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TNO-report

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**Specific processing costs of waste materials in a
municipal solid waste combustion facility**

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Summary and Conclusions

Objectives

The objectives of this study are:

- to develop a methodology in which the different properties of various types of waste materials are reflected in their specific processing costs (SPC's) in an existing Municipal Solid Waste Combustion (MSWC) facility;
- to apply this methodology to calculate the specific combustion costs of PVC in comparison with (mixed) plastics, putrescibles, glass, wood, metals and paper;
- to investigate the effect of reduced putrescibles content in municipal solid waste (MSW) on the SPC's of PVC and other waste materials;
- to provide knowledge on the impact of chlorine (Cl) on process operation in a MSWC facility as well as the resulting environmental impact of processing PVC and other chlorine containing feedstock.

Cost calculations

A useful instrument to calculate cost data for waste combustion is the MSWC FACE model (Municipal Solid Waste Combustion Flow And Cost Expert model), which has jointly been developed by APME (Association of Plastic Manufacturers in Europe) and TNO (Netherlands Organization of Applied Scientific Research). With this model, investments, fixed and variable costs as well as energy recovery and emissions to air, water and soil can be calculated as a function of specific parameters, such as feed composition and operational conditions.

The FACE model enables the investigation of mass, energy and financial effects caused by an addition of a specific waste material to a MSWC facility, in which a well-defined reference household waste ("grey waste") is combusted.

A mathematical relationship has been developed to relate the results of these calculations to the specific processing costs of the waste material under consideration. Fixed and variable costs per tonne can be calculated for each waste material. The revenues of the energy production are included in the net variable costs.

Cost calculations have been conducted from the operator's point of view.

In a fully loaded plant, acceptance of each tonne of an alternative waste material (at a processing fee) will displace a certain amount of the MSWC facility's normal "grey" waste. The processing revenues from the displaced grey waste are forfeited; alternatively, the internal processing costs are avoided.

The calculated SPC's indicate the fee to be charged for the specific alternative waste material to maintain financial break-even with respect to the original situa-

tion. Break-even can be considered either from revenue, or from cost point of view. Both options are covered in this report.

Three scenarios have been considered, each describing a theoretical extreme in MSWC facility operation in terms of throughput capacity:

- Thermal limitation. The throughput of the MSWC facility is limited by the heating value of the waste feed. Addition of the specific waste displaces a quantity of reference grey waste proportionally to the heating value ratio between added waste material and grey waste. The calculated specific processing costs for the added material accounts for the variable costs of this waste as well as the fixed costs, where the latter is proportional to the heating value ratio.
- Mass limitation. The MSWC facility throughput is limited by mass. The addition of one tonne of added waste substitutes one tonne of grey waste. The calculated specific processing costs account for the variable costs of the added waste material and a share in the fixed costs identical to the original share of the displaced grey waste.
- No throughput limitation. The calculated specific processing costs only reflect variable costs.

In The Netherlands, individual MSWC facilities are generally thermally limited, whereas gate fees are charged on a mass basis. The scenario without throughput limitation is only incidentally encountered in real-life MSWC facilities, as obviously it reflects an economically unstable situation.

As an example, the process conditions and cost data (design situation) of a modern (Dutch) MSWC facility, the HVC Noord-Holland at Alkmaar, have been used to tune the MSWC FACE-model. This plant is provided with a spray-dryer for evaporation of purified scrubber effluent. The residues are then landfilled. Alternatively, a configuration with discharge of purified scrubber effluent has been used for calculation as it was anticipated that some waste materials would be affected by this difference in scrubber effluent treatment.

Figure 1 and 2 show the resulting specific processing costs. In the 'no limitation' scenario, these cost data coincide with the variable costs of processing a specific waste material. In the other cases, the data include both fixed and variable costs. In these calculations, soft and rigid PVC need to be distinguished. Soft PVC contains relatively high amounts of plasticizers compared to rigid varieties. As a result, soft PVC is lower in chlorine-content and higher in heating value. As these two parameters are expected to have a substantial impact on the specific processing costs, these two types of PVC have been treated separately in the study.

Conclusions with respect to methodology

- The MSWC FACE-model is based on mass and energy balances, i.e. no material specific assumptions need to be made at any stage. Materials are characterized by their elementary chemical composition. Furthermore, extensive supportive literature has been taken into account.
- A method has been developed to calculate specific processing costs of waste materials from comparing annual operational costs from the MSWC FACE-model, while adding one specific waste material to the feed of the MSWC facility.

Net variable costs per tonne, including the energy proceeds, can be calculated for each waste material separately.

- Only existing plants have been considered. The historical investment is made for processing grey reference waste. The addition of specific waste materials does not require additional investment.
Therefore, in this approach fixed annual cost are constant (i.e. independent of feed composition). Feed changes result in throughput variations, causing largely varying fixed costs per tonne of processed specific waste material.
- Allocation of fixed costs according to different rules per hardware unit is avoided. Such allocation rules are ambiguous as strict allocation rules can hardly be identified.
- Like costing models reported in literature, the developed specific processing cost model accounts for variable costs like the additive consumption and residue disposal costs. However, unlike any model in literature, this model takes allowance of the material specific energy revenues and includes throughput capacity effects in fixed costs.
- The developed method is linear, which implies that calculated specific processing costs are independent of the quantity of waste material added.
- Different situations as to the loading of the MSWC facility have been accounted for: a fully loaded MSWC facility, limited in thermal or in mass throughput, or an underloaded facility with spare capacity. These situations are theoretical extremes, based on the assessment of the MSWC facility operator.
- The methodology follows an incremental approach. Close examination of the actual operational situation at a specific MSWC facility is required to identify a meaningful scenario for modelling the addition of a specific waste material to this particular facility.

- The results of the calculations need to be extended to assess the average costs of waste materials already present in the MSWC facility waste feed. Accumulation to describe the overall future situation in The Netherlands needs additional input.
- Effects of differences in calculated specific processing costs can be logically explained and are internally consistent. On one hand, they are caused by variations in waste material properties such as heating value and elemental composition. On the other hand, they are caused by differences in the scenario with respect to the MSWC facility: thermal or mass limitation, spare capacity, or hardware configuration effects like discharge or evaporation of the flue gas' scrubber effluent.
- The application of the developed method is restricted by the validity of the expert rules of the MSWC FACE-model. This means that specific processing cost model calculations are valid within a limited area around the reference operating point of a MSWC facility.
- An illustration of the restricted validity in interpretation of the specific processing costs is given in the controversy that in thermally limited operation, added high calorific waste materials incur an economical penalty by high SPC's, whereas (the same) high calorific materials already present in the grey waste mixture stimulate the combustion of the waste mixture and thus are beneficial to the process. Therefore, it must be stressed that the specific processing costs calculated in this study are only valid for the situation when waste material is added as a separate material stream to a MSWC facility processing a reference grey waste. Conversely, SPC's cannot be directly applied to these components if these are considered as part of the existing grey waste mixture.
- In quantitative terms, SPC's can only be compared for one single MSWC unit, i.e. for a given hardware configuration and financial parameters. Other MSWC facility configurations, cost structures, energy revenues or additive and disposal fees will generate a different set of SPC's for all materials; SPC's are therefore not constant per material.
- The SPC calculations can be based on financial break-even in terms of identical cost to the operator. Alternatively, break-even can be calculated on basis of identical revenue. In the latter case, the actual gate fee from commercial practice (including profit elements) is input to the calculations. The desired basis for calculation is the operator's choice.
- Calculated model SPC's are only initial inputs to arrive at a real world gate fee in which the MSWC facility operator's commercial and strategic considerations are included.

Conclusions with respect to the calculated specific processing costs

- Specific processing costs have been calculated for soft and rigid PVC, (mixed) plastics (including PVC), wood, putrescibles, paper, glass and metals (see figures 1 and 2).
- The calorific content of the waste materials in relation to the grey waste - reference is dominating the results in many cases: metals, glass, putrescibles have heating values below the grey reference, paper and grey waste have about identical heating value, whereas wood, any type of PVC and all other plastics have a higher energy content.
- In case the MSWC facility is considered thermally limited, high calorific waste materials show relatively high SPC's; wastes with a relatively low heating value incur lower costs.
- In case the MSWC facility is considered mass limited, low calorific waste materials show relatively high SPC's. Wastes with a high heating value benefit from their contribution to the energy proceeds and incur lower costs in this case.
- In the absence of throughput limitation when only variable costs determine break-even, waste materials have specific processing costs that are obviously well below the gate fee for original grey waste and in most cases even are negative. Glass, metals and in some cases PVC are exceptions, as residue disposal costs have a large impact and glass and metals have zero energy content and, as a consequence, do not generate electricity revenues.
- The main distinction in specific processing costs between PVC and other waste materials are its variable costs, resulting from required chloride removal from the flue gases. At MSWC facilities where salt containing effluent from the wet scrubber (after purification) cannot be discharged, this effluent must be evaporated and the resulting solid salt residue deposited in a landfill. These additional variable costs, which are mainly determined by salt disposal, are significantly higher for rigid than for soft PVC. The latter, has a lower chloride content (and consequently lower chloride removal and disposal costs) and generates higher energy recovery revenues. In the case where the purified scrubber effluent is discharged, the additional variable costs for PVC are considerably (70%) lower.

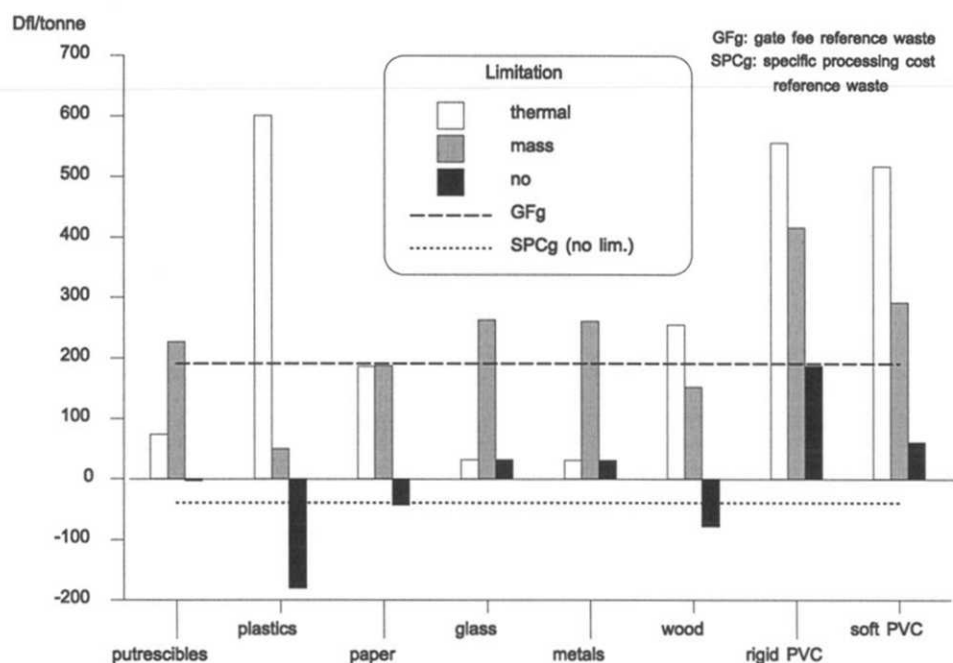


Figure 1 Specific processing costs for a MSWC facility with *evaporation* of the purified scrubber effluent.

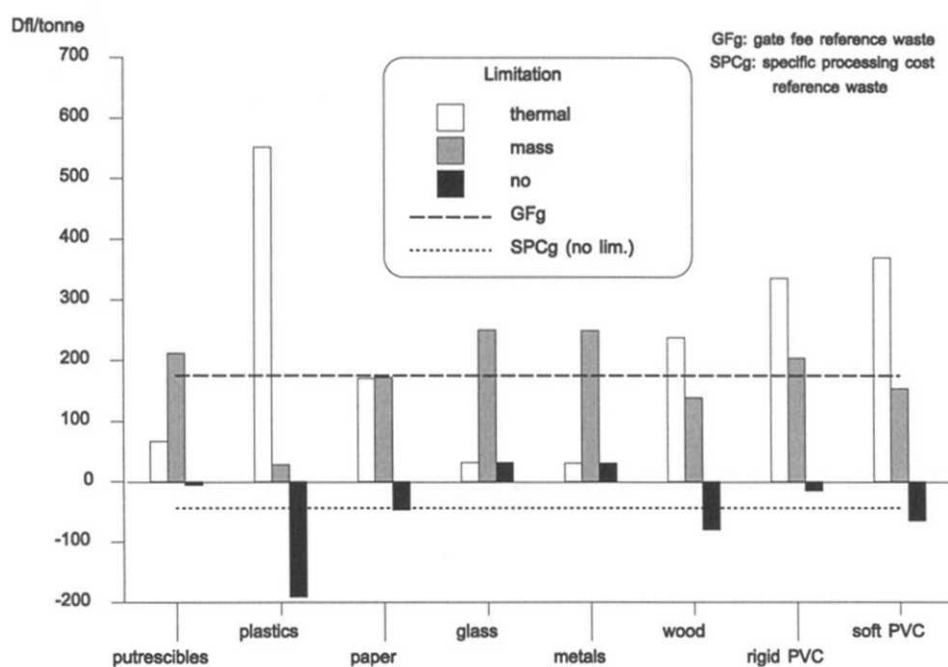


Figure 2 Specific processing cost for a MSWC facility with *discharge* of the purified scrubber effluent.

- Despite the additional variable costs, which add significantly to the specific processing costs of PVC, the SPC of plastics in a thermally limited MSWC facility is higher than for PVC. This is due to the large demand on thermal capacity claimed by plastics, which show the highest calorific value of the materials considered in this study.
- When considering the specific processing costs of one additional tonne of grey waste, constructed from the specific processing costs of waste materials in ratios reflecting their relative presence in grey waste, the contribution of PVC to the total cost is low (<2%), as the concentration of PVC in grey waste is only around 0.6 wt%.
- A reduction of the putrescibles content of the grey waste, used as a reference, from 33.1 to 28 wt%, has no influence on the specific processing costs of the waste materials. However, the costs of combustion of grey waste increase by 5% due to this elimination of part of the putrescibles.

Conclusions with respect to qualitative aspects of chlorine in waste

Literature shows:

- The behaviour of chlorine under MSWC conditions can be considered constant, regardless its source, as, at typical MSWC conditions, no significant difference in behaviour between Cl from different sources can be substantiated. The fate of chlorine from PVC, putrescibles or natural salts is therefore considered identical.
- Plastics, including PVC, as hydrocarbon sources with high energy content enhance volatilization of the waste. The increase in combustion conversion improves the burn-out of the organic residues. The enhanced volatilization can cause a shift of volatile heavy metals from grate-ash to fly ash.
- PVC or other materials as chlorine sources improve volatility of heavy metals, causing their transfer as metal chloride from grate-ash to fly-ash.
- The presence (rather than the concentration) of chlorine in MSW feedstock limits the maximum temperature that can be applied in the steam generating boiler, while keeping corrosion/maintenance costs at acceptable levels. This restriction limits the efficiency of electricity generation in MSWC plants to 20-25%.

Substantial reduction of chlorine in the feed (e.g. by complete elimination of PVC, representing 38% of total chlorine intake) is not expected to change this picture.

- The limiting step in dioxin formation in MSWC operation is not primarily determined by the amount of chlorine in the feed. At a wide range around typical MSWC operation, dioxin formation is determined by plant hardware configuration and operating conditions.

Chlorine mass balance aspects

The quantitative fate of chlorine from any source is illustrated by Figure 3.

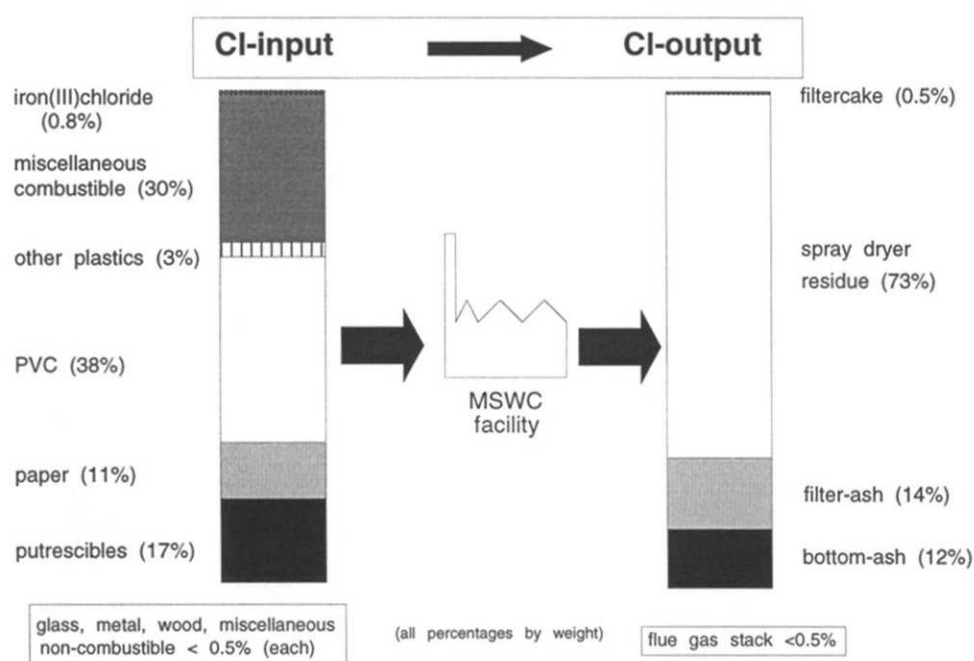


Figure 3 Chlorine mass balance for a MSWC facility (HVC Noord Holland example).

The PVC polymer accounts for 38 wt% of the chlorine input; the remainder is mainly introduced via putrescibles (17 wt%), paper (11 wt%) and miscellaneous combustibles (30 wt%).

It should be noted that waste composition data on chlorine found in literature are scattered over a certain range. However, computer programmes as MSW-FACE need a single figure as an input. Therefore, the calculated mass balance data for the waste feed reflect typical values for the chlorine quantity in the waste materials.

The chlorine is largely (73 wt%) captured in the spray dryer output as solid residue (class C2, hazardous waste) or alternatively as liquid effluent. About 26 wt% ends up in grate-ash (12 wt%) for road construction application, and in filter-ash (14 wt% for road construction application as well or for storage as class C2,- hazardous waste). Filtercake, heavily contaminated with heavy metals, represents

0.5 wt% of chlorine output (landfilled as class C2, hazardous waste).
In all these residues, chlorine is mainly (>99.9999%) present as inorganic chloride.

Finally, 0.1 wt% of chlorine leaves the plant as gaseous hydrochloric acid, via the stack.

Outlook

The developed method provides an initial basis for differential costing to the MSWC facility operator, in those situations where an additional amount of specific waste is offered for processing. From this basis, the operator can determine the gate fee to be charged by adding his specific commercial and strategic considerations to the model's calculated specific processing costs.

Before applying the method, local factors with respect to the variable costs and the positioning of the MSWC facility towards the discussed scenarios to be considered have to be determined and the validity of the assumptions must be checked.

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1. Introduction

1.1 Background and objective of the study

The environmental policy of the Dutch government (Ministry of Housing, Spatial Planning and the Environment: VROM) is targeted at an optimum disposal structure for each waste stream through an integrated approach. After prevention, re-use and recycling, combustion with energy recovery is considered preferable to landfill. Prevention and recycling efforts will a priori not provide complete solutions; for many waste streams combustion is a necessary and unavoidable part of the total disposal structure.

Within this scope, there is a need for improved understanding of the environmental effects and costs that result from the combustion of specific types of waste materials as offered to municipal solid waste combustion (MSWC) facilities. Such understanding is important in decision making to optimise various final processing routes.

An average processing rate (“gate fee”) per tonne of waste offered, regardless its composition, is generally imposed in European MSWC facilities. There is an increasing need for an objective rating system for various individual waste materials as it is realized that different types of materials have different effects on the performance and cost of a MSWC facility.

VROM is notably interested in the effects and costs connected with the co-combustion of PVC in a MSWC facility, as PVC represents a considerable buffer in the chlorine chain. The chlorine stored in PVC will be released in the environment at some point in the future. The ban on landfilling combustible wastes in The Netherlands makes it very likely that this release of PVC will happen by combustion in a MSWC facility. This study has to give insight in perceived costs and expected environmental impacts of processing PVC in MSWC facilities in order to facilitate VROM to validate and possibly review its PVC policy.

One of the goals of the APME (Association of Plastics Manufacturers in Europe) is to contribute to the generation of objective data, based on sound science, and to support decision making in the policies of Industry and Governments in Europe on plastic waste processing. APME is interested in improved understanding of the material-specific combustion costs of plastics, specifically in a comparative relationship with those of other materials which are offered to a MSWC facility, like putrescibles, paper, glass, metals and wood.

Against this background, the TNO Institute of Environmental Sciences, Energy Research and Process Innovation has been asked to conduct the present study. For this purpose the MSWC FACE-model (Municipal Solid Waste Combustion Flow And Cost Expert model), which was jointly developed by APME (Association of

Plastic Manufacturers in Europe) and TNO has been used to calculate the processing costs of MSWC facilities.

The objectives of the project are:

- to develop a methodology in which the different properties of various types of waste materials are reflected in their specific processing costs (SPC's) in a Municipal Solid Waste Combustion (MSWC) facility, accounting for differences in waste characteristics such as elementary composition and heating value.
- to apply this methodology to calculate the specific combustion costs of PVC in comparison with (mixed) plastics, putrescibles, glass, wood, metals and paper;
- to investigate the effect of reduced putrescibles content in municipal solid waste (MSW) on the SPC's of PVC and other waste materials;
- to provide knowledge on the impact of chlorine (Cl) on process operation in a MSWC facility as well as the resulting environmental impact of processing PVC and other chlorine containing feedstock.

1.2 Commissioning

The project has been performed by joint order of the Ministry of Housing, Spatial Planning and the Environment in The Netherlands (VROM) and the Association of Plastics Manufacturers in Europe (APME).

A Technical Committee has been installed to supervise the project, with the following membership:

- Ms. E.C. Bouwer LL M, on behalf of VROM;
- Drs. C.J.G. van Halen of PI Management, for technical support on behalf of VROM;
- Dr. A.H.M. Kayen of Shell International Chemicals on behalf of APME;
- Ir. H. Nieuwenhuijsen for the Steering Committee on PVC and Life Cycle Management.

Considering the impact of the study, the technical committee asked experts to comment draft versions of the report and conduct a peer review.

Drs. H.J.W. Sas of the Centre for Energy Conservation and Environmental Technology at Delft has been asked especially to review the methodology as developed in this study. Dr. J. Vehlow of the Forschungszentrum Karlsruhe GmbH (Germany) has been asked for his technical expertise on the partitioning behaviour of elements and solids in MSWC facilities. Mr. W. Sierhuis of the MSWC facility at Amsterdam (AVI Amsterdam) and Ing. E. Colnot of the MSWC facility at Alkmaar (HVC Noord-Holland) have been invited for their expertise in the field and day-to-day operation of a MSWC facility. Their statements about the report are presented in Appendix E.

Obviously, the final responsibility for the contents of this report remains with TNO.

1.3 Basic methodology

A survey of definitions and abbreviations is included in chapters 7 and 8.

In the past, APME and TNO jointly developed a computer model for calculations and modelling of municipal waste combustion: the MSWC FACE model (Municipal Solid Waste Combustion Flow And Cost Expert model). With this model, investment and operating costs as well as energy recovery and emissions to air, water and soil can be calculated as a function of specific parameters, such as process conditions in the MSWC facility and feed composition.

This FACE model allows, within certain limits, to investigate the overall mass, - energy and financial effects caused by the addition of a specific waste material - offered to a MSWC facility.

Subsequent to the MSWC FACE-model, a mathematical relationship is developed to relate the results of the overall calculations to the specific cost of combustion of the waste material under consideration.

Calculations have been conducted for a broad range of added waste materials: paper, wood, PVC, (mixed) plastics, glass, putrescibles and metals.

Like in any industrial installation, the presence of chlorine in the MSWC feed has an impact on the construction materials. Therefore, in addition to cost calculations, attention is paid to the chlorine balance of a MSWC facility and, in a qualitative way, to other effects of chlorine in such a facility like its effect on corrosion, steam temperatures, energy yield and residue composition.

2. Calculation of specific processing costs

Here the used method for the calculation of the specific processing costs is explained in two ways: first the developed method is derived in a pragmatic way (2.1), secondly, the same formula is explained with more fundamental economical concepts, like fixed and variable costs (2.2).

2.1 Pragmatic calculation of specific processing costs

2.1.1 Economics of MSWC operation

2.1.1.1 Gate fee

The economic environment in which the MSWC plant is operated, determines the operator's philosophy to arrive at the "gate fee", i.e. the amount charged to a waste owner to have 1 tonne of his waste processed in the MSWC facility. The gate fee is a commercial reality. Even though MSWC facilities are generally owned and operated by the public sector, free market forces like supply and demand, the cost of capital, labour, duration of contracts, etc. play a major role.

In a healthy economical operation, the annual net costs to the MSWC owner (i.e. total costs minus proceeds from sales of generated electricity to the public grid) are exceeded or at least balanced by the annual revenues from gate fees.

Gate fees are generally based on average costs per tonne waste, and based on: annual net MSWC cost, amount of waste with the annual average composition processed per year. A profit element can be added, based on short term commercial negotiation or long term processing contracts with waste owners (e.g. local communities).

In principle, gate fees can be looked at in two ways from the MSWC facility operator's point of view: a. they can be considered as an income per tonne of waste, or, b. they can be seen as the net cost per tonne (total cost minus energy revenue). The first approach allows incorporation of commercial and strategic considerations as a profit or discount.

2.1.1.2 Specific processing costs

Integrated waste management triggers separation of waste streams by the individual waste owner or in separation plants, for processing (e.g. composting) in installations specifically suited for typical waste streams. This generates additional waste streams of different composition which may be offered to the MSWC facility operator for processing. Besides, due to the expected reduction in landfill (e.g. ban on landfill of combustible wastes in The Netherlands), other waste streams, like industrial or agricultural waste, building and construction waste will

increasingly become available for combustion. This proliferation of a variety of specific waste streams triggers a need to distinguish between their specific processing costs: different types of waste may require different specific processing costs.

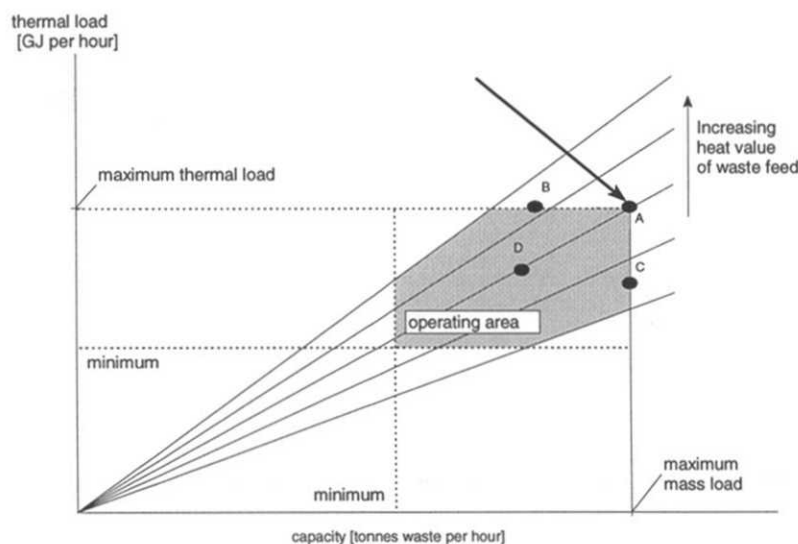
These waste streams have elemental compositions, differing from the “grey” waste stream. The latter was the original basis of design for the MSWC facility, and consequently the basic input in establishing the gate fee.

This chapter provides input to the costing of waste material from the MSWC facility operator’s point of view. The question: “What is the additional (or saved) cost to the MSWC facility owner by accepting 1 tonne of waste material for processing?” is answered.

The original gate fee for average grey waste, after subsequent cost correction as thus calculated, pragmatically provides the financial break even point to the operator when accepting a different kind of waste feed.

2.1.1.3 Plant loading

Plant loading is a predominant factor in the recovery of costs to the MSWC facility operator, as illustrated in Figure 2.1.



Figuur 2.1 *Process operating diagram*
A: design point, both mass and thermally limited operation
B: thermally limited operation
C: mass limited operation
D: not limited (underloaded) operation

A plant has been designed to process a maximum amount (tonnes per hour) of waste with design heat value (MJ per kg). Equipment has been designed to accommodate the heat liberated by its combustion. The plant's design point is represented by point A in Figure 2.1. If waste of above design heating value is combusted, the extra joules can no longer be accommodated and the throughput has to be decreased: the plant is heat limited in processing waste, reflected by point B. If waste with a calorific content below design value is combusted, throughput could be increased to arrive at the original thermal loading. However, the throughput is limited to the original mass throughput based on design: the plant is mass limited in processing waste, reflected by point C.

Finally, in situations where insufficient waste is offered to the facility and amounts and heating value are such that both tonnages and joules can be accommodated at below design value: the plant is underloaded as reflected by point D.

Cost- and pricing philosophy of the MSWC facility operator will be determined to a large extent by the positioning of his particular plant according to the theoretical extremes A, B, C or D.

In The Netherlands, individual plants are generally situated as in point B, thermal limitation. However, at the moment, costing is mainly done on a mass basis, and therefore point C is also relevant.

In this study it is assumed that limitations only occur with respect to thermal or mass throughput. Limitations on other waste characteristics are considered to play no role.

2.1.2 Acceptance of additional waste

In this section we will determine the financial effect to the MSWC facility operator when accepting specific waste material P with net heating value H_p (MJ/kg) in his plant, which usually processes average "grey" waste, with net heating value H_g (MJ/kg), at gate fee GF_g (Dfl/tonne).

In considering these financial effects for the three situations (thermal, mass and no limitation), it is assumed that the acceptance of waste material does not change the operator's position with respect to the theoretical extremes: mass limited remains mass limited, thermally limited remains thermally limited and full loading will not be achieved while accepting additional waste in an underloaded starting situation.

a. MSWC facility is limited in thermal throughput

Thermal limitation is generally incurred in the boiler in which the heat exchanging surface limits the amount of heat which can be transferred from the hot flue gases for steam generation.

In practice, many MSWC facilities may be thermally limited as the average heating value of the grey waste has increased continuously during the last decades (by an increase of high calorific materials like plastic and paper and/or a decrease of low calorific materials like putrescibles).

The MSWC FACE-model is able to calculate the total net annual cost F_s (in Dfl per year) in the starting situation S. It is assumed that in the starting situation S grey waste G with known elemental composition is processed at a throughput such that the plant is thermally fully loaded.

Additional waste P can only be accepted if a calorific equivalent amount w of grey waste is substituted: this means

$$w = t_g / t_p = H_p / H_g \quad (1)$$

wherein:

w	displacement ratio between added P and displaced grey waste [tonnes/tonnes]
t_g	amount of grey waste displaced [tonnes/year]
t_p	amount of waste material P added [tonnes/year]
H_p	heating value of waste material P [MJ/kg]
H_g	heating value of grey waste [MJ/kg]

Each tonne of waste P accepted, will displace w tonnes of grey waste from processing. The new MSWC facility waste feed can be calculated by the MSWC FACE-model in terms of elemental composition. The original composition in situation S is corrected for the added amount of P (with known elemental composition) and the corresponding withdrawal of w times as much grey waste: $t_p * w$ tonnes per year.

The MSWC FACE-model can now calculate the total net cost F_n in the new situation N, based on the adjusted elemental composition. The calculated financial effect on the cost to the MSWC facility operator is $F_n - F_s$ (which can be either positive or negative).

In order to achieve financial break-even these (increased or reduced) costs should be compensated in the operator's income. This compensation is represented as $t_p * SPC_p$, or the amount of P added (t_p tonnes/year) times the specific processing cost of P (SPC_p Dfl/tonne).

However, the fee for processing the displaced amount of grey waste ($t_p * w$ tonnes/year) has been forfeited: $t_p * w * GF_g$.

Therefore:

cost difference = revenue difference

cost (new) - cost (old) = extra revenue - missed revenue

$$F_n - F_s = t_p * SPC_p - t_p * w * GF_g \quad (2)$$

Now, SPC_p (the cost to be charged per tonne of P processed to maintain financial break even) can be calculated:

$$SPC_p = (F_n - F_s)/t_p + w * GF_g \quad (3)$$

F_n and F_s (total annual cost before and after waste addition in Dfl per year) are obtained from the MSWC FACE-model calculation, w is derived from basic feed data and GF_g is a contractual or commercial reality.

b. MSWC facility is limited in mass throughput

Mass loading is mainly limited by the capacity of the grate, on which combustion and inertisation of the waste is achieved. Only when the heating value of the waste has decreased below the design value, facilities may be mass limited. Plants originally designed to accept pretreated waste with a high calorific value (refuse derived fuel: RDF), are known to incur mass limited operation in times when the pretreatment is abandoned (e.g. because of lack of outlets for the fractions co-separated with RDF).

At mass limitation, t_p tonnes of additional waste P can be accepted only, when an equal mass t_g of grey waste is displaced, i.e. $t_p = t_g$. For the substitution factor w we can now write:

$$w = t_g / t_p = 1 \quad (4)$$

Reasoning analogous to the thermally limited situation, as described under a., provides a result identical to formula (3), where w now equals 1 and is determined by mass rather than heating value.

c. MSWC facility is operating below capacity

Situations without throughput limitations only occur in the situation where insufficient waste is offered to the plant to obtain full loading. As mentioned before, this situation is very unlikely to occur other than temporarily, like in early phases of the plant project life time, where temporarily overcapacity has been planned, or due to competition with other waste processing plants, or to obstacles in legislation or contracts prohibiting delivery of waste to a plant (for example, local authorities may not allow interregional transportation).

Obviously, the plant will suffer structurally, in case no financial compensation in the gate fee can be commercially achieved.

However, from a theoretical point of view, this scenario is interesting as it provides the link to specific variable costs as explained in chapter 2.2.

The plant operates below maximum throughput in terms of heat, mass or any other limiting factor. Acceptance of t_p tonnes of waste invariably generates additional income, without missing revenues as no grey waste has to be displaced. From a financial point of view, the MSWC facility operator can accept additional waste as long as the cost difference $F_n - F_s$ is covered, as can be seen from formula (3). As no grey waste is displaced, the substitution factor w equals 0, eliminating the original gate fee for grey waste from the equation:

$$SPC_p = (F_n - F_s)/t_p \quad (5)$$

Though in this scenario only variable costs have to be considered to calculate financial break-even, obviously, an operator will always attempt to realise a higher fee to obtain a maximum contribution to fixed costs.

This illustrates again that calculated SPC's (especially in this unlimited scenario) can only be a first input to the operator in establishing a commercial gate fee.

2.2 Variable and fixed cost; relation with specific processing costs

The specific processing costs in formula (3) have been derived pragmatically thus far, but can also be related to more fundamental cost parameters.

2.2.1 Variable cost element

In (heat or mass) limited cases, the annual fixed costs are not influenced by the substitution of w times t_p tonnes of grey waste by t_p tonnes of P:

- as an existing plant is considered the annual capital costs are not affected by a change in waste feed;
- labour is constant if the overall mass flow is largely unaffected;
- maintenance is not influenced at maximum throughput.

Total annual fixed costs also remain constant if additional waste is accepted in an underloaded plant. (However, maintenance costs may slightly increase in this case, although the costs will be below the original figure at full throughput in the design situation.)

Fixed cost elements are included in both F_n as F_s at the same value and will consequently eliminate from their difference $F_n - F_s$. Therefore, this difference only includes variable cost elements. The expression $(F_n - F_s) / t_p$ in equation (3) reflects the additional (positive or negative) change in variable cost per tonne specific waste material P. It shows differences in residue disposal costs, electricity reve-

nues, chemical consumption, etcetera, as P (with respect to grey waste) has a different ash content, heating value or elemental composition, requiring a different amount of process chemicals.

Taking these considerations into account, formula (3) can be simplified:

Both total annual MSWC costs F_n and F_s include variable as well as fixed cost elements:

$$F_n = F_{f,n} + F_{v,n} \quad (6)$$

and, obviously:

$$F_s = F_{f,s} + F_{v,s} \quad (7)$$

$F_{f,n \text{ or } s}$ fixed annual cost in situation N or S [Dfl/year]

$F_{v,n \text{ or } s}$ variable annual cost in situation N or S [Dfl/year]

and, - as annual fixed cost remain unchanged - :

$$F_{f,n} = F_{f,s} \quad (8)$$

With (6), (7) and (8) substituted, formula (3) turns to:

$$SPC_p = (F_{v,n} - F_{v,s})/t_p + w * GF_g \quad (9)$$

The difference in variable costs between situations N and S is caused by the addition of t_p tonnes of P and the displacement of t_g tonnes G.

Therefore:

$$F_{v,n} - F_{v,s} = t_p * v_p - t_g * v_g \quad (10)$$

wherein:

$v_{p \text{ or } g}$ variable cost per tonne P or G [Dfl/tonne]

t_g tonnes of G displaced [tonnes/year]

Previously (formulae (1) and (4)), we already stated that the displacement factor w indicates the ratio between displaced tonnes G and added tonnes P:

$$w = t_g / t_p \quad (11)$$

Furthermore, the gate fee for the reference grey waste can be written as the sum of the variable and fixed cost, where the latter may be augmented to include a profit element:

$$GF_g = v_g + f_g \quad (12)$$

wherein:

f_g fixed cost per tonne G [Dfl/tonne]

Combining formulae (9) to (12) gives:

$$SPC_p = (t_p * v_p - t_g * v_g) / t_p + (t_g / t_p) * (f_g + v_g)$$

$$\text{or: } SPC_p = v_p + (t_g / t_p) * (-v_g + f_g + v_g)$$

thus:

$$SPC_p = v_p + w * f_g \quad (13)$$

In wording: the specific processing cost of an added waste material contains its variable cost plus a share in the fixed cost depending on the ratio between added P and displaced G.

Though formula (13) is much more transparent, formula (3) contains GF_g , which provides a direct link to the commercial reality in the reference situation. Therefore, both formulae have their benefits and will be used where appropriate in this report.

2.2.2 Fixed cost element

All fixed cost elements are introduced as part of GF_g , the second expression in formula (3) and explicitly through f_g in formula (13).

2.2.3 Profit element

The calculation of the SPC_p through formulae (3) and (13) is based on financial break-even compared to the starting situation for the MSWC facility operator. This may be achieved in two ways:

- a. Break even is required in terms of income to the MSWC facility operator. This is most clear via formula (3), where GF_g reflects the current commercial gate fee, including a profit element.
The additional waste P, charged at SPC_p , would generate break even in revenue, realising the same amount of profit as in the starting situation.

- b. Break even can equally well be required in terms of costs to the MSWC facility operator (as considered so far). In this case, the value for GF_g , entered in formula (3), should contain no profit element but only costs. This value is available to the operator from historical plant performance data. Alternatively, a cost-based value for GF_g could be directly calculated from the MSWC FACE-model, provided the model accurately describes the plant's cost structure. In this case, the additional waste P , charged at SPC_p , would generate financial break even operation, without any profit (on the same basis as in the starting situation).

The choice between either an income or cost based reference is open to the reader or MSWC facility operator.

In this study, based on the HVC Noord-Holland example, the financial section of the MSWC FACE-model has been tuned such, that the model output (net processing costs in the reference situation) equals the actual gate fee (GF_g), charged in 1995, thus including a possible profit element.

2.2.4 General accuracy

Fixed costs, calculated by the model, have been eliminated from formula (3) by $(F_n - F_s)$ (see 2.2.1). True fixed costs have impact on SPC_p through GF_g in formula (3), but are not necessarily separately visible, as the variable costs of processing grey waste and a profit element are also included in the GF_g , the anchor to (commercial) reality. In formula (13), the fixed costs (per tonne) become separately visible in f_g . However, f_g , which can be calculated from GF_g when the variable cost of grey waste is known, as logically:

$$GF_g = f_g + v_g \quad (14)$$

If the break-even situation is calculated on basis of income (2.2.3, under a.) rather than on costs, using GF_g means that the MSWC FACE-model only has to provide the adjustment in variable costs: $(F_n - F_s) / t_p$ for formula (3) or v_p and v_g for formula (13). If GF_g contains a profit-element, the calculated SPC automatically contains the same amount of profit.

In case the break-even situation is calculated on basis of costs (3.2.3, under b.) this "anchor to reality" is missing and the value for GF_g has to be generated by the MSWC FACE-model.

The simulation of only the variable costs with the MSWC FACE-model is more accurate than the simulation of both fixed and variable costs.

This is obvious when realizing that, in the MSWC FACE-model, like in real-life, the uncertainty in the fixed cost calculations (investment, depreciation, etc.) is larger than in the variable cost calculations.

2.3 Scope and limitations of the specific processing costs concept

The limitations incurred in the process of SPC calculations originate from 4 sources:

- the use of the MSWC FACE-model (section 2.3.1);
- the use of SPC-formula (3) (section 2.3.2);
- limitations in generalisation of the results (section 2.3.3);
- limitations of model approach versus real world practice (section 2.3.4).

2.3.1 The use of the MSWC FACE-model

a. Validity ranges in the MSWC FACE-model

Reference situation

Expert rules, based on literature surveys are the foundation of the previously developed MSWC FACE-model [Rijkema, 1996].

Specific input coefficients have been introduced, derived from state-of-the-art technology, supplemented by input data that best describe the specific situation at the HVC Noord-Holland, the reference example in this study.

These inputs are based on average, design operation, e.g. the normal window of operation on which virtually all experience is based. The input coefficients are only valid within a certain range around this average operation point.

Prudence while changing the waste feed around the reference situation

A change in the waste feed (by adding a waste material) may have the effect of leaving the original window of operation of the MSWC facility. For example, addition of too large amounts of glass or metals (with a combustion behaviour completely different from the higher calorific average feed) the model will lead to areas outside the normal operation window, where the used coefficients are no longer valid, which will trigger erroneous conclusions.

Therefore, the validity range is restricted to an unknown area around the grey reference point. The size of this range depends on the type of waste material added, or more specifically, on the difference in combustion behaviour between added waste material and average waste feed. Addition of wood or paper (with a heating value and physical matrix relatively close to average waste) will be tolerated to a larger extent than addition of metals or polymers.

Anyway, in order to maintain validity of the used coefficients in the MSWC FACE-model, deviations from the reference composition must be relatively small.

b. Underlying assumptions in the MSWC FACE-model

- **The distribution behaviour of any chemical element in the furnace is constant, i.e. independent of changes in the waste composition.**

This assumption can be challenged:

The physical matrix of the waste plays a role in more extreme situations.

For example, relatively immobilized heavy metals in glass or sand/minerals are expected to end up preferably in the bottom-ash. However, the same heavy metals, if finely dispersed as part of a combustible matrix (e.g. paper with printing ink or polymers with pigments) would be anticipated to end up preferably in fly-ash (or other flue gas cleaning residues).

Another example: plastics are known to gasify/decompose easily in early stages of the combustion on the grate (in the furnace). This results in high local gas velocities which trigger the entrainment of (heavy metal containing) dust particles to the flue gas. Thus, the ratio bottom-ash/fly-ash is shifted.

This transfer from bottom-ash to fly-ash cannot be quantified and had to be neglected.

Again, it is assumed that the impact of these effects can be neglected when allowing only small enough deviations from the reference starting point.

To increase confidence in the “constant distribution behaviour” assumption, it should be realized that the values in the MSWC FACE-model are based on a variety of literature data from various MSWC facilities, embracing a rather wide span of waste compositions and probably a large variety in furnaces, without showing very wide ranges for the distribution coefficients.

- **Distribution coefficients of chlorine and heavy metals are constant, regardless the chemical environment in the waste feed.**

In section 4.2.2.3 it is explained that the chlorine behaviour in the furnace is not significantly influenced by the chemical origin of the chlorine, i.e. regardless whether the Cl originates from putrescibles, NaCl salt or PVC¹. This also concerns the influence on the volatilization of heavy metals, which is also unaffected by the chemical nature of the chlorine.

1. As the distribution coefficient of Cl was perceived to be rather critical, a sensitivity analysis was executed. For the distribution of Cl from PVC it was assumed that 85% of the Cl was converted to HCl (between 73% for grey waste and 100% as theoretical maximum). This results in an increase in SPC in case of scrubber effluent evaporation of 25 Dfl/tonne for soft PVC and 40 Dfl/tonne for rigid PVC. In case of scrubber effluent discharge these increases in SPC are 7 Dfl/tonne for soft PVC and 12 Dfl/tonne for rigid PVC. It is concluded that the SPC for PVC is rather sensitive to the model's input for chlorine distribution.

In section 4.2.2.3 it is also documented that increasing amounts of chlorine (of any source) triggers additional formation of heavy metal chlorides. These chlorides are in many cases (especially for K, Cu, Zn, Pb, and sometimes Sb and Sn) more volatile than the other heavy metal salts or oxides. Therefore, an increase of chlorine in the feed will directionally lead to an increased transfer of heavy metals from the bottom-ash to the flue gas, and consequently to the fly-ash and other flue gas cleaning residues.

These effects cannot be responsibly quantified and have been neglected. This is justified (again) by allowing only small excursions from the reference situation.

- **The spray dryer residue has a constant composition**

The solid residues from the spray dryer are known to be hygroscopic and alkaline. On storage, water and carbondioxide will be incorporated in the crystalline state and as carbonate.

It was assumed, that addition of waste does not significantly change these effects and has no impact on the residue disposal costs. For the HVC this assumption is valid as the residue is collected from the plant in big bags which are closed and transported in containers. Uptake of water or carbondioxide does not play a significant role under these conditions as the determination of the disposal cost is based on the weighed amount of residue as it leaves the facility, i.e. on dry basis.

- **Changes in residue composition do not affect the disposal cost**

An increase in the heavy metal content of solid residues probably leads to an increase in the leaching of heavy metals from these residues, especially as the effect can be enhanced by increased Cl-content of the residues, which is known to facilitate the leaching of heavy metals [o.a. Hunsinger, 1994]. An increase in leaching of heavy metals might cause a directional increase in costs for treatment and disposal of these residues.

Solid residues are categorized in various classes (4 in The Netherlands: C-1 to C-4) for disposal, each with a corresponding fee. Within the operating window of the MSWC facility, the effects of waste composition changes on the composition of the residues are assumed to be too small to cause a shift to another waste disposal category. As these small changes will occur only within such category, the disposal fees have been kept constant, regardless waste compositional changes.

- **Virgin and waste composition are not identical**

The composition of a waste material offered to the MSWC facility is defined as its composition after separation from mixed municipal solid waste. This means that the waste compositions used are not those of virgin material but represent the composition at the post-consumer stage, i.e. including impurities introduced during end-use of the material (e.g. ink on paper or plastic), including attached dirt (e.g.

food remnants in packaging materials) or with a water content which is not typical for the virgin material. As the values as used originate from the analyses of actual piles of mixed waste (see Appendix C), the paper composition includes a relatively high water content. This is partly due to water transport from putrescibles to paper in the mixed waste. To judge the sensitivity to this water content, calculations were executed under the assumption that 50% of the water in the paper originated from other fractions. These calculations indicated that the specific processing costs of paper changed by approximately +15% for the thermally limited, -5% for the mass limited and -20% for the underloaded MSWC facility (see Appendix D). Though these deviations are considered acceptable in relation with the uncertainty in the calculated specific processing costs, the SPC of especially paper should be scrutinized for the assumed water content, i.e. assumed heating value. Other elements or compounds may also migrate between fractions in the waste but with reference to the migration of water this concerns a minor effect. Correction for these phenomena is not possible due to lack of useful and consistent data.

2.3.2 The use of SPC formula (3).

a. No material specific cost allocations are made.

The only material specific input in the MSWC FACE-model is the elemental composition of the considered waste material and its heating value. On addition of a specific waste material (with known elemental composition and heating value) the model requires the overall elemental composition and heating value of the resulting new mixture.

By using only elemental data on the input composition, the model does not distinguish e.g. Ca from putrescibles from Ca from polymer fillers. This most fundamental approach, based on mass and energy balances has been adopted to avoid more ambiguous allocation rules.

b. Calculation of fixed cost

Only existing plants have been considered. The historical investment is made for processing grey reference waste. The addition of specific waste materials does not require additional investment. This is justified in practice as well as in literature (see 4.1): i.e. the addition or elimination of PVC will not influence the investment.

Therefore, annual fixed costs are constant (i.e. independent of feed composition). Feed changes results in throughput variations, which result in largely varying costs per tonne processed specific waste material.

Allocation of fixed costs according to different rules per hardware unit is avoided. Such allocation rules would be ambiguous and strict allocation rules can hardly be

identified because of the complexity of the MSWC facility (i.e. consisting of different unit operations). I.e. as a consequence, capital cost for the acid scrubber are not specifically allocated to Cl-containing wastes (which would mean 37% to PVC, 30% to miscellaneous combustibles, 17% to putrescibles etcetera, see table 5.1).

Alternatively, allocation of scrubber investment based on flue gas volume would result in approximately 1% allocation to PVC, 12% to miscellaneous combustibles and 11% to putrescibles.

Any of such allocation would make the specific processing cost dependent on feed composition.

c. Effects per tonne of waste are independent of amount of added waste material.

This means, that the effects of waste additions are linear, i.e. doubling a waste addition will double its effect compared to the reference situation. This linearity follows directly from formula (13) and is further supported in Appendix D.

As a result, calculated SPC's are independent of the amount of waste added to the grey reference, as long as the validity of the expert rules of the MSWC FACE-model is sustained.

d. Grey waste "synthesized" from specific waste materials

As a result of linearity of formula (3), it is also demonstrated that the processing cost of 1 additional tonne of grey waste can also be obtained by summation of the products of the specific processing cost per waste fraction and the ratio in which these waste fractions are present in grey waste. In formula:

$$GF_g = \sum_i (y_i * SPC_i) \quad (15)$$

in which y_i equals the concentration of a waste fraction i in grey waste in [kg/kg] and i represents the waste fractions paper, plastics, putrescibles, glass, metals, wood, miscellaneous combustible and miscellaneous non-combustible.

Examples of the calculations which demonstrate the linearity of formula (3) are given in Appendix D.

e. Specific processing costs are independent of the grey waste

For a given MSWC facility with a particular cost structure (additive prices, disposal rates and energy revenues), it can be envisaged from formula (13), that the composition of the grey waste has no effect on the specific processing cost of an added waste material.

Given a starting situation where t_a tonnes of grey waste A are annually processed. In such a MSWC facility the SPC for an added waste material is given by (in analogy to formula (13):

$$SPC_{p,a} = v_p + w_a * f_{g,a} \quad (16)$$

If in the same MSWC facility t_b tonnes of waste of composition B are processed, the SPC for the same added waste P becomes:

$$SPC_{p,b} = v_p + w_b * f_{g,b} \quad (17)$$

Here, it is assumed that the variable cost of processing P are independent of the grey waste. This assumption seems justified as almost all variable cost are linearly related to the elemental composition.

Mass limitation

In a mass limited scenario, grey waste is displaced by added waste P in a kg per kg ratio. This ratio is independent of the composition of the grey waste (1 kg = 1 kg):

$$w_a = w_b = 1 \quad (18)$$

and:

$$t_a = t_b \quad (19)$$

With:

$$f_{g,b} = F_{f,b} / t_b \quad (20)$$

and, - as annual fixed cost remain unchanged - :

$$F_{f,b} = F_{f,a} \quad (21)$$

it follows that:

$$f_{g,b} = f_{g,a} \quad (22)$$

and:

$$SPC_b = SPC_a \quad (23)$$

Thermal limitation

In a thermally limited scenario, the heat recovered is the same, regardless whether grey waste A or B is combusted:

$$Q_a = Q_b \quad (24)$$

wherein:

$Q_{a \text{ or } b}$ heat recovered from waste combustion [GJ/hour]

In other words:

$$t_a * H_a = t_b * H_b$$

or:

$$t_b = t_a * H_a / H_b \quad (25)$$

wherein:

$H_{a \text{ or } b}$ heating value of grey waste A or B [MJ/kg]

For the displacement factor w , we can write in both cases, analogous to formula (1):

$$w_a = H_p / H_a$$

and:

$$w_b = H_p / H_b$$

which leads to:

$$w_b = w_a * H_a / H_b \quad (26)$$

Combining (19) and (22) gives:

$$SPC_b = v_p + w_b * F_{f,b} / t_b \quad (27)$$

Substituting (23), (27) and (28) in (29) gives:

$$SPC_b = v_p + (w_a * H_a / H_b) * F_{f,a} / (t_a * H_a / H_b)$$

or:

$$SPC_b = v_p + w_a * F_{f,a} / t_a$$

thus:

$$SPC_b = SPC_a \quad (28)$$

No throughput limitation

As v_p is assumed to be independent of the composition of grey waste, the SPC in the not limited scenario is also grey waste independent.

It is stressed, that comparisons can be made for one specific hardware configuration and one set of cost parameters only. In other words, the SPC's are valid only for one MSWC facility, with its typical hardware and cost parameters. Therefore SPC's are not typical material constants, but location dependent.

2.3.3 Limitations in generalisation of the results

Results presented in this study were obtained from the HVC Noord-Holland example. The input to the calculations is location dependant. At other locations (plant sites), specific inputs need to be redefined. Examples of these specific inputs are the cost elements for chemicals and utilities (both stoichiometry/dosage and price), solid residue disposal costs and electricity (energy) revenues.

These differences will be more significant when other flue gas cleaning configurations are involved and/or facilities outside The Netherlands are considered. The fixed cost elements play a less dominant role in the redefinition of specific inputs as these can be introduced by using the original gate fee GF_g , as explained in section 2.2.3, sub a.

2.3.4 Limitations of model approach versus real world practice

The specific processing costs are determined based on financial break-even (see section 2.1.2). Therefore, it only provides a starting point input to the MSWC facility operator. Realization of financial break-even is only an economic minimum requirement. Starting from the break-even situation, the operator will allow additional commercial inputs like offered waste volume, contracting party, contract duration, competition, plant loading, etc., to play a role in arriving at a material specific gate fee to be charged in real-life commercial practice. Even his choice to use a thermal or mass limited or underloaded throughput scenario may be determined by commercial or strategic considerations. The scenarios as described in this study, only reflect theoretical extremes. The SPC results should therefore be considered with care, as the results are highly dependant on the throughput scenario as chosen. The material specific gate fees as actually charged in final practice are the results of commercial negotiation and market forces even where a complete free market is not realized.

3. Starting points

In this chapter the starting points for the calculation of the specific processing costs are elaborated. This includes an introduction to the MSWC FACE-model and the HVC Noord-Holland as well as the definition of the used composition for the standard grey waste. Special attention is given to PVC waste composition. Finally, the calculations which were executed are illustrated.

3.1 The MSWC FACE model

The MSWC FACE model is briefly described in Appendix A and a full description of the model is given in [Rijkema,1996].

Generally, the FACE model provides the emissions, residues, energy recovery and cost breakdown for a MSWC facility starting from input data on the process conditions in the plant, the fractional composition of the waste and the elemental composition and heat content on each fraction in the waste.

In the MSWC FACE-model, both investment and operational costs are calculated. In the output, these costs are detailed into fixed costs and variable costs.

Fixed costs include capital costs (interest and depreciation) and fixed operational costs: personnel, maintenance, insurance, taxes and emission measurements.

Variable costs consider chemical costs (additives, utilities) and disposal costs of the residual solid and/or liquid streams.

Besides costs, revenues of the produced electricity are also calculated. Here the net amount as transferred to the public grid is considered (i.e. generated kWh corrected for internal plant consumption).

Data on the elemental composition of each waste material such as paper, plastics, putrescibles, etcetera, and the corresponding literature sources are given in Appendix C.

Furthermore, the MSWC FACE model includes empirical data on the behaviour of elements in the combustion installation, such as on the partitioning of metals between the gas and the solid phase (see 2.3 and chapter 4).

The MSWC FACE model contains cost functions per equipment unit and calculates investment cost, fixed and variable cost and total annual cost for the MSWC plant for any specified capacity.

The model has been validated with the design parameters of the recently built MSWC facility at Alkmaar (HVC Noord-Holland) as well as with yearly production data from the MSWC Bamberg (Germany) and with detailed data from full-scale experiments at the MSWC Würzburg (Germany).

The calculation procedure in the MSWC FACE-model proceeds as follows.

Based on input data concerning the waste amount and elemental composition, the plant's hardware configuration and the process conditions, the in- and outgoing flows are calculated through mass and energy balances. Examples of ingoing flows are: waste, combustion air, consumed chemicals and utilities. Outgoing flows include e.g.: bottom-ash, filter-ash (from ESP, electrostatic precipitator), salt residue, filtercake, coal residue, flue gas emitted at the stack and energy delivered to the grid.

Based on these mass flows the annual costs of operation are calculated.

The investment costs are calculated using expert rules which relate the investment for a certain device to a parameter which characterises this specific device. For example, the investment cost for the ESP is calculated based on the flue gas flow in this ESP.

Most of the fixed costs (capital costs, maintenance, insurance, taxes) are calculated based on the investment costs. These investment costs are calculated by the model using capacity related expert rules. The personnel costs are mainly determined by the size of the plant.

Variable costs are calculated by multiplying the specific flow with the corresponding cost per unit, the electricity revenue by multiplying the amount delivered to the grid by the revenue per kWh.

Examples of in- and output data are given in Appendix B, based on the situation at the HVC Noord-Holland.

These in- and output data are obviously location specific. Calculations based on alternative MSWC facilities should naturally be based on local inputs: the formulae in this report are universally valid but require local adaptation for quantitative input. The HVC Noord-Holland example cannot be generalized.

3.2 The HVC Noord-Holland

The Huisvuilcentrale (HVC) Noord-Holland is a completely new installation, built at a green site. Construction was completed at the beginning of 1995 and in the course of 1995 the facility went into operation. The plant consists of 3 parallel units starting with a moving grate (forward acting type) furnace, in which the waste is combusted. The heat released is generating steam in the boiler which is used to produce electricity through a turbine and generator.

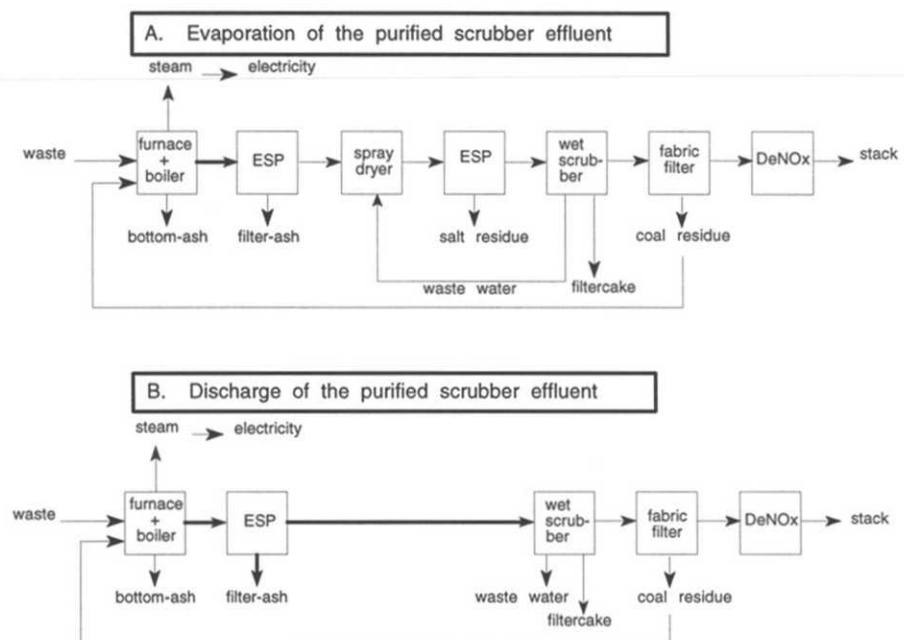


Figure 3.1 Process configurations considered in this study.
(Configuration A reflects the HVC configuration.)

The bottom-ash (from the grate) is quenched, aged and used in road construction. After a first dust removal step in the electrostatic precipitator (ESP), part of the flue gases is recycled to the furnace to be used as secondary combustion air. The rest of the flue gases is thoroughly cleaned in the flue gas cleaning system, which consists of a spray dryer, another ESP, a multi-stage wet scrubber, a fabric filter with injection of activated carbon and a SCR (selective catalytic reduction) DeNOx installation. The scrubber effluent is purified (neutralization, flocculation, precipitation and filtration) and evaporated in the spray dryer. The fly-ash, which is separated from the flue gas in the ESP, is used as filling material in road construction.

The same happens with the residue from the second ESP after the spray dryer. This residue is mainly calciumchloride with some impurities (dust, residual heavy metals) which were adsorbed/captured by the salt particles in the spray dryer. Due to the temperature at which the scrubber effluent is evaporated in the spray dryer, no crystal water is incorporated in the residue when it leaves the ESP after the spray dryer. However, as this residue is highly hygroscopic, it can be expected to take up water from the environment. This is assumed to have no financial impact in the FACE-model calculations.

The filtercake which results after purification of the scrubber effluent mainly consists of gypsum on which as much as possible the heavy metals from the scrubber effluent are precipitated. This residue is landfilled without further treatment in a landfill category with lower disposal costs per tonne than for fly-ash or salt residue.

In the calculations with the MSWC FACE-model, the residue from the entrained flow adsorber (EFA: active coal injection in the flue gases just upstream of a fabric filter) is considered to be landfilled in big bags as hazardous waste. In practice, however, this residue is recirculated to the furnace where it is burned in a special powder coal burner.

This difference is caused by the fact that in early phases of this study design values of the HVC were used in the calculations. After actual startup, some differences with the design have been incurred. See Appendix B for more detail.

As an alternative to the configuration of the HVC, example calculations have been executed for cases where the scrubber effluent is not evaporated but discharged, as it was anticipated that for some types of waste this would have a significant influence on the processing costs.

Both configurations (schematically presented in Figure 3.1) are present among Dutch MSWC facilities. Considering the currently operated or planned MSWC facilities, roughly 40% of the waste (tonnage basis) will be combusted with scrubber effluent evaporation and 60% with discharge configuration.

For the HVC plant, mass and thermal limitation (as discussed earlier in chapter 2) are given by the process diagram (see example in Figure 3.1). As the HVC is designed for 18.5 tonnes per hour with a net calorific value of 10 MJ/kg, the facility is in fact limited to 18.5 tonnes per hour (per unit) and 185 GJ/hour. In practice these limits appear to be not so strict, especially where mass throughput is concerned. Temporarily excursions can be allowed, but the limits cannot be exceeded continuously.

However, for this study we use the limitations according to the design of the HVC as rigid, to clarify the theoretical extremes in these situations. In practice, a facility will preferably be run at either maximum thermal or maximum mass throughput, unless for some reason insufficient waste is available.

In this study, the HVC is used as a general example for MSWC facilities in The Netherlands. Therefore, the quantitative values where limitations occur are not important as these will be different for each individual installation.

3.3 Composition of mixed household waste

A fixed reference composition was assumed for the average “grey” household waste in this study.

The average composition of waste combusted in Dutch MSWC plants in 1993, (Scenario Document) [AOO,1995] was taken as basis for this reference. The various waste fractions, e.g. glass, putrescibles, plastics, wood, etc., were considered not to have changed in composition or fractional amount.

Alternatively, calculations were conducted with identical waste but with an assumed lower content of putrescibles. This has been executed as in The Netherlands separate collection of putrescibles continues to increase since 1993. As a consequence, the putrescibles content of the waste feed to the MSWC facility has decreased.

In this “reduced putrescibles scenario”, the waste contains 28% putrescibles instead of 33.1%. This reduced figure is based on an inventory of calculations and opinions within the ministry of VROM, the Dutch Board on Waste (AOO) and from external experts on the anticipated situation in 2005 [Halen,1995].

The used Scenario Document [AOO,1995] only describes the main components of the waste: glass, putrescibles, plastics, wood, etc. The elemental analysis per fraction needed for the FACE-model calculations is derived from several literature sources. All fractional and elemental composition data are presented in Appendix C with supporting literature references.

3.4 The composition of waste materials

For each waste material for which specific processing costs are calculated in this study, the composition was assumed to reflect the material as it is encountered in municipal solid waste. This means that the waste materials are considered including attached dirt, which may not be present in this waste at the pre-consumer stage. Also, as the literature sources concern analyses of piles of mixed waste (see Appendix C), values used are subject to the effect of migration of substances from one waste fraction to another. This particularly is the case for migration of water from putrescibles to paper. Other elements or compounds may also migrate between fractions in the waste but with reference to the migration of water this concerns a minor effect.

Accounting for these phenomena is not possible due to lack of useful and consistent data.

Special attention has been given to the composition of PVC waste. The original FACE programme contained data derived from a study for APME [Rijpkema,1992]. In this study PVC was characterized by one single composition. An inventory amongst suppliers of PVC products [Nieuwenhuijsen,1995] by the Steering Committee on PVC and Life Cycle Management revealed, that principally soft and rigid PVC should be distinguished as separate types of products. Soft PVC contains relatively high amounts of plasticizers compared to rigid PVC. As a result, soft PVC is lower in chlorine-content and has a higher heating value. As chlorine-content and heating value are expected to have a substantial effect on the specific cost of combustion, these two types of PVC have been considered separately.

The main part of the compositional data on the two types of PVC (Cl, organics, Pb, ash, heating value) is based on this inventory [Nieuwenhuijsen,1995]. The metal

concentrations, are based on the formerly mentioned APME study [Rijpkema, 1992]. It must be noted that data on the heavy metal content of both rigid and soft PVC do not originate from virgin PVC as manufactured, but from PVC waste, where printing inks and attached dirt are additional sources of heavy metals. In this respect, PVC is treated in the same way as the other waste materials (see also 2.3).

The PVC input data are presented in Appendix C.

3.5 Scheme of waste feed combinations for calculations

By the methodology as developed the specific processing costs (SPC) per tonne of waste were calculated for the following waste materials: putrescibles, paper, mixed plastic waste, rigid PVC, soft PVC, glass, metals and wood.

(To check linearity of the formula for SPC, as discussed in chapter 2.3, also the SPC for the waste categories 'miscellaneous combustible' and miscellaneous non-combustible' had to be calculated. As generation of data on the SPC of these waste materials was outside the scope of this study, these wastes are no further considered.)

The SPC calculations were executed for 4 different situations, depending on the configuration of the MSWC facility and the composition of the grey waste. The configuration of the Alkmaar plant (HVC Noord-Holland) was taken as the reference. Additionally, calculations were made for a configuration with discharge of scrubber effluent instead of its evaporation (see chapter 3.2). This was done to separate the effect of the disposal cost of the salts residue. Next to this variation in configuration, the composition of the grey waste was changed (as discussed in 3.3) to investigate the influence of the putrescibles content.

As discussed in chapter 2, the addition of waste to the incinerator feed of a fully loaded MSWC facility will mean that part of the original grey waste is displaced. Depending on whether the facility is thermally or mass limited, the amount of grey waste that cannot be accommodated depends on the thermal or mass ratio of the added fraction to the grey waste. Naturally, in case the MSWC facility is not limited (underloaded) no waste is substituted. Depending on the type of limitation, the amount of reference grey waste G which is substituted by the added waste material was calculated and the amount and elemental composition of the total waste feed to the facility is recalculated. The example, given in Table 3.1 below, illustrates the input for the three situations (thermally, mass or not limited).

Table 3.1 Example of the calculation of the waste feed to the MSWC facility as input in the MSWC face-model. addition of wood, doubling its original amount.

Parameter	Starting situation	New situation Addition of wood: 24.1 ktonnes/year		
		Thermally limited	Mass limited	Not limited
w [kg/kg] ¹	n.r. ²	1.45 ³	1	0
grey substituted [ktonnes/year]	n.r. ²	35.0 ⁴	24.1	0
grey processed [ktonnes/year]	388.9	353.9 ⁵	364.8 ⁶	388.9 ⁷
extra ⁸ wood processed [ktonnes/year]	0	24.1	24.1	24.1
total waste (grey + wood) processed [ktonnes/year]	388.9	378.0	388.9	413.0
% grey ⁸ in total waste processed [wt%]	100	93.62	93.80	94.16
% extra ⁸ wood in total waste processed [wt%]	0	6.38	6.20	5.84

¹ ratio grey waste substituted by added wood [kg/kg].

² n.r. = not relevant.

³ from: $LHV(\text{wood}) / LHV(\text{grey}) = 14.60 \text{ [MJ/kg]} / 10.06 \text{ [MJ/kg]} = 1.45$.

⁴ $w = 1.45$, thus 24.1 kt wood/yr substitutes $1.45 * 24.1 = 35.0$ kt grey/yr.

⁵ $388.9 - 35.0 = 353.9$ kt grey/yr.

⁶ $388.9 - 24.1 = 364.8$ kt grey/yr.

⁷ no substitution.

⁸ Though grey waste contains a certain amount of wood, this is considered included in grey waste; only the added amount of wood is indicated separately here.

4. Literature review

The literature has been searched on 3 topics.

Firstly, information was gathered on previous attempts to quantify combustion costs of specific materials, e.g. chlorine containing wastes. This is done to look for useful (parts of) methodologies for the calculation of the specific combustion costs of PVC and other fractions.

Secondly, information on the distribution coefficients of heavy metals in furnace and boiler in relation to the Cl-content of the waste was surveyed, to investigate the influence of Cl-variations on the heavy metal content of the residues (mainly bottom- and fly-ash).

Finally, the qualitative effects of a change in the chlorine content of the waste on the performance of a MSWC facility were surveyed. This was done to supply additional information in those cases where the MSWC FACE-model cannot further quantify the effects.

4.1 Combustion costs of chlorine containing waste

Literature on the influence of Cl on the costs of combustion is generally focused on PVC as the chlorine containing waste. All these studies try to establish the differences in costs between MSW with and without PVC.

Differences in the amount of additives used and the amount of residues generated are accounted for, for different kinds of flue gas scrubbers: dry, semi-dry or wet. Some studies stop at the determination of the difference in processing cost (or: calculated gate fee) [GRP,1989; Tötsch,1990; Randall,1994] between grey waste with and without PVC. Others extrapolate this to an additional cost per tonne PVC processed [Reimann,1991 & 1992; Rasmussen,1993]. If at all mentioned, these studies assume that the existing scrubbers will be able to cope with the difference in HCl-load of the flue gases, or in other words, no additional investment is needed because of the presence of PVC in the waste [among others Guillet,1994; Randall,1994; Reimann,1992]. On the other hand, elimination of PVC will not reduce investment as without PVC the HCl-content of the flue gases will still be too high to allow emission without scrubbing.

In the calculations some assume that all chlorine from PVC ends up in the flue gas as HCl [among others Rasmussen,1994], whereas others assume a percentage of 60-80%: the remaining 20-40% leaves the process as inorganic salt in solid residues [GRP,1989; Tötsch,1990; Reimann,1991 & 1992].

Literature based extra costs for combusting PVC with MSW vary widely:

- per tonne MSW with PVC compared to MSW without PVC, minor effects:
 - 0.9 to 4.3 DM (1 to 5 Dfl) per tonne MSW depending on flue gas cleaning system [GRP,1989; Tötsch,1990; Reimann,1991 & 1992];
 - less than 1% of the processing cost [Randall,1994];
- per tonne PVC combusted:
 - 100 to 600 DM (110 to 660 Dfl) [Reimann,1991 & 1992];
 - around 620 Dkr (190 Dfl) for a wet scrubber with effluent discharge, and up to around 2400 Dkr (720 Dfl) and 3800 Dkr (1140 Dfl) for semi-dry or dry scrubbers respectively [Rasmussen,1995].

None of the above mentioned methods acknowledges income effects to the waste operators caused by the waste substitution effects in case of mass or thermal limitation. Also the differences in energy revenues between MSW with and without PVC are not taken into account. Finally, none of the mentioned studies applies the calculation method to other materials than PVC. Therefore the calculated costs for PVC as the only material investigated cannot be put in the required perspective versus other materials.

As this study aims to account for all relevant effects and to supply a clear perspective on the results, the methods applied in the studies mentioned above have been fine-tuned and extended to result in the present approach of our study.

4.2 The distribution of elements in the MSWC facility

After conversion in the furnace, the incoming waste is distributed over 2 outgoing flows: bottom-ash and flue gas. In the bottom-ash all components are in the solid phase (liquids/molten phases are not considered as all solidify upon quenching of the bottom-ash). However, the flue gas contains both solids (fly-ash) and true gases.

4.2.1 Distribution coefficients

The partitioning of heavy metals, halogens and sulphur is described in the MSWC FACE-model by applying distribution coefficients, which represent the ratio gaseous/solid and for the solid part the ratio fly-ash/bottom-ash of each element in the furnace output flows.

Heavy metals can be volatilized to a different extent; predominantly as oxides or chlorides and in some cases as zero-valent, “true” metals [Vehlow, 1992]. Halogens are volatilized as HCl, HF and HBr, whereas sulphur is present as gaseous SO₂ in the flue gas.

How much of these elements is volatilized depends on a number of parameters, like: the temperature profile (in the waste layer but also in the gaseous combustion section), the chemical nature in which the compound is present in the waste, the particle size distribution of the waste and factors like the grate and furnace geometry, and some more.

All these equipment related factors' influences cannot be calculated separately. Therefore, the MSWC FACE-model uses a black box approach (see Figure 4.1) in which typical values for the distribution over the different flows are extracted from mass balance data in literature (see Table 4.1). In order to do this, the black box is extended to comprise both furnace and boiler. This is important because some compounds are volatilized in the furnace but condense in the boiler. Thus the figures in Table 4.1 indicate the amounts in the gas phase at the exit temperature of the boiler (200-230 °C).

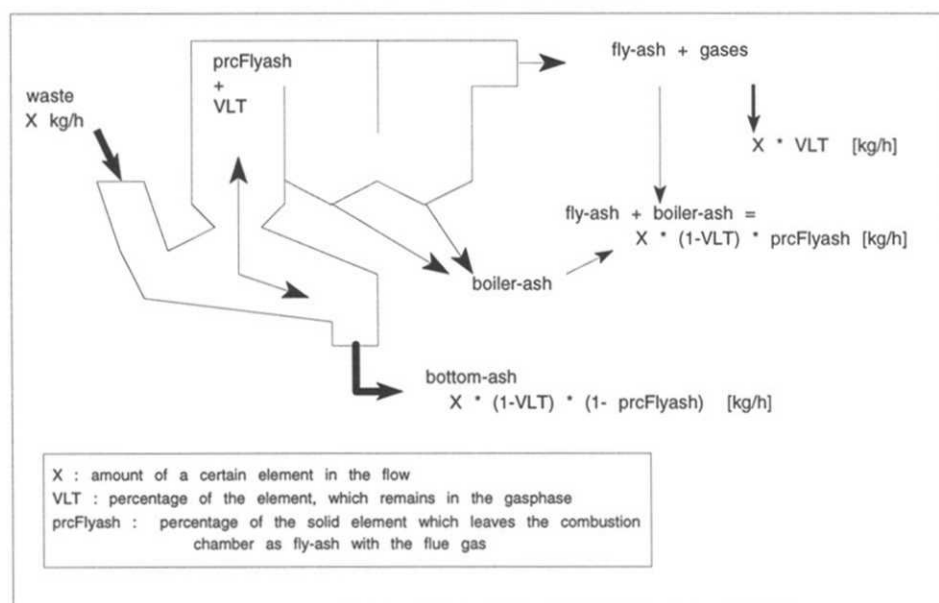


Figure 4.1 Distribution coefficients in furnace and boiler.

The same black box approach is used for the ratio bottom-ash/fly-ash. This ratio is also influenced by a number of parameters which cannot be quantified separately, like the grate and furnace geometry, the ratio primary/secondary air, the velocity of the gases which are blown through the waste layer, the particle size distribution of the waste, etc. Typical mean values for the distribution of the solids over bottom-ash and fly-ash are: 91 wt% of the total ash becomes bottom-ash and 9 wt% ends up as fly-ash [Rijkema, 1992; Schetter, 1991; Angenendt, 1990; Reimann, 1989; Eggels, 1992]. In this typical value, ash from the boiler is included in the fly-ash numbers, as most facilities combine boiler-ash and fly-ash from the dust removal device.

In Table 4.1 the volatility of the considered elements is given as a wt% of the total amount present in the waste feed of the MSWC facility. The remaining solids are split up between bottom-ash and fly-ash. The figures in Table 4.1 represent the wt% of the incoming amount in the waste feed which ends up as volatiles (truly gaseous) in the flue gas, in the fly-ash or in the bottom-ash. Note that although an element may have a zero volatility, this will not imply zero emission with the flue gas, as there will always be non-volatile fly-ash (containing the component) entrained with the flue gas.

Components which are present in the same concentration in the bottom- and the fly-ash are distributed in the same ratio as the total ash. As the base case value for the amount of fly-ash is 9 wt% (see above) a value for the fly-ash exceeding 9 wt% indicates that the concentration of this component in the fly-ash is larger than in the bottom-ash.

It should be noted that the values given in Table 4.1 in fact represent the average of a range of values derived from literature data on several MSWC facilities. The actual values for a facility will be subject to the conditions in the specifically considered MSWC facility.

Specifics on the HVC or any other Dutch MSWC facility are not available; literature indicates that the difference in performance may be considerable.

Table 4.1 Distribution of components over flue gas, fly-ash and bottom-ash.

Component	Gaseous fraction ¹ [wt%]	Solid fraction distribution ¹ [wt%]	
		fly-ash	bottom-ash
Cl	73	15	12
F	24	16	60
S	50	5	45
Hg	90	3	7
Cd	10	67	23
As	0	25	75
Co	0	7	93
Cr	2	6	92
Cu	0	4	96
Mn	0	9	91
Ni	0	5	95
Pb	10	23	67
Sb	2	34	64
Se	7	61	32
Sn	10	23	67
Te	0	9	91
Tl	0	50	50
V	0	9	91
Zn	10	27	63

No data available on Br.

¹ The distribution relates to both furnace and boiler. Therefore, the gaseous fraction is based on a boiler-exit temperature of 200-230 °C [Angenendt, 1990; Eggels, 1992; Reimann, 1989; Reimann, 1992a; Vehlow, 1992; Mark, 1995; Rijkema, 1996].

The literature review concerning the distribution coefficients, as discussed in this paragraph, serves two purposes:

- a check on the validity of the values used in the model;
- the influence of chlorine (and other waste composition related parameters) on the distribution of the heavy metals.

4.2.2 Validity of the distribution coefficients

Data on distribution coefficients has been gathered from:

- experiments in the TAMARA-plant, a pilot-plant for a MSWC facility [Vehlow,1993; Merz,1994; Hunsinger,1994; Vehlow,1995a,b & c];
- analyses at Danish MSWC facilities [Dalager,1993];
- analyses at the Swiss MSWC facility at St. Gallen [Belevi,1993];
- experiments at the Spanish MSWC facility at Barcelona [Fernandez,1992];
- experiments at 2 full-scale MSWC facilities [Brunner,1986];
- experiments at a full-scale MSWC facility in Canada [Rigo,1994];
- experiments in a fluidized bed furnace [Wey,1994].

All these experiments and analyses give evidence that the distribution coefficients of all elements vary within relatively limited ranges. These ranges are obviously caused by differences in parameters like waste characteristics (composition, particle size) and furnace characteristics (geometry, combustion air velocity, grate type, furnace geometry). The values for the distribution coefficients encountered in these additional references confirm the ranges in the original literature used for building the MSWC FACE-model. Therefore, no adjustment of the original distribution coefficients in the MSWC FACE-model has been considered necessary.

4.2.2.1 The influence of process conditions

Most of the experiments and analyses mentioned above were only designed to determine the distribution coefficients for a given waste composition and in a given MSWC facility. Exceptions are the experiments in the TAMARA plant, where the relation between distribution and operational parameters was investigated:

- higher temperatures in the waste layer (due to an increased plastics content of the waste or to a difference in furnace geometry) increased the flux to the flue gas of Pb, Zn and S;
- irregularity in the grate bar movements increased the amount of fly-ash in the flue gas and, as a consequence, the carry-over of heavy metals to the flue gas;
- shorter residence times of the waste on the grate (through more rapid grate forwarding) also increased the amount of fly-ash (with contained heavy metals) in the flue gas.

These process conditions are not affected by the amount or composition of the waste feed, except for the waste layer temperature. However, within the validity

range of the performed calculations, the influence of this waste layer temperature is assumed to be negligible.

4.2.2.2 The influence of the waste matrix

Apart from the impact of process conditions parameters, an influence can also be expected from the macroscopic waste composition as it is very likely that the distribution coefficients depend on the matrix in which they entered the furnace. In other words, finely dispersed heavy metal introduced via pigment in plastics or in paper is expected to end up in the flue gas, whereas the same heavy metal immobilized in glass or in a metal object will be expected to end up mainly in the bottom-ash. Therefore, the distribution coefficient might not be a constant per chemical element, but may be influenced by the waste composition or waste matrix: addition of a specific waste material might cause the distribution coefficients to change.

Literature data on such an effect is restricted to some experiments on the influence of plastics in general and of the Cl-content of the waste feed in particular on the distribution coefficients. The latter was of specific interest to this study as it is known that many heavy metals are volatilized as metal chloride.

As conditions typical for MSWC (or even at reasonably elevated temperatures), no significant difference in chlorine partitioning could be substantiated for PVC and other chlorine sources present in MSW, like putrescibles and natural salt.

4.2.2.3 The influence of the chlorine content

Indeed it was found that an increased Cl-content enhances the volatilization of a number of elements. Though literature is not unanimous it seems to be indicated that K, Cu, Zn, Pb, and sometimes Sb and Sn, show enhanced volatilization with increased chlorine contents in the waste feed [Hunsinger,1994; Vehlow,1995a,b & c; Mark,1995]. This results in a decrease of heavy metals in bottom-ash (used for road construction) and an increase in transfer to the fly-ash and the flue gas cleaning residues, which are generally considered as chemical waste anyhow.

As to the distribution of the Cl itself, on the one hand it was found that addition of inorganic Cl (through NaCl or CaCl₂), increased the absolute amount of HCl in the flue gas, though it decreased the percentage of Cl in the waste feed ending up as HCl in the flue gas [Hunsinger,1994]. On the other hand, addition of PVC did not significantly increase the percentage of Cl ending up as HCl in the flue gas [Vehlow, 1996]. For the increase in volatilization of the heavy metals with increasing Cl-content, as mentioned above, no difference in behaviour was found between organic (from PVC) or inorganic Cl (from NaCl or CaCl₂). Other experiments even showed an increase in Cl-content of the fly-ash with no change in the Cl-content of the bottom-ash when NaCl was added to the MSW [Bianchi,1995]. Apparently, chloride, even provided as inorganic salt, nevertheless causes increased volatilization as reflected by the larger formation of HCl.

Summarizing the experiments on the impact of the Cl-content, it can be stated that an increase in the Cl-content of the MSW (either from PVC or other Cl-containing wastes) increases the volatilization of certain heavy metals, resulting in lower concentrations of these heavy metals in the bottom-ash and higher concentrations in the fly-ash and the flue gas cleaning residues.

An increase in the heavy metal content of solid residues probably leads to an increase in the leaching of heavy metals from these residues, especially as the effect is enhanced by the increased Cl-content of the residues, which is known to facilitate the leaching of heavy metals [o.a. Hunsinger, 1994]. An increase in leaching of heavy metals might cause a directional increase in costs for treatment and disposal of these residues.

All together, the conclusion seems justified that an increase in the Cl-content of the waste feed potentially decreases treatment and disposal costs of the bottom-ash, but might increase such costs for fly-ash and flue gas cleaning residues. Solid residues are categorized in various (4 in The Netherlands) classes for disposal, each with a corresponding fee. The effects of waste composition changes have been considered too small to cause a shift to another waste disposal category. As these small changes will occur only within such category the disposal fees have been kept constant, regardless waste compositional changes.

From this part of the literature study it was concluded that for all calculations the distribution coefficients as present in the MSWC FACE-model are to be used, due to lack of additional data of confirmed superior value. This is justified as any occurring deviation will be small as the validity of the model is restricted to small variations of the feed around the reference composition of grey waste. The distribution coefficients are kept constant and the neglect of acknowledged dependancy of waste composition and waste matrix has to be accepted by lack of more detailed data.

4.3 Non-quantitative aspects of chlorine in a MSWC facility

Some effects of chlorine which cannot be quantified are discussed here:

- combustion behaviour;
- formation of PCDD/F;
- corrosion.

About 62% of the chlorine in the waste feed originates from non-PVC sources. Many literature data, however, concentrate on effects of PVC in combustion. As discussed in section 5.2, the fate of chlorine from PVC, putrescibles (NaCl) or any other waste category is almost identical.

4.3.1 Combustion behaviour

One of the first tests on the effects of adding PVC (or other plastics) to MSW for combustion was executed in the early seventies [Kaiser,1972]. In those experiments the plastics content of the MSW was varied between 1 and 2 wt% and the net heating value of the MSW was relatively low (around 7 MJ/kg). Therefore, it was not surprising that the main conclusion of those tests was that the relatively high energy content of plastics was beneficial for the combustion behaviour: combustion was easier and more complete. The additional HCl in the flue gases from an additional amount of PVC was recognized but was reduced by the scrubbers without problems (according to the regulations in those days). Today, with average heating values more elevated, experiments show that addition of high calorific waste materials (like all plastics) improves the burn-out of the bottom-ash [Mark,1995; Vehlow,1995b], even at the considerably lower levels of uncombusted organic substances.

Other references, however, report an increase in the amount of incompletely burnt gases with increased plastics content of the waste feed, resulting in high CO-levels and large emissions of products of incomplete combustion. This merely is the case in (older) furnaces with little possibilities for secondary (overfire) air and a small burn-out area resulting in short residence times for the flue gases [e.g. Keränen,1990]. This is due to the fact that plastics are gasified very quickly in relation to average MSW and combustion subsequently occurs in the gasphase. If the furnace is designed for waste which predominantly burns at the surface of the solid particles (like coal), problems with the burn-out of the gases from plastics combustion can be expected.

In modern MSWC facilities, like the HVC Noord-Holland, the burn-out of the gas-phase is fully controlled because of adjustable secondary combustion air addition, sufficient residence time for the flue gases at high temperatures and process control. Therefore, in modern MSWC facilities the burn-out of the gases is generally achieved without any problem.

It can be concluded that the addition of plastics or PVC (or other relatively high calorific materials) to the waste feed has a beneficial effect on the burn-out of solids and gases in a modern MSWC facility.

Specific details on the influence of other waste materials on combustion are not known to us or perceived irrelevant.

4.3.2 Formation of dioxins and furans

Logically, the final emission of PCDD/F (polychlorinated di-benzo-para-dioxins and -furans) from the stack is the result of the PCDD/F present in the raw flue gases after the boiler minus the amount which is captured in the flue gas cleaning

system. All Dutch flue gas cleaning systems (including the one at the HVC Noord-Holland) easily meet PCDD/F stack levels below the required limit of <0.1 ng I-TEQ/Nm³ at PCDD/F-concentrations in the raw (= uncleaned) flue gas of up to 30-50 ng I-TEQ/Nm³. The PCDD/F-concentration in the raw flue gas of a MSWC facility typically ranges from below 1 up to 15 ng I-TEQ/Nm³ [Reeck, 1991; Schetter, 1991; Lindbauer, 1991]. Therefore, considering PCDD/F, the actual performance of the MSWC facilities in The Netherlands and their compliance with emission directives is no longer an important issues anymore. Presently, PCDD/F's contained in the residue are generally not a problem anymore. However, the PCDD/F-concentration in the raw flue gas is of interest as the PCDD/F is adsorbed on active coal, and an increase in PCDD/F-concentration results in enlarged active coal consumption.

Overall, a state-of-the-art MSWC facility can be considered a PCDD/F-sink as investigations conclude that the PCDD/F-output is 20-25% of the PCDD/F-input [Mark, 1994].

Still, the PCDD/F in the raw flue gas in principle originates from two sources:

- it was introduced with the waste and not destructed in the furnace, or
- it was formed in the boiler after combustion (denovo-synthesis, while cooling down the flue gas).

Modern emission directives require a residence time of at least 2 seconds at temperatures above 850 °C and an oxygen content of at least 6 vol%. This should sufficiently destroy any organic matter (including PCDD/F), especially when the facility is equipped with adequate control systems, that guarantee steady conditions in the furnace with hardly any incidental CO-formation.

Like all modern MSWC facilities, the HVC Noord-Holland realizes adequate burn-out control of the flue gases. It can be assumed that PCDD/F's introduced with waste are fully destructed in the furnace. Thus, any PCDD/F present in the raw flue gas is assumed to be resynthesized in the post-combustor zone (boiler).

Although, after nearly 20 years of intensive research, this formation of PCDD/F in MSWC facilities is still not completely understood, some conclusions with respect to the formation and possible influences by PVC or chlorine, can be drawn. According to literature, the most important parameters in formation of PCDD/F are the availability of:

- a. incompletely combusted organic fragments (carbon in fly-ashes or CO, unburned hydrocarbons in the flue gas);
- b. a source of chlorine in the flue gas;
- c. a catalyst: heavy metals (especially Cu is mentioned);
- d. the right temperature profile and sufficient residence time in the cool-down phase.

Ad a. Incomplete combustion

Theoretically, it might be possible to achieve complete combustion, but in practice this will never be fully realised. There will always be some unburned carbon present in bottom- and fly-ash, and there will always be CO and C_xH_y (unburned hydrocarbon) in flue gas.

The influence of PVC or plastic in general can be regarded beneficial in this respect as their relatively high calorific value improves burn-out of both solids and gases [Mark,1995; Vehlow,1995b].

Ad b. The presence of chlorine

Many studies have been dedicated to the existence of a relation between the combustion of PVC and the formation of PCDD/F. One of the most recent reports on this topic [Rigo,1995] surveyed literature on real practice combustion facilities, including high chlorine industrial and hospital waste. This study identified 10 facts of an increase of PCDD/F with increasing Cl-content of the combusted waste, 8 cases to the contrary and a majority of 57 cases where a change in the Cl-content did not influence PCDD/F-formation.

Another recent investigation concluded that at low Cl-contents of the MSW (<0.5 wt%) there was no relation between the Cl-content and the PCDD/F-formation, whereas at higher Cl-contents (1-2 wt%) there was a slight increase in PCDD/F formation with increasing Cl-content of the MSW [ECVM,1995]. It should be noted, though, that this study was performed in a fluidized bed pilot plant characterized by high entrainment of particulate matter, which contains less chloride than the typical fly-ash in grate systems. In this fluidized bed pilot plant an increase in Cl-load may cause some effects which are not seen in MSWC facilities where the fly-ash is “saturated” with Cl. Furthermore, the study was performed in very clean laboratory equipment, resulting in PCDD/F-formation of only a few percent of levels normally encountered in “real life” MSWC facilities.

No significant difference in the influence on the PCDD/F-formation between organic (from PVC) or inorganic chlorine (from NaCl or $CaCl_2$) [ECVM,1995; Kanters,1994] is observed in most studies. In some cases it is even concluded that in combusting MSW with both NaCl (with Cl labelled) and PVC, the Cl in PCDD/F predominately originates from NaCl rather than from PVC [Sickel,1994].

It is commonly recognized that even by complete elimination of PVC from MSW, an excess of Cl is available in flue gas for PCDD/F-formation, as PVC only accounts for just over one third of the chlorine in MSW (see chapter 4). This 10^7 to 10^8 fold stoichiometric excess of chlorine for PCDD/F-formation explains the virtual absence of a relation between chlorine in the waste feed and PCDD/F-formation in the normal window of MSWC operation. Furthermore, we conclude that there is no evidence for significant differences in behaviour between Cl from PVC and Cl from other (inorganic) sources (e.g. putrescibles) in the MSW.

Ad c. Catalyst

It is recognized that PCDD/F-formation is catalyzed by heavy metals in fly-ash, especially Cu. An indirect influence of chlorine (and PVC) could be hidden in chlorine enhanced volatilization of Cu (as CuCl_2), thus favouring conditions for PCDD/F-formation [Vehlow,1993; Vehlow,1995b]. However, the relation between Cu and PCDD/F is questioned as often as the relation between Cl and PCDD/F as in some experiments no influence of Cu neither in amount [Martin,1989;ECVM,1995] nor in chemical or physical character (inorganic or organic, finely dispersed or not) [Vehlow,1996] was detected. In this aspect also many tests have been executed to investigate whether PCDD/F-formation could be hampered by introducing more S in the flue gas to poison any Cu-catalyst [Lindbauer,1991]. Partly, this tendency was confirmed through tests with co-combustion of plastics and coal, but the effect could not at all be quantified [Frankenhäuser,1991].

We conclude that apparently, catalytic sites at the fly-ash surface are available at such excess, that their presence is guaranteed. In MSWC operation with different types of waste or heavy metal content, this excess remains abundant, which explains the absence of clear effects.

Ad d. Temperature and residence time

From the theory on the denovo-synthesis it is known that recombination of hydrocarbon fragments with chlorine to PCDD/F predominantly occurs in the cooling down phase of the flue gases. The residence time between 400 and 200 °C appears to be crucial for PCDD/F-formation.

Some studies claim that these conditions are dominating PCDD/F-formation rather than other parameters like the Cl-content of the wastes [among others Vogg,1991]. These cool-down conditions are determined by the configuration of the plant and are not influenced by parameters like the Cl- or PVC-content of the waste feed.

We conclude that, though there might be an occasional influence of the Cl-content of waste on PCDD/F-formation, this relation is not always visible and cannot be quantified. Moreover, such a relation is chlorine-specific, not PVC-specific which means that it depends on the Cl-content of the waste feed, regardless the origin of the chlorine in the waste.

4.3.3 Corrosion

High temperature and low temperature corrosion have been distinguished in MSWC facilities.

Low temperature corrosion occurs at temperatures below the dewpoint of the acid gases (HCl , H_2SO_4). At temperatures above 150 °C this type of corrosion is not

very likely [Ganapathy,1991]. As the temperature of the flue gas is 200-230 °C at the boiler exit, this type of corrosion is only to be expected in the quench and the acidic step of the wet scrubber, where the flue gas temperature is below the dew-point (around 70°C). In some German MSWC facilities the authorities restrict water consumption for wet scrubbers for environmental reasons. This results in scrubber fluids with high acidity and corrosion in these scrubbers is a serious economical problem.

Corrosion at high temperatures can only occur in the boiler. In principle, high temperature corrosion by CO can be very quick when local conditions around steam pipes are alternatingly reducing and oxidizing [Crider,1977; Bolt,1991].

Corrosion can also be caused by (alkali)sulphates or by chlorides [Barniske,1990; Ganapathy,1991; Pröfrock,1991; Vehlow,1992b].

The main cause of corrosion for MSWC facilities is HCl, as such or in combination with CO: sulphate corrosion happens but is hardly ever the reason for steam pipe failure in MSWC [Barniske,1990; Vehlow,1992b].

The corrosion process is as follows: through oxidation a protective layer of metal-oxides is formed on the boiler steam pipes. This layer, however, can be destroyed by reduction through CO and/or by chlorine (Cl₂) which attacks bare iron to form FeCl₂. The FeCl₂ moves through the oxide layer and is oxidized to regenerate Cl₂. This Cl₂ formation is catalyzed by Cu and Fe-oxides [Vehlow,1992b]. Furthermore, corrosion is enhanced by metal salts (mainly lead- and zincchloride and potassiumsulphate) that also attack and break-down the protective oxide layer [Crider,1977].

In MSWC facilities, corrosion rapidly increases at temperatures above 450 °C. Therefore, the steam temperature at the steam pipe surface in MSWC is usually kept below that temperature (400 °C is very common) [among others Barniske,1990; Pröfrock,1991]. In facilities where higher steam temperatures are required (e.g. because they are connected to a steam grid with these high steam conditions) very costly steam tube protecting measures have to be taken.

In fossil-fuelled power plants, however, higher steam tube temperatures are allowed, due to the lower concentrations in the flue gas of HCl and other components. The maximum HCl-concentration or -amount tolerated is not known, but judging from HCl-levels in power plants at least an 80% reduction in chlorine feed is required for MSWC, before higher steam parameters can be allowed without special tube protection measures.

We conclude, that combination of steam tube temperatures above 400-450 °C and the presence of HCl in notable concentrations detrimentally promotes corrosion. Due to higher steam temperatures (and pressures) in fossil-fuelled power plants, increased energy recovery efficiencies can be realized: 40-50% towards 20-25% in MSWC facilities. This means that the presence of chlorine drastically reduces the energy efficiency of the MSWC facility. However, it is acknowledged that even with complete elimination of PVC from the waste feed, the HCl-content of the flue

gases would still be too high to allow steam tube temperatures above 400-450 °C, without extra steam tube protection.

Some manufacturers claim that the presence of PVC does not have an influence on the investment costs for the boiler [Randall,1994]. They see the role of Cl as that of a catalyst for which the amount is not the rate controlling factor. Others recognize that an increase in the Cl-content of the MSW (from PVC or another waste fraction) probably increases corrosion and thus maintenance costs.

However, if the corrosion is affected by the chlorine content of the waste feed this impact is again Cl-specific rather than PVC specific, which means that Cl from PVC contributes to the effect in the same dosage-effect ratio as Cl from other sources in the waste feed (e.g. putrescibles).

On the other hand, a small favourable influence can be attributed to PVC specifically. As PVC beneficially contributes to the burn-out of the gases (see under 4.3.1, combustion behaviour), it reduces the risk of CO-induced corrosion.

5. Chlorine mass balance in a MSWC facility

Because of the specific interest in the influence of chlorine in a MSWC facility, a mass balance has been erected with focus on chlorine. Two cases were considered (see chapter 3.2 and Figure 5.1):

- the configuration of the HVC Noord-Holland with evaporation of the scrubber effluent and disposal of solid salt residue;
- the same configuration but with discharge of the liquid scrubber effluent, with salts dissolved.

In both cases normal grey waste is combusted.

It should be noted that waste composition data on chlorine found in literature are scattered over a certain range. However, computer programmes as MSW-FACE need a single figure as an input. Therefore, the calculated mass balance data for the waste feed reflect typical values for the chlorine quantity in the waste materials.

The overall Cl-balance is presented first.

The fate of Cl through the installation will be discussed in more detail.

On the chlorine input side, only 1 source is of interest: the feed. A negligible amount of Cl is added to the system via FeCl_3 , added as flocculent in the scrubber effluent purification system.

On the emission output, several flows are to be considered. Chlorine predominantly ends up in the residues from the wet scrubber, which is either the salt residue from the spray dryer or the purified effluent discharge.

An overview of the in- and output Cl-flows is given in Table 5.1 and Figure 5.1 and Figure 5.2.

Table 5.1 Chlorine mass balance at the HVC Noord-Holland.

Input	tonnes Cl/year	%	Output	tonnes Cl/year	%
Waste feed			Bottom-ash	296.7	11.9
putrescibles	423.7	16.9	Filter-ash	358.7	14.3
paper	285.0	11.4	Spray dryer		
PVC	938.5	37.5	or	1830.8	73.2
other plastics	71.7	2.9	Scrubber effluent		
glass	1.5	0.1	Filtercake	12.6	0.5
metal	6.7	0.3	Flue gas		
wood	6.6	0.3	stack	2.6	0.1
miscellaneous					
combustible	746.1	29.8			
non-combustible	1.7	0.1			
(total)	(2481.5)	(99.2)			
FeCl_3	19.9	0.8			
Total input	2501.4	100.0	Total output	2501.4	100.0

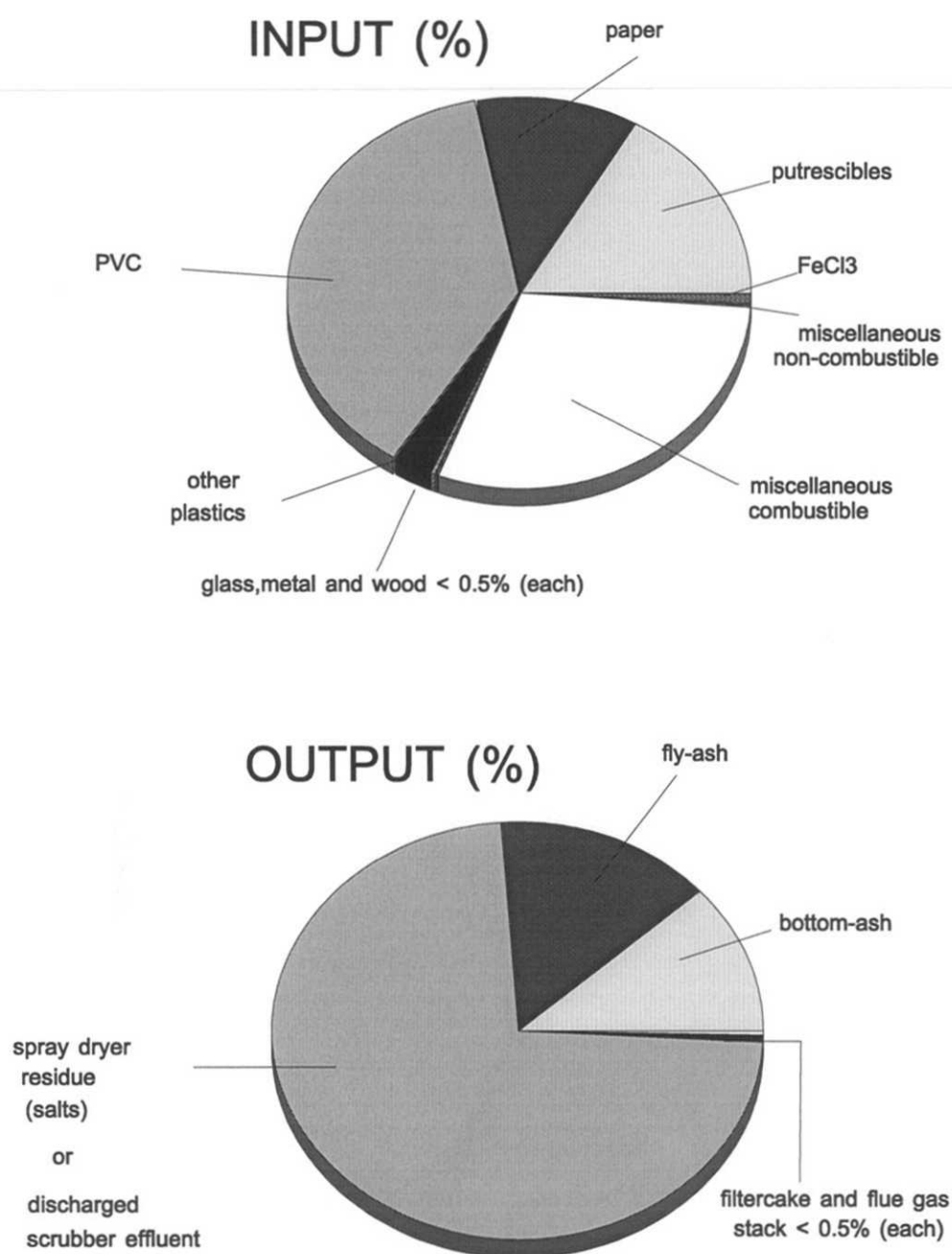


Figure 5.1 Chlorine mass balance of a MSWC facility (HVC example).

From table 5.1 and recalling the final destination of the residues (see chapter 3.2), it can be seen that, in the HVC Noord-Holland example with evaporation of the scrubber effluent, the largest part of the Cl ends up at a controlled landfill site for hazardous waste (Netherlands, class C2): spray dryer residue represents more than 73% of the Cl-output. Almost 26% returns to the environment as part of road construction material (bottom-ash and fly-ash). As the leaching rate of Cl in bottom-ash is low and the fly-ash is treated before usage in road construction, leaching of Cl from bottom-ash can be controlled and tolerated. This leaves 0.1% of the input

to be released to the environment as HCl gas via the stack and a small amount (filtercake) on a landfill (Netherlands: class C2). As the filtercake consists of materials with very low solubilities in water, zero leaching of heavy metals or chloride from this filtercake is expected.

Besides the emission as HCl via the stack, 99.9999% of the chlorine is emitted as chloride via the solid residues.

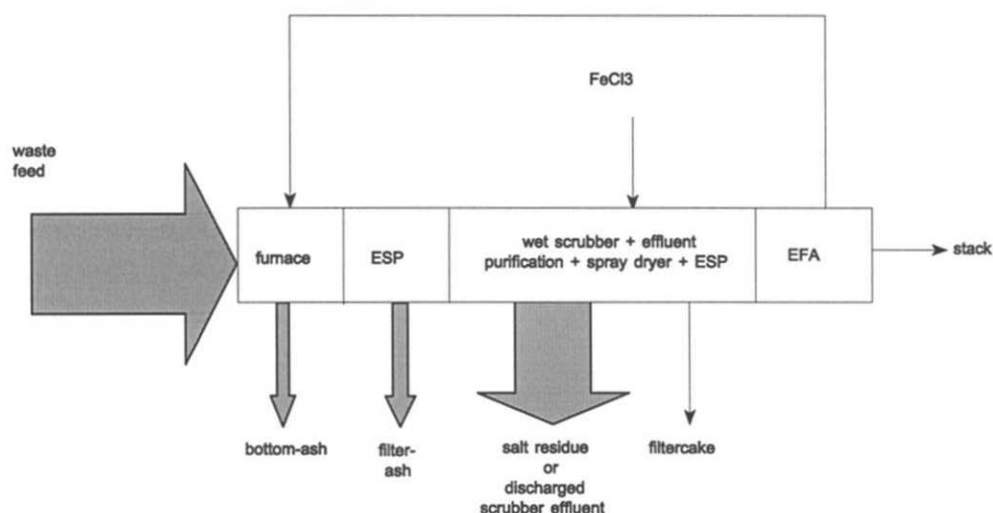


Figure 5.2 The fate of chlorine in the MSWC facility.

Appendix C, which gives the elemental composition per waste fraction) with Table 5.1 it is obvious that despite the relatively low concentration of chlorine in the fractions putrescibles and paper, in absolute amounts their contribution to the chlorine input is not at all negligible. Of course, this is due to the relatively large share of these fractions in grey waste.

Furthermore, it can be seen from Table 5.1 that approximately 38% of the chlorine in the grey waste originates from PVC.

In international literature PVC is very often stated as source for 50 to 70% of all chlorine in grey waste, but in The Netherlands the PVC share in MSW continues to decrease during the last years [Groot,1993, Cornelisse,1995]. (See also Appendix C.)

A brief description of the fate of Cl through the installation starts with the furnace (see Figure 5.2). The Cl enters with the waste into the combustion chamber. After combustion, the major part of Cl is transferred to the flue gas, predominantly as HCl. Furthermore, Cl is volatilized as (heavy)metalchloride. A small part (around 12%) of the Cl in the feed remains in the bottom-ash as inorganic chloride. The Cl which is volatilized as HCl is part of the flue gas (at a concentration of 700-1200 mg/Nm³ in the raw flue gas) until it is absorbed in the scrubber and neutralized in the scrubber effluent purification (for 95-99%). The traces which are not absorbed in the scrubber are adsorbed on active coal in the EFA (entrained flow adsorber). As can be seen in Table 5.1 and Figure 3.1 and Figure 5.2, the scrubber

effluent is the major Cl-outlet of a MSWC facility: around 70% of the Cl leaves the system via the scrubber effluent (in case of discharge) or via the spray dryer residue (in case of effluent evaporation).

With a state-of-the-art flue gas cleaning system like the HVC, the concentration of HCl in the emitted flue gas does not exceed 5 mg/Nm^3 , well below the maximum emission legislation value of 10 mg/Nm^3 . This represents capture of 99.99% of the total chlorine input.

The volatile metalchlorides condensate when the flue gases are cooled down. At the boiler exit, where the temperature is around $200\text{-}230^\circ\text{C}$, the metalchlorides are no longer volatile, except mercuric chloride (HgCl_2) [Vehlow,1992]. Most of the metalchlorides are removed together with the dust particles in the electrostatic precipitator and the wet scrubber.

HgCl_2 is also absorbed in the wet scrubber, in the acidic step. In the scrubber HgCl_2 can be reduced to Hg^+ , which disproportionates in Hg^{2+} and metallic Hg. The latter and the HgCl_2 which is not absorbed in the wet scrubber are adsorbed on active coal in the EFA [Vehlow,1993].

6. Results of the cost calculations

6.1 Overview of the main results

The specific processing cost for the waste materials as summarized in Table 6.1 and in Figure 6.2 and Figure 6.2, were obtained by using the methodology as described in chapter 2 from a starting point as described in chapter 3.

The results clearly show that the specific combustion costs strongly depend on the considered situation with respect to throughput limitation.

6.1.1 Thermal limitation

When the throughput of the installation is assumed to be thermally limited, the heating value is a predominant factor in the cost structure.

Having a high energy content with regard to grey waste, plastics in a thermally limited case require relatively high combustion costs. This is logical, as for each tonne of this high calorific material 3.4 tonnes ($w = H_p / H_g$, formula (1)) of grey waste have to be displaced. The revenue (gate fee) of this 3.4 tonnes has to be compensated by the revenue of only 1 tonne added material (plastics in this case) for financial break-even.

For materials with a zero calorific value, no grey waste has to be displaced and the thermally limited case thus coincides with the not limited case, as no waste is substituted (formula (3) evolves to formula (5), see chapter 2.1.2). In that case, the costs only concern variable cost elements.

Table 6.1 Specific processing costs for various types of waste materials in a MSWC facility.

Reference: Standard grey waste Waste materials	Heating value [MJ/kg]	Substitution factor w [kg/kg] Thermal limitation ¹	Evaporation of scrubber effluent			Discharge of scrubber effluent		
			SPC thermal limit.	SPC mass limit.	SPC no limit.	SPC thermal limit.	SPC mass limit.	SPC no limit.
plastics	34.19	3.40	601	50	-180	552	28	-191
soft PVC	19.98	1.99	518	292	61	370	154	-65
rigid PVC	16.17	1.61	557	417	187	336	204	-15
wood	14.60	1.45	255	152	-78	238	139	-80
paper	9.99	0.99	186	187	-43	170	172	-47
putrescibles	3.39	0.34	74	227	-3	67	212	-6
glass	0.00	0.00	32	263	32	32	251	32
metals	0.00	0.00	31	261	31	31	250	31
grey waste ²	10.06	not relevant	191	191	-39	175	175	-44

¹ In a mass limitation scenario w equals 1 and in a not limited scenario w equals 0, for all materials. Therefore, these are not given here specifically.

² For grey waste, SPC_g in case of thermal or mass limitation is by definition identical to the GF_g used in formula (3), see also chapter 2.

6.1.2 Mass limitation

When the waste mass is the limiting factor, materials with a low energy content - putrescibles, metal and glass - have relatively high processing costs as they provide lower energy revenues than the grey reference. However, materials with a high energy content increase the energy revenue and thus have specific processing costs below this reference.

6.1.3 No throughput limitation

When no limitation is assumed, no waste is substituted and only the variable costs of the added material have to be charged to arrive at financial break-even. In some cases this even leads to negative costs resulting from large proceeds of materials with a high energy content, in those cases exceeding the operational costs. For such materials the MSWC facility operator could afford to pay (rather than to receive) a fee for processing the waste, while maintaining financial break-even. The variable costs are considered in more detail in the next chapter.

6.1.4 Salt disposal

Finally, from Table 6.1, Figure 6.1 and Figure 6.2 it can be seen that the financial effect of the type of scrubber effluent treatment (evaporation or discharge) is limited in all cases except PVC. In the thermally limited situation with evaporation of the scrubber effluent, the magnitude of the SPC of PVC is 80-90% of the SPC of plastic, whereas in case of scrubber effluent discharge the SPC of PVC is only 60-70% of the SPC of plastic.

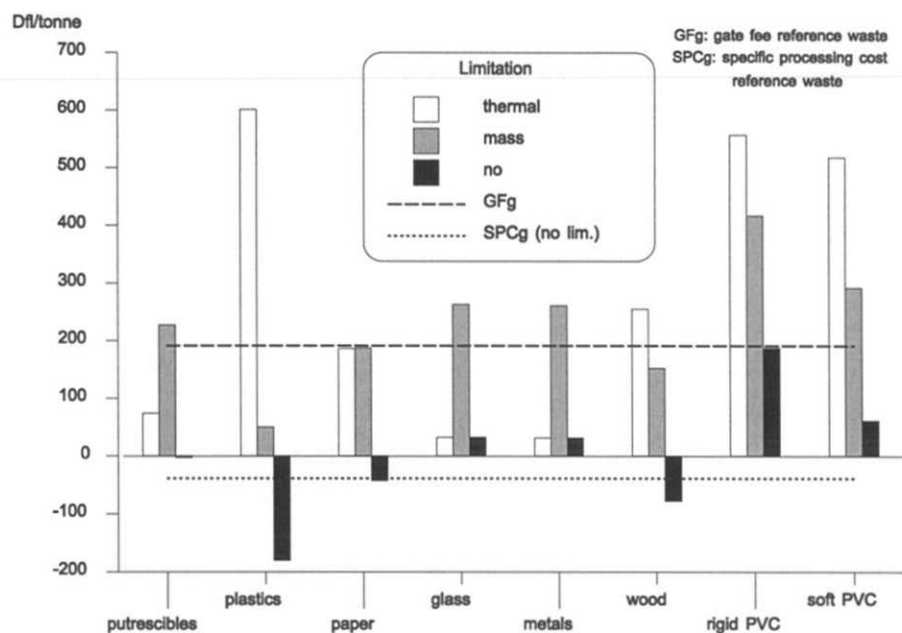


Figure 6.1 Specific processing costs for a MSWC facility with evaporation of the purified scrubber effluent.

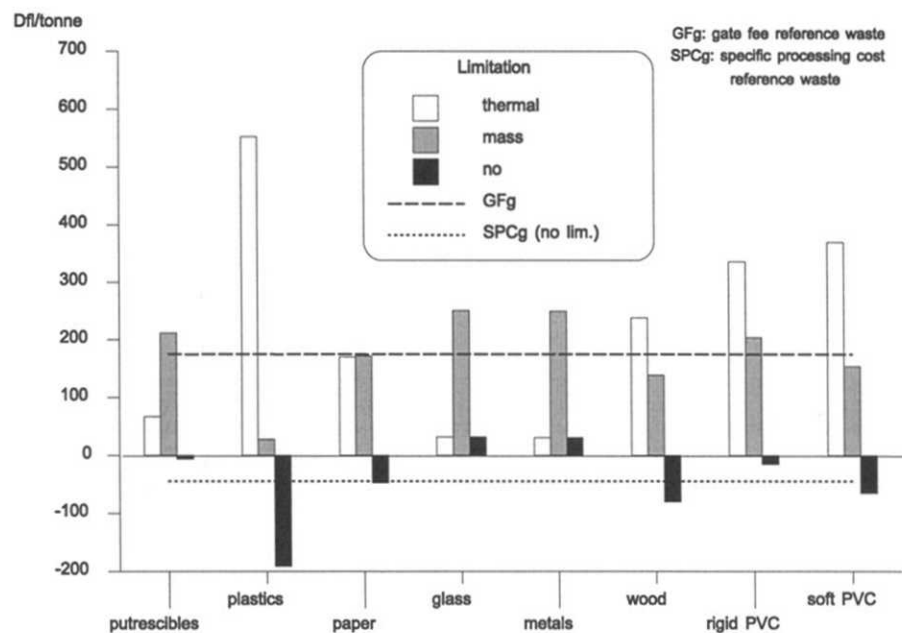


Figure 6.2 Specific processing costs for a MSWC facility with discharge of the purified scrubber effluent.

6.2 Variable costs

The scenario without throughput limitation offers the opportunity to consider the specific variable costs per type of waste material. As in this scenario no grey waste is substituted, the difference in costs only concerns the variable costs of these materials as such (as explained in chapter 2); fixed costs are eliminated. Variable cost elements can also be considered for the throughput limited scenario's, as demonstrated in formula (13).

Table 6.2 provides a break-down of the variable cost of various waste materials.

The cost for chemicals, residue disposal and other variable costs (mainly in-plant solid residue transport and storage costs) and the net energy revenues have been calculated and presented together with the total variable cost for the specific waste.

From Table 6.2, Figure 6.3 and Figure 6.4 it can be seen that in the variable costs the energy revenue is of relatively large importance. Besides for glass, metal, putrescibles and PVC, the energy revenue is dominating. Except for PVC, the cost for chemicals and disposal of solid residues are relatively low and vary within a small range. The large chemical and disposal cost for PVC result from required chloride removal from the flue gas, evaporation of the resulting scrubber effluent and land-filling of the solid salt residue. These disposal costs, combined with a relatively modest profit for energy recovery, gives especially rigid PVC the highest variable cost of the waste materials considered in this study. The variable costs for the acceptance of soft PVC, with lower chlorine content (rigid PVC contains 46 wt% Cl and soft PVC 29 wt% Cl) and increased energy recovery, are considerably lower in this situation.

The choice of disposal method of the solid salt residue has no large impact on the specific variable processing costs of any material, with PVC as clear exception. If the MSWC facility is authorized to dispose of a liquid, salt containing effluent (to a river or sea), disposal costs for both soft and rigid PVC are comparable to those of other waste materials. Tabel 6.1 previously illustrated that the effect of the two types of scrubber effluent treatment is relatively small for the other waste materials.

Table 6.2 Specification of the variable cost (in Dfl/tonne) for processing a waste material. MSWC facility like HVC Noord-Holland (with scrubber effluent evaporation or discharge).

Waste material	Cost of additives	Cost of disposal	Other variable cost	Energy cost ¹	Total variable cost
SCRUBBER EFFLUENT EVAPORATION					
plastics	12	11	0	-203	-180
soft PVC	38	140	0	-117	61
rigid PVC	58	221	0	-92	187
wood	4	0	0	-82	-78
paper	6	5	0	-54	-43
putrescibles	4	5	0	-12	-3
glass	1	15	7	9	32
metals	1	14	6	10	31
grey waste	6	8	0	-53	-39
SCRUBBER EFFLUENT DISCHARGE					
plastics	13	1	0	-205	-191
soft PVC	43	10	0	-118	-65
rigid PVC	65	15	0	-95	-15
wood	4	0	0	-84	-80
paper	6	1	0	-54	-47
putrescibles	4	4	0	-12	-6
glass	1	14	8	9	32
metals	1	14	7	9	31
grey waste	6	3	0	-53	-44

¹ The difference in energy revenue is expressed as a cost in this table. Therefore, a negative value indicates that the energy revenue exceeds all other variable expenses. A positive value means that for the processing of that material electricity is consumed (e.g. for solids handling), while no electricity can be generated (this is the case for glass and metals which have zero calorific value).

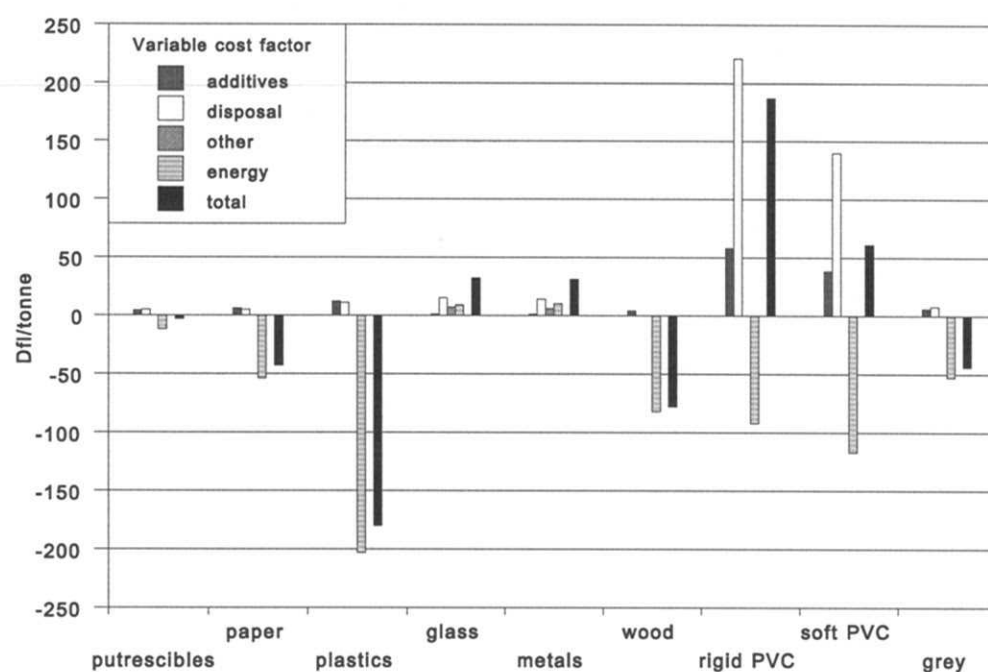


Figure 6.3 Variable cost (Dfl/tonne) for processing waste materials in a MSWC facility with evaporation of the scrubber effluent.

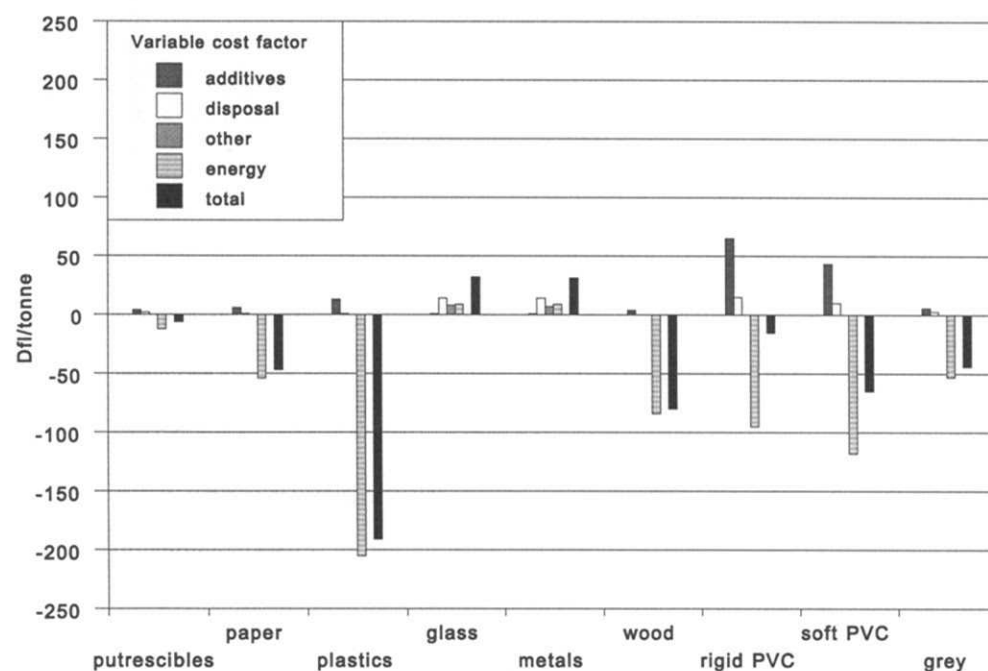


Figure 6.4 Variable cost (Dfl/tonne) for processing waste materials in a MSWC facility with discharge of the scrubber effluent.

6.3 Fixed costs

In formula (13) the specific processing cost is constituted from two expressions:

v_p : describing the variable costs, and
 $w * f_g$: introducing the fixed costs of “grey” waste.

In section 7.2 the variable costs have been detailed for the various waste material types in the not limited situation. In the (mass or thermally) limited scenarios, separate consideration of the two terms in formula (13) shows whether the fixed or the variable costs are dominating the SPC calculation:

$$SPC_p = v_p + w * f_g \quad (13)$$

As explained, f_g can be calculated from GF_g :

$$SPC_p = v_p + w * (GF_g - v_g) \quad (14)$$

In Table 6.3 this overview is presented. For all waste materials the SPC has been broken down in the two terms in case of evaporation of the scrubber effluent. For soft and rigid PVC the case of scrubber effluent discharge is included.

Table 6.3 illustrates that the specific processing costs are generally dominated by the fixed costs in formula (13). The only significant exceptions are:

- the energy revenue from the addition of plastics in the mass limited situation;
- the variable costs for both soft and rigid PVC in case the scrubber effluent is evaporated, caused by the disposal costs of the salt residue.

Table 6.3 Breakdown of the specific processing cost into variable and fixed cost effects.

Waste material	w [kg/kg]	v_p [Dfl/tonne]	$w * f_g$ [Dfl/tonne]	SPC_p [Dfl/tonne]
EVAPORATION OF THE SCRUBBER EFFLUENT				
THERMAL LIMITATION				
plastics	3.40	-180	781	601
soft PVC	1.99	61	457	518
rigid PVC	1.61	187	370	557
wood	1.45	-78	333	255
paper	0.99	-43	229	186
putrescibles	0.39	-3	77	74
glass	0	32	0	32
metals	0	31	0	31
grey waste	1	-39	230	191
MASS LIMITATION				
plastics	1	-180	230	50
soft PVC	1	61	230	292
rigid PVC	1	187	230	417
wood	1	-78	230	152
paper	1	-43	230	187
putrescibles	1	-3	230	227
glass	1	32	230	263
metals	1	31	230	261
grey waste	1	-39	230	191
DISCHARGE OF THE SCRUBBER EFFLUENT				
THERMAL LIMITATION				
soft PVC	1.99	-65	435	370
rigid PVC	1.61	-15	351	336
grey waste	1	-44	219	175
MASS LIMITATION				
soft PVC	1	-65	219	154
rigid PVC	1	-15	219	204
grey waste	1	-44	219	175

6.4 Grey waste “synthesized” from specific waste components

One tonne of grey waste of the reference situation can be put together from the specific waste categories in this study. As reflected by formula (15) in section 2.3.2, addition of 1 tonne grey waste is achieved by addition of each waste material in amounts corresponding to its relative concentration in grey waste.

This “construction” of grey waste has been conducted for thermally, mass and not limited scenario’s as these most clearly represent the theoretical extremes. Figure 6.5 provides the results for the limited scenario’s and Table 6.4 presents the

figures for all three scenario's (a graphical representation of the not limited scenario is confusing due to the occurrence of positive and negative values; therefore it is left out). The concentration of the waste materials in the grey waste is also given in Table 6.4.

It should be noted that this concerns the combustion of 1 additional tonne of grey waste within the operation window where the validity of the expert rules of the model is not challenged as described in chapter 2.3.

Table 6.4 Contribution of waste materials to the specific processing cost of 1 additional tonne of "synthesized" grey waste (explanation see text).

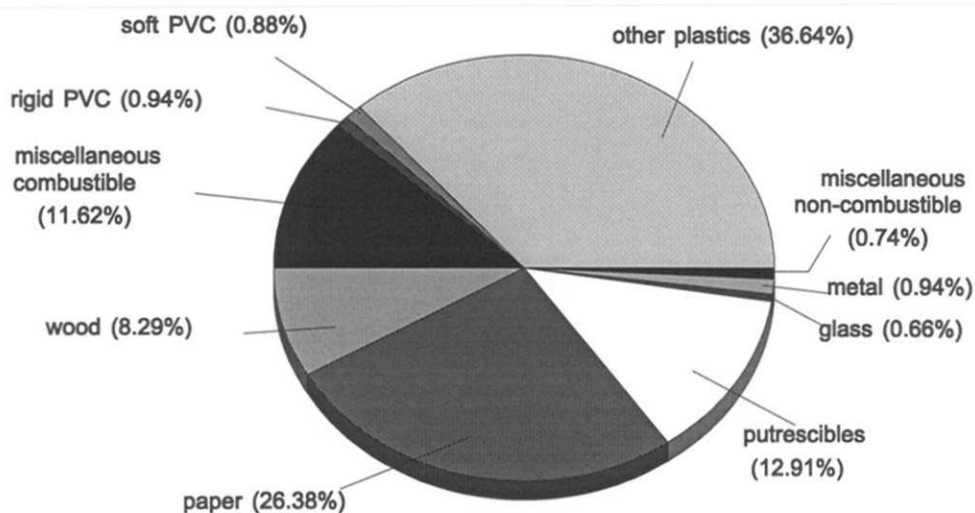
Waste material	Concentration [wt%]	Thermal limitation		Mass limitation		No limitation	
		SPC [Dfl/t]	Contrib. to SPC ₀ [Dfl/t]	SPC [Dfl/t]	Contrib. to SPC ₀ [Dfl/t]	SPC [Dfl/t]	Contrib. to SPC ₀ [Dfl/t]
other plastics	11.6	601	70	50	4	-180	-23
soft PVC	0.3	518	2	292	1	61	1
rigid PVC	0.3	557	2	417	1	187	1
miscell. comb.	7.5	295	22	174	13	-56	-4
wood	6.2	255	16	152	9	-78	-5
paper	27.1	186	50	187	51	-43	-12
putrescibles	33.1	74	25	227	75	-3	-1
glass	3.9	32	1	263	10	32	1
metal	5.7	31	2	261	15	31	2
miscell. non-comb.	4.3	33	1	263	11	33	1
total	100.0	nr	191	nr	191	nr	-39
grey	100.0	191	nr	191	nr	-39	nr

nr = not relevant

Table 6.4 and Figure 6.5 reconfirm the large impact of the type of MSWC facility operation on the cost distribution: thermal, mass or not limited throughput scenarios show largely different results. Additionally, the relative importance of various waste materials is shown:

though the SPC for (rigid and soft) PVC may be relatively high, their contribution to the cost of 1 additional tonne of grey waste is relatively small.

Thermally limited plant



Mass limited plant

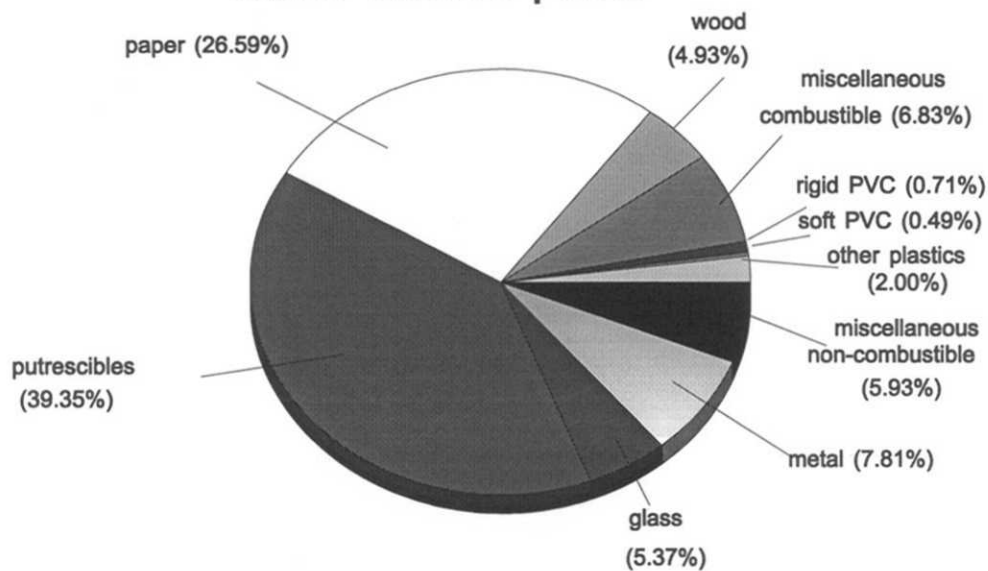


Figure 6.5 Contribution of waste materials to the total processing cost of 1 additional tonne of "synthesized" grey waste (explanation in text).

6.5 Effect of varying putrescibles levels in the waste feed

The policy in The Netherlands tends to an increase in effort for separate collection of putrescibles. As a result, the putrescibles fraction in the mixed household waste will decrease below the present 33.1 wt%, used for the reference situation (see Appendix C). On the long term a percentage of 28 wt% is perceived to be more realistic (see Section 4.3) [Halen,1995].

A “low putrescibles” type of grey waste has therefore been included in this study as secondary reference.

As can be seen in Appendix C, the decrease in the putrescibles content of the grey waste from 33.1 to 28 wt% results in an increase in the heating value of the grey waste from 10.06 to 10.57 MJ/kg. The GF_g for this “low putrescibles” grey waste was calculated based on the HVC Noord-Holland for three scenario's, analogous to those used until now. The results are given in Table 6.5.

Table 6.5 Influence Of The Putrescible Content Of Grey Waste.

Scrubber effluent evaporation	Grey waste with “high” (33.1 wt%) putrescibles			Grey waste with “low” (28.0) putrescibles		
	thermal limit.	Mass limit.	no limit.	thermal limit.	mass limit.	no limit.
GF_g [Dfl/tonne]	191	191	-39	200	188	-42

A decrease in the putrescibles content of the waste from 33.1 to 28 wt% results – for a thermally limited plant – in a 5% increase in processing costs for the remaining grey waste. For a mass limited plant the processing costs decrease by less than 2%. The variable costs (unlimited scenario) decrease by about 8%.

Within the validity of the model, calculated SPC's are independent of changes in the composition of the grey waste, confirming the mathematical demonstration in chapter 2.3.2.

7. Definitions

- **Fixed cost**
Constant cost, unrelated to variations in throughput or composition of waste, includes for example capital cost, labour cost and (general) maintenance.
- **Gate fee**
Price, charged by the MSWC plant to the waste owner for processing 1 tonne of waste.
- **Grey waste**
A theoretical mixed municipal solid waste with a reference composition, identical to the weight-average composition of waste offered over a long period.
- **Heating value**
Net (= lower) heating value of a waste material: the usable energy from the combustion of a waste material at standard conditions (= heat of combustion, condensation heat of water subtracted).
- **Limitation**
The waste throughput of a MSWC is limited. This limitation can have several causes:
 - the throughput is limited on mass, i.e. some part of the facility (e.g. the grate) cannot process more tonnes per hour;
 - the throughput is limited on energy recovery, i.e. some part of the facility (e.g. the boiler) cannot process more joules per hour.
- **Mass limitation**
See limitation
- **Specific processing cost**
Fee to be charged to the waste owner to achieve a financial break-even situation for the MSWC facility operator, when accepting 1 tonne of a specific waste for processing.
- **Thermal limitation**
See limitation
- **Variable cost**
Cost, linearly related to the plant throughput (quantity and composition), i.e. additives, energy production, disposal cost.

8. List of symbols and abbreviations

Symbols

f_g	fixed cost per tonne G [Dfl/tonne];
F_s	Total annual cost of MSWC in situation S (Dfl/year);
F_n	Total annual cost of MSWC in situation N (Dfl/year);
$F_{f,n \text{ or } s}$	fixed annual cost in situation N or S [Dfl/year];
$F_{v,n \text{ or } s}$	variable annual cost in situation N or S [Dfl/year];
GF_g	Gate fee for processing G (Dfl/tonne);
$H_{a \text{ or } b}$	heating value of grey waste A or B [MJ/kg];
H_p	heating value of P (MJ/tonne);
H_g	heating value of G (MJ/tonne);
$Q_{a \text{ or } b}$	heat recovered from waste combustion [GJ/hour];
SPC_p	Specific processing cost of P (Dfl/tonne);
t_a	tonnes of grey waste A annually processed [tonnes/year];
t_b	tonnes of grey waste B annually processed [tonnes/year];
t_g	mass flow of G (tonnes/year);
t_p	amount of waste material P added [tonnes/year];
$v_{p \text{ or } g}$	variable cost per tonne P or G [Dfl/tonne];
w	substitution (or displacement) factor, tonnes G substituted by addition of 1 tonne P (tonne/tonne);
z_g	profit per tonne G [Dfl/tonne].

Abbreviations

APME	The Association of Plastics Manufacturers in Europe
Dfl.	Dutch guilders
EFA	Entrained Flow Adsorber
ESP	Electrostatic precipitator
(MSWC) FACE model	(Municipal Solid Waste Combustion) Flow And Cost Expert Model, jointly developed by APME and TNO
G	Grey waste
HVC Noord-Holland	MSWC facility of Alkmaar in the province of North-Holland
LHV	Lower heating value
Misc(ell).comb.	Miscellaneous combustibles
Misc(ell).non-comb.	Miscellaneous non-combustibles
MSW	Municipal Solid Waste
MSWC	Municipal Solid Waste Combustion
N	New situation after addition of specific waste P
Non-comb.	Non-combustibles
P	Specific waste for which specific processing cost have to be calculated

PCDD/F S	Poly-chlorinated-dibenzo-para-dioxins and -furans Starting situation: MSWC plant combusting “grey” waste with the reference composition
SCR DeNO _x VROM	Selective Catalytic Reduction of NO _x Netherlands Ministry of Housing, Spatial Planning and the Environment

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10. Authentication

Name and address of the principal:

APME - The Association of Plastics Manufacturers in Europe

VROM - Netherlands Ministry of Housing, Spatial Planning and the Environment

Names and functions of the cooperators:

Dr.ir. J.A. Zeevalkink

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Names and establishments to which part of the research was put out to contract:

-

Date upon which, or period in which, the research took place:

July 1995 - July 1996

Signature:

A handwritten signature in blue ink, consisting of a large, stylized 'Z' followed by 'eevalkink'.

Dr. J.A. Zeevalkink
projectleader

Approved by:

A handwritten signature in blue ink, consisting of 'J. de Koning' in a cursive style.

Ir. J. de Koning
Head of the Department
of Thermal Conversion Technology

Appendix A The MSWC FACE model

The combustion of municipal solid waste in large facilities is a complex process. The execution of experiments to investigate the influence of certain parameters in such a process is difficult and expensive because of the many parameters which can be of influence. To understand the most important parameters in order to reduce the number of experiments required, a computer model has been developed which describes the main processes occurring in a modern Municipal Solid Waste Combustion (MSWC) facility. This model calculates the influence of waste composition on mass, component and energy flows, emissions, the composition of the residues, and the capital and operating costs of a MSWC facility. Also the influence of the process conditions can be simulated.

Structure of the MSWC FACE-model

a. Composition of the feed to the MSWC

One of the most widely varying parameters in a waste combustion facility is the composition of the feed. Therefore, the computer model is flexible towards changes in the MSW composition. The waste is divided in several fractions: putrescibles, paper, plastics, glass, metals, textiles, fines, miscellaneous combustible and miscellaneous non-combustible. The model comprises data on the (elemental) composition of these fractions, taken from an extensive literature search using numerous literature sources throughout Europe.

By combining the data on the elemental composition of the fractions with a mix of fractions the waste feed can be composed.

Besides using this included data base on the composition, the model allows the use or addition of extra (own) data.

b. Configuration MSWC facility

In practice, MSW combustion facilities have many different hardware configurations as there are different types of furnaces, boilers and flue gas cleaning systems. Originally, the model has been built for a single, fixed configuration, according to what was considered the state-of-the-art. In a second step, the model has been expanded with extra flue gas cleaning units.

In order to keep the model flexible towards modelling other configurations, a modular setup was chosen. This offers the opportunity to exclude, exchange or add modules.

The following modules have been developed so far:

- a furnace, with a moving grate and a horizontal boiler in which steam is produced for electricity generation;
- an electrostatic precipitator;
- a fabric filter (bag house);
- a cyclone;
- a dry scrubber;
- a semi-dry scrubber;
- a multi-staged wet scrubber consisting of a quench, an acid stage (scrubbing with water) and an alkaline stage (scrubbing with NaOH-solution or $\text{Ca}(\text{OH})_2$ -slurry);
- a waste water purification system with:
 - a) neutralization with $\text{Ca}(\text{OH})_2$
 - b) flocculation and precipitation through addition of FeCl_3 , poly-electrolyte and TMT-15 (tri-mercapto-triazine) and
 - c) evaporation or discharge of the water;
- a steam heater to heat up the flue gases;
- an entrained flow reactor (addition of $\text{Ca}(\text{OH})_2$ /coke-mixture) with subsequent fabric filter;
- an SCR-DeNOx reactor with regenerative heat exchanger and gas burner;
- a chimney.

From these modules the required configuration can be chosen for calculations.

c. Calculation procedure

The physical background of the model consists of mass, component and energy balances of the various parts of the combustion facility. In extension to these mass and energy balances the processes are described by a steady state approach using so-called expert rules. These expert rules are simple (linear) mathematical relations, which describe the occurring processes from a 'black box'-approach, according to the latest state-of-the-art technology and recent literature data.

Furthermore, the efficiency factors of the flue gas equipment are derived from the knowledge of experts and manufacturers. In addition to the physical model also a cost model has been developed, based on over 12 bid documents for new or extended MSWC facilities in the years 1988-1992. This cost model calculates the capital and operating costs depending on the calculated mass and energy flows.

Validation of the model

The MSWC FACE-model has been validated using yearly production data from the MSWC at Bamberg (Germany) and from a full-scale test conducted by APME at the MSWC Würzburg (Germany). In addition, the cost model has been validated with the bid documents on the currently built MSWC facility at Alkmaar (Netherlands). The accuracy in these validations was 15% for the process data and 25% for the costs.

This validation confirms that the MSWC-FACE model is an acceptable tool to simulate reality.

Calculation options

The model allows changes in process parameters as well as in expert rule coefficients to adjust the calculation to a specific configuration or situation. For example the following parameters can easily be adjusted:

- the waste composition: in terms of fraction putrescibles, paper, etc. or fraction PE, PP, etc. as well as in terms of elemental composition (wt% of C, H, O, etc.);
- the heat of combustion of the processed waste;
- the configuration of the flue gas cleaning equipment applied;
- the air factor applied during combustion;
- the mass and thermal capacity of the installation;
- the emission guideline which has to be met (depending on the country in which the facility is located);
- the cost location factor.

Besides calculations for a MSWC facility under design conditions, it also allows to model an installation for a starting set of parameters and then calculate the effect of operating this installation under conditions differing from the original model conditions. This is extremely useful for determination of the effects of a waste feed or process parameter, scrutinized in an existing installation which is running under conditions which do not conform to the design conditions.

Finally, it is possible to change the coefficients in certain expert rules, like:

- the distribution of the heavy metals in the waste into the bottom-ash, the fly-ash and the flue gas;
- the removal efficiencies for pollutants in the flue gas cleaning devices;
- the concentrations or stoichiometric ratios of the additives used;
- the cost per unit of utilities and chemicals as well as the revenues from electricity sale.

Applications of the model

The structure of the model enables modelling of numerous situations. Especially because of the extensive cost calculations, the model can be applied in many situations.

First, the model is very useful in the first stage of planning a new MSWC facility: the so-called pre-engineering. Through calculations the model can demonstrate the effect of the size and the different flue gas cleaning systems on the costs and flows for such new plant. In this way various options with their consequences can be discriminated very quickly.

Secondly, for existing facilities the model can demonstrate the effect of design limitations on flows and costs. From an economic point of view, facilities are operated as close as possible to the maximum load (which can be either thermal or mass limited). When the composition (or more specifically the calorific value) of the waste feed changes, the facilities are restricted to these limits, which may mean a decrease (increasing calorific value) or an increase (decreasing calorific value) in throughput. As the fixed yearly costs of an MSWC facility are relatively high, a decrease or increase in the waste throughput has a direct effect on the processing cost per tonne of waste.

The MSWC FACE-model can also be used to determine the impact of a specific waste stream on the performance and cost of a MSWC facility. This can be used either for differential costing of the waste flows to the facility or to develop an acceptance policy for waste.

Besides determining the effect on a MSWC facility of a change through one waste fraction, the effect of changes in more fractions can be calculated as well. In predictions of future development of the waste feed to the MSWC facility very often scenarios are set up. Each scenario can then be a mixture of several changes for several components (e.g. realisation to some or full extent of recycling targets for paper, glass, etc.). Once these scenarios have been defined, the effects on the MSW composition and the consequences for a MSWC facility can be determined with the MSWC FACE-model.

Finally, the model can be used to acquire in-depth understanding in the operation of a plant. As such it may be used for training MSWC facility staff.

Conclusion

The MSWC FACE-model is a powerful tool to predict effects of changes in waste compositions or process conditions on the operation of a MSWC facility. The calculations that can be executed with the MSWC FACE-model are extremely versatile.

Acknowledgement

The MSWC FACE-model could not have been developed without the technical support of representatives of APME's (Association of Plastic Manufacturers in Europe) Technical and Environmental Centre, which Head Office is located at Brussels. Furthermore, APME's Technical and Environmental Centre supplied the majority of the funding to develop this model.

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Appendix B Simulation of the HVC Noord-Holland with the MSWC FACE-model.

B.1 Introduction

For the calculation of the specific processing cost the MSWC FACE-model was used. In order to give the calculation a more realistic basis than just that of the MSWC FACE-model, the model was tuned to the HVC Noord-Holland prior to the calculations. For this, design data of the HVC were used as in the early phases of the study no actual operating data were available yet.

How the model was tuned to the HVC is described in this Appendix.

B.2 Adjustments to the MSWC FACE-model

Regarding the configuration of the HVC three items need special attention when simulating the HVC with the MSWC FACE-model, as the MSWC FACE-model is not equipped with these three items. These concern: a) recirculation of (part of) the flue gas, b) the evaporation of the waste water in the spray dryer and c) recirculation of the coal residue to the furnace for (co-)combustion.

Ad a. Flue gas recirculation

At the HVC part (up to 20%) of the flue gases behind the first ESP (see Figure 3.1, main report) is recirculated to the furnace where it is injected as overfire (secondary) air. Though the MSWC FACE-model does not contain a flue gas recirculation facility, this can be simulated by using the flue gas flow after recycling as the flow to the flue gas cleaning system. In fact, this means that the flue gas recirculation is incorporated in the 'black box' which describes the furnace and boiler. By doing so, flue gas recirculation can be properly simulated by the MSWC FACE-model.

Ad b. Evaporation of the waste water in a spray dryer

The option 'Evaporation of the waste water' in the MSWC FACE-model considers the evaporation in a separate evaporator with steam as energy supply, whereas at the HVC the waste water is evaporated in the flue gases in a spray dryer using the heat of the flue gases.

This may result in differences where the salt residue is concerned. The ESP behind the spray dryer will remove some of the dust (and heavy metals) in the flue gas together with the salt residue. This increases both the amount as the impurity of the resulting salt residue. In case of separate evaporation practically no dust or heavy metals are present in the salt residue.

Furthermore, with external evaporation all the salt residue is captured, whereas the ESP has 'only' a removal efficiency of, normally, 95-99%. This slightly reduces

the amount of salt residue produced by the spray dryer/ESP compared to external evaporation.

By adjusting the removal efficiencies of the flue gas cleaning devices, and accounting for the difference in steam consumption, this difference in configuration can be simulated by the model.

Ad c. Recirculation of the coal residue to the furnace

In the MSWC FACE-model the coal residue is treated as a residue for disposal for which a fee is charged per tonne. In practice, the HVC recirculates the coal residue to the furnace where it is burned in a powder coal burner.

This difference is assumed to have no influence on the results as the amount of coal residue is practically constant.

First of all, the specific process conditions at the HVC must be entered into the model. These process conditions are listed in Table B.1.

Furthermore, the MSWC FACE-model uses coefficients (in expert rules), which calculate streams in the facility. An example of such a coefficient is the dust removal efficiency of the ESP. Adjustment of these coefficients has been done based on the resulting mass flows and concentrations, as specified by the HVC. In Table B.2 these coefficients are given with the values used for the simulation of the HVC as well as standard values which are used in the FACE-model as base case values.

Table B0.1 Process conditions at the HVC Noord-Holland as used in the simulation with the FACE-model [1].

Parameter	Value	Unity
Capacity:		
- number of lines	3	-
- design capacity per line	18.5	tonnes/hour
- availability	80	%
- total capacity	389	tonnes/year
Net heating value	10	MJ/kg
Airfactor ¹	1.38	mol O ₂ added/mol O ₂ theor.required
Temperature:		
- combustion air	120	°C
- flue gas at boiler exit	200	°C
- steam for reheating flue gas	160	°C
- SCR DeNOx	320	°C
- flue gas at stack	140	°C
Energy recovery:		
- feedwater temperature	140	°C
- steam temperature	400	°C
- steam pressure	40	bar
Emissions: ²		
- dust	3	mg/Nm ³
- HCl	5	mg/Nm ³
- HF	0.5	mg/Nm ³
- SO ₂	30	mg/Nm ³
- NO _x	70	mg/Nm ³
- PCDD/F	0.05	ng I-TEQ/Nm ³
- Hg	0.02	mg/Nm ³
- Cd	0.03	mg/Nm ³
- Sum other heavy metals	1	mg/Nm ³

¹ Normally, airfactors of 1.6 to 2.0 are applied in MSWC facilities. Partly due to the application of flue gas recirculation an air factor of 1.38 is considered to be feasible for the HVC [1].

² All emissions at standard conditions, on dry basis, at 11% O₂.
The MSWC FACE-model does not calculate emissions, but given a certain concentration in the raw flue gas and a limit for emitted flue gas concentrations, the required amount of additive is determined. Therefore, expected emission values have to be introduced.

Table B0.2 Coefficients adjusted in the simulation of the HVC Noord-Holland with the MSWC FACE-model. (explanation in text).

Coefficients	Unity	Value simulation hvc	Standard value face-model
Energy recovery:			
- heat loss furnace	%	1	2
- heat loss boiler	%	2	3
- steam used for electricity generation	%	91	80
- efficiency electricity generation	%	75.3	73.7
- in-plant electricity consumption	kWh/tonne waste	113	65
Dust:			
- distribution fly-ash/bottom-ash	%	5	9
- removal efficiency ESP	%	95	99.2
- removal efficiency scrubber	%	66.6	90
- removal efficiency EFA	%	92.5	99.9
Additive dosage:			
- stoichiometrie SO ₂ -absorption	-	1.1	1.2
- scrubber effluent purification:			
FeCl ₃	g/m ³	690	20
poly-electrolyte	g/m ³	20	6
TMT-15	g/m ³	5600	250
Moisture content residues:			
- bottom-ash	%	15	10
- effluent purification residue	%	60	50
- spray dryer residue	%	100	85
Percentage gaseous SO ₂	%	60	50
PCDD/F in raw flue gas	ng I-TEQ/Nm ³	0.5	8.0
PCDD/F-load active coal	ng/g	10	70
Reference N-content waste feed	%	0.65	1.0
NO _x removal efficiency SCR DeNO _x	%	77.8	98

Explanation Table B.2

- **Energy recovery:**
The difference in steam usage for electricity production is due to the difference in configuration: the MSWC FACE-model uses steam for scrubber effluent evaporation, whereas the HVC doesn't.
The higher internal electricity consumption for the HVC is mainly due to the fact that the value for the HVC includes the consumption for pretreatment of the waste feed and handling of the residues: this is not included in the standard FACE-model value.
- **Dust:**
The amount of inert in the waste feed ending up as fly-ash is relatively low at the HVC: less particulates are entrained with the flue gas. This is attained by applying relatively low gas velocities in the furnace and recirculation of flue gas.
On the other hand, the value used in by FACE is considered to be relatively high ('worst case').
Dust removal efficiencies in the ESP (in the simulation only 1 ESP is used), scrubber and EFA are fitted to the dust concentration values specified by the HVC. In these specified values a safety margin is built in to ensure that the emission limits can be met.
- **Additive dosage:**
Coefficients have been deducted from HVC data. A striking difference is found in the consumption of chemicals in the scrubber effluent purification system. An explanation for these differences is not available.
- **Residues:**
The moisture content of the residues is adjusted according to HVC specifications. As the scrubber effluent is evaporated in a spray dryer at the HVC, the resulting residue does not contain water.
- **Others:**
The coefficients 'Percentage gaseous SO₂' en 'Reference N-content waste feed' have been adjusted to fit the concentrations of SO₂ and NO_x in the raw flue gas to the specified values.
The coefficient 'Reference N-content waste feed' determines the amount of NO_x in the flue gas. An increase in this coefficient reduces the NO_x-concentration of the flue gas. At the HVC this lower NO_x-concentration is due to the flue gas recirculation.
The NO_x removal efficiency can be quite moderate as the SCR-inlet concentration of NO_x is not so high.

B.3 Cost

The MSWC FACE-model calculates investments based on chosen configuration. As the configuration of the HVC differs from the MSWC FACE-model the investment cost break-down also exhibits differences on separate items. As there is little use in comparing investments on separate items, only the total investment is compared.

For the simulation (and the SPC calculations) the cost parameters have been tuned. Table B.3 shows the parameters and coefficients compared to the base case values of the MSWC FACE-model.

Table B.4 specifies chemical prices and residue disposal fees for the HVC.

Table B3 Adjustment financial parameters in the MSWC FACE-model for simulation of the HVC Noord-Holland.

Cost parameter	Unity	Specification HVC	Calculated with base case values FACE-model
Total investment	MDfl	816.9	871.1
Maintenance	MDfl/yr	7.1	14.2
Insurance/taxes	MDfl/yr	6.7	6.9
Emission measurements	MDfl/yr	0.55	0.57
Personnel:			
- number	-	89.4	83
- average salary	Dfl/yr	89185	nr ¹
Electricity revenue (delivered to the grid)	Dfl/kWh	0.085	nr ¹
Interest	%	6	nr ¹
Depreciation period	year	25	nr ¹

¹ nr = not relevant: the values vary a lot between plants: it makes no sense to speak of average or base case values.

Table B.4 Prices for chemicals, additives and residue disposal costs as specified by the HVC [1].

Additive/residue	price/cost in Dfl/tonne
Additives:	
- limestone	196
- sodiumhydroxide	325
- Ammonia	203
- FeCl ₃	455
- Poly-electrolyte	6734
- Na ₂ S	750
- Active carbon	2450
Residues:	
- Bottom-ash	0
- Fly-ash	295
- Effluent cleaning residue	150
- Spray dryer residue	425

¹ It is assumed that the revenue from selling bottom-ash as road construction material equals the treatment cost for this residue at the plant. This is not the case for fly-ash for which the treatment cost exceed the revenue considerably (fly-ash is used as filling material in road construction). For the other residues the costs include treatment and landfill cost (class C2: disposal cost per tonne are different for effluent cleaning and spray dryer residue as the density of these residues is different and landfill fees are imposed per deposited volume).

B.4 Results simulation

With coefficients and values as in Tables B.1 to B.4, a run with the MSWC FACE-model has been executed. Table B.5 compares the results as calculated with the model to the values specified by the HVC. Relative deviations are given to offer an insight in the accuracy of the simulation.

Table B5 Comparison of the simulation results with 'true values' as specified by the HVC.

Parameter	Unity	Specification HVC	Value calculated by FACE	Relative deviation [%]
Waste throughput	t/yr	388500	388944	+0.1
Steam production	t/yr	1316700	1322410	+0.4
Electricity production	MW	42.4	42.2	-0.5
Combustion air	Nm ³ /hr	225000	228492	+1.6
Flue gas (boiler)	Nm ³ /hr	260490	264687	+1.6
Flue gas (stack)	Nm ³ /hr	294000	295821	+0.6
Bottom-ash	t/yr	102900	100144	-2.7
Fly-ash	t/yr	4500	4255	-5.5
Boiler-ash	t/yr	900	1	1
Effluent cleaning residue	t/yr	2961	3215	+18.9
Spray dryer residue	t/yr	3528	4335	+1.6
Coal residue	t/yr	0 - 105	106	+1.0
Limestone	t/yr	1575	1802	+14.4
Sodiumhydroxide	t/yr	1638	1802	+10.0
Ammonia	t/yr	221	205	-7.4
FeCl ₃	t/yr	39	38	-1.4
Poly-electrolyte	t/yr	1.09	1.11	+2.5
Na ₂ S	t/yr	16.8	16.6	-1.4
Active coal	t/yr	35	37	+6.0
Water	m ³ /yr	137844	187559	+36.1
Natural gas	Nm ³ /yr	3529411	2941258	-16.7
Additive consumption ² cost	MDfl/yr	2.34	2.37	+1.5
Residue disposal cost ²	MDfl/yr	3.32	3.63	+9.3

¹ The MSWC FACE-model does not distinguish between boiler-ash and fly-ash. Including the boiler-ash with the fly-ash results in a relative deviation for the fly-ash of -18.2%.

² The total impact of the differences in amounts of additives consumed and residues produced can be judged from the costs. These totals match reasonably well with the values from the HVC specification.

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Appendix C Reference compositions and corresponding literature sources

In this Appendix the reference composition of Municipal Solid Waste (MSW) is given and discussed. First the total MSW is discussed, whereas chapter C.2 focuses on the composition of PVC.

C.1 Municipal Solid Waste

Based on a study on the arising of all types of waste in the Netherlands which have to be processed through combustion in Municipal Solid Waste Combustion (MSWC) facilities [AOO,1995a] the composition of the feed to the MSWC facility can be calculated. In this study the waste situation for the year 1993 is used as a reference point to foresee the future amounts of waste taking into account the effects of economic growth, prevention and recycling and other policy measures. This composition in fractions for the reference year 1993 is presented in Table C.1.

Table C1 Composition of the waste to be processed in an MSWC facility (according to the 1993 scenario from [AOO,1995a]).

Fraction	[wt%]
Putrescibles	33.1
Paper	27.1
Plastics	12.2
Glass	3.9
Metals	5.7
Wood	6.2
Miscellaneous:	
- combustible	7.5
- non-combustible	4.3

For the calculations with the MSWC FACE-model the elemental composition of the feed is needed. This elemental composition can be calculated from the composition as given in Table C.1, and the elemental composition per fraction as given in Table C.2. The data for Table C.2 are derived from several sources. Most data, however, were collected in a study which was executed by TNO for APME [Rijpkema,1992]. In this inventory literature for European waste was examined and used to create an average composition of the fractions in MSW. The data in this study consider the fractions as if they were separated from a pile of waste and then analysed, thus including attached dirt.

Table C.2 Elementary composition of MSW fractions.

		Putres- cibles	Paper	Plastic	Glass	Metal	Wood	Miscellaneous combustible	Miscellaneous non- combustible
C	wt%dry	38,071 ¹	43,392 ¹	77,310 ^{1,5}	0,516 ¹	2,126 ¹	48,210 ³	50,265 ¹	0,505 ¹
H	wt%dry	5,139 ¹	6,199 ¹	11,496 ^{1,5}	0,072 ¹	0,315 ¹	6,310 ³	5,986 ¹	0,072 ¹
O	wt%dry	28,534 ¹	39,626 ¹	2,870 ^{1,5}	0,361 ¹	2,115 ¹	42,610 ³	25,150 ¹	0,361 ¹
N	wt%dry	3,804 ¹	0,252 ¹	0,972 ^{1,5}	0,031 ¹	0,022 ¹	0,490 ³	0,848 ¹	0,031 ¹
S	wt%dry	0,285 ¹	0,252 ¹	0,023 ^{1,5}		0,011 ¹	0,028 ³	0,360 ¹	
P	wt%dry	0,571 ¹	0,009 ¹					0,026	
F	wt%dry	0,001 ¹							
Cl	wt%dry	0,756 ¹	0,369 ¹	2,364 ^{1,5}	0,010 ¹	0,032 ¹	0,032 ³	2,997 ¹	0,010 ¹
ash	wt%dry	22,84 ¹	9,90 ¹	4,963 ^{1,5}	99,01 ¹	95,38 ¹	2,31 ³	14,37 ¹	99,02 ¹
water	wt%total	56,5 ⁴	26,8 ⁴	10,0 ¹	1,7 ⁴	5,8 ⁴	14,5 ⁴	14,7 ⁴	0,0 ⁴
LHV	MJ/kg total	3,39 ⁴	9,99 ⁴	34,19 ^{1,5}	0,00 ⁴	0,00 ⁴	14,60 ⁴	15,39 ⁴	0,00 ⁴
Hg	mg/kg dry	13 ¹	0,1 ¹	0,1 ^{1,5}	0,02 ¹		0,08 ³	0,1 ¹	0,02 ¹
Cd	mg/kg dry	2 ¹	2 ¹	50 ²	1,5 ¹	1,5 ¹	1,3 ³	10 ¹	4 ¹
As	mg/kg dry	6 ¹	0,5 ¹	0,5 ^{1,5}	30 ¹	50 ¹	11 ³	1,5 ¹	10 ¹
Co	mg/kg dry	30 ¹	2,5 ¹	20 ²	4 ¹	70 ¹		8 ¹	50 ¹
Cr	mg/kg dry	300 ¹	10 ¹	50 ²	250 ¹	900 ¹	27 ³	1200 ¹	120 ¹
Cu	mg/kg dry	300 ¹	100 ¹	100 ²	30 ¹	10000 ¹	42 ³	300 ¹	50 ¹
Ni	mg/kg dry	300 ¹	10 ¹	20 ²	40 ¹	800 ¹	1 ³	30 ¹	80 ¹
Mn	mg/kg dry	300 ¹	50 ¹	30 ²	120 ¹	500 ¹	130 ³	30 ¹	500 ¹
Pb	mg/kg dry	400 ¹	100 ¹	500 ^{2,5}	400 ¹	2500 ¹	1170 ³	400 ¹	2000 ¹
Sb	mg/kg dry	2 ¹	2 ¹	40 ²	25 ¹	15 ¹	10 ³	10 ¹	15 ¹
Sn	mg/kg dry		8 ¹	30 ²					
V	mg/kg dry	45 ¹	1 ¹	100 ²	6 ¹	75 ¹		1 ¹	150 ¹
Zn	mg/kg dry	410 ¹	275 ¹	300 ²	60 ¹	3580 ¹	1050 ³	1850 ¹	1960 ¹

No data for Br, Se, Te, Ti: assumed to be 0.

{blanks}: assumed to be zero

¹ [Rijpkema, 1992]² [GfA, 1994]³ [Eggels, 1995]⁴ [AOO, 1995b]⁵ [Groot, 1993]

Besides the standard MSW as presented in Table C.1 calculations were executed with a decreased putrescibles content. The composition of this MSW with a reduced content putrescibles is presented in Table C.3. The composition is calculated by reducing the putrescibles content to 28.0% (based on [Halen,1995]) and increasing the other fractions proportionally, so that a total of 100% results.

Table C3 Composition of the waste with reduced putrescibles content.

Fraction	[wt%]
Putrescibles	28.0
Paper	29.2
Plastics	13.1
Glass	4.2
Metals	6.1
Wood	6.7
Miscellaneous:	
- combustible	8.1
- non-combustible	4.6

The total elemental composition of the standard MSW and the MSW with a reduced content putrescibles is given in Table C.4.

Table C.4 *Elemental composition of Municipal Solid Waste*

Element	Unity	Standard MSW (33.1 wt% putrescibles)	MSW with reduced putrescibles content (28 wt%)
C	wt% on wet	28.505	29.428
H	wt% on wet	3.972	4.106
O	wt% on wet	16.295	16.615
N	wt% on wet	0.788	0.722
S	wt% on wet	0.119	0.118
P	wt% on wet	0.086	0.073
Cl	wt% on wet	0.638	0.661
ash	wt% on wet	20.014	20.732
water	wt% on wet	29.583	27.543
Heating value (lower = net)	MJ/kg wet	10.06	10.57
Hg	mg/kg wet	1.92	1.63
Cd	mg/kg wet	7.19	7.66
As	mg/kg wet	5.96	6.2
Co	mg/kg wet	13.58	13.59
Cr	mg/kg wet	191.94	196.59
Cu	mg/kg wet	635.67	671.0
Ni	mg/kg wet	97.28	94.47
Mn	mg/kg wet	118.17	116.97
Pb	mg/kg wet	455.51	475.87
Sb	mg/kg wet	8.65	9.23
Sn	mg/kg wet	4.88	5.525
V	mg/kg wet	28.43	29.01
Zn	mg/kg wet	599.35	630.41

No data available for Br, F, Se, Te and Ti: assumed to be zero.

The study on MSW in Europe [Rijkema,1992] also supplies data on the composition of the plastics fraction in terms of percentage PE, PP, PS, PET, PVC and other plastics. However, as in the present study special attention is given to PVC, it was decided to put an extra effort in acquiring reliable data on the elemental composition of PVC.

C.2 PVC

The plastics fraction in MSW contains 5.3 wt% PVC [Groot,1993], split up in rigid and soft PVC. [Cornelisse,1995] reports that household waste (not containing bulky or commercial waste) contains 10.4% plastics. 6.7% of this plastics fraction is PVC (0.7% on total MSW).

According to [Groot,1993] approximately 66% of the PVC-fraction is rigid PVC. In Table C.5 the amount of rigid and soft PVC in MSW is determined based on the consumption of soft and rigid PVC in the Netherlands [Nieuwenhuijsen,1996].

This Table concludes a 50/50 distribution of rigid and soft PVC in the PVC-fraction.

As no complete set of data is available, assumptions/estimates were unavoidable in both studies. These assumptions cannot easily be challenged, as both studies are internally consistent. The quality of those data cannot easily be improved. The study by [Groot,1993] concerns household waste (from kerbside) only and supplies no data on size and composition of PVC in bulky waste or commercial waste (from shops and offices). It is expected that through bulky and commercial waste the PVC fraction of total MSW contains less than 66% rigid PVC. The Figure from [Nieuwenhuijsen,1996] is based on consumption Figures and an estimate of the amounts which end up at the MSWC facility to be processed.

Fortunately, in calculations in the underlying report the distribution of the PVC fraction in rigid and soft PVC has little effect on the total elemental composition as it concerns only 0.65%-0.7% of the total waste (MSW contains 12.2% plastics, of which 5.3% is PVC according to [Groot,1993] or 10.4% plastics of which 0.67% is PVC [Cornelisse,1995]).

Therefore, it is decided here to execute the calculations with a PVC fraction assumed to contain 50% rigid and 50% soft PVC. (Any deviation from this “neutral” 50/50 distribution cannot be supported.)

In Table C.6 the composition of PVC is given for soft PVC, rigid PVC and for the total PVC fraction as present in MSW.

The composition of soft and rigid PVC is determined based on the assumption that PVC consists of chemically pure polyvinylchloride, plasticizer and filler.

The elemental composition of the plasticizer is obtained as weighed average of the three most frequently used plasticizers: DEHP, DIDP and DOA, which combined represent over 70% of the plasticizers used in PVC in 1984 [Ceaser,1992]. The elemental composition for this plasticizer mix is calculated from the molar ratios and molar mass, whereas the LHV (lower heating value) is calculated using the Boie equation. This Boie equation is an empirical formula which calculates the LHV of a material, based on its content of the elements C,H,O,N,S and water of a certain material [Boie,1957].

The filler is considered to be inert and thus is considered to end up as ash for 100%.

The heavy metals are taken from [Rijpkema,1992], except for Sn, Pb and Zn which are calculated as a weighted average from the data in Table C.3 [Nieuwenhuijsen,1996].

As the PVC is considered to include attached dirt, a water content of 10 wt% has been assumed [Rijpkema,1992].

Table C.5 Composition of PVC in Municipal Solid Waste [Nieuwenhuysen, 1996].

Product	Classifi- cation soft/rigid	NL-consumption market volume ktonnes/year	Processed in MSWC		Composition (%)			Heavy metals		
			%	ktonnes/ year	PVC	organic (plasticizer)	inorganic (filler)	Sn mg/kg	Zn mg/kg	Pb mg/kg
Rigid foil	rigid	6	100%	6	90	7	3	30		
Soft foil	soft	5	100%	5	60	30	10		400	
Vinyl carpets	soft	13	10%	1,3	53	33	14		600	
Cable isolation	soft	15	0%	0	46	28	26			14000
Boots	soft	1,2	100%	1,2	43	51	6		500	1500
Rooflinings	soft	4,8	0%	0	50	35	15		350	
Construction elements	rigid	7	1%	0,07	80	6	14			2000
Leidingsystemen	rigid	103	1%	1,03	91	6	3			10000
			% of total in MSWC							
Total processed in MSWC	rigid PVC		7,1	50%	90,05	6,85	3,11	25		1470
	soft PVC		7,5	50%	56,07	33,88	10,05		451	240

Table C.6 Calculation of the elemental composition of PVC.

Element		PVC	Organic	Inorganic	Rigid PVC	Soft PVC	Total PVC
C	wt%dry	38,44	74,27		39,70	46,71	43,21
H	wt%dry	4,84	9,9		5,04	6,07	5,55
O	wt%dry		15,83		1,08	5,36	3,22
N	wt%dry						
S	wt%dry						
P	wt%dry						
F	wt%dry						
Cl	wt%dry	56,73			51,08	31,81	41,44
ash	wt%dry			100	3,11	10,05	6,58
water	wt%total				10,00	10,00	10,00
LHV	MJ/kg total	15,41	33,46	0	16,17	19,98	18,07
Hg	mg/kg dry				0,1	0,1	0,1
Cd	mg/kg dry				100	100	100
As	mg/kg dry				0,5	0,5	0,5
Co	mg/kg dry				1	1	1
Cr	mg/kg dry				25	25	25
Cu	mg/kg dry				250	250	250
Ni	mg/kg dry				10	10	10
Mn	mg/kg dry				25	25	25
Pb	mg/kg dry				1470	240	838
Sb	mg/kg dry				10	10	10
Sn	mg/kg dry				25		12
V	mg/kg dry				50	50	50
Zn	mg/kg dry					450	231

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Appendix D Calculation results

D.1 Specific processing costs

In Table D.1 the calculated specific processing costs for the different waste materials are given for evaporation or discharge of scrubber effluent and with two kinds of reference grey waste: the standard grey waste (with 33.1% putrescibles) and the grey waste with less putrescibles (28%).

This data confirms that in the model SPC's are independent of the composition of grey waste (for one single MSWC).

Table D1 Specific processing costs for various types of waste materials in an MSWC facility.

Waste materials	Evaporation of scrubber effluent			Discharge of scrubber effluent		
	SPC thermal limit.	SPC mass limit.	SPC no limit.	SPC thermal limit.	SPC mass limit.	SPC no limit.
Reference grey waste						
putrescibles	74	227	-3	67	212	-6
plastics	601	50	-180	552	28	-191
paper	186	187	-43	170	172	-47
glass	32	263	32	32	251	32
metals	31	261	31	31	250	31
wood	255	152	-78	238	139	-80
rigid PVC	557	417	187	336	204	-15
soft PVC	518	292	61	370	154	-65
'original' grey waste ¹	191	191	-39	175	175	-44
Grey waste with reduced putrescibles content						
putrescibles	74	227	-3	67	212	-6
plastics	601	50	-180	552	28	-191
paper	186	187	-43	170	172	-47
glass	32	263	32	32	251	32
metals	31	261	31	31	250	31
wood	255	152	-78	238	139	-80
rigid PVC	557	417	187	336	204	-15
soft PVC	518	292	61	370	154	-65
'new' grey waste ^{1,2}	200	188	-42	183	183	-47

¹ For grey waste, SPC_s in case of thermal or mass limitation is by definition identical to the GF_s used in formula (3), see also chapter 3, main report.

² New grey waste, i.e. grey waste with reduced putrescibles content.

D.2 Linearity of the specific processing cost calculation

As the model used is linear, specific processing cost are independent of the amount of waste material added. This was demonstrated by calculations in which the amount of added waste (plastics and putrescibles) was varied. The results are presented in Table D.2.

Table D.2 The impact of addition of waste material on the specific processing cost for putrescibles.

Scrubber effluent evaporation Thermal limitation		grey waste	+15% 1	+25% 1	+35% 1	+50% 1
putrescibles added (t_p)	kt/yr	0	19.3	32.2	45.1	64.4
amount of grey displaced ($w \cdot t_p$)	kt/yr	0	6.6	10.9	15.3	21.9
total throughput	kt/yr	389	402	410	419	432
total putrescibles content	%	33.1	36.3	38.3	40.3	43.1
F_s	MDfl/yr	74.4				
F_n	MDfl/yr		74.6	74.7	74.8	75.0
GF_g	Dfl/t	191				
SPC_p	Dfl/t		74	74	74	74

¹ Percentage of the original amount of putrescibles in grey waste.

Table D.3 The impact of addition of waste material on the specific processing cost for plastics.

Scrubber effluent evaporation Thermal limitation		grey waste	+25% 1	+50% 1	+75% 1	+100% 1
plastics added (t_p)	kt/yr	0	11.9	23.7	35.6	47.5
amount of grey displaced ($w \cdot t_p$)	kt/yr	0	40.3	80.6	121.0	161.3
total throughput	kt/yr	389	360	332	304	275
total plastics content	%	12.2	15.1	18.5	22.5	27.3
F_s	MDfl/yr	74.4				
F_n	MDfl/yr		73.8	73.2	72.6	72.0
GF_g	Dfl/t	191				
SPC_p	Dfl/t		601	601	601	601

¹ Percentage of the original amount of plastics in grey waste.

These model results confirm the mathematical verification as provided in section 2.3.2, c.

D.3 Influence of water migration in the waste to paper

As in this study the composition of the waste materials was taken as if these materials were separated from a pile of waste, the water content of paper may be too high as it can be expected that paper absorbs water from other waste materials (mainly from putrescibles).

To investigate the sensitivity for this aspect, the specific processing cost was calculated for paper with half the original water content. The results are given in Table D.4, broken down according to formula 13.

Table D.0.3 The impact of the water content on the specific processing costs of paper.

Situation: scrubber effluent evaporation		Standard paper			Paper with reduced water content		
water content	wt%	26.8			13.4		
H_u	MJ/kg	9.99			11.77		
$H_{u,paper}/H_{u,gray} (w)$	-	0.99			1.17		
Variable costs							
- chemical	Dfl/t	5			6		
- disposal	Dfl/t	4			6		
- other	Dfl/t	0			0		
- energy revenue	Dfl/t	-52			-63		
- TOTAL	Dfl/t	-43			-51		
Scenario		therm. limit	mass limit	no limit	therm. limit	mass limit	no limit
Fixed costs element							
$w * f_g$	Dfl/t	229	230	0	269	230	0
Resulting SPC	Dfl/t	186	187	-43	218	179	-51

Table D.4 shows that only the energy revenue and the product ($w * GF_g$) show significant changes, resulting in a change in specific processing cost of +15% for the thermal limited, -5% for the mass limited and -20% for the underloaded MSWC facility. Consistent with what was found for high and low calorific values, it can be seen that an increase in the heating value of the paper (through reduction of the water content) increases the specific processing cost in the thermally limited scenario and decreases it in the mass limited situation. The specific processing costs in the not limited scenario (which represent the variable cost) decrease thanks to increased energy revenue.

Appendix E Statements of peers

The technical committee, installed to supervise this project, has invited experts to comment draft versions of the report and to conduct a peer review. Statements of the peer on the final draft of the report are presented in this appendix.

E1 Statement by Dr. J. Vehlow of the Forschungszentrum Karlsruhe GmbH (Germany)

As you know I had only few remarks and suggestions for changes regarding the former version of your report. The changes you have made caused some important improvements especially with respect to the methodology and to the question of chlorine partitioning.

The more extended outline of the fundamental approach elucidates the chosen strategy of distinguishing between three different operation models of a MSWI plant and different constant and variable types of costs which are affected in different ways. The use of small parameter changes not leaving the typical operation window of a model plant is a valid method to separate the effect of single waste fractions upon the combustion cost.

It is very important that you clarified the validity of your assumptions and checked in many cases the limits of parameter changes which can be taken into account without influencing the partitioning of an element in a significant way. With respect to chlorine the scenario seems to be complete and convincingly pointed out. It might be useful to give some more emphasis to the influence of temperature. I agree with your conclusions in so far as typical temperatures in MSWI facilities are regarded. At extremely high combustion temperatures ($> 1150^{\circ}\text{C}$) the partitioning of chlorine might depend upon the speciation of the chlorine feed and one result could be unusually high transfer of chlorine as gaseous HCl into the flue gas. In your 'typical operation window' those effects can be neglected.

The model incinerator you used for the calculations is good example for a 'typical' Central European facility. Of course the respective standards of the costs of combustion of grey waste differ from plant to plant and – may be more – from country to country. But following your advises it should be easy to transfer the results of your study of any existing modern incineration plant.

Let me add one remark to your statements concerning the formation of PCDD/PCDF. An estimate of the balance of those compounds in modern MSW incinerators using numerous data sets from literature as well as own data has been presented in 1991 at a conference in Berlin.

Vehlow, J. & Vogg, H. (1991), Thermische Zerstörung organischer Verbindungen. In Müllverbrennung und Umwelt 5 (Thomé-Kozmiensky, K.J. ed.), Berlin: EF-Verlag, pp. 447-467.

These calculations have been supported by Mark 1994 and most analytical data published during the last years support this fact. From these informations it is obvious that more than 90% of the PCDD/PCDF entering the combustor along with the waste stream is destroyed in the combustion chamber. The cited output of 20-25% [Mark 1994] or less are most likely formed in the cooling down phase of the flue gases. The destruction potential for so-called temperature resistant organic compounds has been demonstrated in detail using mainly results from a test incinerator but also those from full scale plants in a presentation I gave in Berlin early this year:

Vehlow, J. (1996), Mitverbrennen von Restabfällen aus dem Siedlungs- und Sonderabfallbereich – eine Frage der Zulassung oder der Verfahrenstechnik? Zukunft der thermischen Behandlung von Restabfällen, Handbuch zum Seminar 02 im Rahmen der UTECH BERLIN '96, FGU Berlin, 199-210.

E2 Statement by Ing. E. Colnot of the MSWC facility at Alkmaar (HVC Noord-Holland)

At your request I inform you that I agree with the applied method and the conclusions drawn in the report: 'Specific processing costs in an MSWC facility'. I am pleased with the fact that the data from the MSWC of Alkmaar (HVC Noord-Holland) is adequately applied, especially because it resulted in a very useful model.

E3 General comments of Mr. W. Sierhuis of the MSWC facility at Amsterdam

- a. Processdiagram: point D is unrealistic (this would be unacceptable to an MSWC facility). Point C is not realistic either, taken into consideration the present and future heating value of the waste.
This should at least be mentioned in the report.
- b. Partitioning of Cl to the flue gas: organic chlorine compounds (PVC) will end up for 100% in the flue gas, furthermore, only part of the inorganic chlorine will end up as HCl in the flue gas. Assuming 700 to 800 mg/Nm³ HCl in the flue gas, as well as 0.9% PVC in household waste, results in 80-85% of the HCl in the flue gas originating from PVC.

Authors reaction:**Ad a** Sense of reality of processing scenarios.

As suggested the report (now) mentions the fact that the scenario represented by point D (no throughput limitation) is not realistic as a permanent situation: it can only temporarily occur. The practical purpose of the scenario is the link to calculation of variable costs.

At present, point C (mass limitation) is less realistic for the operation of most of the facilities in the Netherlands than point B (thermal limitation). Theoretically, it might become more realistic either in future due to changes in waste management routes or in other countries

Ad b Different partitioning behaviour of Cl from organic and inorganic sources.

The only representative data available to conclude whether Cl from PVC (as an organic source) will have a larger tendency to end up as HCl in the flue gas than Cl from other (inorganic) sources are several experiments done in the TAMARA facility at Karlsruhe (Germany). These experiments show, that at typical MSWC conditions a difference in partitioning behaviour cannot be substantiated.

Based on these experiments, the assumption to use the same Cl distribution coefficient for grey waste as for PVC seems justified.

The sensitivity analysis performed (chapter 2.3.1) shows the importance of the assumed chlorine distribution, especially for the SPC of PVC.

Further (small) comments were discussed with Mr. Sierhuis and incorporated as mutually agreed.

E4 Statement by Drs. H.J.W. Sas of the Centre for Energy Conservation and Environmental Technology, Delft**1 Introduction**

The current comments are written in the context of an interactive peer review process, on the TNO-report 'Specific processing costs of waste materials in a municipal solid waste combustion facility', final version d.d. July 1996 (TNO ref.: 'TNO-MEP - R96/238').

The emphasis in this peer review was on methodological points of the study. In line with this, the review report only contains points regarding the question whether the objectives of the study are considered to be met, in view of the methodology applied.

Comments on previous draft reports were exchanged with TNO d.d. June 4, 1996 and July 1, 1996. Comments on scope and design of the study as a whole were exchanged with TNO d.d. December 22, 1995.

The reviewer was assisted by H. Croezen, researcher at CE. The comments expressed in the review, however, solely reflect the opinions of the reviewer.

2 Objectives versus actual results of the study

The objectives of the study, as expressed on p.3 are (rephrased):

- a To develop a methodology to generate data on specific processing costs ('SPC') for waste materials in an existing MSWC facility.
- b To apply this methodology to a variety of different waste materials (PVC foremost, though not exclusively).
- c To investigate the effect of reduced putrescibles content in MSW of the SPC's of other materials.
- d To give insight in the impact of CI on MSWC operation and its environmental impact.

As it is, the presented data on objectives c. and d. are complete and convincing. A minor remark concerning objective c.: the effect of the reduction of putrescibles content in MSW, as computed in this study, is only valid for the **current** MSW-composition. Yet, this is exactly what one would want to know for current waste policy design. In conclusion, both results are extremely relevant to current waste policy design in the Netherlands.

Objectives a. and b. are another matter, since the report may lead to misunderstandings in interpretation here.

The study objective is to generate data on specific processing costs for a variety of waste materials. One may understand that 'specific processing costs of waste materials' are identical to 'processing costs **allocated to** waste materials'. Yet, this could lead to a fundamental misunderstanding. Suppose that one wants to allocate processing costs to a material which, at the working point considered, has a share α in the overall waste under consideration. I expect that policy makers interested in such a material-specific allocation would use the following procedure:

Compute the average costs over all of the material under concern, i.e. integrate SPC's over the full trajectory from share = 0 to share = α .

Suppose one adopts this line of reasoning, then two items need to be addressed:

- A theoretical formulation of the appropriate integral should be derived (covering, particularly for polymers, a trajectory which could be in part mass-limited and in part thermally limited).
- The validity range of the model should be extended, even to the complete individual elimination of all relevant waste components.
(This is obviously not feasible. When considering present combustion literature and state of knowledge, the model is extended 'as far as one can get'.)

Neither of those elements are part of the report. In fact, the report takes a completely different approach. The FACE model applied, essentially generates SPC's

which are valid only around a given 'working point', defined by the current waste composition, treated in existing MSWC's. The SPC of a certain material is equated with the net substitution costs incurred if a certain amount of the average waste is replaced by one tonne of the material under concern.

Yet, as elucidated above, this is **not** what many would see as a **cost allocation** to a material as a whole. In line with the methodology applied, the application field of the results is restricted to those management questions, in individual MSWC's, which are concerned with a possible substitution of certain waste components. Application of the results of the study for a material allocation within the context of national policy making is invalid.

As it is, the report does not state that the SPC's calculated represent a fundamental MSWC-cost allocation to waste materials. It is even stated that (p.6, 4th paragraph): '... SPC's cannot directly applied to ... components if these are considered as part of the existing grey waste mixture.' Therefore, the report is consistent within itself. Yet, it would have been much better if the relation with other possible material allocation procedures in other contexts, would have been stated more explicitly and more prominently (see page 5 and 31, 2.3.2.b).