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PVC and municipal solid waste combustion: Burden or benefit ?

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Summary

The polymer PVC continues to be subject of considerable public debate. Its waste stage, and especially its incineration in municipal solid waste combustion (MSWC) facilities plays a central role. Public perception on incineration in general and certainly of PVC tends to be negative. Its combustion is perceived to be associated with dioxin formation, the generation of large amounts of toxic residues, and high investment costs in air pollution control devices that supposedly could be prevented without the presence of PVC. Corrosion caused by PVC would prohibit MSWC's to realise the much higher electricity recovery yields as achieved in the conversion of fossil fuels by power plants.

The Association of Plastics Manufacturers in Europe (APME) commissioned this study in an attempt to relate perceptions to science-based, consolidated facts from literature and from accepted operational experience.

This report is an expansion of the previous study conducted jointly with the Dutch Environmental Ministry VROM that was used as an input in formulating the Dutch authorities' PVC policy. Widening the scope of this study, TNO was asked to summarise data of PVC specific behaviour during MSW combustion from studies by TNO as well as from other literature, while including and judging the scientific evidence.

As the original studies had focus on The Netherlands, APME requested to responsibly widen the data to European level. It was realised, that by this generalisation the results would unavoidably be more qualitative and at the expense of the original quantitative character. However, the general correctness of the trends within the assumptions as laid down in the underlying studies is not jeopardized.

Obviously, the policy making process not only requires awareness of public perception but also of its relation to consolidated facts and science. Policy makers are faced with questions whether PVC incineration is a burden or a benefit to society. In more operational terms, this translates to the question whether PVC incineration in MSWC should be maintained as a waste disposal method or rather discouraged. As a consequence, the effects of an increase or decrease in the amount of PVC on the ecological, financial or operational parameters of MSW combustion are key considerations in this report.

This study has been peer reviewed by the Forschungszentrum Karlsruhe, which is known and recognised for its relevant experience on specific effects of various feed components in MSWC.

In most general terms we conclude:

Perceived negative aspects with respect to the neutralisation salt residue production are primarily related to MSWC plant design rather than PVC itself.

PVC is, more than most other materials, sensitive to the type of air pollution control system in the MSWC. Within ecological and geographical limitations, and the right type of plant design, PVC is incinerated without extra ecological or economical burden. Plant design - if not optimal for PVC processing - has been selected for other reasons than PVC, which is present for less than 1% in waste. Total MSWC investment costs strongly vary between EU-member states with even substantial geographical differences within these countries.

Allocation of the total environmental or economical burden to specific waste components (e.g. PVC) cannot be achieved unambiguously. The effect of PVC cannot responsibly be "singled out". The PVC-argument may not be used selectively or in isolation.

Factors like dioxin formation, corrosion, electricity yield are determined by many mutually interfering factors. These effects are by no means linear to the PVC amount.

The presence of PVC has negative but also positive effects on MSWC operation. However, **complete elimination or even a strong decrease of PVC from the waste stream will not lead to any substantial ecological or economical gain.** Without PVC, still a significant amount of chlorine remains in the MSWC facility waste feed. Moreover, other factors inherent to MSWC operations, remain and would still be limiting. **No significant improvement in corrosion characteristics, electricity yield or dioxin formation is to be expected from a decrease in the PVC content of MSW.**

Without PVC, Air Pollution Control (APC) devices could be designed at lower capacity (as less hydrochloric acid would be treated) but would not be redundant. Resulting cost savings would be minimal, as APC investment costs are largely determined by the PVC independent volume of the flue gas and not the amount of the acidic species from PVC. Without PVC, virtually the same equipment/investment would be required as the same functions would need to be conducted, of which only some at lower capacity.

In existing MSWC plants running at full thermally limited capacity, the gate fee is dominated by the fixed cost element, resulting from investment costs. PVC processing costs, like wood, are not extreme: above average "grey" waste, but more favourable than plastics in general.

Various allocation methods for investment costs can be envisaged with different conceptual attractiveness. In any approach, PVC related investment costs remain between “average grey” and general mixed plastics waste.

In underloaded MSWC plants, the marginal costs are exclusively determined by the variable cost element. The high energy content of PVC (like other plastics) causes negative costs, i.e. there is an income from generated electricity. In MSWC facilities with the possibility to discharge of their waste water this income exceeds the other cost elements. However, in those MSWC with "waste water free" air pollution control systems, the variable costs for PVC are higher than for any other material. Elimination of PVC leads to only marginal and considerably less than proportional savings in MSWC processing costs.

Overall, it can not be unambiguously decided whether PVC incineration is a burden or benefit to society. However, the overall negative public perception is not supported by scientific, financial or ecological evidence.

More specifically, we comment on the various stages and aspects in the combustion plant:

Corrosion

Chlorine (with PVC contributing 30-70% to total chlorine) has a stimulating effect on corrosion. It is however only one of many simultaneously interfering parameters. These effects cannot be separated. Corrosion is by no means linear to the chlorine concentration. **Even complete elimination of PVC (in practice unrealistic), is unlikely to reduce the corrosion risk substantially.**

Electricity yield

The yield (20-25%) from waste to electricity in MSWC is lower than from fossil fuel in electric power plants (40-45%). This is caused by factors inherent to MSWC operation, rather than the presence of PVC. **As the other limiting factors remain, elimination of only PVC will not improve the situation.**

Dioxin formation

The most determining factors are combustion conditions and design of the MSWC installation, in particular flue gas cool down conditions. PVC, like all other plastics, favourably promotes full combustion conversion. This is the only factor that can be influenced by operating conditions. Chlorine (regardless the presence of PVC) is always available in billion fold excess and is therefore not controlling dioxin formation. **There is no relation between PVC and dioxins amount. Elimination of PVC was demonstrated to have virtually no effect on dioxin formation.**

Incineration residues

Bottom ash

The amount of bottom ash is constant, regardless the amount of PVC.

The effect of increasing PVC contents of MSW on bottom ash quality (heavy metals content) is favourable as chlorine enhances the transport of heavy metals from bottom-ash to fly-ash.

In terms of alkalinity and heavy metals leaching, no general conclusion can be drawn. **The perceived increased leaching caused by PVC can not scientifically be supported or denied. Whether or not such increased leaching is environmentally positive or negative depends on the type of plant design (bottom-ash washing).**

Fly ash

Heavy metals from waste need to be disposed at highest concentration and minimal volume. Fly ash serves this purpose as it is often not recycled. Elimination of PVC would lead to an unfavourable increase in heavy metals content in bottom ash and a decrease of heavy metals concentration in fly ash. **The impact of a change of the PVC content on the fly-ash leaching behaviour cannot be predicted unambiguously.**

Neutralisation residues

Neutralisation of hydrochloric acid from PVC or Cl-sources in MSW like table salt, invariably leads to formation of a non-toxic salt residue, contaminated with heavy metals from all waste fractions with minor (below 7%) PVC contribution. The volume of the solid neutralisation residues which can be allocated to PVC may - for the same waste - vary by a factor 20, from only 3% to even more than 70% wt of the PVC in the feed. This large variation is completely determined by the configuration of the plant's air pollution control system.

Facilities with a "wet APC system" that discharge waste water, concentrate the heavy metals to solid, chemical waste to which PVC contributes only 29 kg/t PVC waste. The non-toxic salts (NaCl, CaCl₂) are disposed of as a liquid effluent.

In the other extreme, with a "dry APC system", separation of heavy metals and neutralisation salts cannot be achieved and up to even 700 kg/t PVC waste needs to be deposited as chemical waste.

The volume of the residue is related to PVC (which contributes overproportionally). The quality is related to heavy metals, mainly (93 to 99.95% varying per heavy metal) derived from non-PVC waste fractions.

There are no established allocation rules in the dilemma: without PVC there is 30-70% less volume; however, without heavy metals clean salts would be produced. Public perception with exclusive allocation of the burden to PVC seems not justified against this background.

The amount of residue is determined by the MSWC plant design and not specific to PVC. Whatever the plant configuration, a decrease of PVC by even

50% would result in a volume reduction of the solid residues by only 10% at unchanged heavy metals contamination.

Cost aspects

MSWC variable costs can be straightforwardly allocated to the waste materials with relative ease, based on chemical composition, as well as mass and energy balances. The more complicated allocation of fixed costs has been conducted from the MSWC operator's point of view: fixed costs are to be covered, regardless the waste composition. In other words: if the acceptance of a specific waste material, e.g. 1 tonne of PVC leads to replacement of existing standard "grey" waste, the same amount of fixed costs remains to be covered. For a MSWC facility operating at full (thermally or mass limited) capacity, the situation is different from an underloaded plant. In the plant running below capacity, variable costs per material are the only discriminating parameter, as the amount of additional fixed costs coverage is independent of the type of any extra waste offered.

PVC's variable costs are largely determined by the plant layout in terms of flue gas cleaning and the amounts of produced solid residues (for costly disposal). In facilities where the absorbed HCl results in a solid residue, the resulting disposal costs allocated to PVC exceed its revenue from electricity generation. In these installations overall variable costs of PVC are higher than for any other material considered. Alternatively, if the facility is designed to discharge the absorbed chlorides as a solution of calcium (lime) salts, PVC's electricity revenues exceed disposal costs. In this case the overall variable costs of PVC are intermediate between standard MSW and mixed plastics waste.

In general, fixed costs are dominating the overall processing costs; variable costs play a smaller role.

PVC's elevated calorific value causes the allocation to PVC of a relatively large fixed cost share in thermally limited facilities. In other facilities PVC benefits from its elevated calorific value as it generates an elevated revenue from electricity production. Though for different reasons, in all these cases PVC takes an intermediate position between standard MSW and mixed plastics waste.

Fixed costs are dominated by the investment costs' depreciation, which have been allocated on "per hour" basis. Alternative fixed cost allocation methods have been considered and yield to unattractive inconsistencies but lead to similar results.

Overall processing costs for PVC are determined by the type of plant design and the facility's geographical location. These costs are not excessive. PVC is positioned (like wood) between mixed plastics waste in general and standard "grey" MSW.

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1. Introduction

In 1997, the Dutch Environmental Ministry VROM formulated its PVC policy. The behaviour of PVC during Municipal Solid Waste Combustion (MSWC) plays a key role in this document. In preparation of formulating its PVC policy [VROM,1997] the Ministry commissioned a study at TNO in which costs and performance of PVC upon incinerating were put in perspective in relation to other materials, like wood, paper, average municipal solid waste (MSW) and plastics in general [Rijkema,1996b]. This TNO study was commissioned jointly with the Association of Plastics Manufacturers in Europe (APME), that owned computer models (developed by TNO) used for these studies.

Additional data were generated by TNO after completion of the 1996 study, as additional questions were raised [VVAV,1997] during discussions while the PVC policy was being formulated by Dutch Government.

Though most of the results of this consecutive study have been communicated to the Dutch Environmental Ministry, it has never been consolidated in an official report for a wider audience.

APME are aware that questions on the incineration behaviour of plastics are frequently asked by several institutions, NGO's and policy makers at various national and EU levels.

In order to support these discussions, APME requested TNO to summarise the data of PVC specific behaviour during Municipal Solid Waste Combustion from its own as well as from other literature studies while including and judging the scientific evidence.

As the original studies had focus on The Netherlands, TNO was requested to responsibly widen the data to European level. It was realised that by this generalisation the results would unavoidably be more qualitative and at the expense of the original quantitative character. However, it was perceived that the general correctness of the trends observed would thus not be challenged.

Finally, in order to gain broader scientific support, the report was peer reviewed by Dr. J. Vehlow from the Forschungszentrum Karlsruhe, known and recognised for his relevant experience on specific effects of various feed components in MSWC.

Policy makers are facing the question whether PVC incineration is a burden or benefit to society. In more operational terms, this translates to the question whether PVC incineration should be maintained as waste disposal method or rather discouraged. As a consequence, the effects of a decrease or increase in the amount

of PVC on the ecological, financial or operational parameters of MSW Combustion are a key consideration in this report.

PVC is subject of frequent discussions at various levels in society. The investigators trust that the report may be instrumental in replacing perceptions and emotions by relevant facts.

2. Approach and methodology

In municipal solid waste combustion (MSWC) discussions, PVC was subject of considerable public and scientific attention over the last three decades. Especially due to the high chlorine levels in PVC and to a lesser extent due to the relatively high content of certain heavy metals, numerous (mostly negative) effects of MSWC have been attributed to PVC. The effects involved in these discussions vary from dioxin formation, corrosion, increased residues from the flue gas cleaning (FGC, or APC: Air Pollution Control) system to a decrease in energy recovery efficiency due to limited steam parameters.

There is no doubt that PVC contributes to most of these effects. This report attempts to discuss (and where possible quantify) these effects for those cases where PVC has a specific impact, different from other components in the feed from MSWC.

Knowledge of PVC-specific effects on MSWC operation, gaseous and solid emissions and costs are essential, but **not sufficient** for decision making to derive PVC or waste management legislation or policies. To derive such policies, knowledge on specific effects needs to be translated to an input for practical decisions for various actors in society. Most MSWC plants in Europe are up and running; their operation can be modified only with difficulty and at considerable cost. However, their feed can be influenced to some limited extent. The question whether less/more incineration of PVC would be a burden or benefit is therefore fully justified both in economical and ecological dimensions.

In this report PVC has been considered as a “real-life” waste fraction, which means that ‘PVC’ refers to PVC product waste and not to virgin PVC polymer. This PVC product waste consists of PVC products beyond their product life. It includes, besides virgin PVC, additives, plasticizers and attached dirt.

It should be realised that the PVC molecule under incineration conditions has dual characteristics. The hydrocarbon part (C, H) qualitatively behaves like any other hydrocarbon source like wood, paper, or other polymers and provides the energy for electricity generation. This part causes no additional specific problems even if the present levels of PVC in municipal solid waste (MSW) were doubled [Mark, 1994].

The chlorine part of PVC is the cause of more specific concern. Its incineration inevitably leads to formation of hydrochloric acid, which like other acidic species (NO_x and SO_x) needs to be neutralised and removed to prevent uncontrolled release into the environment.

It should be stressed that these effects are **chlorine** specific, rather than **PVC** specific, as it was demonstrated (see 4.2 and the references cited there) that chlorine containing waste components behave identically, independent of the source of chlorine, i.e. there is no conceptual difference in MSWC behaviour of chlorine from PVC, bleached paper or table salt etc.

Municipal solid waste shows considerable compositional differences per region. PVC represents 30-70% of the total chlorine load of European MSWC installations. As a consequence, even complete elimination of PVC from the MSWC feed will cause only a change in intensity of the chlorine related specific effects but will **a priori not eliminate** these perceived problems. At least 30% of chlorine from non-PVC sources still would remain in the waste.

The answer to the frequently asked question on the **absolute**, PVC specific effects in MSWC is therefore not sufficient in assessing the real **relative** question to be addressed for legislation, decision making and formation of waste management policies:

what would be the environmental and financial benefit/burden to society resulting from a decrease/increase of PVC as one of the chlorine containing components from the waste incinerator intake feed?

Beyond the **absolute** PVC specific effects, it is also the latter **relative** question that this report attempts to answer.

3. PVC and MSWC plant operation

The aim of municipal waste combustion has always been volume reduction (rather than mass reduction) of waste while destroying pathogenic biological activity. Nowadays, in modern facilities this has evolved into the inertisation of the waste (reduction of residual organic carbon) as a major goal of waste combustion. A second incentive, nowadays sometimes valued over the first aim, is the generation of energy from waste. PVC has an impact on both aspects as the first aim is mainly related to the combustion behaviour of the waste feed, whereas the energy recovery is limited by corrosion, attributed to acidic species, like HCl.

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) at that time. 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 eliminated by the scrubbers without problems (according to the regulations in those days). Today, with average heating values more elevated at around 10 MJ/kg, experiments show that addition of high calorific waste materials (i.e. plastics) improves the burn-out of the bottom-ash [Mark, 1995b; Vehlow, 1996b], even at the nowadays considerably lower levels of uncombusted organic substances (see Figure 1). Elimination of unconverted organic residues is essential to reduce dioxin formation.

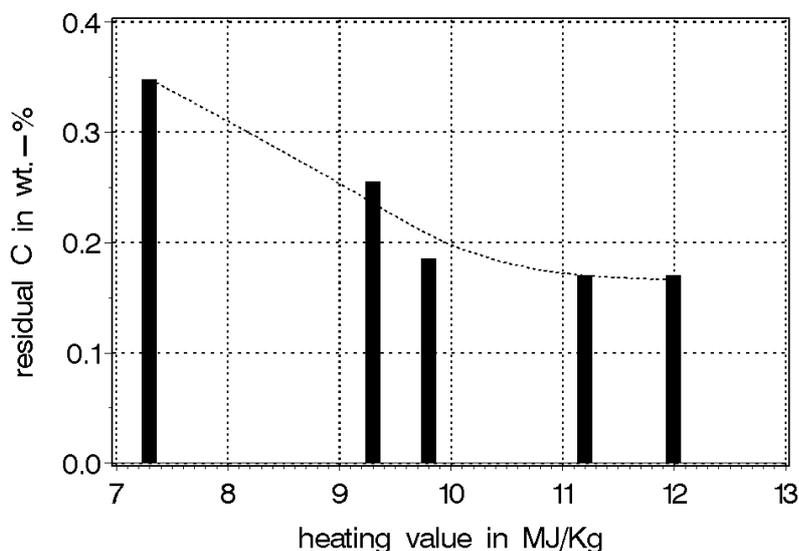


Figure 1 Residual carbon in bottom-ash versus heating value of the feed (combustion temperature 1050°C) [Vehlow, 1996b].

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 substantial emissions of products of incomplete combustion. This merely is the case in (older) furnaces with little possibilities for secondary (overfire) air and a too limited burn-out area resulting in too 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 gas phase. 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.

However, in modern MSWC facilities the burn-out of the gas phase is fully controlled by adjustable secondary combustion air addition, sufficient residence time for the flue gases at high temperatures and improved 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, 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 well controlled MSWC facility.

3.2 Corrosion

High temperature and low temperature corrosion need to be distinguished in MSWC facilities.

Low temperature corrosion occurs at temperatures below the dewpoint of the acidic substances (HCl, H₂SO₄). At temperatures above 150 °C, this type of corrosion is not very likely [Ganapathy,1991]. As the temperature of the flue gas is still 200-230 °C at the boiler exit, this type of corrosion is only to be expected beyond the boiler, i.e. in the quench and the acidic step of the wet scrubber, where the flue gas temperature (around 70 °C) is below the dewpoint. In some German MSWC facilities the authorities restrict water consumption for wet scrubbers for environmental reasons. This results in scrubber fluids with higher acidity and the increased corrosion in these scrubbers or the increased cost for protective materials are a trade off of an economical penalty, versus perceived ecological gain.

High temperature corrosion can only occur in the boiler. In principle, high temperature corrosion by CO may occur at high rate when local conditions around steam pipes are alternately reducing and oxidizing [Crider,1977; Bolt,1991]. Corrosion can also be caused by (alkali)sulphates or by chlorides [Reichel,1989; Barniske,1990; Ganapathy,1991; Pröfrock,1991; Vehlow,1992b].

The main cause of high temperature corrosion for MSWC facilities, however, are the chlorides: sulphate corrosion occurs but is hardly ever the reason for steam pipe failure in MSWC [Barniske,1990; Vehlow,1992b] and the minimum oxygen concentration of 6 vol%, which is maintained in the flue gases, is generally perceived to be sufficient to sustain the protective oxide layer on the pipes and to prevent CO-corrosion [Schirmer,1999].

Though both types of corrosion occur in MSWC facilities, low temperature corrosion is considered less important than high temperature corrosion. Partly, this is due to the fact that low temperature corrosion can be controlled more easily since the use of protective materials in this temperature area is cheaper, much easier, and more effective than in the high temperature area. The other reason for an increased attention to high temperature corrosion is in the discussion on reduced energy efficiencies of MSWC facilities (see further 3.3).

The high temperature corrosion process is still not completely understood but one plausible mechanism is as follows [Born,1997]. Through oxidation a protective layer of metal oxides is formed on the boiler steam pipes. Normally under oxidative conditions this layer is maintained. However, if locally oxygen is insufficiently present this layer can be (partly) destroyed by reduction. Elementary chlorine (Cl₂) can be formed through sulphatation from metal chlorides (mainly lead and zinc chloride) in heat exchanger surface deposits. This chlorine attacks bare iron to form FeCl₂. The FeCl₂ migrates through the oxide layer and (at the surface) is oxidized to regenerate Cl₂ again.

The major question with respect to high temperature corrosion in this study's context is to what extent increased high temperature corrosion can be allocated to the amount of chlorine in the waste feed.

The **amount** of acidic HCl generated per tonne of converted fuel in MSWC is higher than in power plants but still of the same order of magnitude. On the other hand oil and coal are contaminated by sulphur, causing a major burden in the APC systems of power plants where SO₂ needs neutralisation. This leads to a gypsum waste stream with associated outlet/disposal problems. Ironically, the burden of SO₂ (as long as it is in the gasphase) may be beneficial in decreasing the corrosion potential of hydrochloric acid (coal is generally processed with up to 0,2% of chlorine) in power plants. This subduing effect of SO₂ is based on the interference of SO₂ with Cl₂ and HCl [*Tuppurainen,1998*]. This effect is sometimes supposed to play an inhibiting role in dioxin formation as well [*Griffin,1986; Gullet,1995; Lindbauer,1991*]. The quantitative impact of this effect is not fully known (yet).

In the steam pipe deposits sulphates play an opposite role and, as mentioned before, promote chlorine induced corrosion through sulphatation of the chlorides and thus liberation of Cl₂.

In addition, the amount of ashes plays a dual role in boiler corrosion processes, depending on the composition of the ashes. On the one hand ash decreases the chloride density at the tube surface (at a given amount of chlorides) and the silicates in deposited ash can inactivate chlorine atoms. On the other hand, ashes contain (alkali)chlorides which means the ash continuously provides chloride to the tube surface. Ashes will unavoidably contain unburned carbon fragments which upon deposition on a steam tube surface create local reducing conditions and subsequent attack of the protecting oxide layer.

Another aspect of corrosion, which is increasingly causing problems, is the corrosion below protective bricklayers in the areas where temperatures are at their maximum. In these early regions of the boiler (the first parts after the combustion chamber) steam tubes are protected by all kinds of ceramic materials. However, due to high temperatures diffusion through these protective layers is enhanced, leading to condensation of chlorides (especially Pb-, Zn-, Sn- and alkalichlorides) below the protective layers at the steam tube surfaces. Oxygen can reach these areas only by diffusion, (which is less efficient than condensation at higher concentration, like the chlorides). As a result, reducing atmospheres are created, leading to corrosion underneath the protective brick wall. The main cause for this type of corrosion is the increased furnace temperature. This increase in temperature is due to the increased calorific value of the waste feed in the last decades and the tendency towards increased focus on energy revenues. It is also caused by emission legislation demanding a residence time for the flue gases of at least 2 seconds at a temperature above 850 °C (most European legislations).

The maximum HCl-concentration that can be tolerated in MSWC is not known quantitatively as, obviously, the corrosion potential cannot be judged from the chlorine load alone. Even at wood combustion systems where the flue gas shows HCl concentrations 100 times lower than in MSWC facilities (typically around 12 mg/Nm³ against 800-1500 mg/Nm³ for regular MSWC facilities) chlorine induced high temperature corrosion is known to occur to the same extent as in MSWC facilities [Schirmer,1999]. Other sources mention that chlorine induced corrosion is a realistic possibility at Cl-contents in the fuel above 0.1 wt% in general [Bryers,1970; Born,1997] and above 0.2 wt% (leading to around 100 mg/Nm³ in the flue gas) for coal-fired power plants [Jackson,1963; Born,1997].

More parameters are important in judging the corrosion potential. The most important parameters seem to be the amount of metalchlorides in the steam pipe deposit, the ratio between Cl and S in the gasphase and the amount of ash. Other parameters of influence are [Born,1997; Schirmer,1999]:

- flue gas temperature (see Figure 2);
- the tube (surface) material: ferrite, Ni-alloys;
- water content of the flue gas;
- oxygen content of the flue gas;
- flue gas velocity.

From observations in numerous MSWC facilities a so-called “corrosion risk area” was deducted, based on actual flue gas temperature and tube surface temperature: see Figure 2. This “corrosion risk area”, as presented here, is independent of the amount of PVC in the waste feed. In a properly operated plant a change in the calorific value of the waste (within manageable ranges) will not lead to a change in the temperature, except maybe temporarily or locally.

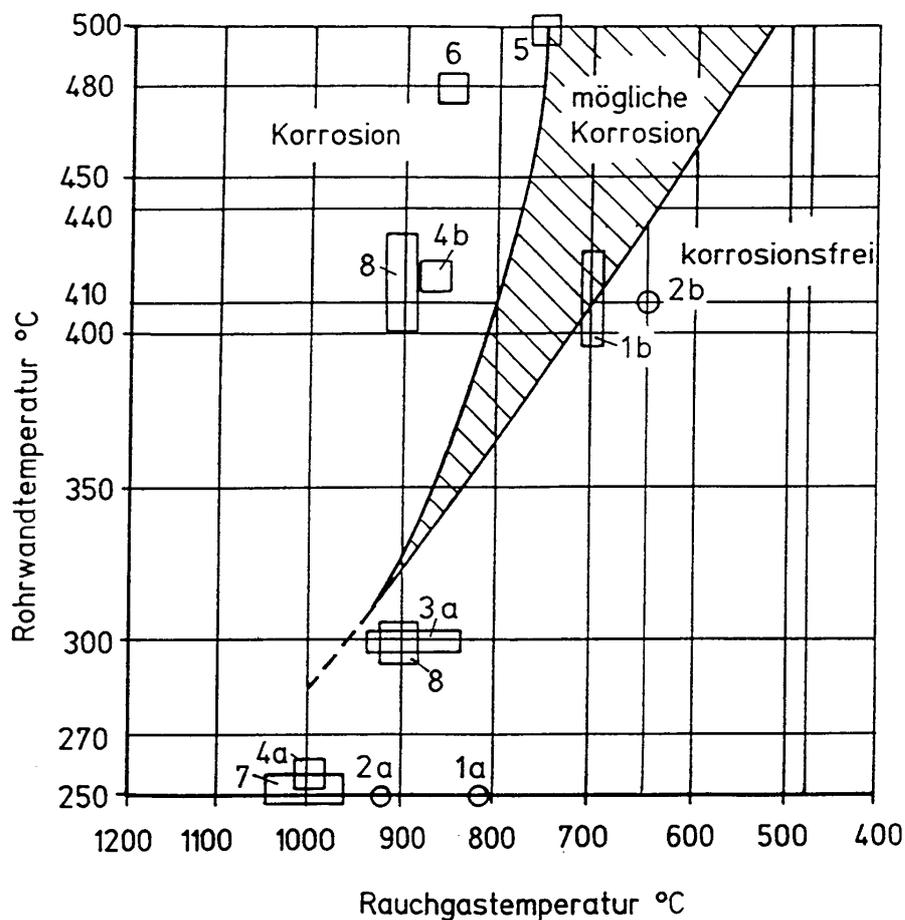


Figure 2 Probability of corrosion depending on the temperature [Born,1997].

Numbers refer to specific MSWC facilities:

a Evaporators in specific MSWC facilities

b Superheaters in specific MSWC facilities

Rohrwandtemperatur = tube surface temperature

Rauchgastemperatur = flue gas temperature

Korrosion = corrosion

Korrosionsfrei = free of corrosion

Mögliche Korrosion = chance of corrosion

However, a further quantitative separation of the various corrosion parameters cannot be achieved responsibly with our current stage of knowledge.

Some boiler 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 promoting corrosion for which its amount is not the rate controlling factor.

Conclusions:

A multitude of parameters determines whether or not there is a risk of corrosion.

No doubt, Cl, as one of these parameters, has a stimulating effect on corrosion. This effect is **chlorine specific**, which is wider than **PVC specific**. **The PVC contribution is 30-70% of the total MSWC chlorine load. Even (in practice unrealistic) complete elimination of PVC is unlikely to substantially reduce the risk of corrosion in MSWC.**

Complete burnout is essential to decrease the unburned carbon content of flue gases and deposits, a corrosion-promoting factor. Unlike other chlorine containing waste sources, PVC (like other plastics) beneficially promotes burnout of combustible matter. Therefore, the relatively high calorific value of **PVC reduces the risk of CO-induced corrosion induced by unburned carbon in deposits to some (not quantifiable) extent**. On the other hand, without appropriate accommodation the more than average calorific value of PVC enhances the heat load to the plant and the flue gas temperature thus increasing the risk of corrosion. This effect is less for PVC than for waste fractions with even higher calorific values, like other plastics.

Corrosion is the result of many simultaneously interfering parameters. The effect of PVC cannot be singled out.

Dramatical benefits of decreased corrosion as a result of PVC elimination from the waste feed are not to be expected.

3.3 Energy yield

Since the last decades, MSWC installations are almost invariably designed to convert the incineration energy into electricity which is easily transported and sold to public or private electricity grids.

Mainly due to geographic factors and lack of cheap transportation options, the incineration **heat** as such cannot easily be commercially exploited. However, this situation is improving, mainly in the Western and Northern parts of Europe, where in some plants energy recoveries of over 70% are realised thanks to the use of the heat or by direct sale of the produced (low pressure, or in some cases, high pressure process) steam. In general, however, electricity is the most highly valued co-product of MSWC operation.

The electricity yield (i.e. the amount of net electric energy produced relative to the heat value of the waste feed intake) is generally 20-25% for MSWC plants. The electricity yield of gas, oil or coal operated power plants is considerably higher, 40-42%. The question has been raised whether (and, if so, to which extent) the presence of chlorine containing waste has an effect. PVC is frequently perceived

as responsible for this "yield deterioration", mainly because the influence of chlorine on corrosion as discussed in the previous chapter (see 3.2).

However, high temperature corrosion, though important, is not the only reason why MSWC facilities on average have electricity efficiencies around 22% and not around 40% like for coal-fired power plants or even higher for gas-fired power plants. Other electricity efficiency reducing causes compared to fossil fuel power plants are [Pfeiffer, 1992]:

- a) larger excess of combustion air, leading to lower temperatures in the boiler and to a larger loss of heat through the flue gases at the exit of the boiler;
- b) increased temperature of the flue gases at the boiler exit: because concentrations of acidic gases are higher in MSWC the temperature must be higher to prevent condensation;
- c) larger own consumption of electricity: mainly due to the more extensive flue gas cleaning system and the larger residue handling systems a larger part of the electricity production (15-20%) is used by the MSWC facility itself;
- d) larger loss of heat through the bottom-ash: as the ash content is much higher for MSW (30% against 10% for coal and 0% for gas) the loss of energy through the bottom-ash is much more substantial.

Most factors are inherent to the differences in technology for MSWC versus power plants, also caused by other feed characteristics than specific for PVC. The absence of PVC would lead to a decreased HCl concentration and to a decrease to the own electricity consumption by flue gas cleaning and residue handling but not necessarily to a decrease in corrosion risk. Other acidic species and corrosive factors would still be operative.

Summarizing, it can be stated that although chlorine has a promoting effect on corrosion, reduction of the chlorine input by elimination of PVC from the MSWC plant input will not allow for higher steam parameters and as a consequence will not substantially improve energy yields.

4. Emissions and residues

In the last few years in MSWC the attention has been severely focused on gaseous emissions and solid residues.

Gaseous emissions mainly concern dioxins and furans (poly-chlorinated-dibenzo-para-dioxins and -furans or PCDD/F). Naturally, PVC is related to other emissions (like HCl) but, in well operated plants, these can be accommodated relatively easily in the flue gas cleaning system. Starting with the discovery of dioxins and furans in municipal waste incinerator ashes in 1977 a huge amount of effort was spent to reduce the emission of dioxins and furans. As Cl is an important element in the elementary composition of PCDD/F, the link with PVC (in which Cl is also an important element) has been made very rapidly and was subject of study ever since.

Dioxin emissions can be controlled within the tight standards - which already rule in some European countries (Netherlands, Germany, Austria) and will rule in all the EU member countries in the near future - if modern plants are well operated. Therefore, in the last few years, attention has shifted towards MSWC residues and the options to influence amount and quality of these solid residues.

4.1 Formation of dioxins and furans

Logically, the final emission of PCDD/F 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. In principle, modern flue gas cleaning systems are well able to meet PCDD/F stack levels below the often 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 modern MSWC facilities and their compliance with emission directives is no longer an overriding issue. Presently, PCDD/F's contained in the residues are generally not perceived as a problem either, provided proper control of the fate of these residues after leaving the plant.

However, the primary PCDD/F-concentration in the raw flue gas is of interest as the PCDD/F is adsorbed on active coal or cokes, and an increase in PCDD/F-concentration results in enlarged active coal or cokes consumption. This generates an intermediate solid residue that in suitable plants is recycled to the feed or is combusted separately. At other plants, it is subject to controlled landfill.

Overall, a state-of-the-art MSWC facility can be considered a PCDD/F-sink as investigations conclude that the PCDD/F-output is only 20-25% of the PCDD/F-input [Vehlow,1991; Mark,1994; Vehlow,1996c]. This means that actually MSW combus-

tion performs reduction of dioxins accumulated in society's waste.

The PCDD/F in the raw flue gas has different origins:

- it was introduced with the waste and not destructed in the furnace,
- it was formed during the combustion process, or
- it was formed after combustion by denovo-synthesis, in or beyond the boiler.

Modern emission legislation (like in Germany, the Netherlands and Austria) generally requires a residence time of at least 2 seconds at temperatures above 850 °C and an oxygen content of at least 6 vol% (which is questioned as too high by the MSWC operators, see 3.2). 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.

With adequate burn-out control of the flue gases, it can be assumed that PCDD/F's introduced as a trace component in the waste feed are **fully** destructed in the furnace [Hay, 1985; Klicius, 1988; Diwel, 1990; Vehlow, 1991; Vehlow, 1996ab]. Thus, any PCDD/F present in the raw flue gas is assumed to be resynthesized in the post-combustor zone, i.e. by 'de novo'-synthesis in the boiler or thereafter.

It has been discussed [Bump, 1980; Nottrodt, 1986] that PCDD/F and other organic micro-pollutants may be formed by gas phase reactions at high temperatures inside the combustion chamber. Due to the excellent burnout in the gas phase, however, these compounds must be redestroyed, like the dioxins fed into the system along with the waste input. One proof is the different distribution pattern of mainly PCDD and lower PCDF in the waste and the profiles measured in the offgas.

Although, after nearly 20 years of intensive research, this formation of PCDD/F in MSWC facilities is still not completely understood in detail, the major conclusions with respect to the formation and possible influences by PVC or chlorine, have been accepted by the scientific community.

According to literature, the most important parameters in formation of PCDD/F are the availability of:

- a. so-called PICs, products of incomplete combustion (carbon in fly-ashes or CO, unburned hydrocarbons and partly burned, highly unsaturated hydrocarbons in soot particles): their formation is determined by plant design and operational conditions;
- b. a source of chlorine in the flue gas (from e.g. PVC, putrescibles/table salt);
- c. a catalyst: heavy metals (especially Cu is mentioned: unavoidably present in any MSW waste);
- d. the correct temperature profile and sufficient residence time in the cool-down phase (determined by plant design and operational conditions).

4.1.1 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 PICs like 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 in this respect be regarded beneficial as its relatively high calorific value improves burn-out of both solids and gases [Mark,1995b; Vehlow,1995b, Vehlow,1996b]: see also Figure 1.

The amount of unburned hydrocarbon residues is mainly determined by operational conditions (feed rate, residence time, amount and distribution of combustion air, mixing of gases in the post-combustion zone, grate movement/waste surface and agitation, temperature profile). These are the only parameter which can be influenced to some extent by the MSWC operator for a given plant design. The other parameters b, c, and d cannot be substantially influenced in already existing facilities and defined waste compositions.

Provided that a state-of-the-art combustion control is achieved, we may conclude that PVC has no promoting effect on the formation of PCDD/F. If any, the improved burnout in all phases is more likely to have favourable consequences.

4.1.2 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 comprehensive 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 [Rappe,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 or-

ganic (from PVC) or inorganic chlorine (from NaCl or CaCl₂) [Rappe,1995; Kanters,1994] is observed in most studies. In some cases it is even concluded that in combusting MSW with both NaCl (with isotopic Cl label) and PVC, the Cl in PCDD/F predominately originates from NaCl rather than from PVC [Sickel,1994]. On the basis of a de novo synthesis this can be explained by the formation of PCDD/F on the surface or in the bulk of dust particles where chlorides a more abundantly available chlorine source than the HCl in the gas atmosphere.

The fact that both positive and negative correlations are found in this kind of studies justifies the assumption that the nature of the chlorine (organic/inorganic) is of no influence on the PCDD/F-formation.

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 one to two thirds of the chlorine in MSW. This 10⁷ to 10⁸ fold stoichiometric excess of chlorine (relative to the amount of chlorine detected in PCDD/F as generated) 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.

We conclude, that the fate of chlorine in MSWC is **independent of the type of chlorine containing waste**; table salt, putrescibles and PVC behave conceptually identical in MSWC (see also 4.2).

Elimination of PVC would decrease the amount of chlorine intake by a factor 2 or 3 and would leave the 10 to 100 million fold excess of chlorine over unburned material virtually unchanged. Therefore, the amount of chlorine (or PVC) is not the determining factor in dioxin formation. **As a consequence, elimination of PVC would not (or only marginally) decrease dioxin formation.**

4.1.3 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 CuCl₂). the consequential larger availability of copper salts in fly ash particles would favour 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;Rappe,1995] nor in chemical or physical character (inorganic or organic, finely dispersed or not) [Vehlow,1996a] 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*].

Apparently, catalytic sites at the fly-ash surface are available in 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 of the presence of copper in the normal window of MSCW operation.

(There is another aspect attributed to copper: it catalyses not only the formation of PCDD/F but their thermal destruction as well [*Hagenmaier, 1987*]. Hence it is rather difficult to speculate about any direction of increasing copper inventories.)

We conclude, that copper salts (though catalytically promoting dioxins/furans formation and destruction) are inevitably available in large excess in fly ash, regardless the waste composition, i.e. the presence/absence of PVC.

PVC (even more than plastics in general) promotes volatilisation of copper salts (especially copper chloride) to the fly ash, but this effect is to be considered negligible in relation to the catalytic excess which is anyhow present regardless the amount of PVC.

4.1.4 Temperature and residence time

According to the denovo-synthesis theory [*Stieglitz, 1987*], the formation of PCDD/F can be described as a combined chlorination and oxidation of active particulate carbon (soot) which occurs predominantly in fly ashes 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 [*a.o. 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.

Again, elimination of PVC would have no impact on temperature/residence time which is largely determined by plant design and operational (throughput) parameters.

Considering all dioxin promoting factors, it can be concluded that elimination of PVC would not yield to a relevant decrease of dioxins formations or emissions. Effects (if any) are probably insignificant and directionally unclear.

4.1.5 Dioxin abatement

The unavoidable presence of dioxin in the flue gas requires a dioxin abatement step. Generally, cokes or active coal are introduced into the flue gas to absorb dioxins. These PCDD/PCDF containing carbon residues are (depending on particular MSWC design) recirculated to the combustion stage, or disposed with one of the solid APC residues. As volume, amount and fate of the dioxins in these residues are independent on the amount of PVC, they have not further been considered within the scope of this study.

In addition, catalysts (similar to DeNOx) are nowadays used, to destroy PCDD/PCDF in flue gas. This does not result in a solid residue as PCDD/PCDF are converted to gaseous compounds like CO₂, H₂O, and negligible amounts of HCl. Therefore, this option is not PVC related and has again not been considered in this study.

4.2 MSWC residues

With respect to the impact of PVC on the amount and quality of the bottom ash, neutralisation residues and fly ash in MSWC facilities calculations have been made in Appendix A. In these calculations the contribution of PVC to the residues is calculated using typical values for waste and PVC compositions. These calculations serve to illustrate the impact of PVC which is qualitatively discussed in this chapter. Some of the figures calculated for this typical situation will be given here as well for illustrational purposes.

One important assumption in these calculations concerns the behaviour of the chemical elements in the MSWC facility, especially with respect to their distribution over bottom-ash, fly-ash and flue gas. Elements (like K, Na, Ca, Si, Fe, Al) present in the waste feed in bulk quantities show identical distribution coefficients. An influence of the chemical component in which they are present in the feed is in reality not observed [Vehlow, 1999]. More specifically, research into the fate of chlorine has shown that, under regular MSWC conditions, there is no difference in behaviour of chlorine from different origin. This means that a chlorine molecule from PVC behaves in the same way as a chlorine molecule from putrescibles or bleached paper. These findings were also confirmed by experiments where through labelling it could be determined that the chlorine in dioxins in the flue gas from MSWC predominantly originated from NaCl in MSW, rather than from PVC [Sickel, 1994]. Given the uncertainties in these kind of studies and the fact that both positive and negative correlations are found justifies the assumption that the nature of the chlorine (organic/inorganic) is of no influence on the PCDD/F-formation.

For the behaviour of heavy metals an influence from the waste matrix would be expected: finely dispersed heavy metals introduced via pigments in the plastics or

in paper would be expected to end up predominantly in the flue gas, whereas the same heavy metal immobilized in glass or in a metal object would be expected to end up mainly in the bottom-ash. However, for other waste matrices like putrescibles (which is a major source of heavy metals), the distribution characteristics are less easy to predict.

Literature data on such effects are limited 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 of heavy metals. Though in detail literature is not without contradiction it seems that an increase in the Cl-content enhances the volatilization of K, Cu, Zn, Pb, and sometimes also Sb and Sn [Hunsinger,1994; Vehlow, 1995a,b;Mark,1995b]. Besides this, an increase in temperature in the combustion chamber is known to enhance the volatilization of heavy metals. In general, the influence of the chemical environment of the metals in the waste matrix seems to be very limited and less important than operating conditions like the temperature and the chlorine content. Therefore, for a given MSWC configuration, the assumption that for the heavy metals in PVC the same distribution coefficients can be used as for the heavy metals in total MSW (as used in Appendix A) seems justified.

The calculations in Appendix A each have been conducted for a.o. a fixed and constant chlorine/PVC content in the feed. Though it is recognised that the input data in waste and PVC composition may fluctuate per region and in time, the trends resulting from variation of the PVC amount or composition remain directionally valid and can be universally applied.

The following chapter provides comments on the effects of varying amounts of PVC in the waste, supported by sensitivity analysis with chlorine input as floating parameter.

4.2.1 Bottom-ash

4.2.1.1 Amount of bottom-ash

Bottom-ash is by far the largest residue stream from MSWC facilities. In weight it represents 20-35% of the total waste intake. As a consequence the need for recycling of bottom-ash in a useful, environmentally acceptable way, is the most urgent. The disposal alternative would be highly expensive, let alone the environmental impact (space demand) of such large quantities of bottom-ash to be land-filled.

The impact of PVC on the amount of bottom-ash is very moderate for two reasons:

- there is only a little amount of PVC in MSW (usually well below 1 wt%);
- PVC resin, like all plastics, has by itself an ash content considerably lower than most other waste fractions (ref. of total in Appendix).

The first reason also explains why the **absolute** contribution of PVC to the heavy metal content of the bottom-ash is also very moderate (see Table 2 on page 45).

The question of **relative** effect of PVC again needs consideration. Apart from metals, bottom ash consists of salts of the main elements present in bulk in bottom ash (Na, K, Ca, Al, Si, Fe, Zn) and traces of (heavy) metals salts (that can be neglected in mass considerations).

These oxidised elements are present in bottom ash as carbonates (Na_2CO_3 , K_2CO_3) or (if the carbonate is thermally unstable) as oxide (CaO , Al_2O_3) $\text{Fe}_2\text{O}_3/\text{FeO}_2$, ZnO , SiO_2). Sulphates are also present. The heavy metals traces are almost invariably present as their oxides or sulphates.

Without doubt, these carbonates/oxides will to some extent be converted into chlorides by the hydrochloric acid, liberated on incineration of PVC/chlorine containing waste. Sulphates are not influenced by PVC/hydrochloric acid. Therefore, the addition of PVC (yielding 30 to 70% of all hydrochloric acid) will have an indirect effect on the weight of the bottom ash derived from all other waste fractions.

However, calculations from Appendix A show the unambiguous absence of any impact of varying amounts of PVC on the amount of bottom ash from other fractions. It should be noted that PVC resin by itself generates at most 2-3% of its weight in bottom ash, versus as much as 20-35% for MSW in general.

We conclude, that the amount of bottom ash is practically constant, regardless the amount of PVC in the feed (see Table 3 on page 46) .

4.2.1.2 Quality of bottom ash

a. Alkalinity

Bottom ash of MSWC's is highly alkaline ($\text{pH} > 11$ is no exception) due to the abundant availability of CaO (this is mainly driving the alkalinity to high pH), Na_2CO_3 and K_2CO_3 . Hydrochloric acid, liberated in the fuel bed on the grate by degradation of chlorine containing waste (PVC), will partly neutralise these carbonates and oxides, yielding the corresponding chlorides in an exothermic process. Since only a small fraction of the chlorine remains in the bottom-ash (the majority ends up in the flue gas), however, this effect is very limited.

b. Heavy metals content and leaching

The contribution of PVC to the heavy metal content is relatively low for most heavy metals as mentioned, i.e. less than proportional to the share of PVC in MSW. Only for Pb, Sn and Zn the contribution is more or less proportional to the PVC input in the waste and only for Cd the contribution is overproportional. The influence of chlorine/PVC on the fate of traces of heavy metals in municipal waste is more complex.

The chlorides of most heavy metals are more volatile than the corresponding oxides. The heavy metals are partly volatilised to the raw gas stream. Therefore, PVC stimulates conversion of these heavy metals oxides into chlorides and consequently decreases the amount of metals in the bottom ash in exchange for a corresponding increase of heavy metals in fly ash [Vehlow,1993; Hunsinger,1994; Vehlow,1996bc]. In view of the wide application of bottom ash (e.g. in road construction) this lower metals content is a quality improving effect of chlorine.

On the other hand, leachability of heavy metals from bottom ash is another relevant quality parameter. For heavy metals the relatively unleachable oxides are to be preferred above the more leachable chlorides that may still remain unvolatilised despite interaction with Cl from PVC. For untreated, directly applied bottom ash, this could theoretically be a negative effect of increasing amounts of PVC.

However, the situation reverses if bottom ash is quenched and washed with water as increasingly practised in many MSWC-facilities. Such washing aims at extracting chlorides and other soluble salts from bottom ash. The bottom-ash inventory of heavy metals content remains, however, more or less unchanged due to the high pH of the quenching effluent. By this alkalinity, most heavy metal salts are converted into hydroxides and oxide hydrates of low solubility. Hence inventories of heavy metals found in the quenching effluent are typically only less than 1 % of the original amount fed in the waste feed [Reimann, 1994].

If bottom ash is quenched, heavy metals are washed out more easily as their soluble chloride (from PVC) rather than their insoluble oxides (without chlorine/PVC). The quenching effluent is either used in the scrubbing section for its alkalinity or it is directly fed to the final waste water treatment installation.

c. Leaching and pH

The degree of leaching of heavy metals from bottom ash is pH dependent. The various elements show different behaviour [Sloot,1997]. At intermediate pH values of 7-9, most heavy metals which form cations in an aquatic medium like Cu, Zn, Cd or Pb show a leaching minimum, whereas other metals which form oxy-anions like As or Mo may leach at their maximum levels. At high alkalinity (pH>11.5) amphoteric heavy metals, especially Pb, start to solubilize again. Utilisation of bottom ashes requires pre-treatment including a certain ageing period. During this storage uptake of CO₂ from the air reduces the alkalinity of the bottom ashes by a factor 10-100 which immobilises amphoteric heavy metals. Hence slight changes in the actual alkalinity of fresh bottom ashes possibly caused by PVC have no significance for the leaching from aged bottom ashes.

We conclude that, in terms of bottom ash alkalinity, the presence of PVC overall might have a slightly reducing effect. The environmental effect - if any - is not clear but minor in any direction.

In terms of heavy metals content, the effect of PVC on bottom ash quality is limited and directionally unclear as well, dependent on plant configuration. An increase in PVC might result in a limited increase in the more mobile metalchlorides and may thus result in an increase of heavy metals leaching. Bottom-ash washing, if applied, will annihilate any quality deterioration from an increased amount of chlorides and a possibly resulting increased content of soluble salts. In less sophisticated plants where such ash purification is absent an increase in PVC might have a directionally unfavourable effect on the bottom-ash quality.

In terms of heavy metals leaching from bottom ash, no general conclusion of the effect of PVC can be drawn.

4.2.2 Fly-ash

4.2.2.1 Amount of fly-ash

Like for bottom-ash, the impact of PVC on the **amount** of fly-ash is negligible as PVC is considerably lower in ash content than average waste.

4.2.2.2 Quality of fly-ash

Fly-ash usually contains a lot of heavy metals. This is mainly because at the high temperatures in the fire zone heavy metals are volatilized (e.g. as chloride), leave the furnace with the flue gas and precipitate on the fly-ash when the flue gas is cooled down in the boiler. For this reason, incineration causes an environmentally beneficial extraction of heavy metals from waste and a corresponding concentration in fly-ash. Therefore, the concentration of the relatively volatile heavy metals is much higher in the fly-ash (around 3% of waste feed) than in the bottom-ash (30% of waste feed) (see Table A.6 in Appendix A). Concentration of heavy metal residues in a small volume of waste (fly-ash) is ecologically favourable. As a consequence of its high heavy metals content, recycling options for fly-ash as filler or for construction purposes, are more limited and in some countries even prohibited as fly-ash is considered hazardous waste. In such cases an inertisation step is required. Another recycling route, however, might gain interest: the recovery of volatile heavy metals enriched in the fly ashes. (This can be combined with an inertisation by high temperature treatment or the 3R process [Vehlow,1990].)

The 'carrier-effect' of chlorine with respect to heavy metals influences the amount of heavy metals counterwise to bottom-ash, meaning that a decrease in the Cl-content of the waste feed would result in a decrease of the heavy metal content of the fly-ash. However, it is not expected that these effects would mean a significant

improvement of the fly-ash quality in terms of possibilities for recycling or decreased costs for treatment or disposal.

We conclude that elimination of PVC from MSWC-feed would result in a directionally undesirable decrease in fly ash heavy metals concentration. On the other hand, if society (apart from generally practised bottom ash recycle) simultaneously insists in recycling of fly-ash (the relatively most hazardous solid MSWC residue), PVC elimination would result in an advantage due to a decreased heavy metalcontent of the fly-ash. This argument needs to be weighed against a possible quality improvement of the bottom ash with considerably larger volume.

4.2.3 Flue gas cleaning residues

Evidently, flue gas cleaning residues are first of all determined by the concept of flue gas cleaning applied. In this study 4 most typical flue gas cleaning configurations are discussed, which conceptually cover most of the MSWC facilities in Europe. In actual operation, some differences will occur.

The following configurations are involved:

- A. wet scrubber system with scrubber effluent discharge
- B. wet scrubber system with scrubber effluent evaporation
- C. semi-dry scrubber system
- D. dry scrubber system

Schematic representations of these configurations are given in Figure 3. A short characteristic on each configuration is given in Table 1.

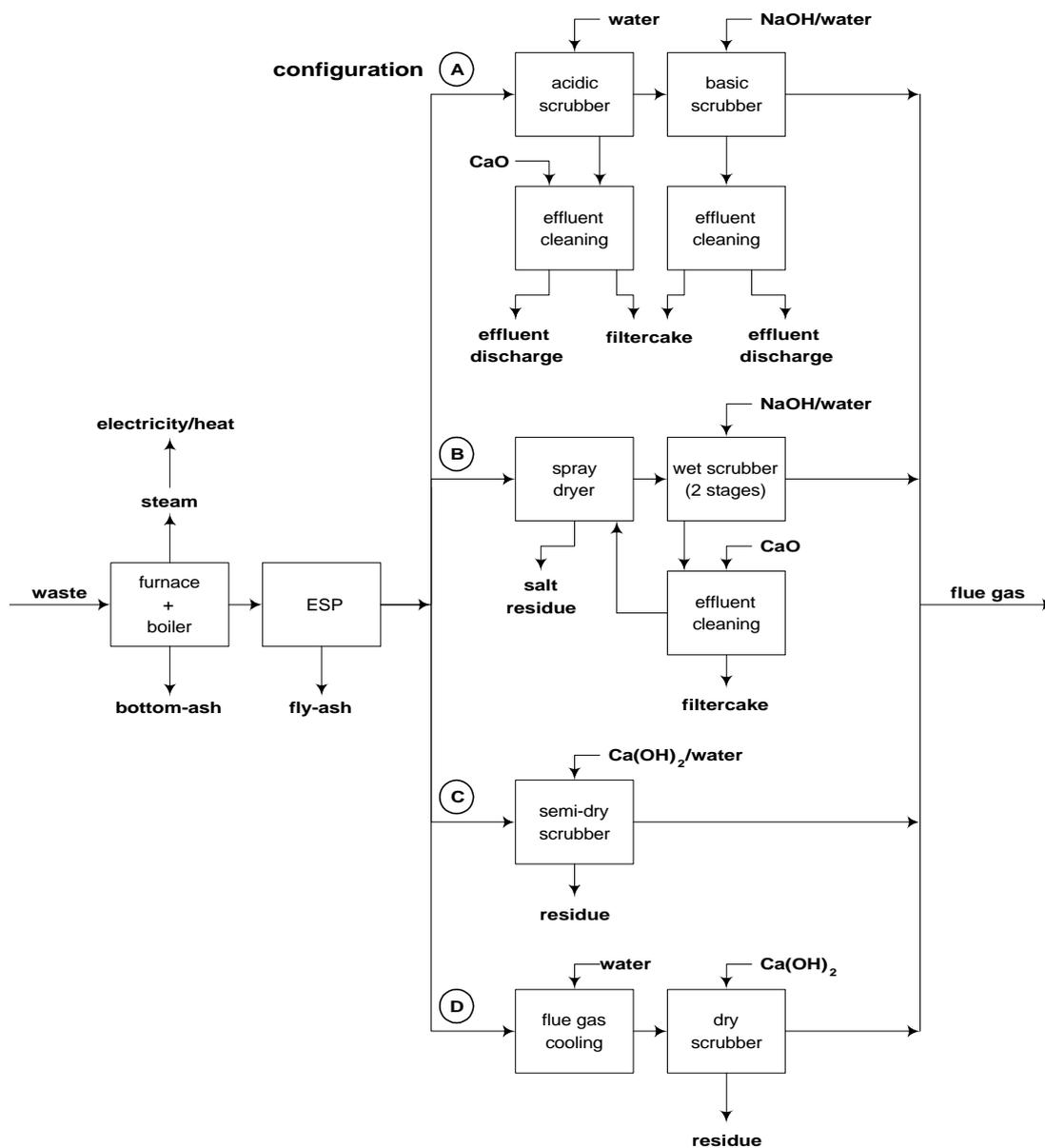


Figure 3 Typical flue gas cleaning configurations.
 (The spray dryer, semi-dry and dry scrubber consist of a reactor plus a subsequent filter. For clarity, the filters have not been drawn separately).

Table 1 Flue gas cleaning configurations with brief characteristics.

FGC Configuration	Reagents	Stoichiometry ¹	Residues	Amount of residue ² [kg/tonne MSW]	Main components
Configuration A: Wet scrubber with effluent discharge	NaOH (for SO ₂)	1.05 (1.0-1.5)	Filtercake	1.6	fly-ash, excess lime
	CaO (for neutralisation HCl)	1.1 (1.0-1.3)	2 Liquid effluents	not applicable	CaCl ₂ (in water) Na ₂ SO ₄ (in water)
Configuration B: Wet scrubber with effluent evaporation	NaOH (for SO ₂)	1.05 (1.0-1.5)	Filtercake	6.9	gypsum, fly-ash, excess lime
	CaO (for neutralisation HCl)	1.1 (1.0-1.3)	Salt residue	8.1	CaCl ₂ , NaCl, fly- ash
Configuration C: Semi-dry scrubber	Ca(OH) ₂	1.8 (1.5-3.0)	Mixed solid residue	20.3	gypsum, CaCl ₂ , fly- ash, excess lime
Configuration D: Dry scrubber ³	Ca(OH) ₂	2.5 (2.0-4.0)	Mixed solid residue	25.4	gypsum, CaCl ₂ , fly- ash, excess lime

¹ Stoichiometry based on amount of acid gases in the flue gas: mole equivalent reagent / mole equivalent sum (HCl + SO₂ + HF).
The first value given is the typical value used: between brackets a range of encountered values is given.

² Typical values of solid residues from the combustion of 1 tonne MSW are given. Amounts are given on a dry basis.

³ In fact, this should be called a “conditioned dry scrubber” since water is injected prior to the dry scrubber. Today, the original “dry scrubber”, i.e. without water injection, is no more applied.

For each of these configurations first some general remarks are made. Subsequently, the overall picture is given.

4.2.3.1 Configuration A: Wet scrubber system with liquid scrubber effluent discharge

In the first step, flue gas is cooled down and scrubbed with water. Hydrochloric acid is removed from the flue gas by dissolution. The consequently highly acidic liquid (typically the pH is kept <1 to improve Hg absorption) needs subsequent neutralisation with alkali, for which lime rather than sodiumhydroxide (NaOH) is generally used for economic reasons. At the resulting high pH value, heavy metals precipitate as (hydr)oxides and are filtered off as “filter cake” with entrained fly ash particles. The filtered clear effluent consists of calcium chloride (from the lime

neutralisation of HCl) and unconverted calcium hydroxide (from excess neutralisation alkali) as main components.

This stream is environmentally harmless [Saft, 1997] and can be ultimately disposed of in surface water, provided the calcium salts content can be accommodated.

After the aqueous first scrubber, the flue gas is subsequently washed in a neutral to weakly-alkaline second scrubber, where the remaining HCl is neutralised by caustic (NaOH) together with SO₂ (which is not absorbed at the low pH in the first acidic scrubber). Lime (though less expensive) is not used for neutralisation in the second scrubber as it would generate insoluble gypsum (CaSO₄) that undesirably adds to the filter cake volume.

On neutralisation, heavy metals will again precipitate as (hydr)oxides and are separated by filtration to be removed as filter cake. The clear filtrate of the second scrubber consists mainly of NaCl (table salt) and Glauber's salt (Na₂SO₄) which is disposed of as a liquid effluent. In this flue gas cleaning configuration **A**, heavy metals (regardless the waste source) are separated at high concentration via the filter cakes and are to be disposed of as solid chemical waste.

The contribution of PVC to the heavy metals content of the filter cake is underproportional; **PVC is therefore not causing any deterioration of filter cake quality**. In terms of filter cake **volume**, the **direct** contribution of PVC's heavy metals is minimal (0,13% of total). However, indirectly PVC contributes overproportionally (11%) due to the presence of the excess of insoluble (toxicologically harmless) lime that was input to the neutralisation after the water scrubber.

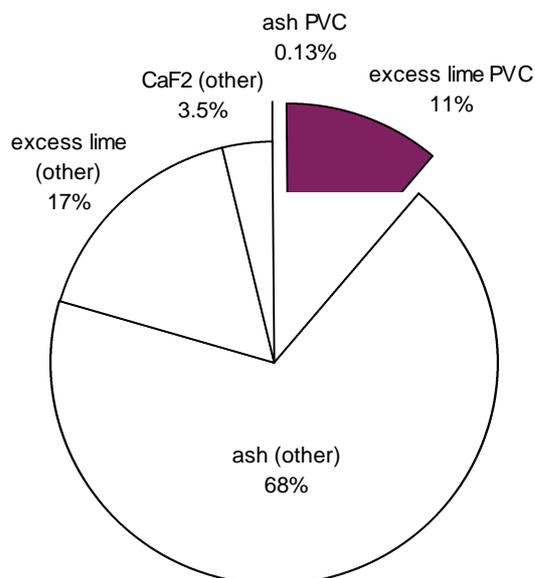


Figure 4 Allocation to PVC in the filtercake: just over 11 wt%.
(Configuration A: Wet scrubber with effluent discharge).

Environmentally, configuration **A** is the most attractive option: the undesirable heavy metals are concentrated at the highest value at the smallest volume of all

APC configurations, provided the salty liquid effluent can be disposed of. This is obviously dependent of MSW location and the local permit regime for salty effluent.

In terms of cost (see further chapter 5) it is obvious that regardless the PVC content of the MSW virtually the same APC equipment would be required. Without PVC, the same instrumentation and equipment arrangement would conceptually remain in place as a two step neutralisation would still be required. The possibly smaller **size** of part of the flue gas cleaning equipment by lack of PVC has only a relatively small impact on the APC investment costs.

We conclude that in MSWC with wet scrubbing / liquid effluent (Configuration A) the amount of solid residues from APC is smaller than any other configuration (below 2% of MSW feed intake). **PVC contributes less than proportionally to its heavy metal content, and overproportionally to its volume. This overproportionality is caused by environmentally harmless calcium salts. Elimination of PVC would not cause any conceptual change. Consequently, it would result in only marginally lower APC investment cost.**

Decrease of the PVC content by 33% would result in only 10% less disposal residue as filter cake (see Table 3).

A variation on this configuration (scarcely practised) is the situation where the effluent from the acidic scrubber step is separately treated and upgraded to produce hydrochloric acid, for commercial use. In this case hardly any PVC related solid residue is produced by the MSWC facility. However, as far as we know, this is only practised at two German MSWC facilities (until now). The economical success of this configuration is endangered by the legal decision whether this hydrochloric acid is to be considered as a product or as a waste material. (Quality recommendations for such hydrochloric acid apply in Germany [LAGA, 1994]). In the latter case this configuration is not considered economically feasible [Menke, 1999].

4.2.3.2 Configuration B: Wet scrubber system with liquid scrubber effluent evaporation

Conceptually, this configuration can be visualised as a two-step wet scrubber, with a subsequent recycle of the aqueous effluent over the scrubber step. In a spray dryer, a solid residue is produced (for ultimate disposal) by heat transfer from the flue gas to the completely evaporating wet scrubber effluent. We describe the system in backwards order.

Final removal of all acidic gases is achieved in the second scrubber where NaOH is introduced for their neutralisation. The alkaline brine is aerated to convert Na_2SO_3 (from SO_2 neutralisation) to Na_2SO_4 , to prevent subsequent re-liberation of SO_2 under acidic conditions.

This aerated alkaline brine is recycled to the first scrubber where it is neutralised by the large excess of HCl primarily present in the flue gas. The resulting first

scrubber effluent is still highly acidic as the excess HCl is still perfectly soluble in the neutralised brine. The now acidic brine (also containing heavy metals from the washings) needs additional neutralisation for which lime (CaO) rather than caustic (NaOH) is used for economical reasons. Heavy metals are precipitated as hydroxides or sulfides from the brine and filtered off in the effluent cleaning unit. However, apart from relatively small amounts of heavy metals, the resulting filtercake mainly consists of gypsum (CaSO_4) originating from neutralisation of sulphur containing waste fractions. The cleaning unit's aqueous filtrate is evaporated with the heat from the flue gases in the spray dryer before the flue gas enters the scrubbing system. By this evaporation, the salts (and small amounts of unprecipitated heavy metals) crystallize and are separated as solids in the ESP or bag filter following the spray dryer. Here, direct contact is achieved between the flue gas (which has only been primarily dedusted) and the salty effluent to be evaporated. As a result, part of the fly-ash and heavy metals, which were not caught in the primary dedusting will be adsorbed and incorporated in the resulting salt residue. This residue mainly consists of calciumchloride, from neutralisation of chlorine containing waste fractions.

Filtercake

The contribution of PVC to the quality of the filtercake is relatively low compared to the other fractions as PVC's heavy metal input is relatively minor. Therefore, it can be stated that PVC does not worsen the quality of the filtercake.

Also the contribution to the amount of filtercake is very moderate (see Figure 5) since the largest part of the filtercake consists of gypsum from the capture of SO_2 , to which PVC has no contribution (PVC contains no S).

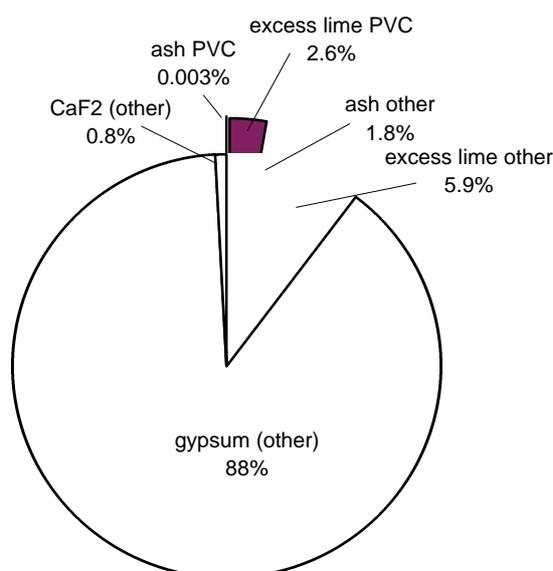


Figure 5 Allocation to PVC in the filtercake: less than 3 wt%.
(Configuration B: Wet scrubber with effluent evaporation).

Salt residue

Like in all cases the contribution of PVC to the quality of the salt residue in terms of heavy metal content is very moderate and no quality deteriorating effect can be attributed to PVC in this respect. However, PVC does significantly contribute to the Cl-content of the salt residue which is unpopular in terms of leaching to the environment. The same significance can be seen in the contribution of PVC to the volume of the salt residue produced (see Figure 6).

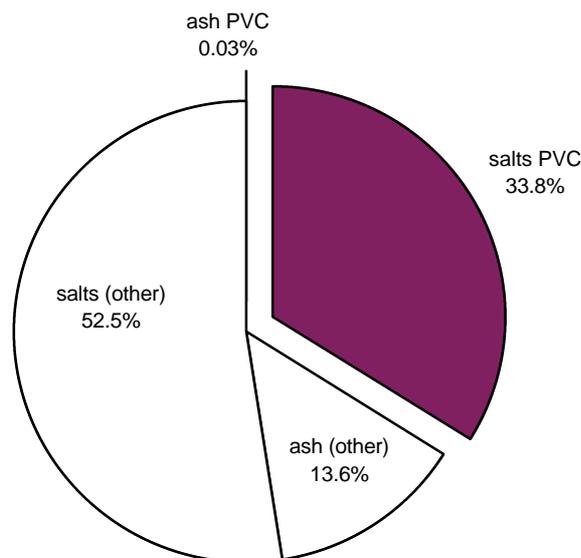


Figure 6 Allocation to PVC in the salt residue: 34 wt%.
(Configuration B: Wet scrubber with effluent evaporation).

In terms of costs, no impact on the investment costs can be expected from a change in the PVC content of the MSW in this configuration. However, in variable costs the impact of PVC mainly through residue disposal costs can be considerable (see further chapter 5).

From the above, we conclude that PVC does not deteriorate the quality of both filtercake and salt residue in terms of heavy metals. Nevertheless, the salt residue is still classified as hazardous (in the Netherlands), due to the abundant presence of chlorine, in which PVC does have a substantial share.

Regardless the impact of PVC, this design produces much more solid residues per tonne of MSW than in configuration A's design.

The filtercake mainly consists of gypsum from the SO₂ absorption, in which PVC has no share. As a consequence the contribution of PVC to the filtercake volume is quite moderate. The large share of PVC in the MSWC input translates in a large share in the amount of salt residue produced. Related to the PVC weight input of the MSWC facility the contribution of PVC to the salt residue is highly overproportional.

From Table 3 it can be concluded that even a decrease of the PVC content of the MSW by two thirds would only result in a 2% decrease in the amount of filtercake and a 29% decrease in the amount of salt residue.

4.2.3.3 Configuration C: Semi-dry scrubber

Conceptually, this is the most simple operation. All acidic components (SO_2 , HCl, HF) in the flue gas are absorbed in a spray dryer in one single step. In this semi-dry scrubber an aqueous lime slurry is injected in the flue gases. Evaporation of the water from the lime decreases the flue gas temperature. During this process of evaporation of water and gravitation of the initially moist and subsequently dry solid limeous particles, acidic gases have to be absorbed and consecutively neutralised. In this concept, the initial presence of a water phase around the solid particles facilitates this absorption/adsorption process. Therefore, lower stoichiometries for the adsorbens are needed than in the dry scrubber (configuration D) to be discussed hereafter.

The solid residue at the bottom of the spray dryer consists of:

- CaCl_2 (from neutralisation of HCl),
- gypsum (from neutralisation of SO_2),
- lime ($\text{Ca}(\text{OH})_2$) from the unavoidable excess of unneutralised alkalinity, required to prevent acid slipping through
- some fly-ash, slipped through from the preceding dust removal device.

Heavy metals precipitate on the limeous particles and are thus captured in the semi-dry scrubber residue. Since the behaviour of heavy metals is identical, regardless their origin, the contribution of PVC to the heavy metal content of the semi-dry scrubber residue is in line with the general share in heavy metal content of PVC. Therefore, the PVC-specific contribution to the heavy metal content of the semi-dry scrubber residue is relatively low (0.04 tot 6.8%; see Table A.2).

The considerable share of PVC in the total amount of semi-dry scrubber residue (Figure 7) is caused by the neutralisation of HCl from PVC and the required excess of alkaline reagent needed. Semi-dry scrubbers usually are operated at stoichiometric ratios of 1.5 to 3.0 [Reimann, 1991]. In our calculations, an average value of 1.8 for a typical modern facility is used. Like in the other configurations, the risk of exceeding emission limits versus reduced additive consumption is judged differently at various plants. Obviously, higher stoichiometries will increase the amount of scrubber residue, and dilutes the heavy metal amount over a larger volume.

One aspect of the semi-dry scrubbing process needs extra attention in determining the amount of residue which can be related to PVC. In the semi-dry scrubber (configuration C), at contrast to the wet scrubber (in configuration A or B), all

acidic species HF, HCl and SO₂ have to be removed from the flue gas **in one step**. The reactivity for adsorption and neutralisation, however, is different for these gases: based on thermodynamics the order of reactivity is: HF > HCl >> SO₂ [a.o. *Metschke,1997; Horvay,1989*]. In practice this means that for the removal of SO₂ larger excess ratios of adsorbens are required than would be needed if only HCl and HF were present in the flue gas. As PVC does not contribute to the SO₂ content in the flue gas, it is not correct to allocate the effect of PVC to the semi-dry scrubber residue based on the excess ratio needed for SO₂ removal. From literature no exact figures for the required excess ratios for HCl removal alone are known, but estimates are that for HCl an excess ratio of 1.3 instead of 1.8 would be sufficient [Reimann, 1991]. From the numerous data on the experiments at the Würzburg MSWC facility [Bach,1996] it was clear that an increase of the HCl concentration in the raw flue gas caused the consumption of alkali to increase only marginally more than stoichiometrically. However, an increase of the SO₂ concentration triggered a clear over-stoichiometric increase of alkali consumption for neutralisation.

For this reason we calculated the allocation to PVC in the residue with an excess ratio of 1.3 whereas for the total MSW an excess ratio of 1.8 is applied.

(Remark: Without recognizing this difference in reactivity between HCl and SO₂ than the allocation to PVC in the semi-dry scrubber residue would increase from 16.4% to around 21%.).

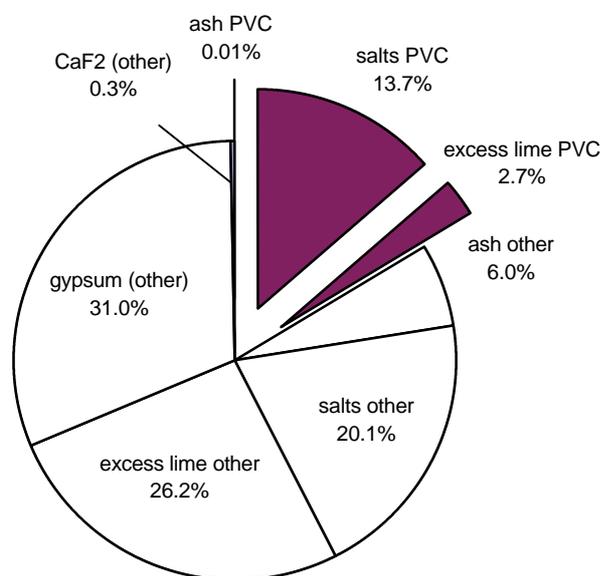


Figure 7 Allocation to PVC in the semi-dry scrubber residue: 16.4%.
(Configuration C: Semi-dry scrubber)

In terms of costs, this configuration is intermediate between configurations A or B versus configuration D:

- investment costs for C are lower than in configuration A and B, but higher than in configuration D;

- variable costs, especially disposal costs are more elevated than for configuration A or B, but less than in configuration D.

We conclude that for a semi-dry scrubber residue PVC has a moderate contribution to the heavy metal content and therefore does not deteriorate the quality of this residue.

The contribution to the amount of residue is considerable and is highly over-proportional to the share of PVC in the input.

4.2.3.4 Configuration D: Dry scrubber

In the first step, the flue gas is cooled down by evaporative water injection without condensation below the dew point. This allows more efficient absorption in the next step where (as alkalinity source) solid lime is introduced in the dry scrubber. All acidic species (not only HCl from chlorine-waste, but also HCl, NO_x and SO_x from other waste fractions) need to be neutralised in **one** step at the surface of (gravitating) alkaline particles in the dry scrubber.

Chemically and physically, this neutralisation is the least efficient of all concepts A-D. It explains why the highest stoichiometric excess of lime relative to acidic species is needed to guarantee a sufficient level of flue gas cleaning.

Like in the semi-dry scrubber, the solid residue at the bottom of the spray dryer consists of:

- CaCl₂ (from neutralisation of Cl containing waste);
- gypsum (CaSO₄ from neutralisation of SO₂: non-PVC related);
- lime (from the unavoidable excess of unneutralised alkalinity, required to prevent acid slipping through);
- some fly-ash (escaped from previous dust removal).

This design inherently generates the highest amount of neutralisation residue allocated to PVC of all concepts A-D, regardless the amount of PVC in MSW (Table 2 and Table 3). Sulfur in the MSW feed (not related to PVC) unavoidably generates a solid gypsum residue in this design.

Like a semi-dry scrubber system, also in dry scrubbers the excess of reagents (stoichiometric ratios of 2 to 4 occur) is needed for the adsorption of SO₂ rather than for HCl. The latter is easily removed from the flue gas and an excess ratio of 1.5 for HCl would be more realistic [Reimann, 1991] and has been used in our calculation of the allocation to PVC in the residue (see Figure 8).

(Remark: If this difference in reactivity between HCl and SO₂ remains unaccounted, the allocation to PVC in the dry scrubber residue from the combustion of MSW would increase from 14.5% to around 22%.)

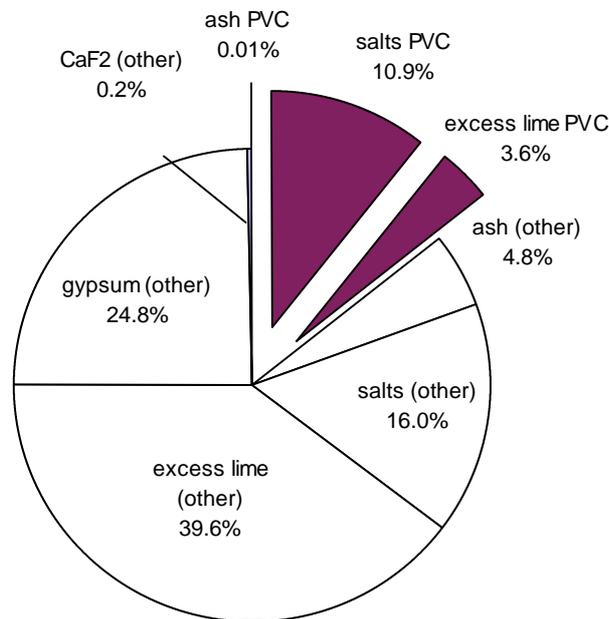


Figure 8 Allocation to PVC in the dry scrubber residue: 14.5 %.
(Configuration D: Dry scrubber)

Like in the semi-dry scrubber, heavy metals indiscriminately coprecipitate on the solid dry scrubber residue, and together with the Cl-content cause its "chemical waste character" which generally requires a specific storage regime. This dry scrubber APC design probably has the lowest investment cost but causes relatively high variable costs in terms of chemicals use and chemical waste storage costs at dedicated sites.

Though (in dry scrubber type APC) PVC is responsible for the **volume** of the solid neutralisation residue, its **quality** is determined by the heavy metals from all waste fractions in which PVC contributes less than 3% and less than proportional. If (in theory) PVC would be processed separately, **its heavy metals would even be present in such low amount that PVC's "own" neutralisation residue would not even be considered as chemical waste in many EU countries.**

Figure A.6 (Appendix A) shows that the content of heavy metals in PVC's "own" specific neutralisation residues would by no means exceed the values to be considered chemical waste according to Dutch legislation. In this respect, PVC compares favourably with average municipal solid waste.

We conclude that clearly PVC disproportionately adds to the VOLUME of the dry scrubber neutralisation residue. Conversely, PVC is NOT responsible for its QUALITY as chemical waste in terms of heavy metals.

The heavy metals from *other waste fractions* contribute for as much as 96% to the chemical waste character of the MSW neutralisation residues, whereas PVC contributes to only 14.5 % of its volume (dependent on PVC and sulphur content of MSW).

The quality of the relatively clean salty residue from PVC combustion is deteriorated by the heavy metals from other fractions.

Conversely, it can correctly be argued that without PVC virtually the same amount of heavy metals would be concentrated in a considerably smaller amount of neutralisation residues. There is no generally accepted allocation of the burden between PVC and the rest of the waste.

In terms of overall sensitivity, we calculated the effect of an increase/decrease of the amount of PVC in MSW by as much as 50%. It can be concluded from Table 3 that the effect of such measures is limited. The amount of residue in any configuration would change by only 6 to 10%.

4.2.3.5 Conclusion flue gas cleaning residues

(The calculated amounts are summarized in Table 2 and Table 3 below.)

We conclude that the design of the MSWC predominantly determines the PVC specific mass balance.

The amount of bottom ash or fly ash is independent of the amount of PVC in the MSW feed. The directional impact of PVC on bottom ash quality in terms of heavy metals is either positive or negative, dependent on MSWC plant configuration.

Elimination of PVC would cause a generally undesirable decrease in fly ash heavy metals concentration. However, in the rare cases that MSWC fly ash would be reused in non-waste products with positive economic value, elimination of PVC would lead to a decreased potential for leaching of heavy metals from the fly ash application, which in that case would be beneficial.

The *volume* of neutralisation residues is dominated by the type of design of the MSW plant, rather than PVC specific factors. Pending on plant design, the amount of residue to be allocated to PVC may vary by more than a factor 20, from 3% to 70% of the PVC intake weight.

The *quality* of the PVC neutralisation residues is deteriorated by heavy metals from all other waste fractions; the calculated theoretical neutralisation residue of PVC by itself (apart from the rest of the waste) would not even be considered as chemical waste in terms of heavy metals. The PVC residue by itself is environmentally innocent apart from its salty character.

The share of PVC to the *amount* of neutralisation residue is overproportional, its share in *quality* deterioration by heavy metals is underproportional.

The positive and negative effect of PVC cannot be separated from other factors in their contribution to volume and quality of the solid neutralisation

residues. Therefore, in no case can problems in residue disposal be exclusively related to PVC.

Elimination of PVC would not or only marginally decrease the magnitude of these problems. The effect of 50% PVC reduction in the waste input on the total of flue gas cleaning residue is below 10%, irrespective of plant configuration.

Table 2 Amount of residues per tonne MSW and per tonne PVC; allocation to PVC of the residues.

Material	Type of residue	any configuration		wet scrubber, effluent discharge (config. A)	wet scrubber, effluent evaporation (config. B)		semi-dry scrubber (config. C)	dry scrubber (config. D)
		bottom-ash ²	fly-ash	filtercake (dry)	filtercake (dry)	salt residue	residue	residue
MSW	kg/tonne MSW	215	15.2	1.6	6.9	8.1	20.3	25.4
PVC - total	kg/tonne PVC	66	4.5	29	28	430	520 ³	580 ³
- rigid	kg/tonne PVC	22	1.6	36	35	520	640	710
- soft	kg/tonne PVC	93	7.5	23	22	330	400	440
Allocation to PVC ¹	%	0.19	0.19	12	2.6	34	16.4	14.5

¹ The allocation to PVC of the residues from the combustion of MSW (based on PVC content of 0.64 wt%).

² Bottom-ash contains 15 wt% water.

³ For the absorption and adsorption of flue gas with only HCl (from mono-combustion of PVC: theoretically) a different excess ratio is used as for flue gases which contained both HCl and SO₂ (e.g. from combustion of MSW: see text for explanation).

The data used in Table 2 reflect a typical MSW composition in which the PVC waste fraction is considered including attached dirt. In this PVC waste fraction a 50/50 distribution between rigid and soft PVC is assumed.

Supporting argumentation is provided in Appendix A.

*Table 3 Effect of changes in PVC content of MSW on residue amounts.
Absolute and index figures; base case = 100.*

Residue ¹ in kg/tonne MSW	MSW 0.32 wt% PVC (50% decrease)		MSW 0.64 wt% PVC (Standard = 100)		MSW 0.96 wt% PVC (50% increase)	
	absolute	index	absolute	index	absolute	index
Bottom-ash ²	215.5	100.2	215.0	100	214.5	99.8
Fly-ash	15.23	100.2	15.20	100	15.17	99.8
Configuration A: Wet scrubber with ef- fluent discharge: - filtercake ²	1.53	94	1.62	100	1.71	106
Configuration B: Wet scrubber with ef- fluent evaporation: - filtercake ²	6.82	99	6.89	100	6.96	101
- salt residue	6.7	83	8.1	100	9.4	116
- total	13.5	90	15.0	100	16.4	109
Configuration C: ³ Semi-dry scrubber: - residue	18.7	92	20.3	100	21.9	108
Configuration D: ³ Dry scrubber: - residue	23.6	93	25.4	100	27.2	107

¹ In this table in some cases more decimals than scientifically significant are given, just to demonstrate the impact of a change in PVC content.

² Bottom-ash is including 15 wt% water, other residues are on dry basis.

³ For the dry and semi-dry scrubber the fact that HCl is more easily absorbed or adsorbed is acknowledged and accounted for, in the same sense as for the figures in Table 2.

5. Processing costs of PVC in MSWC facilities

5.1 Methodology

Several studies [Reimann,1991; Randall,1994] have been executed in the past, to calculate the costs which can be allocated to the combustion of the PVC in MSW. With respect to operating costs such as the purchase of additives or chemicals and the disposal costs of residues this usually is not problematic, as a linear relationship between the amount of PVC and these parameters can easily be derived from the mass balance. However, it is far more difficult to find an unambiguous allocation method for maintenance costs (e.g. due to corrosion effects) and especially for investment costs. As modern MSWC facilities are complex industrial installations, investment costs are relatively high. Capital costs represent as much as 60 to 80% of total processing costs. Therefore, when calculating the cost of PVC in MSWC facilities it is very important that capital costs are properly accounted for.

In MSWC facilities, none of the equipment is installed specifically for one single waste feed component: e.g. a scrubber takes care of acidic gases like HCl, HF and SO₂ as well as fine dust particles and volatile heavy metals which slipped through the ESP. As a consequence, it cannot be stated that a scrubber is installed uniquely for e.g. PVC or any other component and the investment costs for this scrubber cannot be allocated completely to PVC.

In the study on specific processing costs for various materials [Rijkema,1996b], a methodology was developed in which capital costs were allocated. Starting points in this methodology were that the MSWC facility is operated at full capacity within its regular operating window and that the acceptance of any specific material for processing inevitably replaces a certain amount of the regularly combusted 'grey' waste. For the replacement of this grey waste by accepted waste three scenario's were considered with respect to the plant operation:

- a) the plant is running at maximum thermal capacity: i.e. thermal limitation;
- b) the plant is running at maximum mass throughput capacity: i.e. mass limitation;
- c) the plant is running below capacity in terms of both mass and thermal capacity: i.e. no throughput limitation and no substitution of grey waste as a consequence. Additional waste can easily be processed.

Modern individual MSWC facilities generally are running at full thermal capacity (a). The scenario without throughput limitation (c) should only be incidentally encountered in real-life MSWC facilities, as obviously it reflects an economically unstable situation on the longer term. However, we understand that at present some German MSWC facilities find themselves in this situation as a result of diversion of MSW to non-incineration outlets.

Cost calculations are conducted from the MSWC facility operator's point of view. The calculated processing costs reflect the fee to be charged for the accepted waste material to maintain financial break-even with respect to the original situation. It takes the present commercial or contractual gate fee for standard grey waste in the MSWC facility as a starting point.

Obviously, processing costs are split in fixed costs (capital costs) and variable costs. Variable costs were calculated straight from the elemental waste composition, the mass balance and chemical fate of the elements. Fixed costs were determined based on the approach that the newly accepted waste has to take the burden of the same amount of capital costs which were originally covered by the amount of average (= 'grey') waste replaced. For the different scenarios the amount replaced is different:

- a) at thermal limitation, replacement is on thermal equivalent basis: 1 MJ of new waste replaces 1 MJ of grey waste;
- b) at mass limitation, replacement is done on mass equivalent basis: 1 kg of new waste replaces 1 kg of grey waste;
- c) in case there is no capacity limitation, no grey waste is replaced. As a consequence the processing costs for the accepted material do not need to cover capital costs but only variable costs. A gate fee at variable costs for the new specific waste yields a break-even financial result in an underloaded plant. In practice, gate fees far above variable costs need to be realised for underloaded plants for obvious commercial reasons. This argument, however, equally applies to each waste type.

This leads to the following formula for calculation of the specific processing costs (SPC) of PVC:

$$SPC_p = v_p + w * f_g \quad (1)$$

with: f_g fixed cost per tonne grey waste G [Dfl/tonne]
 w displacement ratio between newly added PVC and displaced original grey waste [tonnes/tonnes]
 v_p variable costs of processing PVC [Dfl/tonne]
 SPC_p specific processing costs of PVC [Dfl/tonne]

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

f_g in formula (1) can be calculated from:

$$GF_g = v_g + f_g \quad (2)$$

with: GF_g contractual or commercial gate fee charged for processing grey waste [Dfl/tonne]
 v_g variable costs of processing grey waste [Dfl/tonne], calculated from a model or excerpted from the MSWC financial records over a sufficiently long period of steady operation.

This methodology and some calculatory examples are further explained in Appendix B. [*Rijkema, 1996b*] provides much more explanatory detail. Only the conclusions with respect to the specific processing costs of PVC are given here.

5.2 Specific processing costs

In calculating the SPC for PVC, two major aspects dominate the results:

- the relatively high (compared to average MSW) calorific value of PVC;
- the relatively high variable costs, as a result of the required chloride removal from the flue gases.

5.2.1 Relatively high calorific value and fixed costs

Usually, MSWC installations operate at full capacity, limited in thermal throughput. If high calorific waste like plastics with a net heating value (NHV) above 30 MJ/kg, is offered for processing in such an existing, thermally limited plant, at least 3 tonnes of standard grey waste (with NHV of 10 MJ/kg) is substituted (as the calorific throughput per hour cannot exceed its maximum). In order to maintain financial ‘break-even’ (i.e. cost-neutral), the fixed cost element allocated to this added plastics must be at least three times as high compared with the normal grey waste feed.

In this reasoning, fixed costs in an existing MSWC facility are essentially allocated on a “per hour” basis, allowing the MSWC facility operator to fully recover the annual fixed costs, regardless the composition of the waste.

In this respect, PVC takes an intermediate position. Its energy content is 16 MJ/kg for rigid PVC with 46 wt% of chlorine and 20 MJ/kg for flexible (soft) PVC with 29 wt% chlorine, due to the presence of chlorine-free, high-calorific plasticiser (typical values).

In any case, the fixed costs burden allocated to PVC is between grey waste and chlorine-free plastics and therefore not extreme or exceptional.

In a mass limited plant, however, all waste types are allocated the same fixed costs as replacement is on a one-on-one weight basis ($w = 1$, in formula (1)). Therefore, in these plants, fixed costs allocations are identical for PVC and grey waste (and any other waste material).

In an underloaded plant, where no waste substitution occurs ($w = 0$), fixed costs considerations are absent.

Gate fees are generally dominated by the fixed costs element as can be seen from Figure 9 and Figure 10, by comparison of the underloaded, no limitation case (where only variable costs are essential) with the other cases where throughput is limited by full capacity (and fixed costs do play a role).

5.2.2 Chlorine content and variable costs

Variable costs arguments apply irrespective of the loading of the MSWC facility. Variable costs for PVC processing include the costs of alkali to neutralize HCl in the flue gas. The amount of alkali applied varies with the stoichiometric amount of alkali that is required, dependent of the design configuration. These costs of neutralisation as such, are often perceived as extremely high. Appendix B shows, however, that the associated costs of alkaline additive are relatively minor. An increase of the stoichiometric neutralisation rate by even 40% results in extra costs of around 20 Dfl/tonne PVC.

More important however, are the costs of solid handling, transport and disposal of the solid neutralisation residues generated from PVC. This, however, is again completely dominated by the MSWC flue gas cleaning configuration.

In configuration B (wet scrubber, effluent evaporation), about 460 kg residue per tonne PVC (Table 2) needs to be deposited at high costs. These costs are only partially compensated by the income from the generated electricity (kWh's) from PVC. In this type of MSWC plant design (configuration B), the variable costs of PVC processing are positive and higher than for any other waste material.

However, the situation is quite different in plants with a wet scrubber/effluent discharge type of configuration (type A). In this case, only about 30 kg solid residue is generated per tonne of PVC processed. These costs are very small and (even when all other variable costs are included) are easily compensated by the income from the electricity generation from PVC (Table 2.2 in Appendix B). In this type A of MSWC plant design the overall variable costs are negative, i.e. PVC processing generates income.

Now, average PVC takes an intermediate position: less favourable than non-chlorine plastics or wood, but still more attractive than standard grey MSW.

Configurations C and D were not involved in the SPC calculations but will be even more sensitive to the stoichiometric ratio applied and to the disposal costs since these configurations use higher ratios and generate higher amounts of solid residues.

In Figure 9 and Figure 10 the specific processing costs of PVC and other fractions from MSW are compared for flue gas cleaning configurations A and B and for the: thermally limited, mass limited and not limited scenario.

(The SPC for total PVC is not provided in this diagram, but obviously can be calculated as the weighed average of soft and rigid PVC).

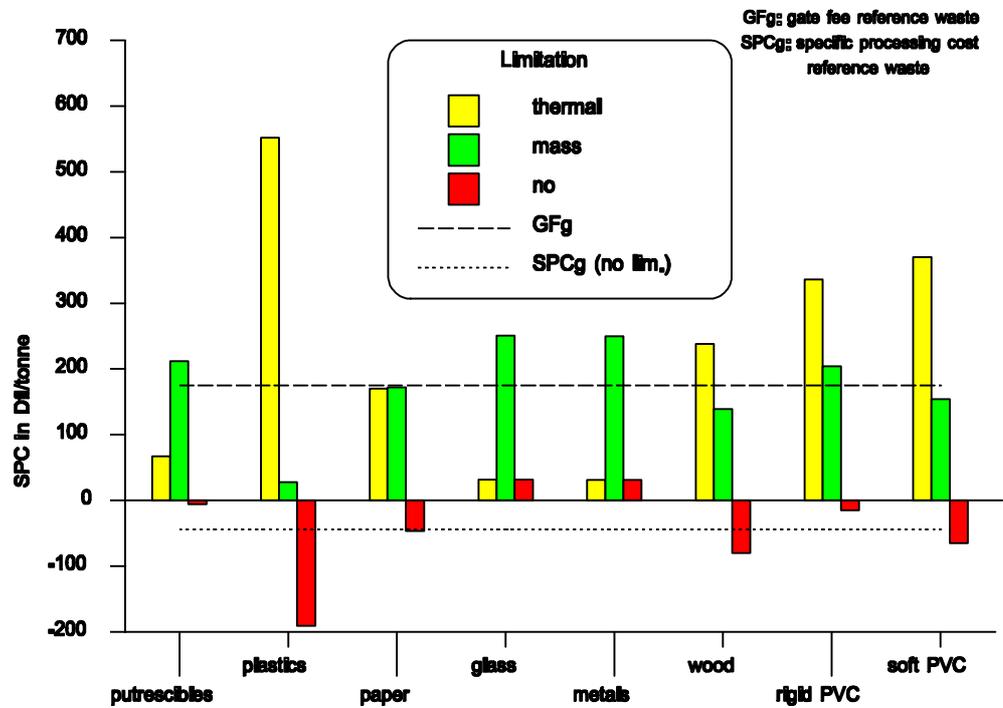


Figure 9 Specific processing costs for a MSWC facility with discharge of the purified wet scrubber effluent (configuration A).

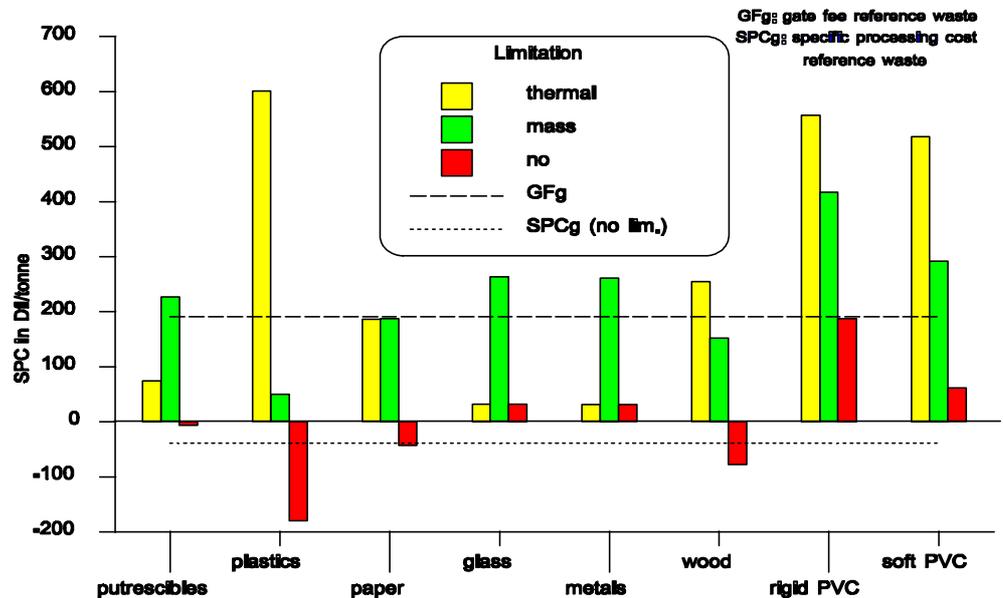


Figure 10 Specific processing costs for a MSWC facility with evaporation of the purified wet scrubber effluent (configuration B).

5.2.3 Alternative fixed cost allocations

Besides variable costs for residue disposal, incineration of PVC is frequently associated with a high share in costs of maintenance (corrosion) and of capital of the APC section where HCl is removed.

For maintenance costs due to corrosion, we refer to the absence of a clear relation between chlorine and corrosion as explained in 3.2. It was concluded there that corrosion is a complex process with many interfering parameters and that no significant change in corrosion effects is expected from a change in the PVC content of the waste. As a consequence, we consider unambiguous allocation of the maintenance costs to PVC (with the present knowledge) as impossible.

The above presented method of specific processing costs is allocating fixed costs to an additionally accepted waste material. By doing so, this SPC method looks at an existing facility and does, obviously, not consider any changes (additional investment costs) to the hardware of the MSWC facility.

An alternative approach would be to look at the facility and the waste composition it was designed to process and then to investigate which part of the facility was installed for which waste component; i.e. which part of the investments can be allocated to which waste fraction. Such an approach would require a clear understanding of the functionality of the different parts of the installation. In other words, which waste feed characteristics are determining the investment costs for which installation part? The second stage would then be to draw up a relation between these waste feed characteristics and the investment costs for the considered installation part. Then, finally, the share of PVC in the waste characteristics would result in the allocation of the fixed costs to PVC.

Essentially, allocation in this way would convert fixed costs into a kind of variable costs, as implicitly a linear relation between amount of a waste fraction (e.g. PVC) and its capital effect would be assumed.

However, the difficult part in this alternative approach is to draw up the relation between the waste characteristic and the investment cost as many equipment parts are fulfilling more than one function; e.g. a wet scrubber removes both HCl, HF, SO₂, heavy metals and fly-ash from the flue gas. Separation of parameters cannot be achieved.

As a result, these costs are by no means related to the amount of PVC. Elimination of PVC would lead to only marginal investment costs savings as the same equipment in practically the same size and the same (costly) instrumentation would still be required for the neutralisation of the acidic species from other waste fractions.

In fact, capital costs, especially those of the APC, are largely determined by the flue gas volume, rather than the concentration or amount of acidic species. This resulted from a previous survey [*Rijpkema, 1996a*] in which capital costs versus processing capacity were related from enquiries to equipment manufacturers.

Since the flue gas volume is closely related to the calorific value of the waste material, this would imply that part of the investment costs would be allocated to PVC, based on calorific value.

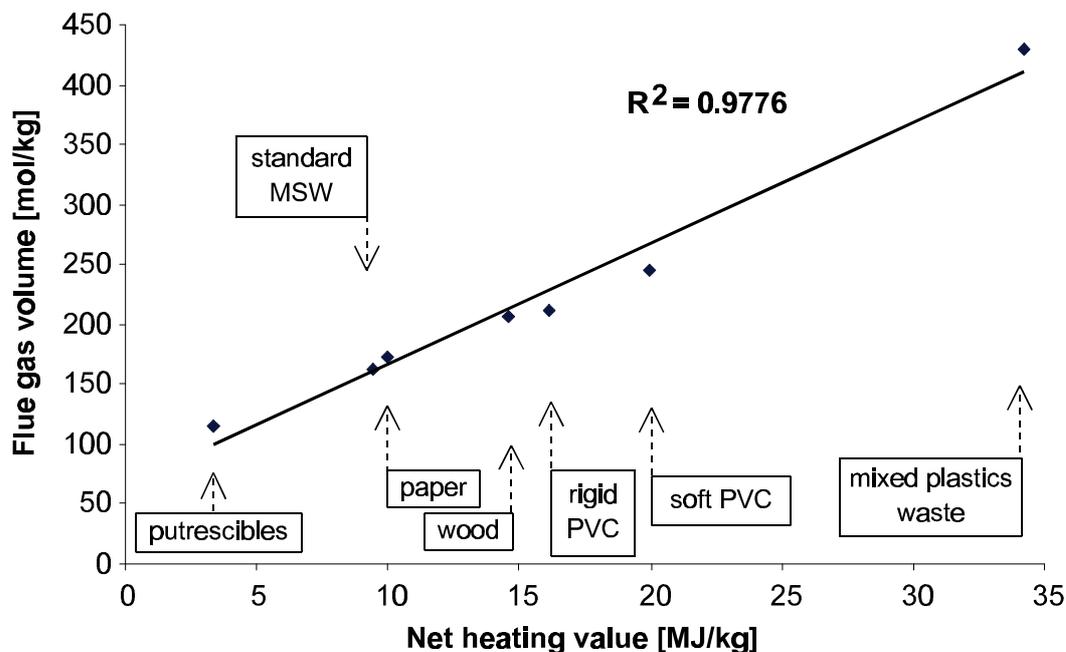


Figure 11 Flue gas volume versus net calorific value.

At contrast, for the boiler the flow of generated steam was indicated to be the most important parameter in terms of investment costs. For the furnace the heat load seems to be most relevant [Rijkema, 1996a]. Both the steam flow as well as the heat load are obviously determined by the calorific value of the waste and the throughput. As a consequence, the calorific value seems the most essential and universal factor in determining investment cost parameters.

Unlike public perception, which associates PVC with extremely large investment costs, this means that PVC takes an intermediate position in the allocation of the investment costs, between standard MSW and mixed plastics waste and close to wood.

However, if this approach is fully followed, it would mean that waste fractions with less calorific value only take a small share in the investment costs. Without some high calorific waste material, however, they cannot be burned at all. This in combination with the fact that many assumptions and simplifications (by assuming **one** determining parameter for the investment costs) are made in this approach, leads to the conclusion that such an allocation is not realistic.

In conclusion:

If fixed costs are allocated to PVC on a “per hour” basis, PVC would take a position about equal to wood, i.e. between general “grey” waste and plastics in general. Allocation based on investment costs, judged by the most relevant capacity/costs determining factors is less straightforward and seems less defensible but would lead to the same result.

5.2.4 Specific processing costs conclusions

We conclude:

- As far as we know, the specific processing costs methodology is presently the only published approach which accounts for both fixed costs as variable costs. Thus far, other methodologies only account for variable costs.
- The overall processing costs of MSW in fully loaded plants are dominated by the fixed costs element.
- The fixed costs element is determined by the throughput rate versus “standard”, “grey” waste, as processed by the MSWC facility under consideration.
- In case of full thermal capacity operation, the throughput rate is dictated by the calorific content of the specific waste.
- In terms of fixed costs, PVC (with elevated energy content) is positioned, like wood, between non-chlorine containing plastics (with high energy content) and average, grey waste.
- Fixed costs (dominated by the costs of investment), have been allocated on “per hour” basis. Alternative fixed costs allocation methods yield unattractively inconsistent consequences, but would lead to similar results.
- Variable costs play a smaller role.
- The elevated heat content of PVC generates an elevated income from electricity production.
- Disposal costs of solid neutralisation residues are relatively high.
- The amount of solid residues is dependent on the type of design of the flue gas cleaning system.
- In installations with wet scrubber/effluent evaporation design, high amounts of solid residues are generated. Their disposal costs overcompensate PVC’s electricity income. In these installations, overall variable costs for PVC are higher than for any other material considered.
- Installations with wet scrubber/effluent discharge design generate relatively small amounts of solid residues from PVC. The electricity income now exceeds the disposal costs. In these installations PVC has an intermediate variable costs position: less favourable than non-chlorine plastic wastes but still more attractive than general standard MSW.

- Overall, variable costs are therefore dominated by the type of MSWC facility design.
- No other waste material considered is more sensitive to the effect of flue gas cleaning design than PVC.

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7. Symbols and abbreviations

Symbols

f_g	fixed cost per tonne grey waste G [Dfl/tonne];
GF_g	Gate fee for processing G (Dfl/tonne);
SPC_p	Specific processing cost of material P (Dfl/tonne);
t_p	amount of waste material P added [tonnes/year];
$v_{p \text{ or } g}$	variable cost per tonne waste material P or grey waste G [Dfl/tonne];
w	substitution (or displacement) factor, tonnes G substituted by addition of 1 tonne P (tonne/tonne);

Abbreviations

APC	Air Pollution Control
APME	The Association of Plastics Manufacturers in Europe
Dfl.	Dutch guilders
ECVM	European Council of Vinyl Manufacturers
EFA	Entrained Flow Adsorber
ESP	Electrostatic precipitator
FGC	Flue Gas Cleaning
(MSWC) FACE model	(Municipal Solid Waste Combustion) Flow And Cost Expert Model, jointly developed by APME and TNO
HVC Noord-Holland	MSWC facility of Alkmaar in the province of North-Holland
NHV	Net heating value
MSW	Municipal Solid Waste
MSWC	Municipal Solid Waste Combustion
PCDD/F	Poly-chlorinated-dibenzo-para-dioxins and -furans
PVC	Poly vinyl chloride
SCR DeNO _x	Selective Catalytic Reduction of NO _x
VROM	Netherlands Ministry of Housing, Spatial Planning and the Environment

8. Authentication

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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:

May - November 1999

Signature:

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