

# Multi-recovery from Waste in a Novel Compound Shaft-Reactor-Plasma-Mixing-Destruction-Chamber Approach

Jens Hetland<sup>1</sup> Ph.D. and Steinar Lynum MSc<sup>2</sup>

*Nowadays, waste is prone to be conceived as a potential valorising source rather than a problem. The negative image of incineration may explain a growing interest in new technologies. Increased focus on emissions, effluents and residues may give rise to novel solutions with quite new features. Processes that employ thermo-chemical conversion - such as pyrolysis and gasification – may have an important role to play because of their inherent ability of retrieving materials and values. Even though such processes were introduced in the 1970s, they are still referred to as novel in contrast to landfills and incineration. In this paper a new thermo-chemical process is addressed that facilitate pyrolysis, gasification, vitrification and melting. The core technology designated PyroArc comprises a compound thermal unit that is capable of decomposing all organic components into simple molecules. A full dissociation of the gas is obtained by exposure to the extreme temperatures and dynamic impact generated by a plasma jet. The concept offers in-situ multi-recovery (metals, inorganic materials and energy) with a safe and inert rendering of residues. Economical viability is claimed even for small-scale plants. This leaves the option for local treatment in a dispersed energy context, which again may reduce the extent of transportation and pertaining infrastructure.*

## Introduction

There is a growing concern of the environment that seems to act as a key-drive for new standards imposed on waste handling. Most directly this applies to the classification of waste and the pertaining regulations for waste processing and disposal. On this basis waste treatment seems to become more sophisticated and new groups of materials will be termed hazardous. Intensified recycling, reuse and substitution of toxic materials that may reduce the relative amounts of hazardous waste may obtain some mitigating effect. However, since the total amounts of waste tend to grow, hazardous waste is prone to remain a serious problem. By this reasoning it becomes obvious that there is a growing demand in the market for new treatment processes that are capable of handling practically any waste material in a safe and environmentally sound manner.

## Thermo-chemical conversion

In this paper *pyrolysis* and *gasification* should basically be interpreted as a group of thermo-chemical processes that favours gas formation, commonly referred to as *gasification*. These processes are used for degradation of carbonaceous material that take place at temperatures around 400 – 800 °C mainly without flame combustion. This may happen in inert systems in the absence of oxygen (pyrolysis), or

when allowing partial oxidation sufficient to sustain heat while restricting the oxygen supply so much that flame-combustion is omitted (gasification). In this manner solid material is split into substances that can be used as fuels. Pyrolysis may proceed in two directions: either through conversion of carbon to charcoal – known as ‘slow pyrolysis’ (carbonisation), or by liquids and gas formation, referred to as ‘fast pyrolysis’. The latter direction usually applies to most thermo-chemical waste treatment processes. In gasification the majority of carbon contained by the solid waste is converted into gaseous products, leaving an inert residue similar to incineration. In contrast to incineration which aims at a complete reduction of hydrocarbons to basically CO<sub>2</sub> and water without calorific value, gasification on the other hand aims at a partial break-down of the organic molecules leaving a gaseous product usually referred to as synthesis gas – or just *syngas*. Although the calorific value of the syngas is rather low, the gas is still combustible and can in principle be used to fuel an air-breathing engine.

In contrast to incineration processes that usually result in heat as the only product, gasification processes offer more possibilities for recovering additional value from these materials.

<sup>1</sup> Senior Scientist, SINTEF Energy Research, Dept. of Thermal Energy, Trondheim, NORWAY

<sup>2</sup> President, EnviroArc Technologies AS, Oslo, NORWAY

*The 6<sup>th</sup> International Conference on Technologies and Combustion for a Clean Environment  
Workshop on New Technological Solutions for Wastes, Porto, 10<sup>th</sup> July, 2001*

## **New solutions**

In several countries there seems to be a growing interest in thermo-chemical conversion technologies, particularly for municipal solid waste (MSW). One reason may be that such systems are being promoted or conceived as better alternatives to incineration - which may be the case, especially when environmental aspects and public acceptance are addressed. Even though processes based on gasification have been applied for waste treatment for almost thirty years such concepts are still referred to as new solutions. Usually gasification processes facilitate recovery of materials and energy at reasonable efficiency - even on smaller scale. Especially the new regulations on landfills in the EU combined with emerging technologies can motivate the introduction of new small-scale solutions. The immediate advantage is a reduced need for transportation combined with improved energy utilisation. This may help soliciting new deployment schemes for dispersed energy systems that include waste.

## **Market considerations**

According to Juniper [1] more than 30 types of wastes are being considered as feedstock for gasification processes. The largest potential is identified to be 1) municipal solid waste (MSW), 2) post-consumer waste and 3) waste from the forest products industries. It is further expected that although the number of facilities that process MSW will basically remain unchanged over the coming ten years, the average plant size tends to increase. The market for gasification technology is expected to grow over the next ten years, partly by penetration of existing markets and partly by diversification into new applications and also by developing 'new' market niches around the world.

The market for waste treatment technology that employ gasification has grown from around 3 new plants per year in the early 1990s to some 10 plants per year in the late 1990s. Further prognoses indicate that more than 200 plants are going to be built over the coming ten years. In this perspective the European MSW market is likely to maintain its position as the largest market segment in terms of throughput and energy recovery where some 20% of all new plants may employ gasification technology. It is further anticipated that the sales in Europe will be significantly higher than in other markets, maybe more than 2.5 times the sales in the next largest market, Japan, all according to Juniper [1]. In the US the sales are likely to be

lower than one could expect when comparing the size of its economy and population. The main reason for this is the well established policies and reliance on landfills.

A growing interest is identified in the processing of sewage sludge, particularly in Europe. This is much due to increased concern over public health issues and a potential contamination threat to the food chain. It is still uncertain how various thermo-chemical gasification processes may turn out when compared to their alternatives such as anaerobic digestion, composting and incineration. It appears that land-spreading may become less acceptable in the time to come due to a growing concern of the food chain. Over the latest couple of years other important issues have appeared such as the threat from infectious diseases like *BSE* and the *foot-and-mouth-disease*. According to recent news reports a substantial increase in allergic reactions are reported as a direct consequence of the enormous fires set up to destroy the reminiscences of dead animals, particularly in the UK. These serious events clearly demonstrate how vulnerable society is, and how important it is to keep the strictest control of the potential contaminants. From this reasoning it seems obvious that the handling of effluent streams and the final disposal of residues will become key-issues to future solutions.

## **New markets and opportunities**

To some regions waste tends to threaten the future existence due to lacking solutions for their waste handling. This particularly applies to industrial waste, either because no sufficient method exists that complies with the regulations, or simply because the cost of waste transportation exceeds the operating margins of the enterprise. Therefore waste treatment on smaller scale is regarded relevant in order to maintain the existent infrastructure. A future need is also identified for efficient waste treatment plants that could fit into local societies and be self-supplied by some 20-30 thousand people. In a European context this would be equivalent to some 10 000 tons of waste per annum with a yield of some 3 - 5 MW heat and power.

Two emerging areas are pointed out by Juniper [1]:

- Agri-wastes due to huge amounts of residues that perpetually occur each year
- Industrial wastes of various kinds – such as
  - residues from the paper and pulp industry

- end-of-life products (in particular cars, computers, tyres etc) for which pertinent processes are likely to be motivated, funded or supported by the primary manufacturers as part of environmental legislation

Other areas of growing concern are waste from hospitals, chemical industries and the military activity.

According to Juniper some countries like Canada, France, Japan, USA and China have been supporting national efforts to develop gasification processes. In Japan there seems to be a particular demand for hybrid solutions for stabilising of the residues (combining *gasification-vitrification-and-melting technologies*) such as those developed by Nippon Steel and NKK. Recently (in 1999) Sumitomo obtained a license for German technology developed by Krupp Uhde facilitating *fluid-bed-gasification-and-residue-stabilisation* [1, 2]. In contrast to Japan, however, the market tends to look for simpler solutions that primarily maximise the production of syngas with less or no regards to residue stabilisation.

### Proven technology

Although gasification processes, at the time being, enjoys a higher level of acceptance in the market, a major disadvantage seems to be that these technologies are lacking references from long-term commercial operation. For this reason gasification may continue to be associated with high risk as compared to conventional technology. Therefore, especially in Europe, USA and Japan incineration seems to be preferred by the majority of municipal decision-makers. On the other hand gasification is expected to be preferred in Canada and Korea and possibly in some emerging markets in Asia and Australia [1].

### Market players

In a waste-to-energy context it may be assumed that conversion efficiency and cost constitute the main drives of technology development. In contrast to public decision criteria in the past, the decisions are gradually becoming cost-driven as the waste management shifts from the public sector to private enterprises.

The number of suppliers of technology is expected to decrease. It is further assumed that the successful players will be those with the best and most appropriate technology proven on larger scale. Therefore the first commercial orders are so

vitaly important. It is likely to believe that in some markets two-years of trouble-free operation at full scale in the hands of a customer would be required as a measure of critical reliability, whereas less than one year would be sufficient in other markets.

Comparing cost among various technologies is rather difficult. This is much due to an inherent mismatch between initial cost, revenues and maintenance and operating cost. Strategic pricing motivated by the need for obtaining initial orders, or as a response from established suppliers to a substitute solution, may affect the comprehension of the relative price levels. In some cases suppliers may lend themselves to ownership arrangements, or even undertake to operate the plant and thereby be in full control of the revenues (i.e. the gate fee and recovered values). In areas where the landfill disposal cost is high, gasification processes tend to be competitive versus alternative technologies.

### Market mechanisms

At the time being there seems to be a window for commercial launch of new waste treatment processes. This is mainly due to:

1. The need for safe and inert rendering of waste
2. Valorisation potential (recovering values)
3. Increased interest in combined heat and power
4. Sustainable development approach
5. Recovery of materials and energy seen as complementary to reuse and recycling
6. Differing waste compositions requiring new methods
7. Reduced landfill allowances (due to legislation or shortage of suitable sites)
8. Restrictions to wet organic waste imposed on landfills
9. Growing interest for volume reduction
10. Incentives (gate fee and subsidies)
11. Mitigating environmental impact (large portion of renewable energy source with less greenhouse gas emission)
12. Increased concern of infectious diseases (e.g. BSE and the foot-and-mouth disease)
13. Deregulation of the energy markets (growing interest in electricity)
14. Local applications, small scale solutions (less extent of transportation)

### Technology description

The subject concept is backed by the unique properties of a high-temperature plasma jet for decomposing organic materials into simple gas molecules. Various technologies from metallurgy,

chemistry, physics and heat engineering are combined so that literally any material - except for nuclear waste - can be safely treated. Since the system returns no bottom ash, nor fly ash, the handling of effluent streams are trivial, and, thus, environmentally sound. Typical of the process are the huge temperature span and the multiple processes taking place simultaneously and almost in the same enclosure. This results in an overall efficiency that probably is superior to any alternative process provided the residue stability remains the same.

*chamber*. This is quite essential for the complete decomposition of the syngas. Due to extreme temperatures from the plasma two immediate advantages over any known alternative technology may be identified: 1) a complete decomposition of the highly toxic halogenated organic compounds, and 2) the higher heating value of the produced fuel gas.

The extreme temperature of the plasma zone can be used to resolve the tar problem associated with the syngas at the outset. This is explained by the decomposition reactions that reform the naphthenes into basic hydrocarbons. The absence of tar also makes the down-stream gas cleaning easier and even more efficient. The long chains of hydrocarbons of the naphthenes are simply broken and added to the fuel instead of being removed by the above filtering-scrubbing-catalytic techniques. Thereby, the process could roughly double the net electric conversion factor known from the current steam-based processes. This implies that around 30% of the energy supplied by the waste may be returned as net electricity.

*Figure 1: Concept image showing the feed system, the shaft-furnace-gasification reactor, the plasma-augmented-high-temperature-mixing-destruction reactor*

## Concept

The basic concept is shown in Figure 1. It comprises a *feed system*, a *shaft-furnace-gasification reactor*, a *plasma-augmented-high-temperature-mixing-destruction reactor*, a *dust collection-gas-cleaning system* (volatile metals and alkaline salts). A consecutive downstream *energy recovery train* is further attached.

The process involves three different conversions:

- a) *gasification sustained by counter-current partial oxidation* combined with *vitrification and melting*.
- b) complete dissociation of syngas combined with *prevention of recombination* by partial air intrusion.
- c) Energy recovery (heat and power – either directly by fuelling an air breathing engine, or via combustion).

## Core technology

The unique technology of the process is the plasma chamber, protected by intellectual law, and the way it is used in a *plasma-mixing-destruction*

## Brief process description

Plastic baled waste material from a remote storage or shredded bulk waste material of various sources is charged into the shaft reactor in which the organic components convert into a partly oxidised gas, while the remaining inorganic species are prone to melt. Consisting mainly of carbon monoxide and nitrogen the syngas may be associated with a rather high content of tar-forming components (naphthenes), and most often chlorinated hydrocarbons, hydrogen and water vapour. This gas is dangerous. Except for being burnt it cannot be used for any purpose without a thorough post treatment. Depending on the moisture of the feed, the temperature of the syngas will be around 400 – 700 °C when it leaves the gasifier. In the consecutive plasma-augmented decomposition reactor the gas decomposes entirely due to a temperatures of 3000 – 5000 °C combined with strong dynamic forces excited by the plasma jet. Essential to waste treatment is that no material leaves the gas converter without being exposed to sufficiently high temperatures. The outcome is the fuel gas, leach resistant slag, molten metal and small amounts of secondary dust that may be subjected to recovery of materials like zinc, lead and mercury. More than 70% of the heating capacity of the waste is retrieved in the form of fuel gas, whereas 20% is sensible heat. Therefore,

the process may be used for local co-generation based on a gas engine system.

The foremost important features are the complete mixing and the instant initiation of the decomposition reactions. This implies, as confirmed by testing:

- a complete dissociation of hydrocarbons with no indication of recombination
- no toxic nor carcinogenic organic compounds present because no such compounds can survive at the reactor temperature

- dioxin content of the fuel gas well below 1/10 of a nanogram per cubic meter of fuel gas
- NO<sub>x</sub> content within 10 – 30 ppm (even for nitrates)

The reforming of the syngas to a produced fuel gas can be controlled by the intrusion of air to the mixing zone. The gas then diverts into the expansion zone followed by the equalising zone. The total residence time is 0.3 - 0.6 s.

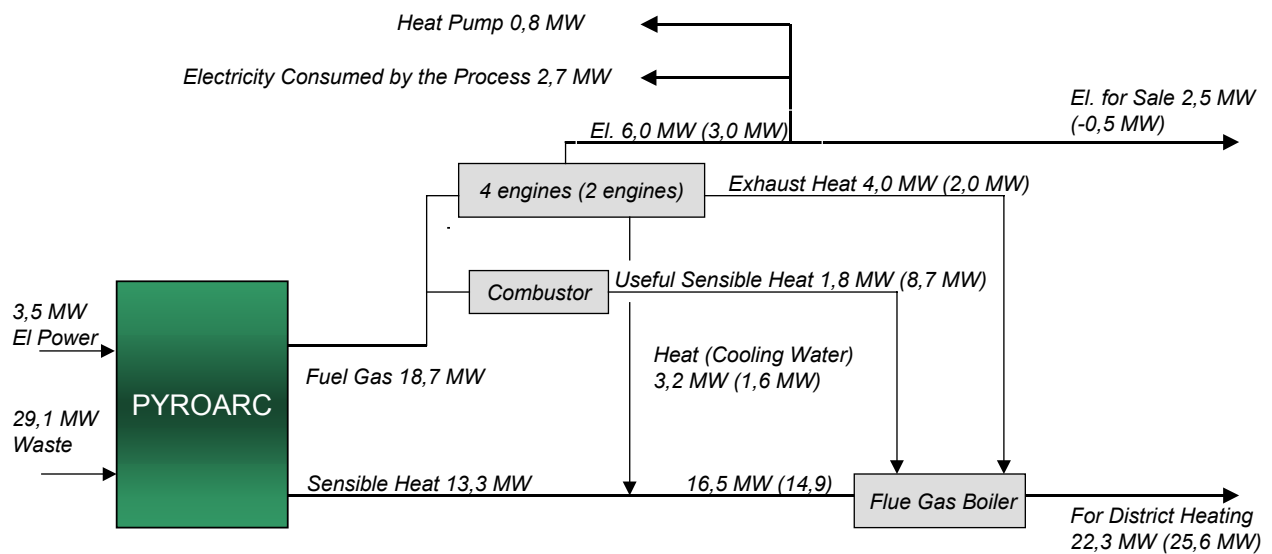


Figure 2: Typical energy balance of the process with four gas engines and optionally two gas engines.

## Plasma generator

The purpose of the plasma generator is to:

- Provide a zone of high energy density
- Excite strong dynamic forces to ensure a uniform temperature of the entire gas volume
- Supply heat in order to control the temperature level of the decomposition reactor.

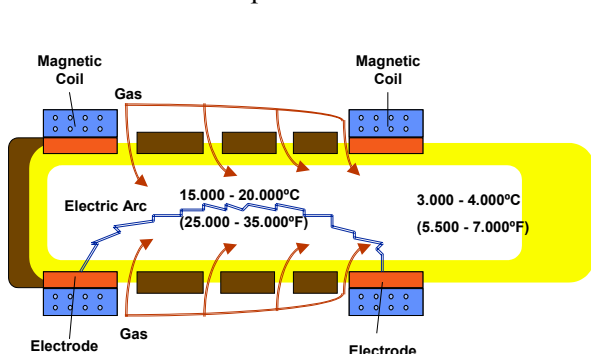


Figure 3: Image of the arc plasma showing in principle how the high temperature plasma is being generated.

Recordings of the dioxin level of the fuel gas were used to interpret the decomposition. All tests based on various materials from household waste to concentrated PCB oil, show that the dioxin level was kept well below 0.1 nanograms per cubic meter of fuel gas [4,5].

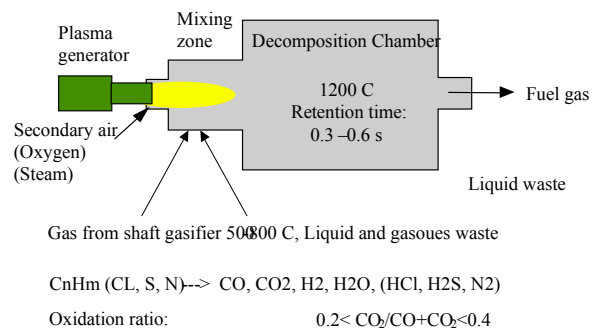


Figure 4: The functioning of plasma generator and decomposition chamber and secondary air intrusion. The heat required is 90-98% by partial oxidation and 2-10% electric power depending on the water content, typically 95% and 5% respectively [5].

The oxidation of the produced fuel gas is controlled by additions of secondary air. The content of CO and CO<sub>2</sub> of the produced gas is continuously recorded. The secondary air should be carefully controlled so that the oxidation ratio (as defined in Figure 4) is kept between 0.2 and 0.4. Experience shows that if the oxidation ratio becomes lower than 0.1 HCN may be formed. This should be avoided, especially in combination with wet gas cleaning. Vice-versa if the oxidation ratio exceeds 0.5 formation of NO<sub>x</sub> may take place.

### Shaft Gasifier

Owing to the extreme temperatures of the plasma the reaction rates in the decomposition reactor may become very high. For this reason a well premixed gas is required. For solid material this can only be obtained by up-stream gasification. The gasifier is a down-draft, counter-current-flow shaft reactor, known from the steel works, shown in Figure 5. The internal heat dissipation is controlled by the introduction of preheated air.

This type of shaft gasifier combines easy and rugged design with low thermal losses and long lining life. It is fully sealed so that no material can leave the unit without having been gasified or completely melted.

The solid waste material is being fed into the shaft gasifier through a lock hopper system for shredded material, or an evacuated chamber for baled waste. A short duct diverts the syngas from the top of the gasifier to the decomposition reactor.

As shown in Figure 5 the shaft reactor is characterised by three distinct zones:

- a) evaporation
- b) carbonisation
- c) partial oxidation and vitrification

In the latter zone c), the charcoal descending from the carbonisation zone is mainly reduced to carbon monoxide by under-stoichiometric reactions with preheated air. Owing to these exothermic reactions the temperature of this zone reaches 1450-1550°C. At this level all inorganic materials are prone to melt, and thus, leaving a homogeneous slag. Since waste materials may contain silica (or glass) the slag becomes glassy. Depending on the silica content the slag may obtain high leaching resistance.

The behaviour of metals appears to be slightly different:

- Metals from the waste may be collected as molten metal from the shaft
- Metals with higher affinity to oxygen than iron (like Al, Ti, Mg, Ca) oxidise and are dissolved in the slag
- Iron can be reduced to molten iron by adding coal and limestone to the charge
- Volatile metals like zinc, lead and mercury are evaporated and leave the gasifier as part of the syngas.

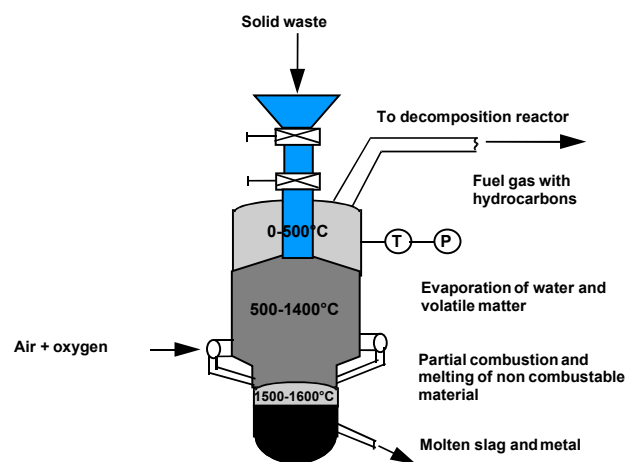


Figure 5: Illustration of the shaft reactor with indication of the characteristic zones

In the middle zone (carbonisation) the solid material is being carbonised at a temperature of around 1000°C. The carbon-fix associated with most waste materials tends to form a low grade char with a carbon content of 15-30% only, the rest being inorganic material. In spite of the low carbon content the energy from this partial oxidation is sufficient to melt most inorganic components.

All materials with some substantial vapour pressure, such as water and hydrocarbons, evaporate in the upper zone (a). The vapours leave the gasifier jointly with the syngas.

### Gas Cleaning

The produced gas is quenched from 1200 °C to 800 °C when it leaves the decomposition reactor. A conventional down-stream gas cleaning system is further used for which the characteristics may depend on local conditions and emission demands.

Compared to conventional technology some immediate differences appear:

- The volume of produced gas amounts to only 30-40% of the corresponding volume from an incineration process
- The gas is a LCV fuel gas
- Practically no dioxins, and no chlorinated and halogenated hydrocarbons are present
- No components that form tar at low temperatures
- Less than 30 ppm NOx
- Sulphur mainly appears as metal sulphides
- Option for capture of mercury, zinc and lead either as secondary dust or venturi sludge. (It should be noted that the emission of mercury depends more on the gas volume than on the total amount of mercury. Hence, a process offering low gas volume means substantially lower emission of mercury [4,5].)
- Should the content of zinc and lead exceed 20-25% the recovery of these metals may become economically viable on an independent basis.

## Products

### Fuel Gas

The produced fuel gas is a low calorific value gas (LCV) with a heat value of about 4 MJ/m<sup>3</sup>. The content of carbon monoxide plus hydrogen amounts to 35-40%. Since the fuel-NOx is low only small amounts of NOx may occur when combusted.

### Slag

The slag properties depend on the waste material. In many cases the fraction of silica in the waste is sufficiently high to ensure a glassy structure with low leaching values. Suitable slag formers (e.g silica oxides or glass) can be added to influence the slag properties. The leaching of different components have been tested at a Dutch laboratory. The following table shows values obtained for the PyroArc process and normal bottom ash from municipal solid waste (MSW) to be compared to the thresholds given by the Dutch U1-standard. Contrary to the bottom ash, the values of the PyroArc process clearly tell that there is no restriction of using its slag in buildings.

**Table of leaching resistance of slag:**

Technology	PyroArc MSW	Bottom ash MSW	Dutch U1 limits
Elements	mg/kg	mg/kg	mg/kg
As	<0.01	0.14	0.3
Ba	0.017	190	4
Cd	<0.0007	2.4	0.1

*The 6<sup>th</sup> International Conference on Technologies and Combustion for a Clean Environment  
Workshop on New Technological Solutions for Wastes, Porto, 10<sup>th</sup> July, 2001*

Co	0.0014	1.9	0.2
Cr	0.75	1.4	1
Cu	0.071	375	0.35
Hg	N/A	N/A	0.005
Ni	0.19	12	0.35
Pb	0.01	49	0.8
V	<0.1	0.75	0.7
Zn	0.08	1120	1.4

*According to Dutch U1-standard (CEN TC 292)*

### Metals

Metals with a lower affinity to oxygen than iron can be recovered as molten metal, tapped separately from the shaft. This represents an interesting valorisation option for some kinds of waste like electronics and computer scrap. Especially copper alloys containing nickel, tin, silver and gold are easily retrievable.

The dust from zinc and lead can often be used for metal recovery. The alkaline salts usually extract the entire amount of chlorine present in the waste material. Depending on the local conditions and subject to proper treatment the alkaline salts could possibly be used for de-icing purposes, or they have to be disposed of either as liquid residue or as solid salt following a de-watering process [4,5].

Mercury capture always leaves a certain amount of filter mass that requires special precautions.

### Summary

The development of the plasma jet and its interaction with the decomposition reactor has been strongly supported by extensive testing mainly carried out in a technology demonstrator build to semi-industrial scale. So far the concept has proved its versatility and capability of converting almost any solid waste material. Conversion of traditional fuels like biomass, coal and residue oils to fuel gas has been successfully demonstrated. And the possibility of combining gaseous and liquid fuels with waste materials leaves an interesting option for improving the energy flexibility in a waste-to-energy context. This option may offer the ability to cope with the fluctuating energy demand that is typical of the market.

### Conclusions

There is an obvious market demand for novel technologies that can handle and retrieve values from multiple of wastes in an efficient manner, that may offer inert and safe rendering of residues. For this task processing technology that employs

pyrolysis and gasification seems to attract particular interest. The process described herein can be seen as an important contribution due to its unique features.

In the European political context there is a pronounced need for dispersed energy solutions. In particular local European societies, touristic islands, and remote areas are being addressed. In response to this political message the subject technology may have an important role to play mainly because of its high electric yield, even on smaller scale – and the fact that its fuel has a negative price (gate fee). Most importantly, though, is its capability of treating almost any waste material (except nuclear) with no adverse environmental effect.

## References

1. Juniper Consultancy Services Ltd. 'Pyrolysis & Gasification of Waste, a Worldwide Technology & Business Review', Vol. I: Markets & Trends, March 2000.
2. Juniper Consultancy Services Ltd. 'Pyrolysis & Gasification of Waste, a Worldwide Technology & Business Review', Vol. II: Technologies & Processes, March 2000
3. Sørum, L.; Fossum, M.: 'Energigjenvinning av avfall – Anleggsleverandører' , SINTEF Report, April 2001
4. Information proprietary to ScanArc Plasma Technologies AB, Sweden
5. Information proprietary to EnviroArc Technologies AS, Norway