

## NAWTEC16-1929

A Fourth Generation WTE Facility Designed for Energy and Materials Recovery:  
The Amsterdam AEB Waste-Fired Power Plant  
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### Summary

This paper describes a fourth generation WTE facility, the Waste-Fired Power Plant (WFPP<sup>®</sup>) owned and operated by the City of Amsterdam. This plant is designed with the Best Available Technologies (BAT) to achieve the lowest possible emissions to air, water and soil, thereby creating the lowest possible nuisance levels to neighboring residents, offices and industries. The plant is also designed to maximize electricity production, and to recycle and recover the maximum amount of materials which include ferrous and non-ferrous metals, sand and granulate to produce building products and gypsum and salt from fluegas.

In addition the paper describes the design features applied to achieve the world's best energy efficiency and includes a discussion on the life cycle economic advantages of BAT applications and the positive effect of BAT on Green House Gas emissions.



### Introduction

The Amsterdam Waste & Energy Company (AEB) is owned by the City of Amsterdam and operated on a self-sustaining, for profit basis. AEB and its predecessors have been in the waste management business since the late 1800's and designed, built and operated Waste to Energy facilities since 1919. Details can be obtained from AEB's 2006 Annual Report and

the brochure "Value from Waste", at the websites referenced at the end of this paper.

Late last year AEB started its fourth generation WFPP<sup>®</sup>, so named because it is designed to produce electric power with a net efficiency of 30%, and an overall material recovery of 98%, leaving less than 2% of the initial MSW feed, to be landfilled. The 530,000 metric tons WFPP<sup>®</sup> capacity raised the total annual capacity of the AEB facility to 1.5 million tons, making it the largest single WtE facility in the world. Robust AEB designs result in an actual availability of the facilities of 94% and keep maintenance cost down. Consequently AEB's tipping fees are the lowest in The Netherlands.

AEB also operates one of the cleanest plants in the world with stackgas emissions below 20% of the maximum permissible levels by the EPA. This factor and the low "nuisance factor" of the original plant enabled AEB to plan and build the WFPP<sup>®</sup> without a single protest by the local community or by NGO's.

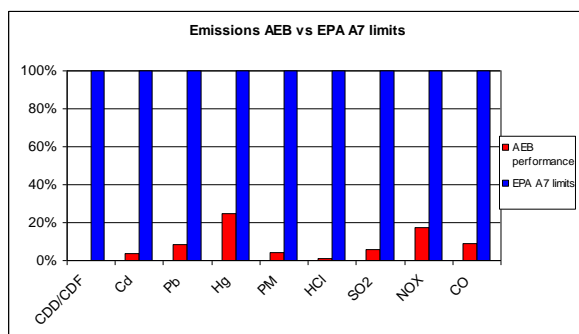
The result of the very high energy production and material recovery rates of the WFPP<sup>®</sup> is a reduction in greenhouse gas emitted. The balance of direct emissions, biomass input and avoidance effects of the energy and materials produced, amounts to a net avoidance (negative emission) of 215 kilograms CO<sub>2</sub> per ton of MSW. This issue will be addressed in detail by Marcel van Berlo of AEB in another paper presented at NAWTEC 16.

In this presentation we will start with the overview of the most important aspect of AEB's operation, the environment. Following this we will present details of the high energy efficiency design, an overview of bottom-ash treatment and material recovery system and close with a review of the life cycle economics of the WFPP<sup>®</sup> operations.

## Environmental Considerations

Both the original WtE as well as the WFPP<sup>®</sup> have been designed using the Best Available Technologies (BAT), for two reasons; firstly to lower the burden on the environment, in casu the neighboring community and secondly to extend the economic life of the plant, as will be explained in later in this paper.

This concept resulted in stackgas emissions well below the Dutch and European standards which are considerably more stringent than those of the EPA. The following graph compares AEB emissions with the EPA standards.



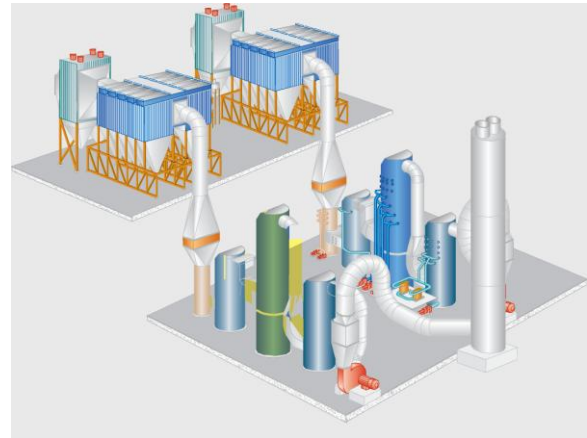
The excellent operating parameters of the existing WTE Plant have raised the bar of the Dutch environmental standards, which have been tightened as the result. We believe these standards are amongst the most stringent in the world.

As in the existing plant, Selective Non-Catalytic Reduction (SNCR) is used to reduce nitrogen oxide emissions. To help optimize efficiency, compressed air instead of steam is used to inject ammonia, diluted with softened water.

For the first stage separation of fly ash, an electrostatic precipitator has been installed after the boiler. Because of this, in combination with the boiler's two-way bottom ash collection system, the maximum amount of fly ash can be recovered for recycling.

A fabric filter has been fitted to remove fine particles. Fine powdered activated carbon or blast-furnace coke is injected as the adsorption medium for the filter. Powdered limestone is added to the coke injection to eliminate the risk

of fire and explosions. It also forms a filtering layer on the filter bags. The coke adsorption medium separates out dioxins and furans right at the beginning of the flue-gas cleaning process. Heavy metal content is also reduced to such an extent, that products from the wet flue-gas cleaning process can be reused directly.



A flue-gas heat exchanger installed after the fabric filter preheats the condensate. Underneath the heat exchanger a water quench system is installed to cool flue-gases to the point of saturation. The evaporation of this water in the quench also ensures that the acid solution from the next scrubber is concentrated, and goes to the salt production stage as a 10% solution.

The hydrochloric acid and sulfur dioxide scrubbers are the next stages in cleaning acid components and ammonia from the flue-gases. The hydrochloric acid scrubber is a packed bed scrubber that captures the acid remaining in the flue-gas after the quench. The spray from the hydrochloric acid scrubber is sent to the quench as a concentrated hydrochloric acid solution. The sulfur dioxide scrubber is an open scrubber in which a lime-milk solution is added as a neutralizer. At a pH of 6, this scrubber captures sulfur dioxide that reacts in the scrubber to form gypsum slurry. By using a fabric filter, relatively clean gypsum can be produced that is suitable for reuse. A centrifuge separates the gypsum from the slurry as a dry product that is stored in a container for transportation and reuse.

After the sulfur dioxide scrubber a separate polishing scrubber also functions as a heat exchanger. The scrubber consists of a packed bed over which water circulates that is cooled by one of the economizers. This cooling reduces condensable gasses thus reduces emissions. The recovered heat is the first stage in preheating the condensate used as boiler feed water. By under-cooling the flue-gas, the polishing scrubber in combination with one of the economizers, produces virtually pure condensate that can be reused in the hydrochloric acid scrubber and the quench of the flue-cleaning system.

Finally, the purified flue-gas is kept at a vacuum by an induced draft fan. This runs 'wet' in the saturated flue-gases that pass through a drip tray and emissions monitoring equipment to the chimney stack.

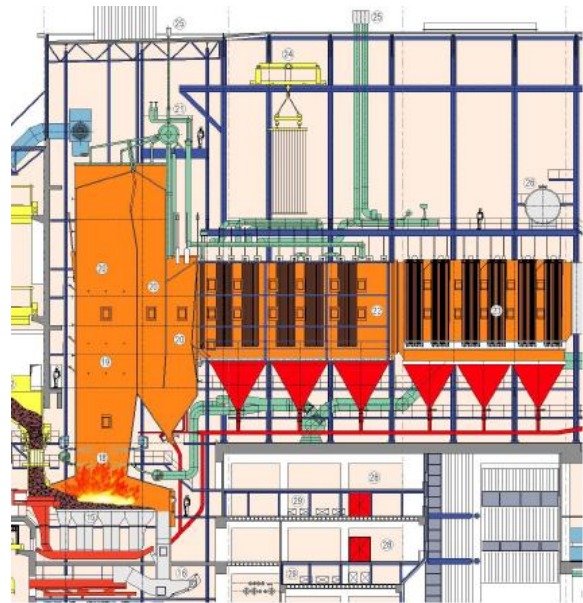
An environmentally related issue is the low "nuisance factor" which facilitated permitting of the WFPP<sup>®</sup>. MSW can be transported to the plant by road, rail and water. These options considerably lowered the burden on the roads around the plant and helped to secure AEB's acceptance by its neighbors.

Another advantage of AEB's proximity to its neighbors is the application of district heating. This is made available to the community at advantageous rates. Heat production at AEB is more efficient than at individual homes, consequently reduces the environmental impact.

### WFPP<sup>®</sup> Energy Efficiency

The WFPP<sup>®</sup> has two processing lines each with a capacity of 265,000 metric tons per year of MSW. With an average caloric value of 10 GJ/ton MSW, the plant generates a net total of 57 MW electricity, in one turbine generator set.

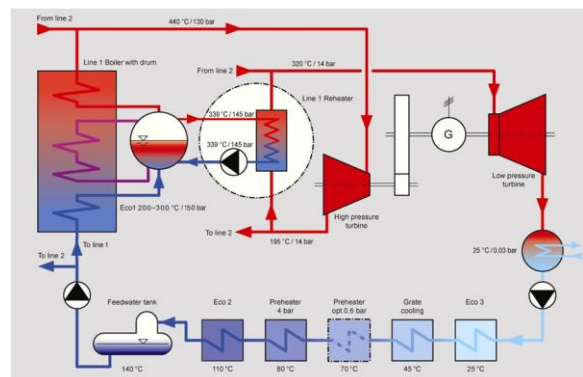
The boiler has two vertical radiation sections and a horizontal convection section, housing the steam production and superheating bundles. The boiler has been designed with a total volume close to twice the customary design, to reduce heat loads and fluegas velocities, increasing plant availability and life cycle.



The exceptionally high energy efficiency of the WFPP<sup>®</sup> is accomplished by the following design features:

- Intermediate Superheating
- Excess air
- Steam temperature/pressure
- Back pressure
- Boiler feed water/condensate preheating

The following diagram shows the design of the thermal cycle:



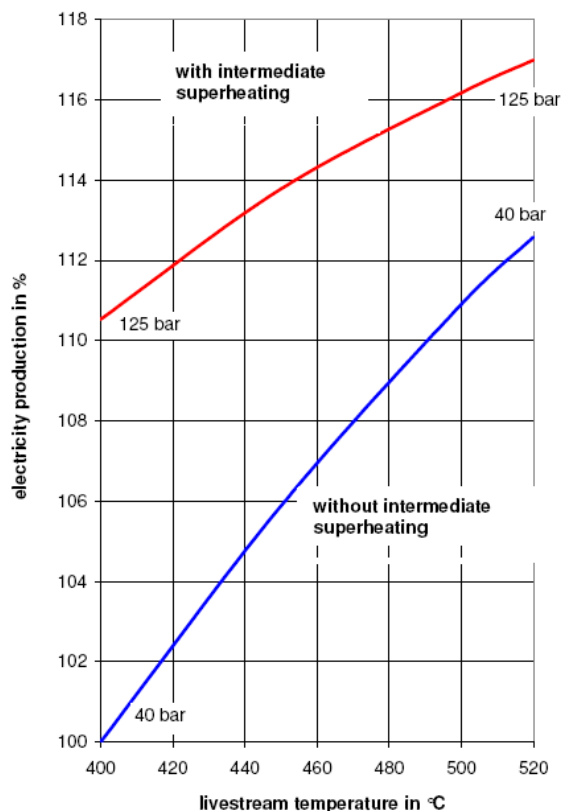
### *Intermediate Superheating*

Intermediate superheating is a technology used in conventional power plants, but thus far there has not been a precedent for its application in WtE plants. The reason for this is that corrosion on the gas side of the boiler tubes affects the superheaters the most. Intermediate superheaters placed in the fluegas stream,

would be subject to corrosion just as much as the final superheater; and as a consequence, the failure rate of the boiler would significantly increase. This is why AEB decided to use saturated steam from the boiler drum, essentially eliminating corrosion. This advantage outweighs the disadvantage of a lower heat transfer rate.

Each boiler has its own intermediate superheater, so that varying boiler loads do not cause unbalanced operation. The superheaters are located near the turbine so as to minimize piping, and consequently also pressure losses of the medium-pressure turbine steam. Intermediate superheating uses a high live-steam pressure set at 130 bar.

Reheating the steam between the high pressure and low pressure sections of the turbine produces a drastic increase in the usable enthalpy difference. This is illustrated in the following graph.



#### Excess Combustion Air

The low amount of excess air lowers the stackgas heat losses and reduces the power

consumption of the ID fan, thus increasing plant efficiency. At the other hand, the varying, uneven caloric value of the MSW, requires a safety margin at which the minimum level excess air can be set, to avoid incomplete combustion. Stable operating conditions at AEB's facilities enable us to operate the plant at 6% dry volume, (5% wet) instead of the customary 8 to 11 %. A closely controlled low boiler fluegas exit temperature of 180°C, instead of the usual 200-240°C results in additional energy recovery.

The size of the combustion grate also plays a significant role. The larger the grate, the lower the affect of the boiler wall on the average combustion temperature of the MSW. In the case of our WFPP® with grates of more than 12 meter wide, the walls have relatively little impact on the average temperature.

Moreover, three grate sections each with four drive zones and seven air zones provide a wide range for control. The addition of primary air can be measured and individually adjusted for each zone. The narrow tolerances of the water-cooled grate surface ensure reliable air distribution and permit low amounts of excess air. The system is equipped with a two-stage steam-heated air pre-heater for improved temperature control.

To ensure stable, staged post-combustion process, flue gas is first re-circulated as secondary air through nozzles on the front and rear-walls. Tertiary air is then added through the nozzle level above the grate.

Control of MSW combustion is standard and without surface ultrasonic temperature measurement, or camera surveillance. The combustion control system has been designed to operate at a maximum deviation of  $\pm 2$  % steam flow.

Start-up ignition or support burners are not needed; start-up is simply affected manually using a gas lance or a burning rag.

#### Steam Temperature

The turbine efficiency is directly dependent on the steam temperature as higher temperatures

permit a greater usable enthalpy difference. However, the corrosion rate of the boiler limits the steam temperature. Other limiting factors are the chlorine content of the fuel, and the ash melting temperature. The superheater tube surfaces, as well as the diaphragm walls are particularly affected. As a consequence steam temperatures of around 420°C, are common in Europe, even in new state-of the-art installations.

The WFPP® steam system has been designed for a steam temperature of 440 °C. This increase is sufficient to reach the targeted efficiency and is just 10 °C above the temperature at which our original facility is operating, although it was designed for a lower temperature.

To allow this higher steam temperature, the diaphragm walls in the first boiler pass have been provided with inconel cladding, including the roof and behind the brick lining. In the second pass the entire inlet area is similarly lined.

Since the super heaters are most vulnerable to corrosion, they have been designed in such a manner that they can be exchanged within 72 hours. A permanent crane has been installed to facilitate replacement, and easy access for maintenance has been ensured. Work can be carried out at different levels simultaneously.

The boiler cleaning system also contributes to a lower corrosion risk. Regular cleaning is accomplished with explosives. Provisions have been made for water-jet cleaning to be installed at a later date if needed.

As mentioned, generous over-dimensioning of the boiler further reduces the risk of erosion. The design calls for a low gas space-rate, a low gas temperature upstream the superheater and a generous rating in general, including the water/steam side, tube pitch and wall thickness.

The selected live steam temperature of 440 °C represents a moderate increase in comparison to the original facility. Preparations have been

made for a further increase in temperature to 480 °C, depending on the operating experience.

In the design of the boiler, room has been left to install an additional tube bundle. Operating experience such as fouling and the consequent temperature profile of the boiler, will determine whether to add economizer or superheater surface. Other components in the water/steam cycle have been designed to accommodate such change.

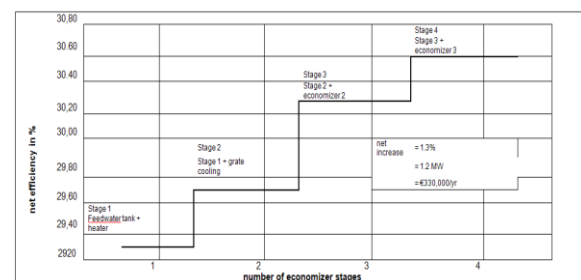
### Back Pressure

The achievable back pressure is another major factor determining plant efficiency. The availability of water for cooling and condensing was a factor in the siting of the original AEB facility, the other, as mentioned being MSW transportation.

Water at the adjacent harbor has an average mean temperature of 15°C which permits the turbine to operate at a back pressure of 0.03 bar and results in a net electric efficiency of 30% plus.

### Boiler Feedwater Pre-Heating

This graph depicts efficiency increases in the various heat recovery/economizer stages.



Pre-heating of condensate returned as boiler feed water takes place in five stages as shown in the Steam Cycle Diagram. The dearator is operated at a controlled temperature of 140°C with a 4 bar steam feed. A feedwater pump delivers the feedwater via an attemporator to Economizer #1 located the boiler.

The attemporator controls the boiler fluegas outlet temperature at a stable 180°C, making it independent from boiler fouling, by heating the feedwater in a heat exchanger in the drum.

Economizers 2 and 3, recover heat from the flue-gas system. In addition the economizer system utilizes the waste heat from the grate cooler and a 4-bar steam-heated pre-heater using extraction steam. The latter is rated to balance out the fluctuations in the heat recovered from cooling the grate.

An option for a fifth pre-heating stage has been provided for an economizer which would use 0.6 bar extraction steam, to further increase the energy efficiency.

Instead of just quenching the fluegas entering the scrubber AEB uses a heat exchanger, Economizer #2, to recover additional energy. To allow it to operate under wet conditions at low temperature, the economizer is lined with a combination of double enameling plus a coating of PFA (Perfluoroalkoxy), a material similar to Teflon. The heat transfer rate for each line at nominal capacity is 3 MW. As can be seen in the graph this economizer makes a considerable contribution to the efficiency increase.

An additional source of energy is heat that can be recovered from the scrubbing water cycle of the wet flue-gas cleaning system. For this purpose a water/water titanium plate heat exchanger has been installed. The nominal heat transfer amounts to 2 MW per line.

An advantage of this heat exchanger is the enhanced cleaning effect of the scrubber as a result of the lower operating temperature which causes condensation of the particular aerosols.

#### Evaluation of Energy Efficiency

Energy efficiency of a WtE facility can be measured in a number of different ways, the most common of which are

- Total energy expressed in calories or Btu's:

$$E_c = \frac{E_{pe} + E_{ph}}{(E_w + E_i) \times 0.97}$$

This formula however, ignores the enthalpy difference between hot water and electricity.

- The European R1-D10 Formula:

$$E_{R1-D10} = \frac{(2.6 \times E_{pe} + 1.1 \times E_{ph}) - (E_f + E_i)}{(E_w + E_i) \times 0.97}$$

whereby the enthalpy difference between heat and electricity is set at a 1.1: 2.6 ratio.

- Exergy Efficiency:

$$E_x = \frac{E_{pe} + E_{ph} \times K_{heat}}{(E_w + E_i) \times 0.97}$$

This formula defines the efficiency as that part of energy that can perform (mechanical) work, somewhat similar to the R1-D10 Formula.

All energy values in GJ/year

$E_{pe}$  = annual energy produced as electricity.

$E_{ph}$  = annual energy produced as heat

$E_f$  = annual energy input to the system from fuels contributing to the production of steam

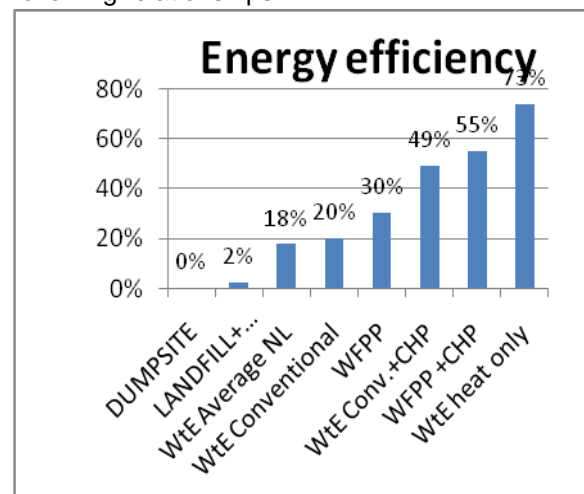
$E_w$  = annual energy contained in the treated waste calculated using the lower net calorific value

$K_{heat}$  = enthalpy factor

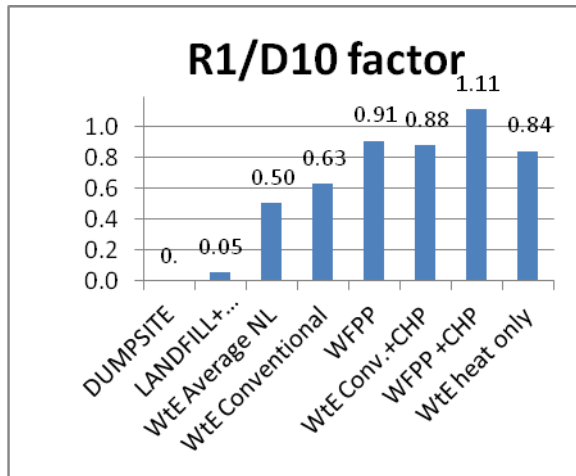
0.97 = heat loss factor in radiation and bottom ash.

The following graphs show the differences in energy efficiency between the various MSW processing technologies as well as the difference in the energy efficiency measurement methods.

Measured in the most common manner, total Btu's or calories, the efficiencies have the following relationships:

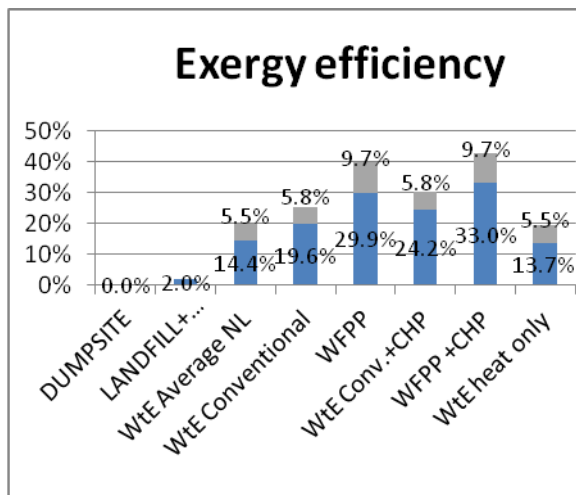


Using the R1-D10 Formula the numbers turn out as follows:



Please note that the WFPP<sup>®</sup> shown at 0.91 has almost double the value of the average WtE plant in The Netherlands. With maximum heat production the number increases to 1.11, more than double the average plant.

The following graph show energy production expressed in terms of Exergy. The blue bars show Exergy values related to the production of electricity. The gray extensions are Exergy values related to the recovery of metals from bottom ash, which add about 1/3<sup>rd</sup> to the electricity alone values.



### Bottom Ash Recovery

Bottom ash is the main resulting fraction after WtE processing of MSW. About 20 million tons of bottom ash is produced in Europe per year of which about 1.1 million tons in the Netherlands.

Bottom ash from MSW is usually regarded as a problematic material because of the risk of groundwater and surface water contamination as a result of the leaching of salts and heavy metals from the residues. This limits the use of bottom ash to low-grade applications such as the foundation of roads or landfill covering. In many cases in Europe bottom ash is landfilled without recovery of metals other than large pieces of iron.

The “perspective of mining” however shows bottom ash as an ore or raw material which contains concentrations of metals rarely found in nature. Indeed bottom ash actually represents a large potential for the recovery of ferrous and non-ferrous metals. For example, one ton of Amsterdam’s bottom ash contains about 130 kg of ferrous metals, 15 kg of aluminum, 7 kg of copper, zinc and lead, 1-2 kg of stainless steel, 10 grams of silver and 0.3 grams of gold. It is of interest to note that the silver content in Amsterdam’s MSW equals 10% of the Dutch silver consumption and the bottom ash produced, has a higher copper content than the copper ore in Chili!

To explore the options in recovery of these materials and simultaneously optimize the design of the system, AEB designed, built and operated a commercial size pilot plant with a capacity of 50 metric tons per hour.



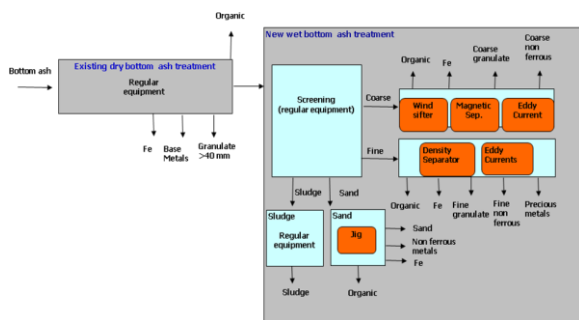
The plant recovers ferrous and non-ferrous metals from three different size fractions of the ash with a high grade and high recovery efficiency. The process uses conventional but improved, magnet and eddy-current separation

techniques as well as several new density separation approaches.

At the same time, because of the optimized wet process, the plant produces aggregates with very low concentrations of metals and organics. The deep removal of the metals and organics improves the engineering and environmental properties of the aggregates. The aggregates comply with strict civil-technical and environmental requirements and therefore are suitable as unrestricted construction material, for example in brick making or concrete production.

General application of this kind of Sorting After Incineration (SAI) could provide a significant contribution to the environmental performance of Waste-to-Energy. The main contributions are the recovery of metals, thereby saving primary resources, and a significant reduction of landfill by producing construction materials.

The following block flow diagram represents the major process steps of the AEB bottom ash recovery system.



The bottom ash from MSW processed at AEB is separated on site. The total treatment consists of 3 steps. In a first step the material is screened and shredded to below 40 mm. The main purpose of this step is to remove the ferrous scrap and the very coarse >40 mm, non-ferrous metals. At the second step the fraction between 0-40 mm is separated by an eddy current separator. The eddy current separator removes the +15 mm non-ferrous metals. The residue from the eddy current separator continues to the new wet physical separation pilot plant where

the -20 mm ferrous and non-ferrous metals are removed.

The wet pilot plant separates the pre-treated bottom ash according to size and density of the particles. The non-ferrous fractions are removed by eddy current separation, density separation and jigging. The resulting fractions are the coarse non-ferrous (6-20 mm), fine non-ferrous (2-6 mm) and the very fine non-ferrous (<2 mm) products. The 2-6 mm aluminum material is separated from the heavy non-ferrous by density separation.

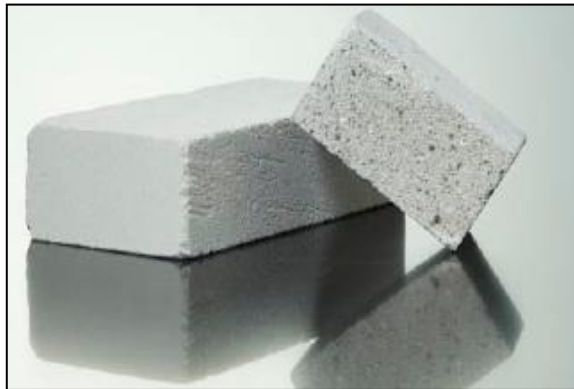


The main part of iron scrap (7%) is separated by dry physical methods at the beginning of the bottom ash treatment cycle. Another part, particles below <20 mm are then separated by wet physical methods. The 6-20 mm magnetic fraction (5%) contains 20% of iron scrap, the rest is magnetic stone. The 2-6 mm magnetic fraction (1.3%) represents another source of iron scrap. Further tests will be conducted to explore the recovery of these small amounts of iron.

Three different building products are produced by the wet physical separation. The first is the 6-20 mm granulate, the second is 2-6 mm granulate and the last one is the sand (100 µm-2 mm).



All three products are sold to building companies for the production of bricks,



and concrete



From each ton of Amsterdam's MSW AEB is able to recover and recycle the following marketable products:

Non-Ferro metals	5.50	kg
Ferrous metals	25.00	kg
Granulate	100.00	kg
Sand	100.00	kg
Salt	7.00	kg
Gypsum	5.00	kg
Fly ash (road filler)	<u>9.00</u>	<u>kg</u>
Total	251.50	kg

This is in addition to:

Electric Energy	850	kWh
District Heating	30	kWh*

Residues are:

Fines (Solid sludge-cake)	24.00	kg
Dry APC-residue	<u>5.00</u>	<u>kg</u>
Total	29.50	kg

While income from the sale of energy and recycled products are important contributions to the economics of AEB's operations, the avoided landfill costs are even more important to AEB's customers. The environmental benefits, lower impact on the environment and the reduced use of the earth's resources may well outweigh any monetary consideration.

### Plant Economics

It will be obvious that the investment cost for a plant of this size, complexity and redundancy in design is substantial. The benefits of the excellent environmental performance are important, although at present this does not translate into additional income in The Netherlands. This may change when the laws and regulations concerning CO<sub>2</sub> emissions change and energy produced from MSW will be regarded as clean energy and carbon credits monetized.

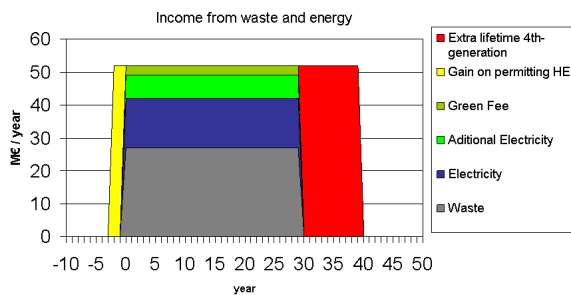
Still, and without the benefit of carbon credits, at €70 per ton, AEB has the lowest tipping fees in The Netherlands. This can be contributed to the robust design of the plant, which results in a high availability of 94%, low annual maintenance cost, scheduled maintenance shut-down once every two years and high energy production and material recovery rates.

There is another reason why AEB decided to design the WFPP<sup>®</sup> as advanced and robust as it is. The plant is designed to operate for a much longer period than the usual 20 or 25 years and we believe that 40 years is not an unreasonable expectation. That not only means that the bulk of the equipment will have to last that long. More important is that that plant is able to meet future environmental standards, which no doubt will become more stringent every year.

Our 2nd Generation WtE facility had to be shut down in 1993 after only 24 years of operation because it did not meet new, more stringent environmental standards. The cost of modifying the plant to meet the new standards would have been prohibitive, reason why AEB decided to build the new facility at the present location.



The impact of AEB's design concepts on the life cycle economics of the WFPP<sup>®</sup> can best be



demonstrated in the following diagram.

The gray area represents the usual income from the tipping fees AEB receives, and the blue colored area income from electricity produced and delivered at 22% plant efficiency.

The areas represented in other colors all show income derived from the advanced design of the WFPP<sup>®</sup>. Green is additional income having raised the efficiency from 22 to 30%. The moss color for the financing consideration AEB received, but could also be future carbon credits. Yellow is the permitting time saved by exceeding environmental standards, shortening the permitting time. And lastly the red area represents the extension of the economic life of the plant through a robust design and ability to meet future environmental standards.

### Conclusion

In the many years of its existence, AEB has developed new technologies, many of which are patented, and gained experience in the planning, design, building and operation of WtE

facilities. These efforts culminated in the largest and one of the most efficient WtE facilities in the world.

AEB has an interest in sharing this experience, license its technologies, and provide services to third parties planning to buy build or operate advanced WtE facilities.

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### References

Further information can be obtained at AEB's web site [www.afvalenergiebedrijf.nl](http://www.afvalenergiebedrijf.nl) and the brochure "Value from Waste" at <http://www.afvalenergiebedrijf.nl/bijlagen/value%20from%20waste.pdf>

The author gratefully acknowledges the following sources of data and information:

- Marcel van Berlo, AEB, [berlo@afvalenergiebedrijf.nl](mailto:berlo@afvalenergiebedrijf.nl), various publications
- Lenka Muchová et al, TU Delft, [L.Muchova@tudelft.nl](mailto:L.Muchova@tudelft.nl), Innovative Technology for the Treatment of Bottom Ash, ISWA/NVRD World Congress 2007
- Jörn Wandschneider, w+g engineering company, Hamburg, [wandschneider@wg-ing.de](mailto:wandschneider@wg-ing.de), Optimization measures for increasing efficiency using HR AVI-Amsterdam, ISWA/NVRD World Congress 2007