.11 THE VOEST ALPINE PROCESS

General
The Voest Alpine process involves a fixed bed, updraft reactor where the gasification is carried out at high temperature - more than 1500 ^{o}C (≈1600). This high temperature is obtained with air as gasification medium by means of a fuel mixture to some extent including materials with high heat contents. With the high temperature a molten slag is quenched and collected in the bottom of the reactor.

The specific feature giving Voest Alpine a special character is a coke bed through which the gas is cleaned from certains components. This coke bed is built into the gasification reactor.

It is claimed that the raw gas from the gasifier can be used in a conventional combustion unit or an internal combustion engine (see the attached figure).

Process description
In the pilot plant reactor a mixture of about a third of waste oil (including a part of fuel oil), a little more than half of RDF and some ten percent of coke is used as fuel. These different parts are introduced at various positions: the oils at the bottom of the shaft, the RDF in the middle and the coke at the top in a special shaft through which the top gas passes.

The hot coke bed acts as a catalytic bed where tar and other tar components are broken down. (This idea for gas cleaning is also used in a German process where, however, the coke bed is placed in a separate reactor). Some of the coke is gasified during the processing and this is why it is considered a fuel.

The raw gas leaving the coke bed is claimed to contain very small amounts of dioxins and furans. The metal contents are not reported. After combustion they are less than 1 mg/m^3 flue gas; for Cd, Hg, Ti, As, Co, Ni and Se less than 0.01 mg/m^3. Although the gas is clean enough to be used in an internal combustion engine, a flue gas cleaning is still suggested for the process.

For the molten slag approximately 1 m^3 of water is used for quenching per ton of fuel. The amounts of slag are less than 100 kg per three tons of fuel (28 kg per ton).

The energy efficiency of the process is reported 83 % and RDF as well as shredded car waste has been run.

Status
The pilot or demonstration unit of Voest Alpines high temperature gasification had a capacity of 400 kg of feedstock per hour. The maximum capacity is claimed 3 tons/h.

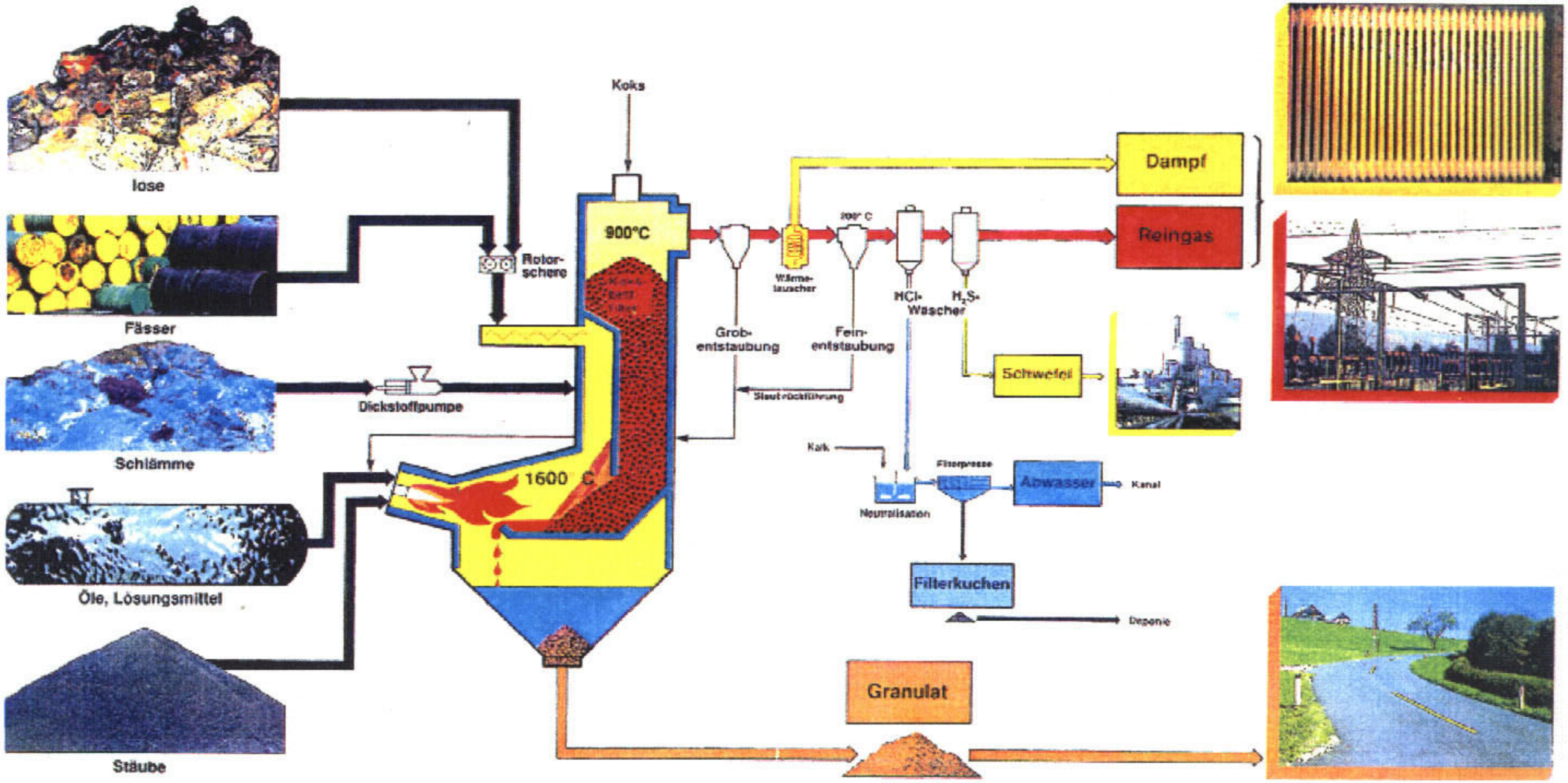
Hardly any economic data seem to have been published but an investment on 24 M$ is indicated for the 3 tons/h unit (1991). This corresponds to almost 1.000 $/ton of feed which may be double the specific investment for an Andco-Torrax unit (some 250 $/ton in 1980).

The difference seems large but the Voest Alpine gasifier is probably a more complicated construction than the Andco-Torrax gasifier; two fixed beds, three inlet positions, etc.

In addition to the comparitively high investment, the Voest Alpine technique also carries quite large operational costs in the form of high value fuels in combination with the RDF. The costs for waste oil, fuel oil and coke is roughly 40-80 $/ton of RDF in the feedstock mixture that was used in the 400 kg/h unit.

Present situation and future

If this economic assessment is correct, it may be the reason why Voest Alpine has abandoned the technique. According to the Bridgwater/Evans report the company is concentrating on metallurgical processes.



Voest Alpine

8.12 SCANARC (PLASMA) PROCESS

General
The Plasma Gasification technique evolved from metallurgical process developments by SKF Steel in Sweden. In attempts to produce reducing gas for iron manufacture a plasma was introduced in the bottom of the shaft producing (H_2 and) CO from air and coal. The effectiveness of the plasma in this application was discovered, leading to a number of processes proposed.

Two of these processes were installed full-scale: the PlasmaZinc and the PlasmaChrome for handling Zinc dust and Chrome materials. Several processes for coal gasification using the Plasma Gasification technique were designed during the early eighties. None of them were however realized.

Following the falling prices on energy, the interest during the eighties focused on the Plasma Gasification as a tool in waste handling, in particular special types of waste such as hazardous wastes, medical wastes, etc.

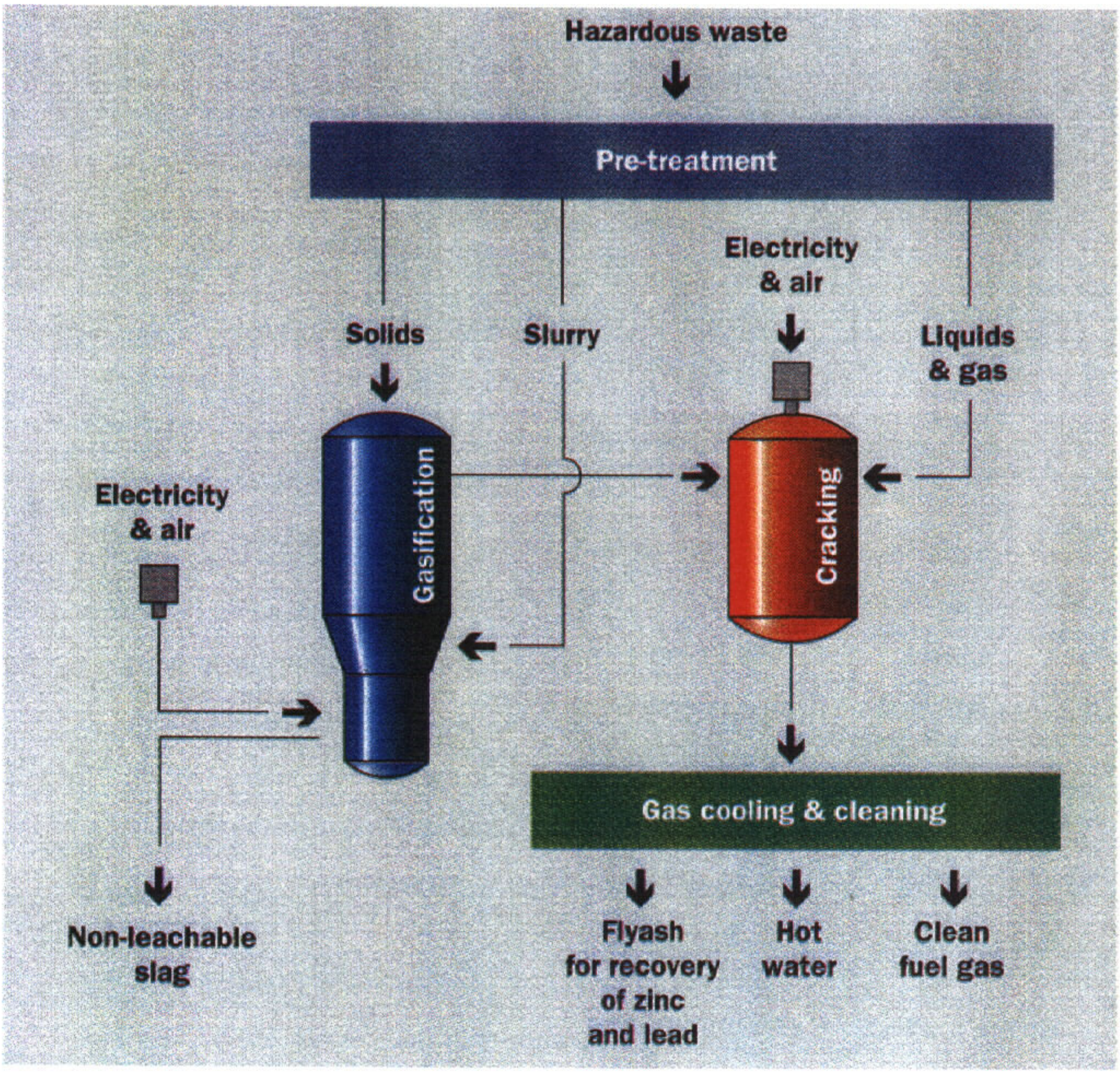
The Scanarc (former ”SKF Plasma”) process is a fixed bed, high temperature process with a molten slag in similarity to the Andco-Torrax and Voest Alpine processes. In line, the gasification is also carried out in an updraft shaft. Differences between the processes are at hand in the means to acheive the high temperature and in the cleaning of the raw gas.

In the ScanArc process the gas cleaning is obtained in a plasma where the gas is heated to very high temperatures causing a decomposition of tar, chlorinated hydrocarbons and ammonia.

Process Description
The ScanArc process uses a shaft reactor outlined as simple as possible and fed with a mixture of air and oxygen in the bottom, or - rather - in the middle. Oxygen is needed when the effective heat content of the wastes is too low to result in a temperature of 1200 ^oC or more. For fuels to the reactor with heat contents above 10-15 MJ/kg this constitutes no problem. These heat contents are, however, not always met with MSW unless other wastes are added.

The raw gas is fed to a second reactor which in fact is more or less an empty shaft with a plasma generator on top. The electric plasma generates a theoretical temperature of more than 15.000 ^oC through which the gas is passed (lowering the temperature) into the shaft. The fuel to the plasma is composed of power and air for combustion (oxidation). After the second reactor, chlorine is present as Cl_2 or HCl, nitrogen as N_2, etc; e.g. all organic compounds and several others are decomposed.

The gas after the plasma reactor is cooled and washed. The fly ash is collected and may be sent for recovery of some metals since they are separated in a reduced state. Beside the wash water, a ”clean” gas and hot water is obtained. Available data do not provide information to what extent a flue gas treatment is required after combustion.



SKF Plasma/Scanarc

The molten slag is tapped from the bottom of the first reactor and as the slags from Andco-Torrax and Voest Alpine it is claimed non-leachable and easily disposable.

Only few data are revealed from the process. The power consumption for the plasma is reported 200-400 kWh/ton of feed - depending on heat value of the feed. These figures imply an energy efficiency of roughly 65-80 % calculated on the gas and the hot water.

Status

The ScanArc gasification is tested on MSW in a pilot unit. The gasification is designed for capacities of 50-100.000 tons per year and in this interval the investments are indicated 700-1.000 $/ton of feed; e.g. less than the Voest Alpine but more than Andco-Torrax.

The cost for electricity in Sweden would be 10-20 $/ton of feed.

Up till now offers have been made for MSW but no unit has been installed. At present the Scan-Arc gasification focuses on hazardous wastes where the higher requirements on the process can afford the technique more easily.

Present Situation and Future

A close co-operation is established with Kvaerner to promote the process for hazardous waste.

As spin-off from these processes the Plasma has also been suggested for vitrification of fly ash from different processes; i.e. gasification processes. Another development has led to a black liquor gasification process ”Chemrec” today also a part of Kvaerner Pulping.

8.13 THE BATELLE (OHIO) PROCESS

General
The Batelle gasification process basically involves a fast fluidized reactor but instead of generating the process energy internally in the reactor, it is generated separately through combustion of the char from the gasification.

The intention of this is to enable a Medium Heating Value (MHV) gas without the use of oxygen. (In other MHV processes oxygen is used as air dilutes the MHV to LHV (Low Heating Value) if other indirect methods are not used. A consequence of this process concept is that there must exist a balance between the energy requirements of the gasification and the energy supply in terms of char. For biomass such a balance exists and it is here assumed that at least some RDF's (Refuse Derived Fuel) may offer the same possibility.

As far as known, the Batelle gasification has been tested in the PDU unit for waste. Thus it is regarded as potentially feasible for some wastes, and the gasification is also described in this context.

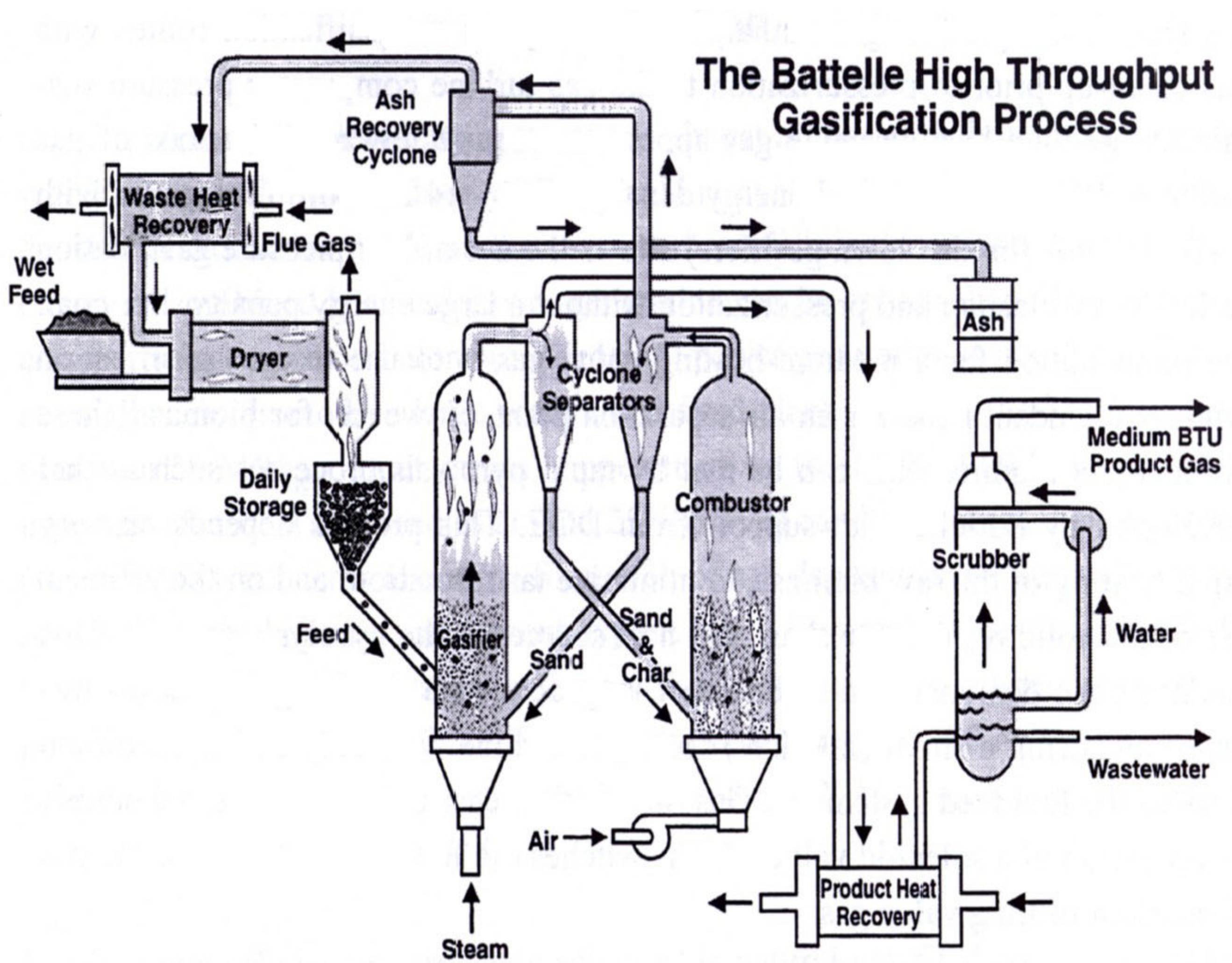
Process Description (Gasification)
The gasification is carried out in a fast fluidized bed with sand as bed material - with biomass feed or RDF.

The bed material is also the heat medium and it is heated in a separate reactor through combustion of the char. Thus, the inert bed material as well as the char is withdrawn from the top of the gasification reactor and led to a bubbling fluidized bed combustion unit where air is introduced. The combustion of the char raises the temperature of the solid bed material and it is recycled to the gasification reactor.

To maintain a continous run of these operations the char (fuel) production in the gasification must balance the gasification requirements on energy (including losses of energy in transports, radiation, etc). With biomass as feed this has been proved providing the size of the equipment is within certain limits and the gasifications are run at certain temperatures. (In addition, the moisture content of the biomass has to be controlled as well as other energy influencing parameters).

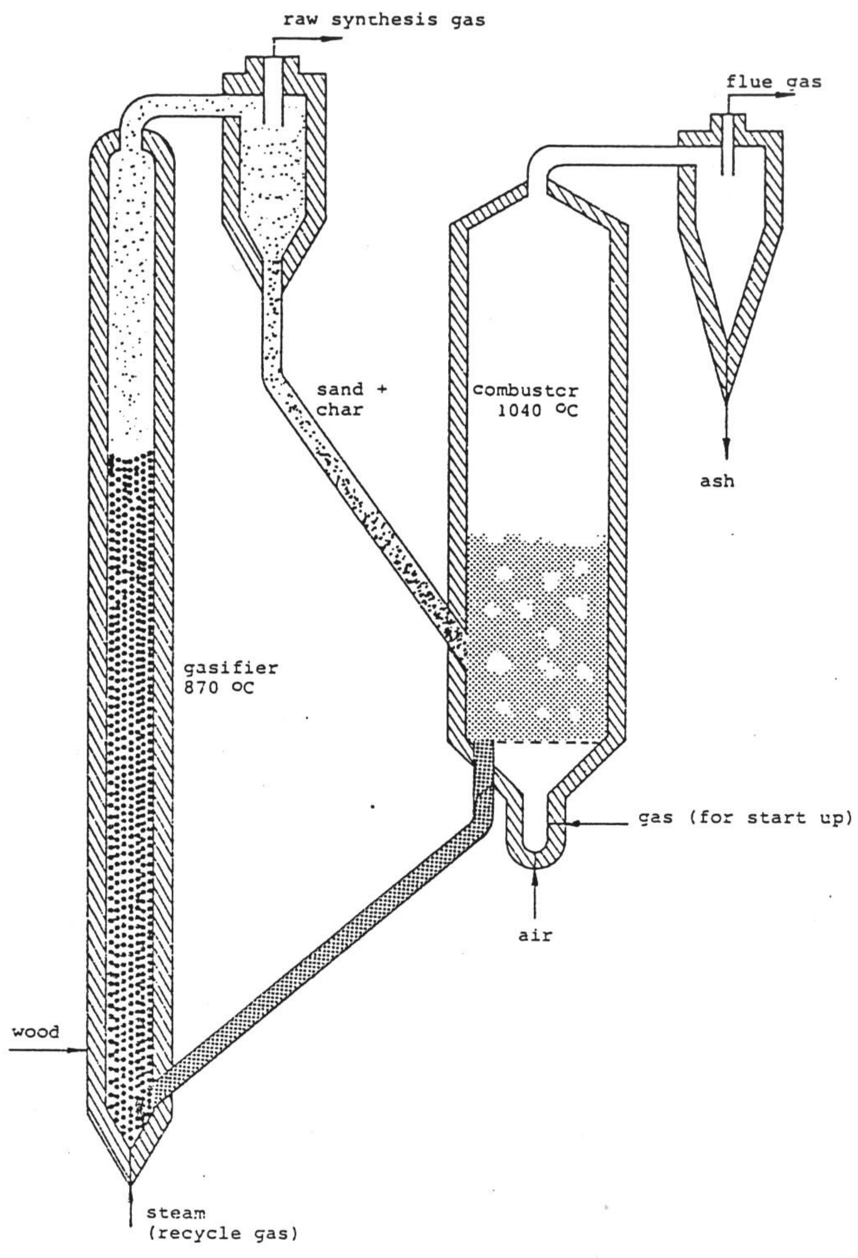
A specific feature of the process is that the gas heating value is not dependent on the fuel moisture content. It is instead the amount produced that varies with the moisture content.

Some RDF´s are similar to biomass in properties and they should be feasible in this gasifications system. For biomass a possible "balance temperature" of some 850 ^{o}C has been verified. This gasification temperature offers another degree of freedom in the design regarding different feeds. The possibility of using external fuel - as gas (product gas) - represents another possibility.



Schematic representation of the Battelle/FERCO gasification process.

Battelle Columbus



Multi-Solids Double Fluidized Bed Gasifier

(Battelle)

The method of heat supply limits the gasifier operational temperature and probably makes downstream tar treatment necessary. In a gasification process for RDF, the pretreatment of MSW (Municipal Solid Waste) is required in accordance with what is the case for other similar gasification processes. Further, the same gas treatments are likely to be applied. The handling of the ashes may differ though. In the Batelle gasification the ashes evolve in a critical part of the process not permitting too much deviations from the process requirements.

Status

The Batelle gasification has been run in a Pilot Unit since 1980. For different fuels the capacity can be altered within quite a large range and the maximun capacity seems to be 4-5 MW. Different applications such as methanol and combined cycle have been considered. A first demonstration unit aiming at combined cycle is currently under erection in Burlington, USA. The first stage includes the gasifier, and the gas will be burned in an existing boiler. A cost-sharing between DOE FERCO (Future Energy Resources Company) is established for the 25 milj.$ project (200 tpd). RDF has been tested in the PDU unit in Columbus, Ohio.

Present Situation and Future

Until now the Batelle gasification has focused on biomass as raw material. It is one of three often mentioned options for biomass gasification in the USA and it seems likely that the main stream will continue to be biomass.

8.14 THE THERMOSELECT PROCESS

General
In the Thermoselect process MSW (Municipal Solid Waste) is gasified and melted in two steps: first an indirect drying/pyrolysis step and secondly a high temperature gasification by means of oxygen.

The high temperature treatment effects a molten slag and enables the process to handle a large range of solid wastes. The product gas is treated in a rather complex gas cleaning system resulting in a "pure" fuel gas which may be used in power production; through a conventional steam cycle or a combined cycle.

Process description
The high temperature gasification is achieved by oxygen and support fuel taken from the product gas but also - to some extent - by the preceding drying and pyrolysis of the wastes. This reaction is carried out in a compressing and feeding system attached directly to the high temperature gasifier.

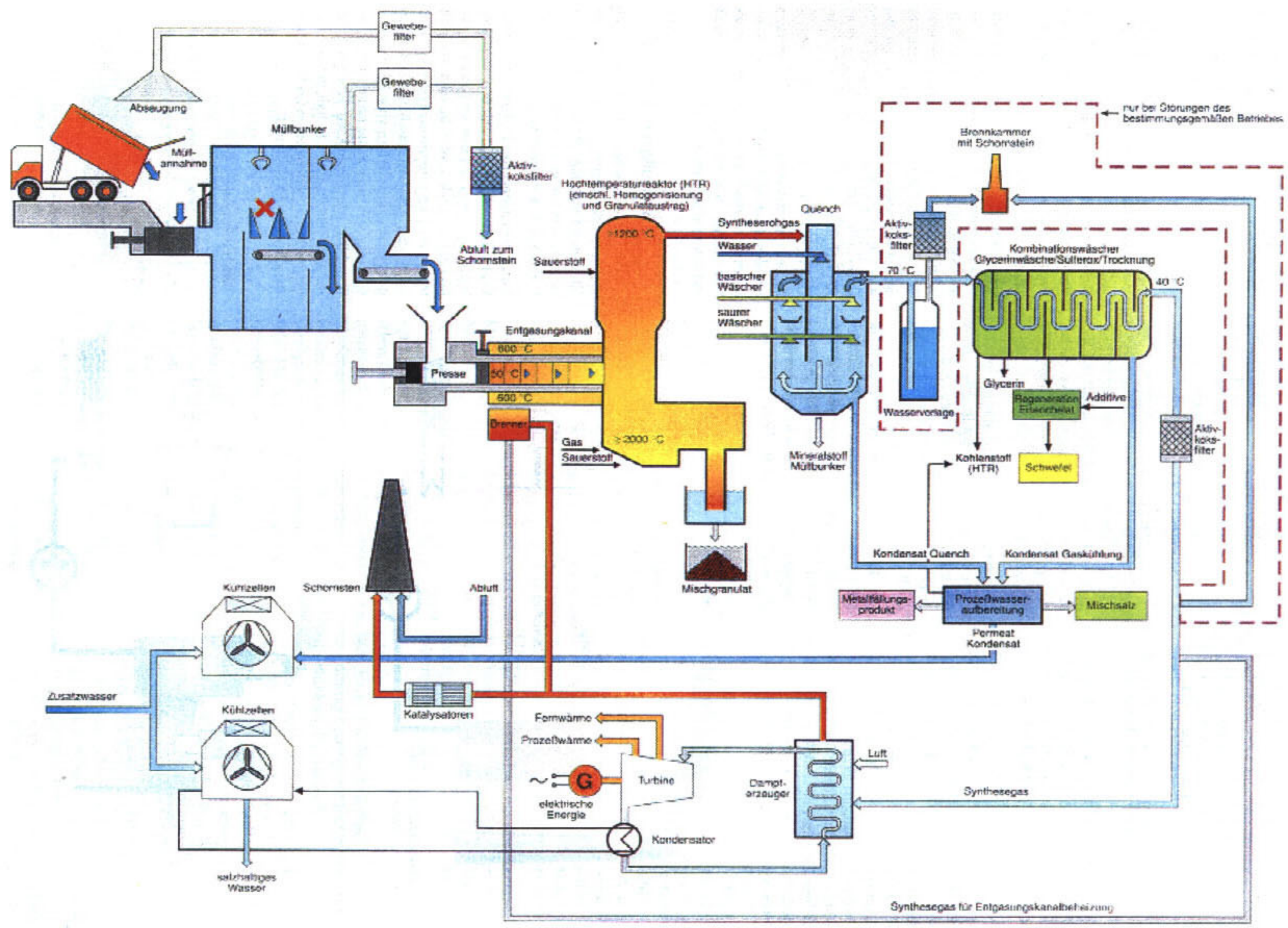
The solids (MSW) are mechanically compressed and transported through a "tube" by a piston. In the indirectly heated tube reactor the temperature is gradually raised to about 600 ^oC effecting a drying of the material and subsequently a pyrolysis (see the attached figure).

The pyrolysis solid residues are intermittently pushed into the gasifications shaft where the temperature is raised to 1200-2000 ^oC by means of oxygen and extra fuel provided from the product gas. The gases and volatiles (tars) are concurrently fed into the shaft together with the solids. The required amount of "extra fuel" obviously is a function of the type of wastes fed to the process.

Metals, minerals and other types of inorganic material in the wastes are melted in the gasifier and withdrawn as a liquid (• 1800°C) inte the bottom. After cooling, a harmless solid residue is claimed which might even be used as a raw material source for certain metals but which is basically deposited.

The exiting raw product gas consists to a large extent of carbon monoxide and hydrogen giving a fuel gas of medium heating value or what might be called a synthesis gas. The volume of product gas is rather low as the heat is supplied indirectly and with oxygen. It is quenched with water and the impurities are subsequently cleaned in a complex liquid washing. The latter contains several steps with various liquids. Finally the gas is passed through an activated carbon filter.

From the product gas a fraction is is used for heating the drying/pyrolysis reactor. The rest constitutes a clean fuel. The overall thermal effeciency is not revealed in general descriptions. However, judging from the stated net gas production it can hardly be larger than 50-60 % calculated as gas before a potential power generation. I a dutch evaluation (Novem



Thermoselect

Thermoselect

355100/0023, 1994) the thermal effeciency to power was a little more than 20 % mainly due to high power consumption for oxygen production.

Status
The Thermoselect process is established in a 32.000 tons per year of MSW Pilot Demonstration Plant in Verbania in Italy (100 tpd). The technology has been actively marketed in Europe for a couple of years, and an order for a demonstration in Switzerland is claimed. Several other locations have been discussed.

Present situation and future
The environmental effects of the Thermoselect process have been discussed, some engineers denying the "emission free process" - a marketing phrase used earlier by the Thermoselect Srl. The market effects of this dispute are not known but they may influence the future possibilities.

As other high temperature gasifications, the Thermoselect process avoids some common problems in the treatment of Municipal Solid Wastes. The molten and solidified ash is a major advantage. The high temperature on the gases in combination with the thorough gas cleaning means that the risks for dioxines, etc are minimized. Thermoselect has the potential to be a good destruction process with minimal environmental impact.

These effects do have a cost though as the high temperature requires oxygen and/or support fuel. The economic advantages still have to be demonstrated in several units.

8.15 THE LURGI CFB PROCESSES (ÖKO-GAS, WIKONEX)

General

These processes are applications of the Lurgi CFB (Circulating Fluidized Bed) gasification process. Run at atmospheric pressure the fluidized bed is fed with biomass, RDF (Refuse Derived Fuel) or similar raw materials and fluidized by oxygen enriched air.

As in other similar CFB processes, the municipal waste has to be sorted and milled/screened into a uniform product (RDF) to ensure the function of the process.

Lurgi has developed several process concepts around the CFB. Depending on the use and requirements of the product gas, different gas treatments are applied when wastes are used as raw materials; clean gas in the Öko-Gas concept, power generation in the Wikonex (see the attached figures).

Process Description

The fluidized bed reactor requires a certain homogenity in the feed material. This has been clearly experienced in several processes. Thus, the municipal waste has to be sorted, milled and sometimes dried into a RDF before entering the CFB gasifier.

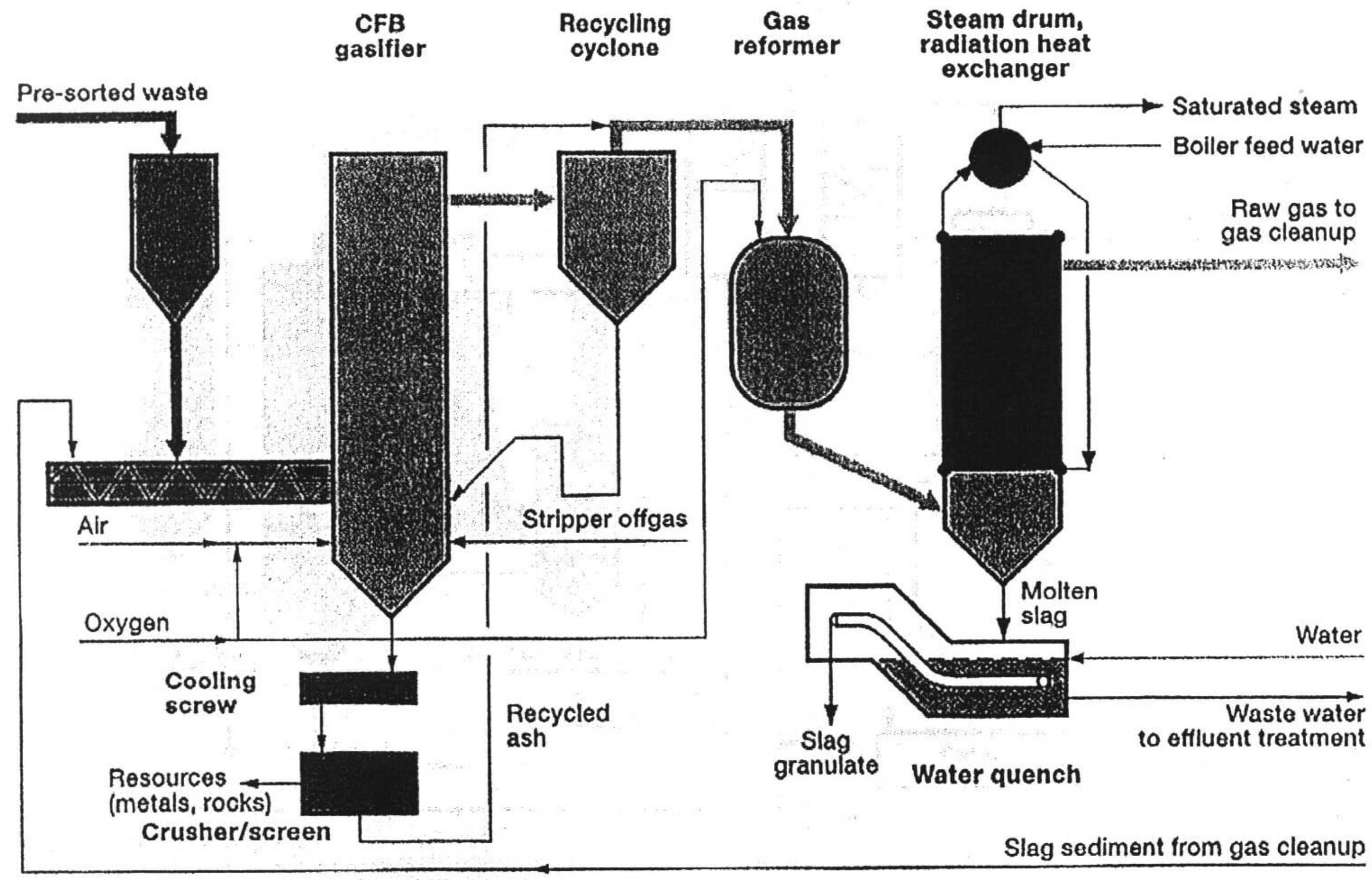
In the fast fluidization shaft the material is gasified with air and oxygen in an inert bed. The temperature is about 900 ^{o}C and the reaction time averages some seconds. At the top unreacted material and other solids are separated in a cyclone and recycled to the fluidization shaft. From the bottom of the reactor ashes are taken out, cooled and separated from metals.

From the cyclone the raw product gas is fed to a gas "cracker" which operates at some 1400 ^{o}C. The temperature is raised by oxygen in the raw (fuel) gas. At these temperatures a cracking or rupture of dioxines, etc is ensured as well as no further formation of them. (In addition a molten slag formation is obtained as described above.) The remaining fly ashes in the gas are then introduced into the high temperature gas cleaning reactor for melting into "molten/solidified ash". By this measure a rest product similar to the product from high temperature gasifications is obtained.

The gas is cooled in a waste heat boiler and further quenched by water. After a subsequent scrubber where ammonia, metals, etc are removed, specific cleaning of sulphur and mercury are applied. A considerable amount of waste water has to be treated with precipitations and neutralizations.

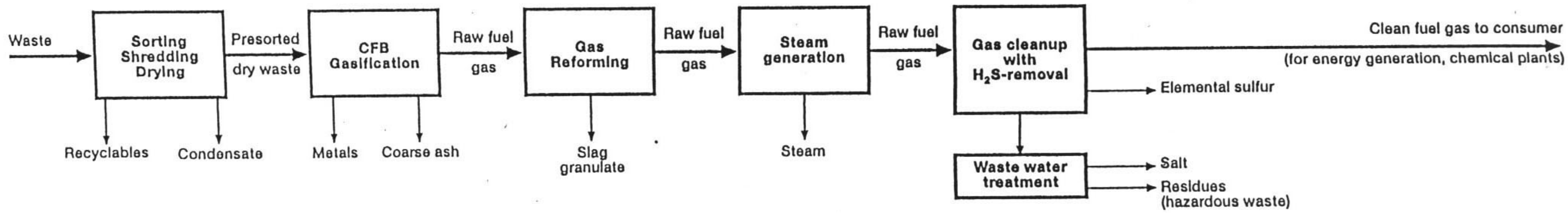
With the extensive gas treatment a pure fuel gas with medium heat value may be distributed (Öko-Gas). Alternatively, the gas after the waste heat boiler may be fed to a combustion unit. A flue gas treatment then is required after this unit.

The thermal effiencies are reported roughly 60 -70 %, calculated as energy in the cold gas, depending on - among other things - these alternate gas treatments.

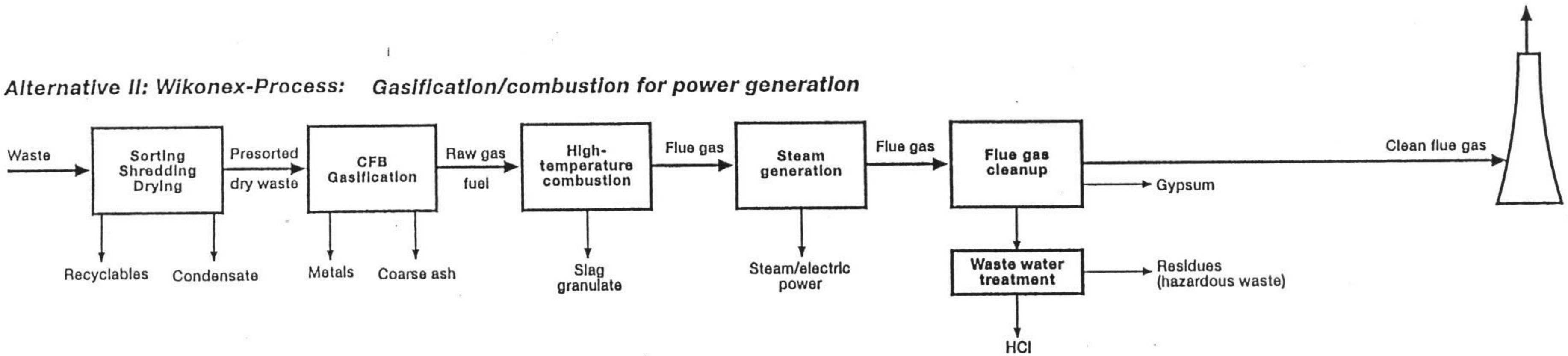

CFB
gasifier
Recycling
cyclone
Gas
reformer
Steam drum,
radiation heat
exchanger
Pre-sorted waste
Saturated steam
Boiler feed water
Raw gas to
gas cleanup
Air
Stripper offgas
Oxygen
Molten
slag
Water
Cooling
screw
Recycled
ash
Waste water
to effluent treatment
Slag
granulate
Water quench
Resources
(metals, rocks)
Crusher/screen
Slag sediment from gas cleanup

Lurgi

Alternative I: Öko-Gas-Process: *Production of clean LHV gas*



Alternative II: Wikonex-Process: *Gasification/combustion for power generation*



Lurgi Two Stage Processes for Thermal Waste Disposal

Status

Lurgi has been working with several CFB processes in a Pilot Unit of 1.7 MW since the mid-eighties. For partly utilization of specific wastes - sludge, spent carbon, rubber etc, units of 27 (Polz limekiln wood residues) and 100 MW (Radersdorf cement kiln lignite) have been built. A demonstration unit for biomass (12 MW_e) is also scheduled for 1998 (THERMIE project in Italy Pisa Electrica).

On RDF or other municipal wastes, however, there seem to be no reports on planned or erected units.

Present Situation and Future

The CFB technique still reamins to be demonstrated on RDF in a commercial project. In the pilot unit the primary gasifier has been demonstrated. A co-operation with SCE (Southern California Edison) has not yet led to any plants. The Lurgi process is one of the CFB gasification processes still waiting for a commercial breakthrough.

8.16 THE TPS/ANSALDO RDF GASIFICATION PROCESS THE GRÉVE-IN-CHIANTI PLANT

General
Since the mid-1980s, TPS has been working on the development of an atmospheric-pressure gasification process. The initial driving force for such development was the possibility of fuelling lime kilns with biomass-derived gas. Although TPS was successful in developing a CFB (circulating fluidized bed) gasifier, no commercial units for this particular application were sold. However, in the late 1980s TPS licensed their CFB gasifier technology to Ansaldo of Italy and provided the design for two RDF-fuelled CFB gasifiers for a commercial plant in Italy. (See the attached photographs and figure.)

A gasification plant in Gréve-in-Chianti, Italy, fuelled by RDF (Refuse Derived Fuel) pellets employs two CFB (circulating fluidized bed) gasifiers of TPS design. The gasifiers operate at atmospheric pressure and use air as gasification agent. The total process lay-out was designed by STING (Studio Ingegnaria Ambientale) and built by ANSALDO Aerimpiante. Plant owner is S.A.F.I. (Florence area Environmental Services).

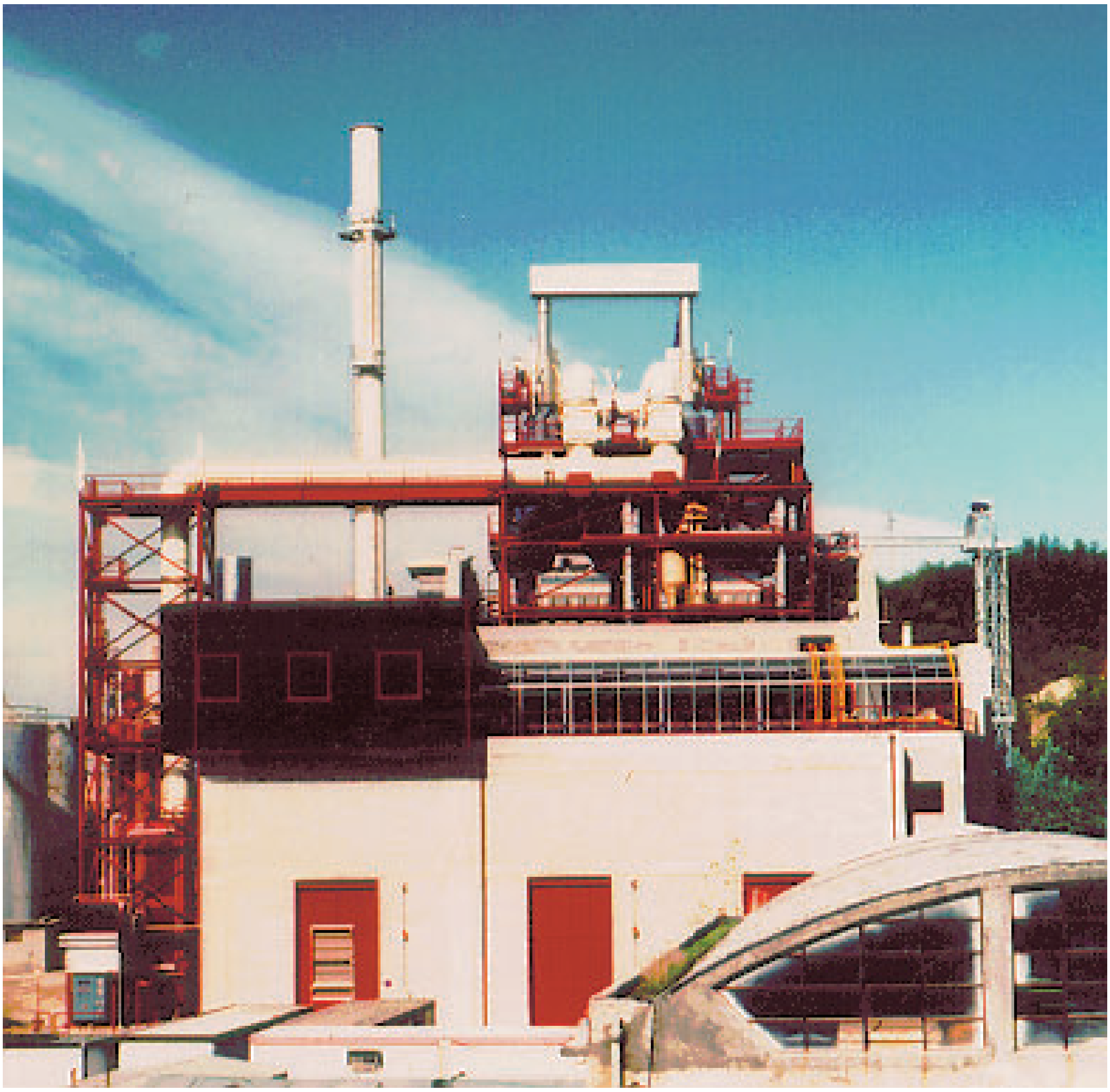
Process Description
RDF fuel is delivered to the plant in pellet form. The pellets are fed into the lower sections of the two CFB gasifiers, each of 15MW fuel capacity. The TPS-designed gasifiers operate at close to atmospheric pressure at a temperature of approximately 850^{o}C, employing air as the gasification/fluidizing agent. Part of the air is injected into the gasifier vessel through the bottom section, the remainder being injected part way up the vessel. This pattern of air distribution creates a high-density bed in the lower part of the vessel which allows the gasifier to handle relatively large-sized fuel particles. The maximum length of the RDF pellets delivered to the plant is 150 mm (Note: TPS has stated that its gasifier can operate on RDF fluff and that from the gasification point of view there is no need to pelletize the fuel).

The raw gas from each gasifier passes through two stages of solids separation before being fed to a furnace/boiler. The gas heating value is high 8MJ/Nm^3. Alternatively, part of this raw gas stream can be led to a nearby cement factory to be used as fuel in the cement kilns. The flue gas exiting the boiler is cleaned in a three-stage dry scrubber system (technology from Research-Cottrell) before being exhausted through the stack. Steam produced in the boiler drives a 6.7 Mwe steam condensing turbine.

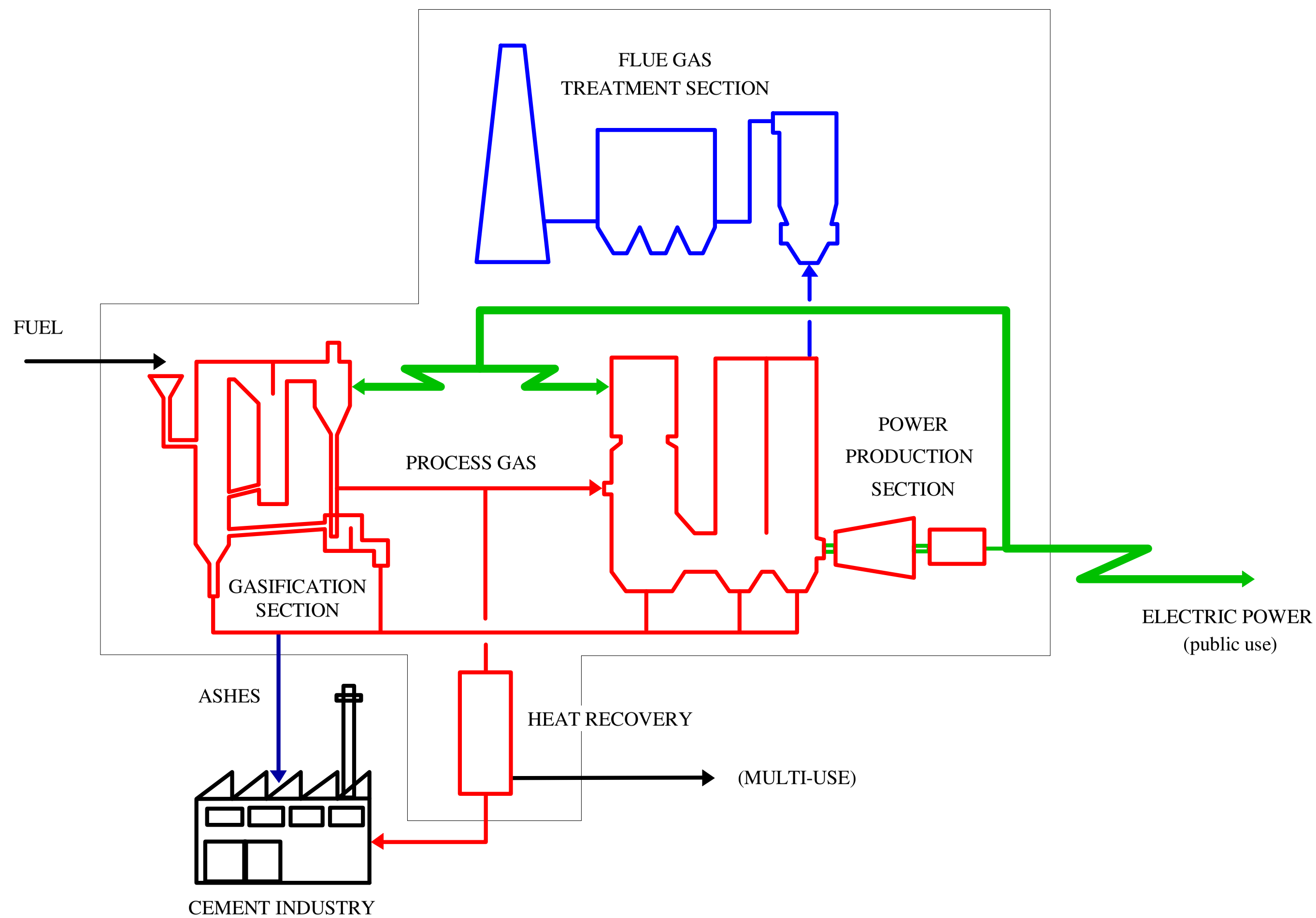
Due to local restrictions no flaring of the gas is permitted.

Status
The Gréve plant was turned over the customer in 1993.

Pilot tests 2MW fuel in Studsvik 1989-90 with RDF pellets. Operational problems in the Gréve plant have mainly been related to combustion of the gas with high dust content. Fuel supply to the plant (RDF pellets) has been limiting for the operation of the plant.



TPS/ANSALDO RDF GASIFICATION GRÈVE ITALY



TPS/ANSALDO RDF GASIFICATION GRÈVE ITALY

TPS/ANSALDO RDF GASIFICATION GRÈVE ITALY

Present Situation and Future

The original process layout of the plant included a dedicated furnace/boiler and flue gas cleaning system for each gasifier. To date, only one such line has been installed. A decision on whether to complete the plant as proposed originally or to install a proprietary TPS hot gas cleaning system is still to be taken.

An RDF-pellet production factory is being commissioned presently (May 1996) and shortly thereafter the Gréve-in-Chianti plant will again be taken into continuous operation.

8.17 THE TPS GASIFICATION AND HOT GAS CLEANING PROCESS (TPS TERMISKA PROCESSER AB, NYKÖPING, SWEDEN)

General

Since the mid-1980s, TPS has been working on the development of an atmospheric-pressure gasification process. The initial driving force for such development was the possibility of fuelling lime kilns with biomass-derived gas. Although TPS was successful in developing a CFB (circulating fluidized bed) gasifier, no commercial units for this particular application were sold. However, in the late 1980s TPS licensed their CFB gasifier technology to Ansaldo of Italy and provided the design for two RDF-fuelled CFB gasifiers for a commercial plant in Italy.

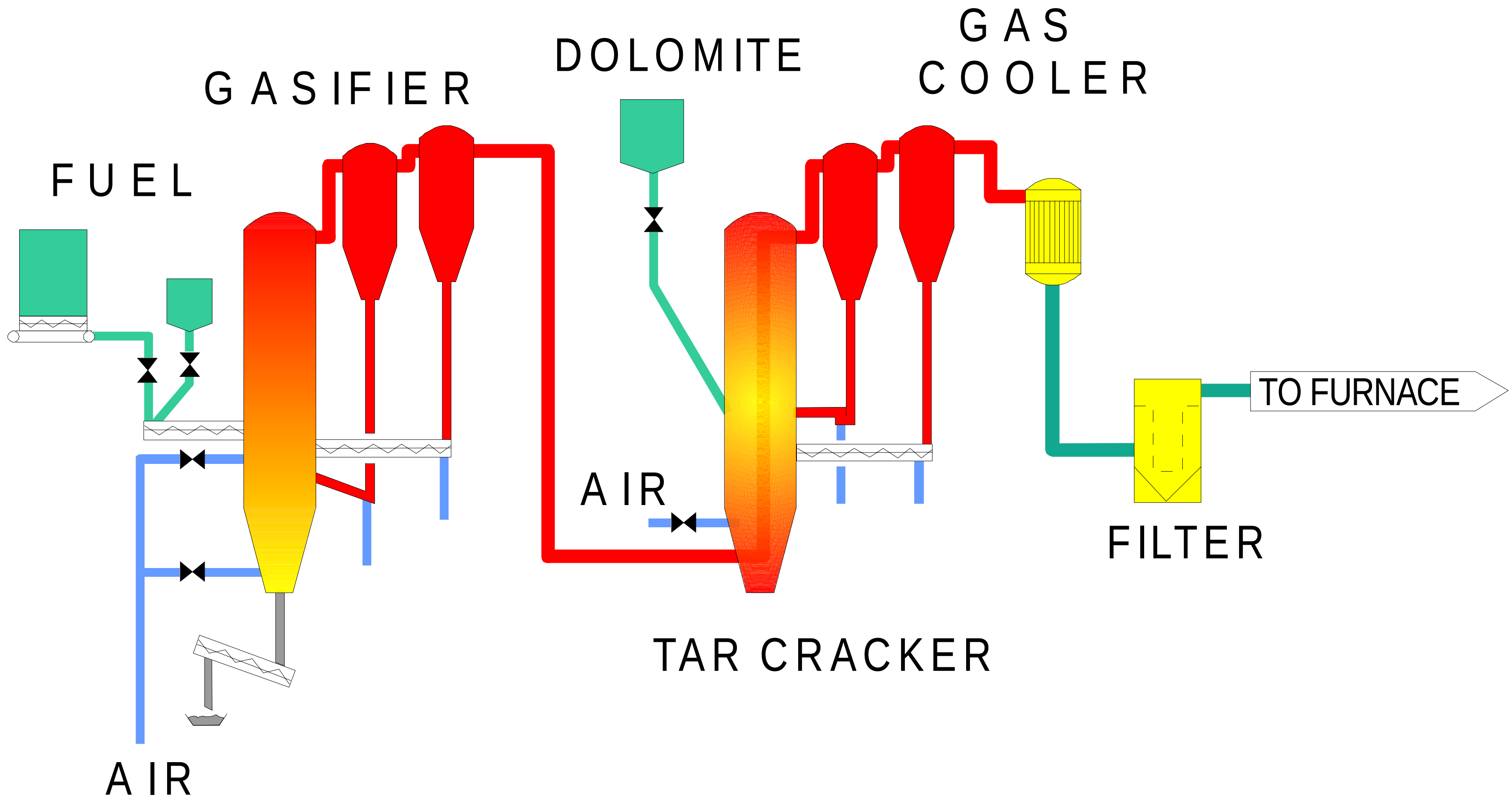
Since the latter part of the 1980s, TPS has been working on the development of a hot gas cleaning process for application to biomass and waste-derived gases. This hot gas cleaning technology was first demonstrated over long operational periods at pilot scale in the late 1980s, the gas being fired successfully in a dual-fuel engine. At that time, it was thought that a sizeable market existed in Sweden for the commercial application of TPS's gasification/hot gas cleaning technology to small-scale electricity production plants (say 5 to 20 Mwe). Although TPS has not succeeded in selling any small-scale plants based on this gasification/hot gas cleaning technology, TPS still believes today that this technology can provide a good technical solution for biomass-based electricity production plants.

Since the early 1990s, TPS has concentrated its gasification development work on the application of its gasification/hot gas cleaning technology to IGCC systems. TPS is involved in several important projects aimed at proving the technical and commercial viability of biomass-fuelled IGCC systems.

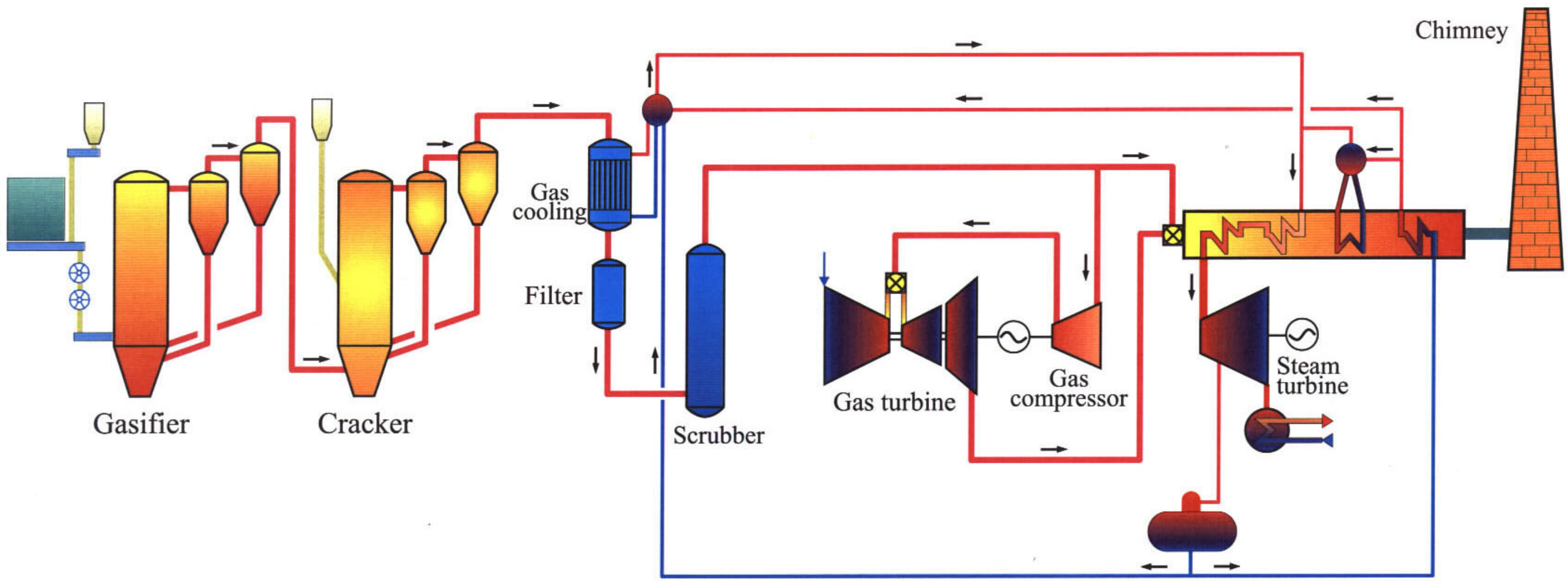
Process Description

The TPS gasifier is of CFB type and operates at close to atmospheric pressure and typically between 850 and 900^{o}C, using air as gasification/fluidizing agent. The raw gas leaving the gasifier passes through two cyclone solids separators arranged in series before it enters the hot gas cleaning vessel. Due to the dense bed section in the lower part of the gasifier the TPS gasifier is said to be able to handle relatively large-sized fuel particles.

The hot gas cleaning vessel is also of CFB type. The main fluidizing agent for this vessel is the raw gas from the gasifier. The vessel operates at close to atmospheric pressure and at a temperature of approximately 900^{o}C. The main function of the hot gas cleaning vessel is to catalytically convert the heavy hydrocarbons present in the raw gas to lighter compounds; this is done by passing the raw gas through the vessel and over dolomite which forms the major part of the bed material within the vessel. Reducing the amount of tar in the gas in this manner allows gas cooling and cold gas cleaning equipment to be positioned downstream without fear of them becoming clogged by tar that would otherwise condense and foul the equipment. Conventional cold gas cleaning equipment (e.g. filter and wet scrubber) can be used to remove



TPS GASIFICATION AND GAS CLEANING



CFBG Combined-cycle Scheme

TPS GASIFICATION AND GAS CLEANING PLANT

particulates, chloride (as $CaCl_2$), residual organics, alkali, ammonia, moisture, etc., from the product gas, as required.

In the view of TPS, there are three main applications for cold tar-free biomass-derived gas for electricity production:

- firing of the gas in a furnace/boiler without further flue gas cleaning (see figure attached)
- firing of the gas in a gas engine/dual-fuel engine
- firing of the gas in an IGCC system (see figure attached).

Status
The TPS gasification/hot gas cleaning technology has been extensively tested in pilot plant scale (2MW fuel, see enclosed photograph), and is to be demonstrated in IGCC plants. The plants are due for start-up in 1999. The fuel is woody biomass. For RDF pellets and to some extent fluff, initial pilot testing took place 1990-91, and further pilot tests are planned in 1996.

The gas quality from biomass after gas cleaning is acceptable for gas turbine with LHV 6-7 MJ/Nm^3 low alkali, ammonia and dust content. For waste the heating value depends on the source, but generally, similar heating values are expected.

Present Situation and Future
A World Bank/Global Environmental Facility (GEF) sponsored project in Brazil is aimed at the construction and operation of a eucalyptus-fuelled IGCC plant of 30 Mwe capacity. The gas turbine for the plant will be a General Electric LM 2500. Similar projects in both Sweden and Holland are under serious consideration.

An EU-sponsored project in the UK includes the construction and operation of an $8Mw_e$, short rotation forestry-fuelled IGCC system. The company that owns the plant, ARBRE Energy Limited, is the recipient of a 15 year contract which provides a guaranteed preferential price for electricity generated (i.e. a so-called ‘NFFO contract’).

According to TPS, the aims of the company for the near future is to demonstrate the technical feasibility of its gasification/hot gas cleaning technology in biomass-fuelled IGCC systems. TPS believes that in the long-term biomass-fuelled IGCC systems will be able to compete with fossil-fired plants in terms of both plant efficiency and overall plant economics, especially in the perspective of the need for sustainable energy sources.

In the case of waste fuels, TPS believes that in the long-term their use in IGCC systems is feasible. However, in the short-term TPS is concentrating on demonstrating its gasification/hot gas cleaning technology for the production of cold clean gas production as feedstock for a boiler/furnace; a project aimed at the construction of such a plant in Holland is in the early evaluation stage. The advantage of this option over conventional combustion boiler plants is that higher electrical efficiencies can be achieved as HCl is removed from the gas on dolomite present in the system, and thus superheater steam temperatures are not restricted due to worries of corrosion by HCl in the gas, as is the case in conventional waste-fuelled combustion plants.

8.18 THE KIENER-SIEMENS PROCESS

General
The Kiener-Siemens process focuse on the handling of waste, the volumetric reduction of it and on the possibilities of using the end products. Basically, the energy considerations are similar to what is achieved in an incineration technique.

The process may be regarded as an advanced combustion unit where the pyrolysis/gasification is entered as a pretreatment to a conventional combustion. The latter part is equipped with flue gas cleaning, etc as incinerators are. Early attempts to clean the fuel gas were not successful (tar cracking, Kiener), and conventional flue gas treatment after gas combustion has been chosen.

Process Description
Unsorted wastes of different types such as MSW (Municipal Solid Waste), industrial waste and sludge are mixed and somewhat homogenized. They are then treated in a rotating pyrolysis drum indirectly heated with flue gases to some 450 ^oC. In the drum a drying and pyrolysis occur, producing gases (including tar) and solids.

In the end of the drum the gases are fed direcly to the air blown combustion unit running at high temperaure; some 1300 ^oC.

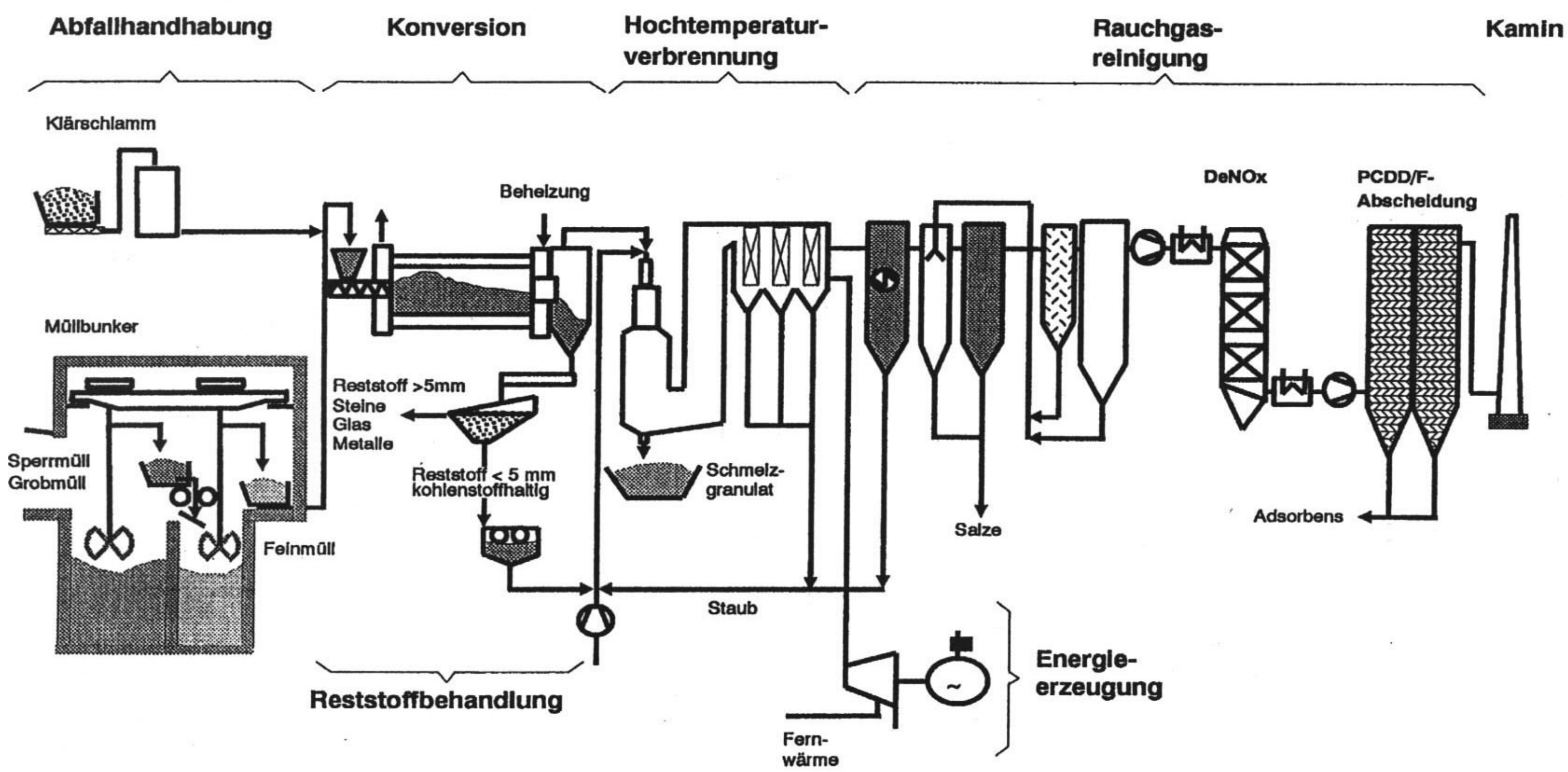
The solid residue is separated primarily into three fractions; a coarser fraction containing metals and minerals and a "fine fraction" consisting almost exclusively of carbon or - at least - combustible material. This fraction is also fed to the high temperature combustion. The effected temperature is sufficient to obtain a molten ash or slag.

The flue gases from the combustion are subjected to conventional flue gas cleaning. With the main object to handle the wastes effectively, the result of the process is a decrease in waste volume from 1 to < 0.2-0.3. Up to 75 % of the energy content in the wastes may be recovered.

Status
A Pilot Unit of 5-10 t/h was run in the late-eighties and in the begining of the nineties. The marketed technology is close coupled gas combustion with flue gas cleaning.

A commercial unit on 100.000 ton per year is scheduled for 1998 with construction start 1995.

KWU UMWELTTECHNIK



Siemens Kiener

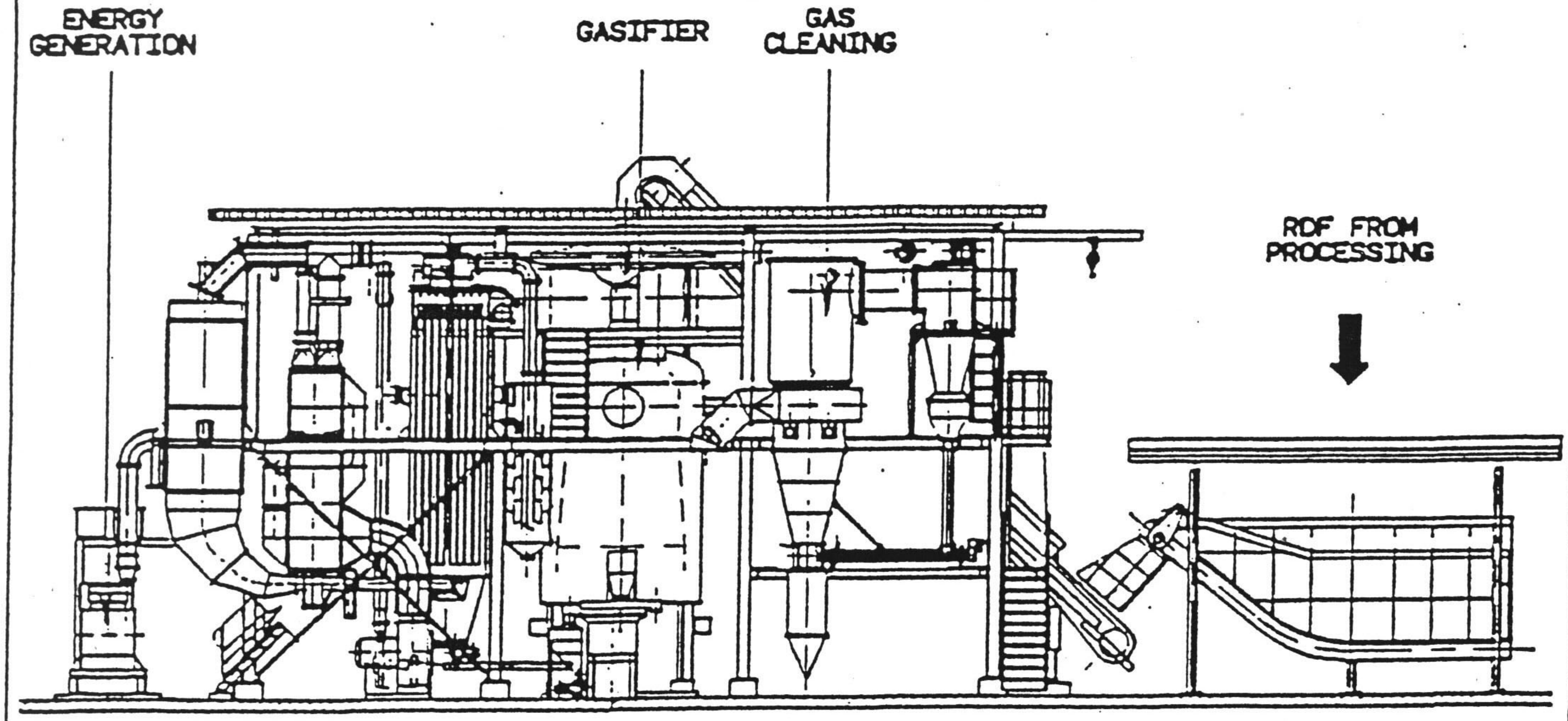
8.19 DANECO

General
An Italian waste treatment company, DANECO is now in addition to RDF plants also marketing an RDF pellets gasifier. The 10MW air blown updraft gasifier is coupled to a gas cleaning system with a novel tar cracking unit and fuel gas cooling and cleaning.

Process Description
A 10MW airblown updraft gasifier is fed with RDF pellets from the top. Air is fed through a rotation bottom grate. The raw gas is fed to a fixed bed cracker with recycled ashes and fuel gas cleaning residues (lime). The cracking temperature is around 800^{o}C and soot is recycled to the gasifier. After gas cooling with air and steam heat exchangers to 600^{o}C the gas enters a recovery boiler. A wet dry lime system operating at approximately 250^{o}C precedes a baghouse filter.

After scrubbing/cooling the gas is sent to a dual fuel engine.

Status
The authors have no information regarding the technology background or present test units. The process is actively marketed.



DANECO **GASIFICATION**