Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft
Wissenschaftliche Berichte
FZKA 6726

Material Flows and Investment Costs of Flue Gas Cleaning Systems of Municipal Solid Waste Incinerators

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2002

Impressum der Print-Ausgabe:

Als Manuskript gedruckt

Forschungszentrum Karlsruhe GmbH
Postfach 3640, 76021 Karlsruhe

Mitglied der Hermann von Helmholtz-Gemeinschaft
Deutscher Forschungszentren (HGF)

ISSN 0947-8620

Englische Übersetzung von:
M. Achternbosch, U.Richers:
"Stoffströme und Investitionskosten bei der Rauchgasreinigung von Abfallverbrennungsanlagen".
Forschungszentrum Karlsruhe, Wissenschaftliche Berichte, FZKA 6306, Juli 1999.

Material flows and investment costs of flue gas cleaning systems of municipal solid waste incinerators (MSWI)

Abstract

The aim of this study is a comparison of different kinds of flue gas cleaning systems of municipal solid waste incinerators (MSWI). This comparison will be done with the aid of material flow analysis. In addition, investment costs will be taken into consideration. The main topic of the investigation is the relationship between type of flue gas cleaning system and resulting material flow including auxiliary chemicals and solid residues.

Material flow analyses are performed by model calculations. Data used for these calculations are representative of operating values for technical-scale plants. As starting point a model plant with grate firing is considered. For this plant 10 different flue gas cleaning systems are analysed, 6 of them being equipped with a wet cleaning system. Additionally, 2 systems operating in a semi dry sorption and 2 systems operating in conditioned dry sorption are taken into account. The system boundaries for the material flow analysis performed include the entire flue gas cleaning system, starting with the raw gas downstream of the boiler and ending downstream of the stack. The elements chlorine (Cl), sulfur (S), mercury (Hg), cadmium and lead are considered.

The balances calculated for chlorine and sulfur are different for the considered flue gas cleaning systems - nevertheless limit values of legal regulations are not exceeded. In contrast, no such dependence on the type of flue gas cleaning system can be seen for the heavy metals balanced in this study. The wet flue gas cleaning systems with fine purification downstream show the lowest emissions, the emissions of the semi dry and conditioned dry sorption are slightly higher.

The need of auxiliary chemicals and therefore the amount of residues is lowest for the wet cleaning system and highest for the conditioned dry sorption. Moreover, the balances show that the emissions of the semi dry and conditioned dry sorption can be controlled by plant operation, particularly by the auxiliary chemicals used.

For cost analysis, only the investment costs for pure plant components of the flue gas cleaning system are taken into consideration - construction work, control engineering etc. are not included. In the last few years a collapse of prices for investment costs of flue gas cleaning systems occurred. There are only slight differences in the investment costs between semi dry and conditioned dry sorption systems. These plants have the lowest investment costs. A wider range for the investment costs is calculated for wet flue gas cleaning systems. A wet system constructed in a relatively simple manner is only slightly more expensive than a semi dry sorption system.

As a result of this work, two flue gas cleaning concepts seem to be very interesting for the construction of new plants: A plant with a wet flue gas cleaning system equipped with fabric filter followed by a two-stage scrubber system generates small amounts of residues by low investment costs. Moreover, semi dry sorption seems to be a respectable alternative, but this study shows that the operation of the semi dry sorption can be optimized.

Stoffströme und Investitionskosten bei der Rauchgasreinigung von Abfallverbrennungsanlagen

Kurzfassung

Ziel dieser Studie ist ein Vergleich unterschiedlicher Rauchgasreinigungsanlagen von Abfallverbrennungsanlagen mit Hilfe von Stoffstromanalysen und ergänzender Betrachtung der Investitionskosten. Im Mittelpunkt der Arbeiten steht der Zusammenhang zwischen dem Aufbau der Rauchgasreinigung und den entsprechenden Stoffströmen einschließlich Hilfschemikalienbedarf und Rückstandsmengen.

Die Stoffstromanalysen werden mit Hilfe von Modellrechnungen durchgeführt, deren Daten typischen Betriebswerten großtechnischer Abfallverbrennungsanlagen entsprechen. Ausgehend von einer Modellanlage mit Rostfeuerung werden insgesamt 10 verschiedene Rauchgasreinigungsanlagen betrachtet, von denen 6 als Naßverfahren arbeiten. Außerdem werden jeweils 2 quasitrockene und trockene Rauchgasreinigungsanlagen berücksichtigt. Der Bilanzraum für die Stoffbilanzen umfaßt jeweils die gesamte Rauchgasreinigungsanlage und beginnt nach dem Kessel und endet am Kamin. Im Rahmen der vorliegenden Arbeit werden die Elemente Chlor (Cl), Schwefel (S), Quecksilber (Hg), Cadmium (Cd) und Blei (Pb) bilanziert.

Die berechneten Bilanzen zeigen unter Einhaltung der Grenzwerte bei den Elementen Chlor und Schwefel zwischen den einzelnen Rauchgasreinigungsverfahren Unterschiede auf, dagegen kann bei den Schwermetallen keine Abhängigkeit von der Rauchgasreinigung ermittelt werden. Die nassen Rauchgasreinigungsverfahren mit nachgeschalteter Feinreinigungsstufe zeigen die niedrigsten Emissionen, die Emissionen der trockenen und quasitrockenen Rauchgasreinigungsanlagen liegen auf einem etwas höheren Niveau.

Der Hilfschemikalienbedarf und folglich die Rückstandsmengen sind bei den Naßverfahren am geringsten und im Fall der trockenen Verfahren am höchsten. Ferner zeigt sich, daß die Emissionen der quasitrockenen und trockenen Rauchgasreinigung durch die Betriebsweise der Anlage, insbesondere durch den Hilfschemikalieneinsatz, beeinflußt werden können.

Bei der Analyse der Kosten werden nur die Kosten für die Anlagenteile ohne Bauleistungen, Meß- und Regeltechnik usw. betrachtet. In den vergangenen Jahren ist bei den Investitionskosten von Anlagen ein Preisverfall eingetreten. Zwischen der trockenen und der quasitrockenen Rauchgasreinigung gibt es bei den Kosten nur geringe Unterschiede. Diese Anlagen haben die niedrigsten Investitionskosten. Die nasse Rauchgasreinigung weist bei den Investitionskosten einen weiten Bereich auf. Eine relativ einfach aufgebaute nasse Rauchgasreinigungsanlage ist nur unwesentlich teurer als eine quasitrockene Rauchgasreinigung.

Als Ergebnis der Arbeit erscheinen für den Bau von neuen Rauchgasreinigungsanlagen zwei Anlagen sehr interessant. Eine nasse Rauchgasreinigungsanlage, aufgebaut aus einem Gewebefilter und einem zweistufigen Wäschesystem, erzeugt bei niedrigen Investitionskosten geringe Rückstandsmengen. Außerdem ist die quasitrockene Rauchgasreinigung als Alternative anzusehen, aber die durchgeführte Arbeit zeigt bei diesem Verfahren insbesondere bei dem Hilfschemikalieneinsatz noch Optimierungsmöglichkeiten.

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1 Introduction

In the Federal Republic of Germany, thermal waste treatment is a major disposal path for the so-called “waste to be transferred to disposal” following the separation of reusable waste material. Up to now, large-scale plants are being operated at 53 different locations in Germany. In these plants, about 11 mio tons of waste are incinerated annually. This means that presently about one third of the total amount of waste arising is being disposed of by means of thermal waste treatment plants.

Due to legal regulations, in particular the Technische Anleitung Siedlungsabfall [TASi], thermal treatment will gain importance in the long term. As a consequence, new waste incineration plants will have to be built and old incineration plants replaced in order to maintain the disposal capacities in the Federal Republic of Germany.

When building a thermal waste treatment plant, two principal questions arise. First, the actual thermal treatment process has to be selected. In addition to conventional incineration on a grate, new processes were developed in the past years. The waste is pyrolyzed or gasified or pyrolysis or gasification is coupled with subsequent incineration. Furthermore, a flue gas cleaning system has to be designed for all thermal waste treatment processes.

Conception of the flue gas cleaning system is influenced by the thermal treatment method selected. Due to the large number of flue gas cleaning technologies available, very different flue gas cleaning systems may be installed for the different thermal treatment methods. Nearly all flue gas cleaning systems currently operating in Germany differ from each other.

In the past, there was a tendency to build increasingly complex and expensive flue gas cleaning systems for different reasons. This development started with the “17th Federal Emission Control Ordinance; Ordinance Regarding Incineration Plants for Waste and Similar Materials (17th BImSchV)”, according to which a reduction of emissions was required. In addition, public and politics requested the actual emission values to be far below the legal limits.

This led to the construction of very extensive flue gas cleaning systems by the plant constructors. However, it should be kept in mind that extensive flue gas cleaning systems have a positive effect on the turnover and profits of the plant constructors.

In view of this situation, the question arises, how an ecologically and economically reasonable flue gas cleaning system should be designed when building a new plant. In general, it may be assumed that simple flue gas cleaning systems of low investment costs are characterized by a high need for operation agents and larger amounts of residues produced. Minimum amounts of residues usually require more sophisticated methods of flue gas cleaning, which lead to higher investment costs.

Comparisons based on a detailed analysis of the distribution of pollutants in the flue gas cleaning system, the materials flows resulting from the use of auxiliary chemicals, and the investment costs of the plants are still lacking.

2 Focus of Work

Different flue gas cleaning systems may be compared by analyzing the materials flows. Materials flow analysis is an instrument to determine and visualize the use and fate of different types and volumes of materials and substances, taking into account all branches and conversions in the system investigated. This system may extend over the entire life cycle of materials, i.e. from the extraction of raw materials up to the various production steps, the phase of use, possible reuse, and fate. It may also be restricted to certain stages of life, e.g. certain production plants.

However, an investigation limited to materials flows is not sufficient for comparing flue gas cleaning systems. Materials flow analysis concerning the pollutants and auxiliary chemicals required for operation have to complemented by economic studies, as flue gas cleaning systems of simple design and low investment costs are characterized by a relatively high need for auxiliary chemicals during operation. With increasing amounts of auxiliary chemicals, the amounts of residues generated by flue gas cleaning increase as well. Both effects result in increased operation costs. Analyses revealing the direct relationship between the setup of a flue gas cleaning system, the amounts of residues generated, and the costs are still lacking.

In principle, comparison of different flue gas cleaning systems is not limited to thermal waste treatment. Flue gas cleaning systems are also required in conventional power plants, cement production, ore processing or other technologies.

Flue gas cleaning systems in these sectors are designed more simply, as here requirements with regard to emissions are usually smaller. This situation and the fact that large-scale thermal waste treatment at present nearly exclusively takes place in grate incinerators make a restriction to grate incinerators appear reasonable.

To identify ecologically and economically acceptable process combinations for flue gas cleaning systems by means of materials flow analyses, it is first required to carry out a survey of flue gas cleaning systems operated on a large technical scale. Based on this survey, reasonable combinations of flue gas cleaning systems will have to be selected for materials flow analysis.

For the flue gas cleaning systems selected, materials balances will have to be set up and economic aspects assessed. It is known from previous studies that the operators of large-scale plants mostly do not possess the set of data required for a reliable materials flow analysis to be preformed. Moreover, materials flows are significantly influenced by the mode of operation of the flue gas cleaning system [Achternbosch-1], [Achternbosch-2].

Another possibility of acquiring data for balancing is to evaluate literature. Here, the problem is that incineration capacities of large-scale grate incinerators may differ. Furthermore, the flue gas cleaning systems are set up differently.

It is therefore reasonable to determine materials balances of the flue gas cleaning systems selected on the basis of a model incineration plant which serves as “flue gas supplier”. The model plant given in this study consists of two independent incineration lines with grate incineration and boiler. A flue gas cleaning system is attached to each boiler. Annual incineration capacity of both lines amounts to 200 000 tons. The selected flue gas volumes and pollutant concentrations leaving the boiler of the model plant are based on data from extensively studied and representative waste incineration plants with grate furnaces. Materials flows are calculated from known information and literature data.

Comparison of the balances then allows statements to be made with regard to a favorable combination of flue gas cleaning units in terms of auxiliary chemicals and amounts of residues. Economic analysis focuses on the costs of the individual concepts.

The present study is aimed at identifying an optimum configuration of a flue gas cleaning system in a waste incineration plant on the basis of the materials balances calculated and the economic data. Sections 3 and 4 of this study shall outline the fundamentals of waste incineration in grate incinerators and give an overview of the process technologies available for flue gas cleaning. Section 5 shall focus on the model plants, i.e. a model incineration plant and 10 different flue gas cleaning systems. Section 6 shall deal with the methodology of balancing. The balancing volume, data sources used, and procedure shall be presented. In addition, system assumptions and boundary conditions required for balancing the flue gas cleaning systems and units selected shall be explained. Section 7 shall present the materials balances for each element balanced. For reasons of transparency, the balances shall be explained in detail. Hence, it could not be avoided that this section became rather long. The reader is free to select individual flue gas cleaning systems that are of interest to him. Sections 8 and 9 shall deal with the amounts of auxiliary chemicals used and the resulting residue volumes. Analyses are complemented by an estimation of the pure investment costs of individual system components and entire flue gas cleaning systems. The results and conclusions shall be summarized in Sections 11 and 12.

3 Technology for Combustion

In Germany, thermal waste treatment is accomplished mainly in grate incinerators. The individual components of such a waste incineration plant are shown in Fig. 1.

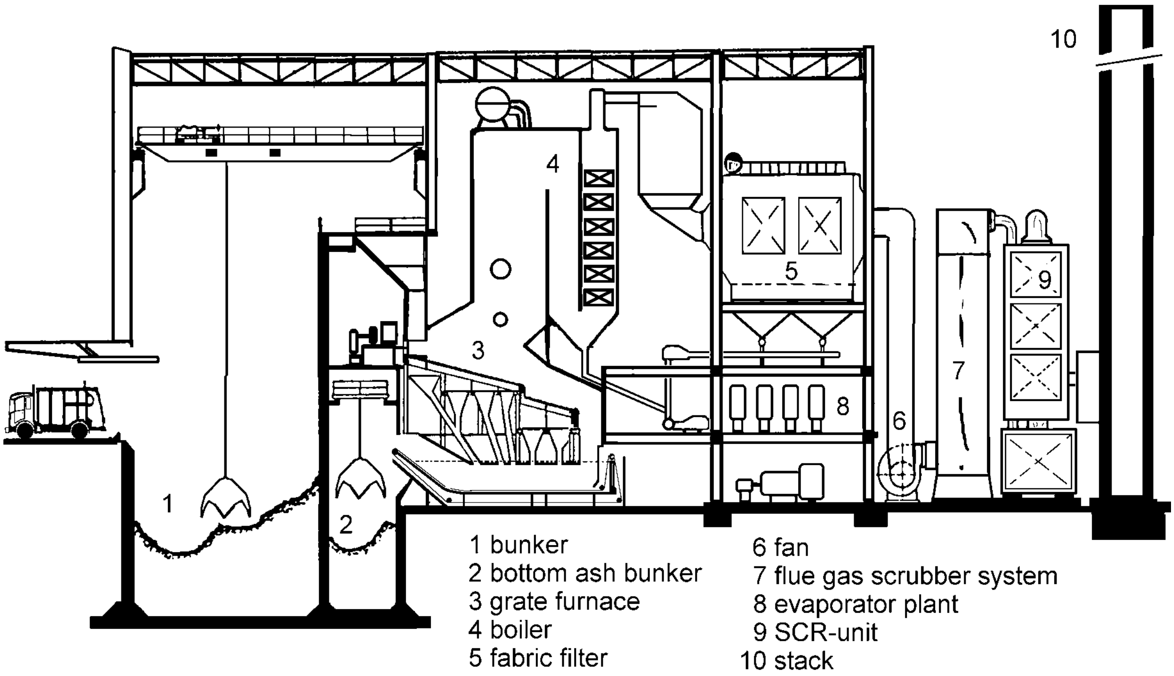

Fig. 1 Scheme of a municipal solid waste incinerator with flue gas cleaning

The waste delivered is first stored in the bunker (1). By means of a crane, the waste is then transferred to the charging unit of the furnace (3). Here, the partial steps of drying, degasification, gasification, and incineration take place on the grate. The grate ashes, i.e. the residues generated during incineration, drop into a water bath at the end of the grate. By a conveyor, they are transported to the slag bunker (2).

Thermal energy of the flue gases generated during incineration is transferred to the water steam circuit of the boiler (4). Gas temperatures in the furnace chamber are above 850 °C. When leaving the boiler, flue gas temperature is about 200 °C. In the downstream flue gas cleaning system, pollutants are separated from the flue gases. The flue gas cleaning system shown in Fig. 1 consists of a dust filter (5), a downstream flue gas scrubber (7), and a stage for the removal of nitrogen oxides (9). The fan (6) is used to compensate the pressure losses in the plant. The cleaned flue gases are released into the atmosphere via a stack (10).

The flue gas cleaning system shown in Fig. 1 is only one of several systems available. The individual pollutants in the flue gas and separation technologies shall be dealt with in detail in Section 4. Further data on large-scale incineration plants shall be given in Section 5.

4 Chemical Engineering for Flue Gas Cleaning

4.1 Introduction

Incineration of waste in grate furnaces results in the formation of exhaust gases that contain various pollutants. These pollutants include particulate fly ashes and gaseous flue gas constituents.

Gaseous pollutants include inorganic gases, such as CO, HCl, SO_2, HF, and nitrogen oxides (NO_X). The group of nitrogen oxides comprises various compounds. More than 90 % of the nitrogen oxides contained in the flue gas of a waste incineration plant are nitrogen oxide (NO). Concentration values, however, always refer to nitrogen dioxide (NO_2). The toxic heavy metal of mercury nearly exclusively exists in the gaseous form as mercury chloride ($HgCl_2$) or metal mercury (Hg).

Fly dust particles mainly consist of aluminum and silicon oxides as matrix compounds. Furthermore, fly dusts contain heavy metals, e.g. lead, cadmium, copper, and zinc. The filter dusts arising in waste incineration plants are disposed of as "waste requiring particular monitoring" (special waste), irrespective of the filter selected.

Another group of pollutants are hydrocarbon compounds which may exist both in the gas phase and adsorbed by the filter dust. This group includes among others simple alkanes (methane (CH_4), ethane (C_2H_5), etc., benzene compounds, phenols, polycyclic aromatic hydrocarbons (PAH), and polychlorinated dibenzo-p-dioxins and dibenzo-p-furans (PCDD/PCDF).

Prior to the emission of flue gases into the atmosphere, concentrations of the pollutants mentioned must be reduced by technical measures. The legal limit values are specified in the 17th Federal Emission Control Ordinance. Raw gas concentrations of waste incineration plants and the emission limits to be observed are compared in TABLE 1.

TABLE 1 Raw gas concentration, emissions and required separation rate of flue gas cleaning devices

	raw gas concentration [mg/Nm³ tr.]	emission limit [mg/Nm³ tr.]	precipitating rate [%]
fly ash	2000 - 10000	10	99,9
HCl	400 - 1500	10	> 99
HF	2 - 20	1	95
SO2	200 - 800	50	94
NO_X (as NO_2)	200 - 400	200	50
Hg	0,3 - 0,8	0,05	88
Cd, Tl	3 - 12	0,05	> 99,5
dioxins /furans	< 1 - 5 ng TEQ/m³	0,1 ng TEQ/m³	98

Flue gas cleaning systems do not only have to reach the very high separation efficiencies. In many cases, the actual emission values must be far below the limits, because several permits granted for the operation of waste incineration plants require values which are far below those specified in the 17th Federal Emission Control Ordinance. Some examples are given in TABLE 2.

TABLE 2 Emission limits of municipal solid waste incinerators

	emission limit	permit		
	17th BImSchV	MSWI A	MSWI B	MSWI C
SO2 [mg/Nm³]	50	10	5	35
HCl [mg/Nm³]	10	5	5	10
NOx [mg/Nm³]	200	70	70	100
Hg [mg/Nm³]	0,05	0,01	0,01	0,02

It must also be noted that plant operation requires much smaller operation values for the limit values being complied with in a reliable manner.

To reduce pollutant concentrations and meet the required limit values, primary and secondary measures may be taken in thermal waste treatment. Primary measures comprise reduction measures in the area of the furnace chamber and boiler. They include among others an optimized air supply which is of great significance to CO and hydrocarbon concentrations in the flue gas. Moreover, the SNCR process may be considered as a primary measure.

As primary measures affect the concentrations of several pollutants to a limited extent only, secondary measures have to be taken. These are technical cleaning stages installed downstream of the boiler.

The various technologies for flue gas cleaning in waste incineration plants, which shall be presented in the following sections, are based on separation operations of process technology. For the exact fundamentals and calculation of these separation operations, it is referred to literature (see e.g. [Stieß], [Fritz], [Schultes], [Reimann-1], [Christmann-], [Scholz], [Albert]). With the exception of the SNCR process, primary measures shall not be dealt with in further detail.

4.2 Fly Ash Separation

To separate dust particles from the flue gas, cyclones, electrostatic precipitators, and fabric filters are installed at large-cale MSWI. Functioning and characteristic features of the individual dust separators shall be described in detail below. The major data shall be compared in Section 4.2.4.

4.2.1 Cyclone

These dust separators are widely used in many sectors of industry, because cyclones are characterized by a simple setup and high operation reliability. In the sixties, flue gases of waste incineration plants were dedusted by a cyclone only without additional cleaning stages being used [Vogg-].

Dust separation in cyclones is based on centrifugal forces generated by an appropriate gas supply construction. Cyclone designs only differ in the way of how the dust-containing gas is fed into the cyclone.

The dust-oaded raw gas enters the cyclone in tangential direction. Due to the centrifugal forces occurring, the dust is deposited on the walls and drops down into the dust discharge unit. The dedusted raw gas leaves the cyclone upwards through the so-alled immersion pipe.

Pressure loss of a cyclone may be assumed to range between 500 and 3000 Pa [Fritz]. By means of a cyclone, about 80 % of the dust contained in the flue gas of a waste incineration plant can be separated [Noell-1]. Due to its functioning principle, fine particles with higher concentrations of heavy metals remain in the flue gas [Birnbaum-1]. The small separation efficiency led to an increased use of electrostatic precipitator and, later, fabric filters in the thermal waste treatment sector.

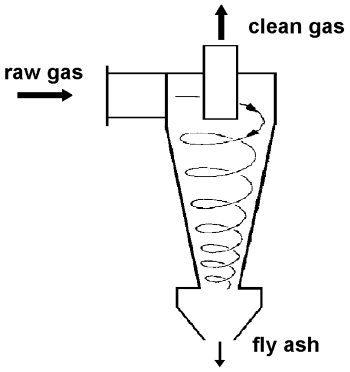

Fig. 2 Scheme of a cyclone

Compared to other dust separtors, however, the cyclone has an advantage that may gain significance in the future. Cyclones can be used at gas temperatures of up to 1300 °C [Turegg]. Hence, the cyclone is suited for hot-gas dedusting which is required for an SCR system installed directly downstream of the boiler (see Section 4.4.1).

4.2.2 Fabric Filter

Fabric filters are filtering separators operating as surface filters. Separation of the particles takes place mainly on the surface of the filter medium, which is passed by the gas flow. On the surface of the filter medium, the particles retained form a layer, the dust cake, which causes an increasing pressure loss with increasing layer thickness. For this reason, the dust cake has to be removed regularly.

By the construction of the filters and selection of filter media, these separators may be adapted optimally to the operation conditions and properties of the dusts, such that they can be used in various industrial sectors. Materials serving as filter media are fiber layers, membrane-ike materials, sintered metals or ceramics. For dedusting flue gas in waste incineration plants, for instance, PTFE membrane filter hoses are applied [Pranghofer].

The filter areas can be cleaned by shaking or compressed air. In case of compressed-air cleaning, the filter elements are usually passed by an air flow from outside to inside and cleaned by a jet pulse (0.1 to 1 second [Fritz]) that is blown into the filter element. The setup and functioning of a fabric filter with jet-pulse cleaning are shown schematically in Fig. 3.

Fabric filters with this pneumatic cleaning system are characterized by a homogeneous differential pressure behavior and an increased filter surface load compared to mechanical recleaning. For these reasons, such filters have been widely accepted for use in technology, in particular downstream of spray absorbers.

Operation temperature of a fabric filter is limited decisively by the filter materials used. In large-scale waste incineration plants, fabric filters are operated at temperatures ranging from 170 to 200 °C. As the filter elements may be damaged or destroyed when exceeding this temperature, a quencher is usually installed upstream of the fabric filter. In this unit, flue gas temperature is decreased by the injection of water. In modern waste incineration plants, the quencher is no longer required due to an improved boiler construction [Schäfers].

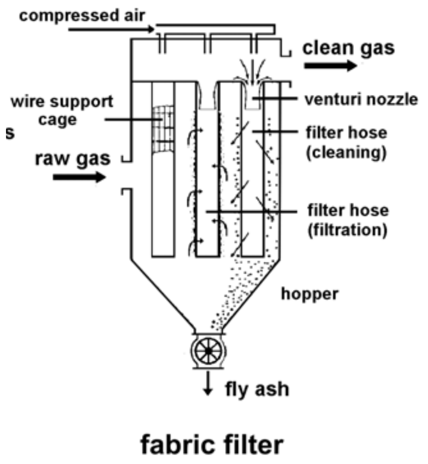

Fig. 3 **Fabric filter with compressed air cleaning**

Fabric filters reach a very high separation efficiency of more than 99 % [Turegg]. In particular for fine particles, i.e. at particle sizes in the range of 10 µm, fabric filters represent a very efficient separation system. However, fabric filters are associated with the drawback of a relatively high pressure loss which ranges between 500 and 2000 Pa [Fritz]. This pressure loss must be compensated by an increased fan power.

When coated with adsorptive or reactive substances, fabric filters may also be applied for further gas cleaning (see Sections 4.3.1, 4.5.2, and 4.5.3).

4.2.3 Electrostatic Precipitator

Separation of solid particles or liquid droplets in an electrostatic precipitator is based on the action of electrostatic forces in an electric field. The separation process is subdivided into several partial steps, as obvious from Fig. 4.

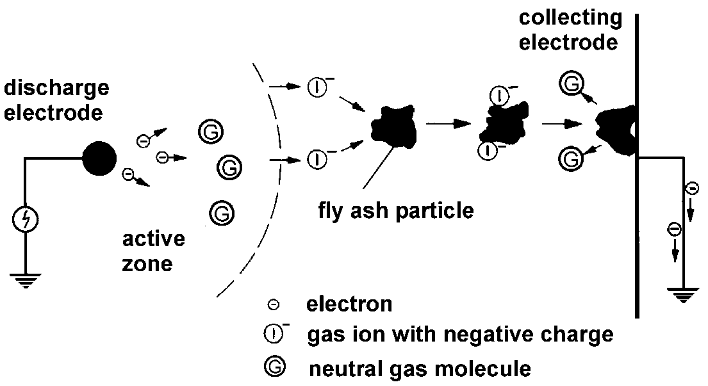

Fig. 4 Scheme of the separation process in an electrostatic precipitator

For a separation to take place, the dust particles have to be charged electrically. Charging of the particles takes place by negatively charged gas molecules which are formed in the active zone near the spray electrode. After this, the charged particles are transported in the electric field towards the so-called precipitation electrode. There, a dust layer deposits, which has to be removed regularly by shaking the precipitation electrode.

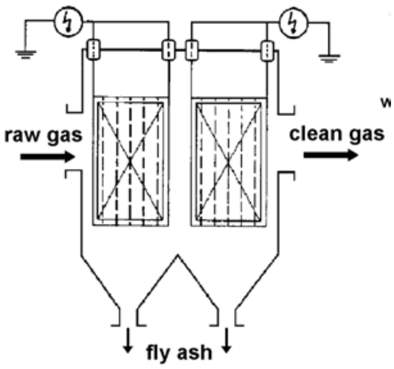

Fig. 5 Scheme of an electrostatic precipitator

For particles of less than 0.1 µm in size, separation is based on another process. Brownian movement leads to the particles depositing on the precipitation electrode. A detailed description of the very complex processes in an electrostatic precipitator for dust separation can be found in literature (see e.g. [Kern]).

In large-scale waste incineration plants, mainly plate-type electrostatic precipitator sare employed, as shown in Fig. 5. The precipitation electrodes are large plates. Between them, the spray electrodes are arranged in the form of wires. Eelectrostatic precipitators in waste incineration plants are divided into one, two, or three fields having a separate voltage supply.

Dust separation efficiency of an electrostatic precipitator is very good and reaches up to 99 % in practice. Moreover, electrostatic precipitators are characterized by a small energy consumption. Pressure loss of an electrostatic precipitator is relatively small and ranges from 50 to 300 Pa [Fritz].

The operation range which extends up to about 450 °C is not used completely such as to prevent a de-novo synthesis of dioxins and furans [Bruce], [Eichberger], [Hunsinger], [Vogg-1], [Vogg-2]. Today, operation temperatures of electrostatic precipitators in waste incineration plants are in the range of 200 °C.

4.2.4 Comparison of Separators

Here, the major differences of the separators presented shall be outlined. Of particular relevance are the dust separation efficiency and pressure loss (see TABLE 3).

TABLE 3 Separation efficiency and pressure loss of the individual dedusting units

	precipitating rate[%] fly ash	pressure loss [Pa]
cyclone	ca. 80 %	500 - 3000 Pa
fabric filter	> 99 %	500 - 2000 Pa
ESP	ca. 99 %.	50 - 300 Pa

The fly dust in the flue gas of waste incineration plants does not possess any uniform grain size. Particle size varies from less than 1 to 10000 µm. Fig. 6 shows the separation efficiencies of the individual separators as a function of particle size.

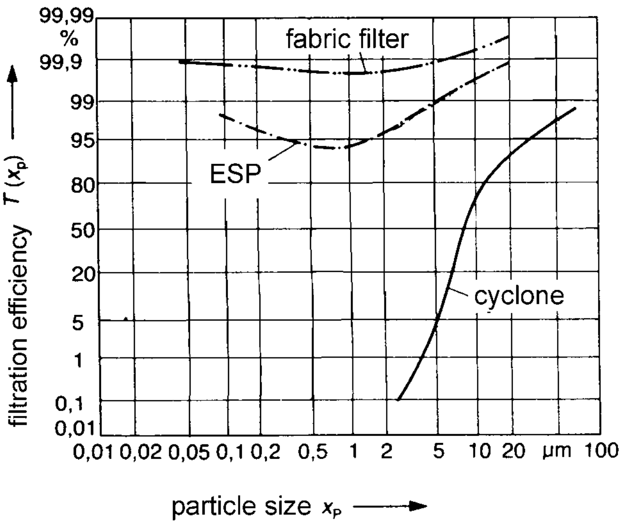

Fig. 6 Filtration efficiency of dust separators

In filtering separators, such as fabric filters, separation efficiencies are in excess of 99 % for all particle sizes. The two different separation mechanisms – Brownian movement and impact ionization – lead to a decreased separation efficiency of electrostatic precipitators at particle sizes ranging from 0.1 to 5 µm [Turegg]. Dust separation efficiency of a cyclone decreases strongly for particles of less than 20 µm in size. Due to this bad separation efficiency, cyclones are currently used as preliminary separators only.

Selection of the dust separators is of relevance to the quality of residues from other flue gas cleaning units. When using a fabric filter, heavy metal concentrations in the residues of the downstream flue gas cleaning components can be reduced, as particularly heavy metals are accumulated in the fine fractions of the fly dust [Birnbaum-2].

4.3 Separation of acid pollutants

To remove acid pollutant gases, mainly HCl, SO_2, and HF, three process variants are applied, i.e. the dry, quasi-wet, and wet process. The quasi-wet variant is also referred to as "semi wet".

The different process technologies are based on similar chemical processes, as the acid pollutant gases are always neutralized with alkaline substances. In most cases, sodium hydroxide (NaOH), lime (CaO), calcium hydroxide ($Ca(OH)_2$) or calcium carbonate ($CaCO_3$) serve as neutralization agents. In addition, dolomite, a double salt of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), is applied. The respective chloride and sulfate salts are generated as reaction products. The reaction equations governing conversion shall be given in the next Section.

4.3.1 Dry Flue Gas Cleanaing

Separation of acid pollutants from the flue gas by a dry process represents the most simple solution in terms of process technology. Very few process stages only are employed in flue gas cleaning. A solid adsorbent, usually $Ca(OH)_2$, is injected directly into the flue gas as a finely ground solid.

An exception that shall not be dealt with in more detail is the Neutrec® process offered by the Solvay company. For the separation of acid flue gas constituents, sodium hydrogencarbonate ($NaHCO_3$) is applied. At temperatures above 140 °C, it is converted into sodium carbonate [Höltje]. Due to the very large surface, relatively small amounts of neutralization agents are required [Solvay].

However, purely dry processes with the use of $Ca(HO)_2$ are no longer used today. A modern system for dry flue gas cleaning is represented in Fig 7.

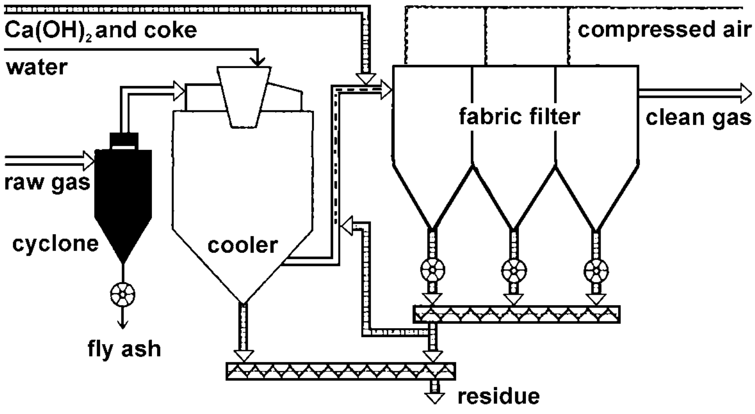

Fig 7 Scheme of semi dry flue gas cleaning

It consists of an evaporation cooler, a downstream nozzle for the injection of the dry adsorbent into the flue gas channel, and a fabric filter. For optimum conversion of the neutralization agent, certain temperatures and water contents have to be adjusted in the flue gas. These values are set e.g. by an evaporation cooler or quencher. This type of dry process is also referred to as conditioned dry process or dry process.

Dry flue gas cleaning can be combined with flue gas dedusting. In Fig 7, preliminary dedusting takes place by means of a cyclone. The remaining fine dust is removed by the fabric filter together with the neutralization agent. The neutralization agent may also be metered directly into the non-dedusted flue gas.

Chemical reaction between the acid pollutant gas components and the neutralization agent takes place at two points in the flue gas cleaning system. Reaction starts in the flue gas channel. Further conversion of the neutralization agent is accomplished in the filter cake of the fabric filter. Using the fabric filter, the neutralization agent introduced is removed from the flue gas.

The adsorbent separated in the fabric filter represents a mixture of various salts and non-converted $Ca(OH)_2$. To reduce calcium hydroxide consumption, part of the solid separated in the fabric filter is reinjected into the flue gas channel.

Up to now, residues removed from the system cannot be utilized in a reasonable manner. They have to be disposed of.

Separation of acid pollutants with calcium hydroxide ($Ca(HO)_2$) takes place according with the following reactions (simplified):

$2\ HCl + Ca(OH)_2 \rightarrow CaCl_2 + 2\ H_2O$ eq. 4.1
$2\ HF + Ca(OH)_2 \rightarrow CaF_2 + 2\ H_2O$ eq. 4.2
$SO_2 + Ca(OH)_2 \rightarrow CaSO_3 + 1/2\ H_2O$ eq. 4.3
$SO_2 + Ca(OH)_2 + 1/2\ O_2 \rightarrow CaSO_4 + 1/2\ H_2O$ eq. 4.4

The chemical reaction processes are rather complex due to the various gas/solid phases involved. In addition, effects of gas humidity and temperature have to be taken into account. Reactions take place on the surface of the $Ca(OH)_2$ particles and depend on various diffusion processes.

Consumption of the neutralization agent is influenced decisively by its specific surface area. Usually, lime hydrates with a specific surface area of 3 – 20 m^2/g are applied [Nethe], [Herbig]. Using these commercially available lime hydrates, a relatively large excess of neutralization agents is required for the emission limits of acid pollutants being observed. As explained in Section 6.4.5, the stoichiometric factor describing the excess of chemicals ranges between 2.4 and larger than 3. This high consumption of chemicals automatically leads to large amounts of residues, which have to be disposed of.

Other neutralization agents used have a much larger active surface area. For instance, products supplied by the Rheinische Kalksteinwerke Wülfrath have an active surface area of about 40 m^2/g, as a result of which stoichiometric consumption is much smaller [Herbig], [Labuschewski].

4.3.2 Semi dry Separation

The semi dry process for the separation of HCl, SO2, HF, etc. is very similar to the conditioned dry process as far as the arrangement of technical units is concerned. Fig. 8 shows the setup of a semi dry flue gas cleaning system.

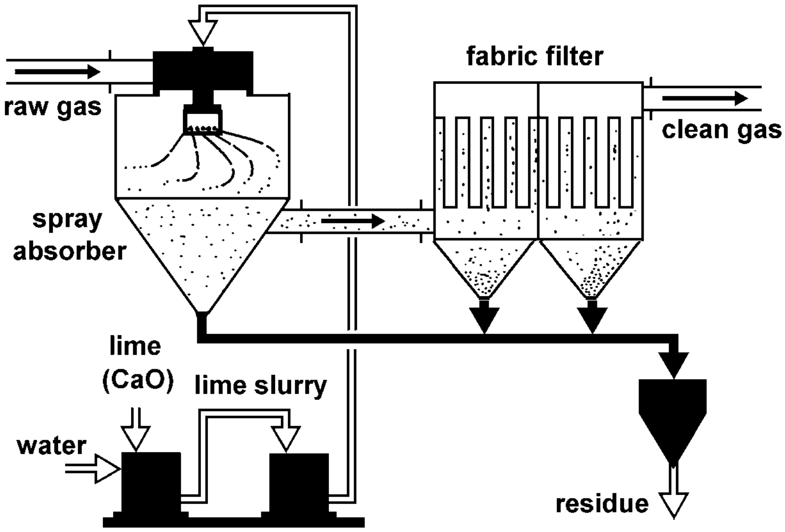

Fig. 8 Scheme of semi dry separation

In this process, the fly dust is removed separately from or together with the reaction products. In case of separate fly dust removal, a dust separator is installed upstream of the spray tower. In the other case, the dust-containing raw gas is led directly from the boiler to the spray absorber tower.

In the spray absorber, also called spray tower or spray absorption reactor, a solution or suspension of the alkaline substance is sprayed such that a large contact surface with the gas phase is generated. The reaction products are salts which leave the spray absorber together with the gas flow. In a downstream dust separator , electrostatic precipitator or fabric filter, the salts are removed from the gas flow.

Reaction processes for the separation of acid pollutants are as complex as those of the conditioned dry process. The acid pollutant gases are absorbed by the liquid droplets or later react with the solid obtained from the liquid droplet by evaporation, crystallization, and drying. The energy driving these processes originates from the hot flue gas.

In this semi dry process, the neutralization agent is made better use of than in dry separation. As a result, smaller amounts of neutralization agent are required for reaching the same separation efficiency. A stoichiometric factor of 2.2 to 3.0 is given in literature. Selection of the stoichiometric factor value shall be explained in detail in Section 6.4.5.

4.3.3 Wet Separation

In most large-scale plants, wet separation of HCl, HF, and SO2 takes place. Following the dedusting of the raw gas, the acid pollutants are separated from the flue gas by absorption in aqueous solutions. Wet flue gas cleaning is usually designed in two stages, as shown in Fig. 9.

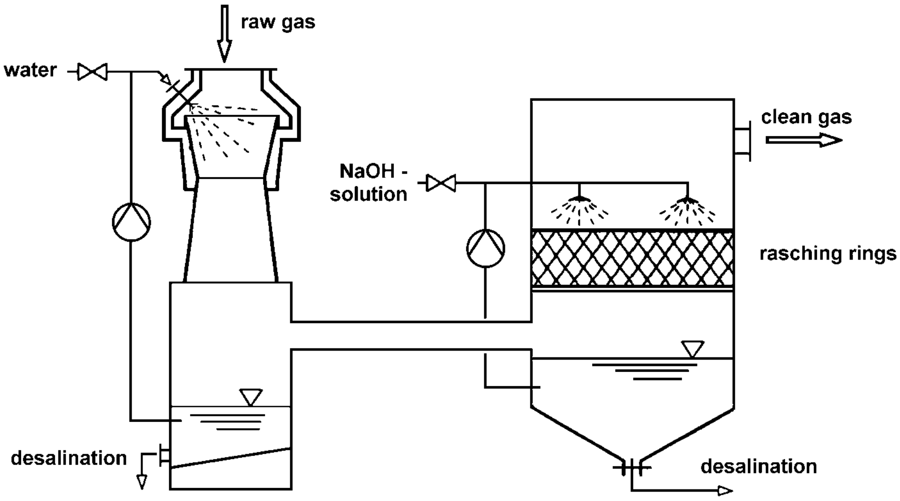

Fig. 9 **Example for wet flue gas cleaning system**

In the first scrubber stage, on the left in Fig. 9, the halogenides HCl and HF are separated from the flue gas. Moreover, mercury in the form of $HgCl_2$ is taken up by the aqueous phase, whose pH is in the range of 1. For the absorption of HCl, HF, and Hg, only water is required. No auxiliary chemicals are needed. The halogenides are absorbed with aqueous acids being formed. These reactions are represented by the following simplified equations:

$$HF + H_2O \Leftrightarrow F^- + H_3O+ \qquad \text{eq. 4.5}$$
$$HCl + H_2O \Leftrightarrow Cl^- + H_3O^+ \qquad \text{eq. 4.6}$$
$$HBr + H_2O \Leftrightarrow Br^- + H_3O^+ \qquad \text{eq. 4.7}$$
$$HJ + H_2O \Leftrightarrow J^- + H_3O^+ \qquad \text{eq. 4.8}$$

Of the four acids studied here, HF is the weakest, i.e. the equilibrium in eq. 4.5 is largely on the left. In contrast to this, the equilibria of the strong acids HCl, HBr, and HJ are located practically completely on the right hand side. Acid strength increases from HCl to HJ.

Mercury is dissolved as chlorocomplex, e.g. as $[HgCl_4]^{2-}$ [Braun], [Kind], [Ulbrich]. Discharge of the absorbate or water supply are controlled as a function of the pH or an equivalent parameter.

In some large-scale plants, absorption of HCl is divided into a preliminary and a main stage. This option that results in a three-stage scrubbing system is not shown in Fig. 9. Subdivision does not affect the materials balances of the chemical separation processes.

The second scrubber stage, on the right in Fig. 9, mainly serves for the separation of SO_2 from the flue gas. To ensure separation, a pH of 7 has to be maintained by the addition of auxiliary chemicals. The auxiliary chemicals used are sodium hydroxide, calcium hydroxide, or calcium carbonate. In addition, dolomite is applied, a double salt of calcium carbonate and magnesium carbonate.

Conversion of SO_2 in the scrubbing liquid takes place in several steps, as shall be explained by the example of sodium hydroxide. The first step is the absorption of SO_2 in water $(SO_2)_{\text{dissolved}}$. Chemical conversion into sulfurous acid (H_2SO_3) takes place in the second stage only. In the aqueous solution, the acid exists in dissociated form. These reactions are summarized by equation 4.9:

$$2\ (SO_2)_{gelöst} + 4\ H_2O \Leftrightarrow 2\ H_2SO_3 + 2\ H_2O \Leftrightarrow 2\ HSO_3^- + 2\ H_3O^+ \qquad \text{Gl. 4.9}$$

During the formation of sulfurous acid, the equilibrium strongly is on the left hand side, i.e. a relatively small part of the dissolved sulfur dioxide only is converted into sulfurous acid. Due to the acid strength of sulfurous acid, the equilibrium is shifted further to the left in the direction of sulfur dioxide in the presence of another stronger acid. Consequently, a small SO_2 separation efficiency is reached e.g. by the HCl scrubber at pH = 1.

At small H_3O^+ concentrations, i.e. at higher pH values, only can significant amounts of sulfurous acid be formed, which are then neutralized in the SO_2 scrubber with sodium hydroxide solution or other neutralization agents. In practice, it is operated at a pH of 7, as was mentioned above:

$$2\ H_2SO_3 + 4\ NaOH \rightarrow 2\ Na_2SO_3 + 6\ H_2O \qquad \text{eq. 4.10}$$

In the aqueous phase, oxidation with oxygen, e.g. from the flue gas, results in sodium sulfate (Na_2SO_4) being produced from sodium sulfite (Na_2SO_3) [Gutberlet]:

$$2\ Na_2SO_3 + O_2 \rightarrow Na_2SO_4 \qquad \text{eq. 4.11}$$

As a rule, the sodium sulfate formed is converted into gypsum with the help of calcium hydroxide ($CaSO_4$ x 2 H_2O) following the transfer of the scrubber effluents to a waste water treatment plant.

The auxiliary chemicals used for the separation of SO_2 in the second scrubber stage are associated with advantages and drawbacks. Compared to the different calcium compounds, sodium hydroxide is relatively expensive. In addition, the sodium sulfate formed has to be treated with calcium hydroxide for gypsum production during waste water treatment. In contrast to this, use of the less expensive calcium compounds leads to the direct formation of sparingly soluble calcium sulfate (gypsum). In this case, however, an additional technical expenditure results from the gypsum suspension having to be circulated in the scrubbers. This may cause problems during dosage or due to crust formation.

As compared to other processes, wet systems are characterized by a smaller consumption of neutralization agent. Very high separation efficiencies may be achieved with a nearly stoichiometric consumption of auxiliary chemicals. In literature, a stoichiometric factor of 1.1 to 1.4 is given, as obvious from TABLE 14. Accordingly, the amounts of residues arising are small. A drawback is the increased technical expenditure required by wet processes, which leads to considerably increased investment costs.

Technical implementation of the absorption processes requires the generation of a maximum mass exchange surface between the flue gas and the liquid phase. Technical components used in flue gas cleaning systems of waste incineration plants are spray and packed scrubbers. In these scrubbers, the flue gases are cooled down to a limit temperature of about 60 °C. Downstream of the scrubbers, heating is required, depending on the further setup of the flue gas cleaning system.

In accordance with legal regulations [AbwV], effluents of new waste incineration plants may not be discharged into receiving water courses. Scrubber liquids have to be neutralized and evaporated to a solid residue.

For this process, two variants are distinguished. Evaporation with the help of the hot flue gases may take place in a spray dryer or in a downstream particle separator, both of which are integrated in the flue gas cleaning system upstream of the scrubbers. It is also possible to construct a separate evaporation plant which is heated with the steam from the boiler.

4.4 Removal of nitrogen oxides

Nitrogen oxides have to be removed of from the flue gas. Of all nitrogen oxides, flue gas of waste incineration plants mainly contains NO. The limit value indicated in the 17th Federal Emission Control Ordinance, however, refers to NO_2.

Three different mechanisms are distinguished for NO formation in incineration processes. At high temperatures, thermal NO is generated from the nitrogen and oxygen contained in the incineration air. Fuel NO results from the oxidation of the fuel nitrogen fractions, while “prompt” NO may form e.g. via nitrogen-containing radicals generated during incineration together with oxygen atoms.

Nitrogen oxides in the flue gas of a waste incineration plant are formed largely from the nitrogen contained in the fuel. By optimized combustion, and in particular air distribution, as well as by flue gas recirculation, NO concentration of the exhaust gas can be minimized. Still, the given emission limits cannot be complied with.

To reduce NOx concentrations in the flue gas of waste incineration plants, various processes are employed on a large technical scale, which are widely used in other industrial sectors as well. The major processes, the SCR and the SNCR process, shall be dealt with in detail below.

4.4.1 SCR Process

The process of selective catalytic reduction (SCR) is a secondary measure for the reduction of nitrogen oxides, which is frequently applied in power plants. The schematic setup of an SCR system is shown in Fig. 10.

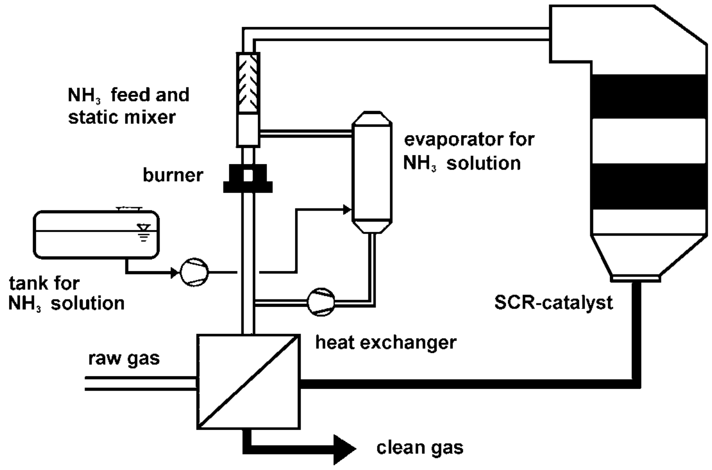

Fig. 10 **Scheme of the SCR process**

The SCR process is based on the use of a catalyst and ammonia gas or ammonia water as auxiliary chemical for the reduction of nitrogen oxides. The chemical reaction depends on the auxiliary chemical used and may be described by the following simplified reaction equations.

$$4\,NO + O_2 + 4\,NH_3 \leftrightarrow 4\,N_2 + 6\,H_2O \qquad \text{eq. 4.12}$$

$$4\,NO_2 + O_2 + 4\,NH_3 \leftrightarrow 3\,N_2 + 6\,H_2O \qquad \text{eq. 4.13}$$

In waste incineration plants, an aqueous solution with 25 wt.% of ammonia is applied in most cases. As the volume flows and NO_X concentrations here are smaller than in large power plants, smaller amounts of ammonia are required. The technical expenditure is reduced, as pressure vessels are no longer needed [Glinka]. In addition, an accident analysis is not necessary for the respective storage facilities within the framework of the licensing procedure.

Honeycomb catalysts based on titanium dioxide and doped with vanadium, molybdenum, tungsten, and iron compounds are used. Operation temperatures of these catalysts are usually in the range of 300 °C, such that the SCR system has to be equipped with a burner downstream of the scrubbers. In the future, use of new catalysts will result in the operation temperature being reduced to a smaller level. More detailed information on catalysts, their manufacture, and the chemical reactions may be obtained from literature [Köser]. Separation efficiency is in excess of 70 % [Karl].

The SCR process may be installed at various points of the flue gas cleaning system. Possible variants are shown schematically in Fig. 11.

In the high-dust mode, the flue gas leaving the boiler is directly passed into the catalyst [Kempin]. At the boiler outlet, temperature of the flue gases is so high that an additional heating is not required. Installation of the SCR system directly downstream of the boiler is widely used in power plants, but associated with several drawbacks in waste incineration plants. As demonstrated by practical tests, heavy metals in the filter dust cause the catalyst activity to be decreased. Fly dusts may result in depositions and clogging [Glinka].

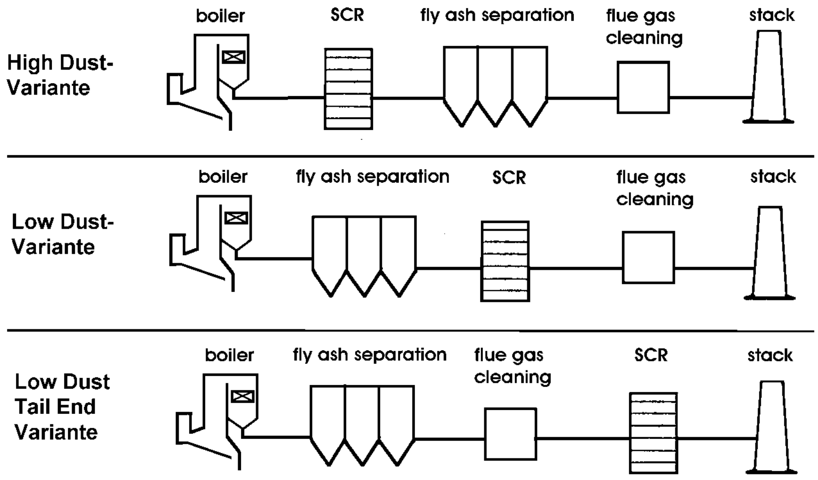

Fig. 11 **Integration of the SCR process in the flue gas cleaning system**

Due to the problems associated with the high-dust mode, the low-dust tail-end mode has been established in waste incineration plants. The SCR catalyst is installed in the flue gas cleaning system downstream of the dust and acid pollutant separator. In this setup, reheating of the flue gas to the operation temperature of the catalyst is required.

In principle, the SCR catalyst may also be installed between the fly ash separation and the separation unit for acid pollutants (low-dust mode). Due to the required operation temperatures of the catalysts, however, such an arrangement is not reasonable, as the flue gas temperatures downstream of the electric or fabric filter are too small for SCR system operation in the temperature range of 300 °C.

Recent developments may cause the arrangement of the SCR unit in the flue gas cleaning system to be modified in the future. These recent developments include catalysts working at smaller operation temperatures [Paulsen], [Brunner], [Jessen], [Dittrich], [Walter], [Herber]. Up to now, waste incineration plants with a high-dust catalyst are being constructed, as the advantages of this arrangement are easy to see. A gas/gas heat exchanger and an additional reheating unit are not required. Thus, the setup is simplified and costs are reduced.

In September 1996, a large-scale plant with a high-dust SCR catalyst, built by ABB, was taken into operation in Malmö (Sweden). An example of a different catalyst arrangement is the newly constructed third incineration line of the Würzburg waste incineration plant. There, the SCR unit is integrated in the boiler area. Downstream of the convection part of the boiler, the flue gas is first dedusted in a cyclone. The dedusted flue gas then enters the SCR unit. Residual heat of the flue gases is used for feedwater preheating in the economizer [ZVA]. In Rostock, it is planned to build a waste incineration plant with an SCR unit installed directly downstream of the boiler [Fritsche].

A modified SCR catalyst may also be used as oxidation catalyst for the destruction of organic pollutants. This option will be presented briefly in Section 4.5.4.

The calculation of the amounts of NH_3 required for NO_x-removal is referred to Section 8.4.

4.4.2 SNCR Process

Scientific fundamentals of this NO_X-removal method were developed in the beginning of the seventies already for compliance with the nitrogen oxide reduction requirements made in Japan and the USA. The SNCR process (selective, non-catalytic reduction) is a relatively simple method, by means of which nitrogen oxides are reduced in the furnace chamber already by a gas-phase reaction with ammonia or other auxiliary chemicals, e.g. urea.

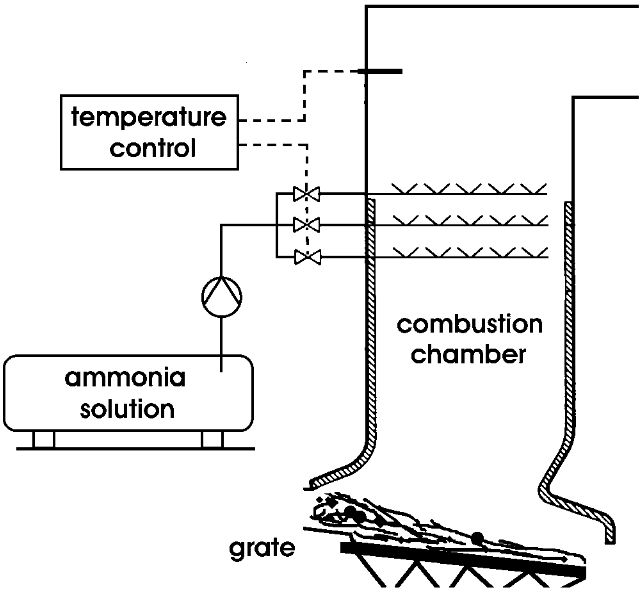

Fig. 12 Schematic representation of a SNCR system

Fig. 12 shows the arrangement of the nozzles in the furnace chamber of a waste incineration plant. For maintaining the optimum reaction temperature which is between 850 and 1100 °C (temperature window), nozzles for the injection of NH_3 solution are installed on various boiler levels [Jessen], [Dittrich]. Conversion optimum of the gas-phase reaction is reached at temperatures of 950 °C.

Removal of NO_x according to the SNCR process is less expensive than the SCR process due to lower investment and operation costs. In particular, expenses for heating the flue gases are no longer incurred.

Separation efficiency amounts to about 50 % [Karl] (up to 60 % [Fritz]). In addition to the moderate separation efficiency, the SNCR process is associated with further drawbacks. The reductant is not completely converted in the boiler. Incomplete conversion of the reductant always leads to an increased consumption of chemicals.

The non-converted fraction leaves the boiler and enters the flue gas cleaning system together with the flue gas. This slip of reductant may result in an adsorption of ammonia on the filter dusts with a later release of gaseous ammonia from the flue gas cleaning residues [Egeler].

In a large-scale plant, peak ammonia concentrations (NH_4^+) of 800 mg/kg were found in flue gas cleaning residues. In room air, NH_3 concentrations reached 30 mg/Nm^3 [Egeler]. The maximum acceptable workplace concentration is 30 mg/Nm^3. For the calculation of the NH_3 amounts required, it is referred to Section 8.4 (see also [Franck]).

4.5 Other Flue Gas Cleaning Methods

The flue gas cleaning methods described so far allow for a reliable compliance with the limit values specified in the 17th Federal Emission Control Ordinance, except for dioxins and furans. By additional separation stages (fine cleaning) at the end of the flue gas cleaning system or by the modification of the flue gas cleaning units described above, all limit values can be complied with.

For old plants, however, this statement is true with certain limitations only. Moreover, it is often required to remain far below the limit values, such that further flue gas cleaning units or backfitting measures are required.

4.5.1 Carbon Adsorber

In waste incineration, coke adsorbers are applied for the fine cleaning of flue gas following the separation of acid pollutants. It is focused on the separation of dioxins, furans, and residual amounts of mercury. For the adsorption of the pollutants, so-called travelling-bed adsorbers or carbon adsorbers are employed. Here, the flue gas passes a coke layer for pollutant separation. The setup and functioning of a carbon adsorber are shown schematically in Fig. 13.

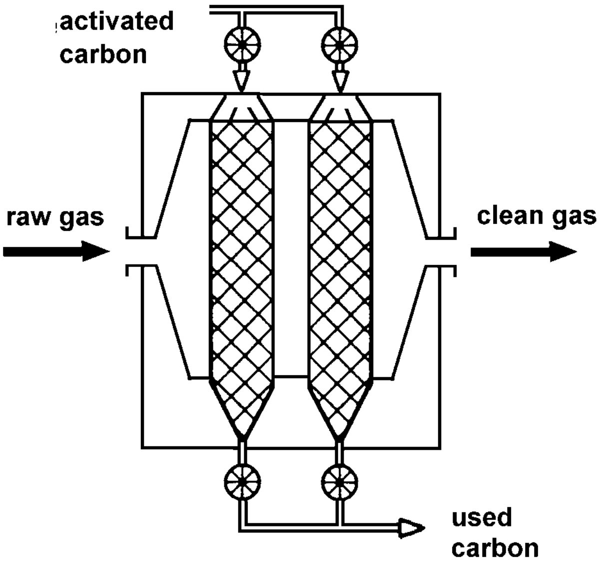

Fig. 13 Scheme of a carbon adsorber

The coke loaded with the pollutants is discharged from the adsorber from below and replaced by supplying fresh coke. Technical-scale carbon adsorbers differ in the supply and discharge of the flue gas and adsorbent. As a rule, the pollutant-loaded coke is fed into the furnace of the waste incineration plant.

In coke adsorbers, activated carbon or various types of coke are applied for adsorption. As far as adsorbent consumption is concerned, various values are indicated in literature. Usually, lignite coke is used. The amounts consumed are given in TABLE 4.

TABLE 4 Coke consumtion of carbon adsorbers

material	amount	literature
lignite coke	0,45 kg/t waste	[Franck]
activated carbon	1 kg/t waste	[MVV-1]
lignite coke	ca. 1 kg/t waste	[Rheinbraun-2]
activated carbon	ca. 1,5 kg/t waste	[MVV-2]

The strongly varying coke consumption depends on the process technology. Based on the information available, average consumption is about 1 kg/twaste.

Lignite coke possesses a good separation efficiency in terms of HCl, HF, SO_2, NH_3, basic amines and gaseous heavy metals as well as dioxins and furans by adsorptive and catalytic effects. Thus, H_2SO_4 may be formed from SO_2. Even particle-bound pollutants, such as cadmium and lead, may be separated. The advantage with respect to mercury is that also metal mercury may be removed. Compared to other fine cleaning methods, travelling-bed or carbon adsorbers are most effective [Stegemann], [Rheinbraun-1], [Cleve], [Grodten].

Like all other flue gas cleaning units, carbon have various advantages and drawbacks. The advantage is the relatively easy disposal of the loaded adsorbent. It may be incinerated in the furnace without any residues, except for the ashes, being generated.

A drawback is the risk of fire due to insufficient removal of the thermal energy released during adsorption. Use of a coke adsorber may adversely affect CO concentration in the clean gas and dust load by abrasion.

As a recent development, the Kombisorbon process is offered on the market [Klose]. This process is based on the use of a mixture of activated carbon and inert material as adsorbent so as to reduce the risk of fire. Current expenses for the Kombisorbon process are supposed to be about 50 % of the financial expenditures required for a carbon adsorber [Klose].

4.5.2 Entrained flow reactor

The carbon entrainment process represents another possibility for the fine cleaning of flue gases. As carbon adsorbers, it is installed downstream of the acid pollutant separator [Stegemann].

A finely grained mixture of activated carbon or coke and a calcium compound is injected into the flue gas and removed from it in a downstream fabric filter. On their way from the point of injection to the fabric filter and in the filter cake, the remaining constituents of the acid pollutants, mainly SO_2 and HCl, react with the calcium compound. In addition, mercury and organic pollutants are adsorbed on the activated carbon particles.

Separation efficiency among others depends on the type of the finely grained mixture of activated carbon and the calcium compound as well as on the amounts of these auxiliary chemicals. The calcium compound/coke ratio is in the range of 10:1 to 4:1 [Stegemann]. For instance, about 2500 – 3000 g/t_{waste} of a mixture of CaO/coke in the ratio of 90/10 is applied in the refuse-fired heating power plant of Bamberg [Reimann-6]. This means that the coke load is 250 – 300 g/t_{waste}. Other values given differ between 300 and 900 g/t_{waste} [Bayer], [Brunner], [Böhmeke].

The carbon entrainment process allows very small emission values to be reached [Gottschalk-1], [Gottschalk-2], [Rheinbraun-1]. The separation efficiencies achieved are comparable with those of a travelling-bed adsorber. As far as dust emission is concerned, the carbon entrainment process possesses certain advantages compared to the travelling-bed adsorber [Gottschalk-2]. According to [Rheinbraun-1], the carbon adsorber seems to be somewhat more efficient in acid pollutant removal.

The residues arising from the carbon entrainment process are mainly disposed of. However, they may also be reused partly as neutralization agent.

4.5.3 Dosing of coke

The use of coke for the adsorption of gaseous pollutants is not limited to the carbon adsorber or the entrained flo reactor. Activated carbon or lignite coke may also be metered into other flue gas cleaning stages.

In large-scale plants equipped with a fabric filter for dedusting, addition of coke to the flue gas flow upstream of the dust separator allows for a very good separation of dioxins, furans, and mercury to be reached. Activated carbon may also be added upstream of the spray dryer with a downstream fabric filter [Thomé-1]. Coke may also be used in dry flue gas cleaning systems. In this case, the coke is metered into the flue gas channel together with the neutralization agent.

Coke concentrations of 50 – 200 mg/Nm^3 in the flue gas upstream of the fabric filter or load values of 250 – 1000 g/t_{waste} have been published [Korte], [Lüder]. Variation may even be larger, since coke loads of 1000 – 3900 g/t_{waste} are found in literature as well [Rosenheim], [Menke], [Würzburg], [VGB 97], [MVB].

4.5.4 Oxidation Catalyst

The oxidation catalyst represents another possibility for compliance with the limit values of dioxins and furans. The oxidation catalyst is no independent process stage in the flue gas cleaning system, but integrated in the SCR unit. The SCR catalyst which usually consists of two catalyst layers is complemented by another third layer, the oxidation catalyst. In some cases, installation of an oxidation catalyst is envisaged as an option in new plants.

It was demonstrated in test facilities that the organic pollutants are destroyed reliably. Furthermore, no new pollutants are generated during the destruction of dioxins and furans in the catalyst [Glinka]. Oxidation also causes the concentrations of elementary mercury and carbon monoxide to be reduced [Glinka].

As an advantage, use of the oxidation catalyst does not result in any additional auxiliary chemicals being needed. The oxygen content of the exhaust gases is sufficient for pollutant oxidation. Another advantage of the oxidation catalyst is its residue-free operation. However, residual concentrations of the acid pollutants HCl and SO_2 cannot be reduced by an oxidation catalyst.

5 Description of the Model Plant

The present Section focuses on the model plants, on the basis of which the materials balances of the various flue gas cleaning systems have been set up. Calculation of materials balances is based on a grate furnace with a steam generator (boiler), which is typical of modern large-scale waste incineration plants. The furnace is combined with various flue gas cleaning systems. Hence, the model plants only differ in flue gas cleaning.

5.1 Furnace and Boiler

Calculation of the balances is based on a grate incinerator with its furnace and steam generator corresponding to the current state of the art.

As far as the number of incineration lines is concerned, the grate incinerator selected corresponds to a new facility built at Velsen. Each line has a waste throughput of 14.3 t per hour. For two incineration lines, each of which consists of a furnace and a flue gas cleaning system, with an availability of 7000 h per year, an annual incineration capacity of 200000 t results. The plant in Velsen, also equipped with two furnaces, has a throughput of 15 t/h and an annual capacity of 105000 t for each furnace with its availability being 7000 h [Bayer].

Determination of the other technical data for the model plants turned out to be problematic, as the data given in the sources available varied considerably. For instance, flue gas volumes differed significantly in literature. A selection of specific flue gas volumes is presented in TABLE 5. The values referring to the dry state range from 3950 Nm^3/t_{waste} to 5300 Nm^3/t_{waste}.

In addition, the flue gas volume data are subject to uncertainties, since frequently there is no information available on whether a flue gas recirculation system has been installed or not. Recirculation of flue gas replaces part of the secondary air. Consequently, the total amount of flue gas can be reduced. Furthermore, recirculation leads to a slight reduction of nitrogen oxide concentrations in the flue gas.

The effects of flue gas recirculation are obvious from [ABB-1]. In the case considered there, the specific flue gas volume is reduced from 5360 Nm^3/t_{waste} (wet) to 4600 Nm^3/t_{waste} (wet) by recirculation. Comparison of these values with the data given in TABLE 5 suggests that plants with small specific flue gas volume flows might be those equipped with recirculation systems.

As far as the higher values are concerned, it is not always clear from the information sources, whether they represent design data of the flue gas cleaning system with safety margins or typical operation values.

TABLE 5 Specific flue gas volumes

Site	flue gas volume [Nm^3 (wet)/t_{waste}]	flue gas volume [Nm^3 (dry)/t_{waste}]	Quelle
Hamburg Borsigstraße		3950	[Lüder]
Berlin Ruhleben	4694	3954	[ABB-6]
Würzburg	5056	4259	[Noell-2]
Mannheim	5200	4380	[MVV-1]
Würzburg		5000	
München Süd	6000	5055	[ABB-4]
Bamberg		5200	[Reimann-2]
München Nord	6338	5340	[ABB-3]
Mannheim		5778	[Achternbosch-1]
Köln	7138	6013 (max.)	[ABB-7]
Neufahrn	7300	6150	[ABB-2]
Weißenhorn	7385	6221	[ABB-8]
Zirndorf	7500	6318 (max.)	[ABB-5]

For calculating the balances, a flue gas volume of 4700 Nm^3/t_{waste} (dry) is assumed. The model plant is not considered to be equipped with a flue gas recirculation system.

In the past, 300 to 350 kg of grate ashes were produced by grate incineration of 1 t of waste [Demmich-2]. Meanwhile, the slag volume has been reduced by waste management measures. Today, only 250 to 300 kg of slag are generated in a modern waste incineration plant [Zwahr].

Another problem are the amounts of dust which have to be taken into consideration in the balancing calculations. In older waste incineration plants, the amount of dust is about 30 kg/t_{waste} and comprises both boiler dust and filter dust [Reimann-4]. In modern plants, 10 to 20 kg/t_{waste} of fly ash arise only [Pranghofer]. As a rule, the amount of filter dust arising in the dust separator of the flue gas cleaning system is much higher than the amount of boiler dust. Latest boiler constructions, where far more dust is separated due to special integrated components [Schäfers], are not considered by the present study. This study is based on the assumption of 4 kg/t_{waste} of boiler dust and 16 kg/t_{waste} of fly dust being generated.

In addition to flue gas volumes and amounts of residues, concentrations of pollutants have to be specified for balancing. These data are in agreement with the experience gathered in large-scale plants and given in TABLE 6. The specific values were calculated for substances covered by balancing only.

TABLE 6 Data of the model plant used for calculation

flue gas volume	4700	Nm^3/t_{waste} (dry), 11% O_2
boiler ash	4	kg/t_{waste}
fly ash	16	kg/t_{waste}
raw gas concentration with fly ash		
Cl	1253	mg/Nm^3 (dry), 11% O_2
S	269	mg/Nm^3 (dry), 11% O_2
Hg	0,35	mg/Nm^3 (dry), 11% O_2
Cd	1,23	mg/Nm^3 (dry), 11% O_2
Pb	28	mg/Nm^3 (dry), 11% O_2
NO_x as NO_2	400	mg/Nm^3 (dry), 11% O_2
clean gas concentration		
Cl	1,5 - 5	mg/Nm^3 (dry), 11% O_2
S	2 - 10	mg/Nm^3 (dry), 11% O_2
Hg	0,004	mg/Nm^3 (dry), 11% O_2
Cd	0,001	mg/Nm^3 (dry), 11% O_2
Pb	0,02	mg/Nm^3 (dry), 11% O_2
NO_2	170	mg/Nm^3 (dry), 11% O_2
	(70	mg/Nm^3 dry, 11% O_2 für 1/2 17 BImSchV)

influence of flue gas cleaning sytem possible; see Section 6.4

More detailed information on the elements selected, the pollutant concentrations specified, and the balancing volume shall be given in Section 6.

5.2 Selection of balanced flue gas cleaning systems

Based on the process options available for the separation of pollutants from flue gas, as described in Section 4, very different flue gas cleaning systems can be designed.

Actually, it is impossible to find two plants of perfectly identical design among the 53 large-scale waste incineration plants in Germany. The waste incineration plants at Rugenberger Damm and Borsigstraße in Hamburg will be largely identical, except for the last flue cleaning stage [Schäfers]. A survey of large-scale flue gas cleaning systems is presented in TABLE 7. All plants listed, except for those in Bamberg, Ingolstadt, and Krefeld, are operated in a sewage-free manner with partly separate processing facilities being used.

TABLE 7 Flue gas cleaning systems installed at various sites

Site	Flue gas system
Berlin-Ruhleben	SNCR / fabric filter
Bonn	SNCR / spray dryer/ ESP / scrubber-scrubber / entrained flow reactor
Hamburg Borsigstraße	SNCR / fabric filter/ scrubber-scrubber / wet ESP
Coburg	SNCR / spray absorber / fabric filter/ scrubber-scrubber / wet ESP
Hameln	SNCR / ESP / fabric filter / carbon adsorber / SCR
Krefeld	fabric filter / scrubber-scrubber / SCR / entrained flow reactor
Köln	spray dryer / fabric filter / scrubber-scrubber /SCR/ carbon adsorber
Stellinger Moor	spray dryer / ESP / scrubber-scrubber / SCR / carbon adsorber
Herten	spray dryer / ESP / scrubber-scrubber / carbon adsorber /SCR
Augsburg	ESP / scrubber-scrubber / wet ESP / SCR/ entrained flow reactor
Essen-Karnap	ESP / scrubber-scrubber / carbon adsorber / SCR
Bamberg Ingolstadt Burgkirchen	ESP / scrubber-scrubber /SCR/ entrained flow reactor
Offenbach	cyclone / ESP / spray dryer / ESP/ scrubber-scrubber / SCR / oxid. catalyst
Mannheim	ESP / spray dryer / ESP / scrubber-scrubber / SCR / carbon adsorber
Bielefeld	ESP / spray dryer / ESP / scrubber-scrubber / SCR / entrained flow reactor
Stuttgart	ESP / spray dryer / ESP / scrubber-scrubber /SCR / oxid. catalyst
Rosenheim	SNCR/ spray absorber / fabric filter
Schwandorf	fabric filter/SCR
Düsseldorf	spray absorber / ESP / SCR
Frankfurt	spray absorber / ESP / entrained flow reactor

The list does not cover all waste incineration plants, as no reliable information is available on all locations in the Federal Republic of Germany. Still, it is evident from this list already that very different flue gas cleaning systems are employed.

To reduce to an acceptable level the expenditure needed for comparing the various flue gas cleaning systems on the basis of materials flow analyses, reasonable process combinations have to be selected from the large number of large-scale flue gas cleaning systems existing. In the present study, semi dry, semi wet, and wet flue gas cleaning systems are taken into consideration.

It must be noted, however, that not all existing flue gas cleaning systems would be reinstalled again in new plants. Due to the repeated reduction of legal emission limits, the existing flue gas cleaning systems were backfitted with additional process stages in the past. Moreover, knowledge on the chemical flue gas cleaning processes has improved constantly.

This situation is reflected by the plant in Frankfurt , where a semi wet flue gas cleaning system is applied. To separate the flue gas cleaning products, an electrostatic precipitator is installed downstream of the spray absorber. For compliance with the limit values specified in the 17th Federal Emission Control Ordinance, the plant is equipped with an entrainement flow reactor for further fine cleaning of exhaust gases.

This combination of steps results from the history of plant technology, which was influenced by constantly lower emission limits. In this case, the electrostatic precipitator could be replaced by a fabric filter with the use of the carbon entrainment system being no longer necessary. But several arguments speak against this:

- Another flue gas cleaning stage, i.e. fine cleaning by the carbon entrainment method, meets with better political acceptance.
- During backfitting, operation may be continued. This is not possible when exchanging the filter units and removing the electrostatic precipitator.
- Both backfitting and the exchange of filter units require investment costs for a new fabric filter, such that hardly any differences in costs are to be expected.

An additional remark has to be made with regard to dry flue gas cleaning systems. The present study focuses on the semi dry process with an upstream evaporation cooler, as purely dry methods without flue gas moistening are obsolete.

Based on the knowledge and requirements outlined above, the flue gas systems listed in TABLE 8 are selected for this study.

TABLE 8 Flue gas cleaning systems selected and locations of their technical use

system	**model plant**		**technical scale example**
wet	wet 1	ESP / scrubber-scrubber / SCR / entrained flow reactor (external treatment)	Bamberg
	wet 2	ESP / scrubber-scrubber /SCR/ carbon adsorber (external treatment)	Essen-Karnap
	wet 3	ESP / spray dryer / ESP / scrubber-scrubber /SCR/ entrained flow reactor	Bielefeld
	wet 4	ESP / spray dryer / ESP / scrubber-scrubber / SCR / carbon adsorber .	Mannheim
	wet 5	spray dryer / fabric filter / scrubber-scrubber /SCR	-
	wet 6	SNCR / fabric filter / scrubber-scrubber (external treatment)	Hamburg-Borsigstraße see: chapter 7.6
semi wet	semi wet 1	SNCR / spray absorber / fabric filter	Rosenheim
	semi wet 2	spray absorber / fabric filter / SCR	München-Süd
semi dry	semi dry 1	SNCR / fabric filter	Berlin-Ruhleben
	semi dry 2	fabric filter /SCR	Würzburg

Of the ten flue gas cleaning systems selected, six use the wet process and two plants each are based on a semi dry or conditioned dry process. TABLE 8 also indicates where the flue gas cleaning systems selected are applied on a large scale. In the case of the plant "wet 6", Hamburg Borsigstraße is given as location, although the flue gas cleaning system used there is equipped with an additional wet electrostatic precipitator. Its effects on the emissions, however, cannot be measured [Schäfers] and therefore Hamburg Borsigstraße corresponds to the model plant "wet 6".

As demonstrated by the new plant of the Braunschweigische Kohlen-Bergwerke AG in Buschhaus, a fine cleaning system is no longer required downstream of a two-stage scrubber.

The flue gas cleaning system of the Buschhaus plant consists of a spray dryer, a fabric filter with the addition of coke, and a two-stage scrubber [Michel].

Of the six model plants with a wet flue gas cleaning system, four plants use an electrostatic precipitator for dedusting and a fine-cleaning stage at the end. The other two plants are not equipped with a fine-cleaning stage upstream of the stack, but use a fabric filter with the addition of coke for the removal of dust, dioxin, and mercury.

Three of the flue gas cleaning systems selected are equipped with a spray dryer for the evaporation of scrubber effluents. In the remaining three plants, the effluents are transferred to an external processing facility. The options of external processing, recycling or separate evaporation facilities are not specially considered by balancing.

All semi dry and conditioned dry systems are equipped with a fabric filter for dust removal downstream of the absorber or adsorber. They only differ in the NO_x reduction method.

6 Description of the Balancing Method

The present Section describes the system used for calculating the materials balances. This includes an exact definition of the system boundary and the specification of boundary conditions. After this, the methods and data used for calculating the materials balances of the flue gas cleaning systems selected shall be explained in detail. The different flue gas cleaning stages shall be dealt with in separate sections.

6.1 System boundary

The system boundaries define the balancing volume the covered by balancing. An exact definition of the system boundaries is the prerequisite for exact and reproducible materials balancing. For a detailed comparison of various flue gas cleaning systems, it is recommended to use a balancing volume that is limited to the flue gas cleaning system exclusively. The balancing volume of the present study is shown in Fig. 14.

The system boundary starts with the dust-containing raw gas leaving the boiler and ends with the clean gas leaving the last flue gas cleaning stage before entering the stack. For balancing, all materials flows entering and leaving this system boundary have to be determined. This also applies to auxiliary chemicals and the various flue gas cleaning residues.

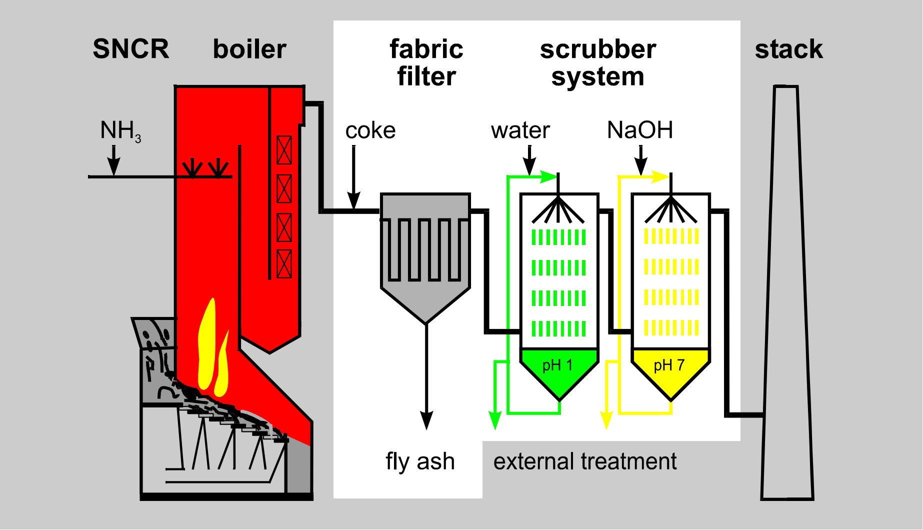

Fig. 14 **System boundary**

In the three wet flue gas cleaning systems, effluents are produced in the scrubbers and processed in a separate evaporator. Balancing takes into account the neutralization agents required for this evaporation. The resulting residues are mainly identical with those from the spray dryer of the other wet processes.

Recycled materials flows, e.g. evaporation of effluents for hydrochloric acid production, are not taken into account.

The system boundary specified does not cover two materials flows which are not indicated in Fig. 14, as they are of no significance to this study. At the end of the incineration grate, the incineration residue, also called slag or grate ashes, is discharged from the furnace. In addition, boiler dust is not included in balancing. In large-scale plants, boiler dust is usually disposed of together with the filter dust from the flue gas cleaning system.

As the system boundary starts with the dust-containing raw gas leaving the boiler, the SNCR system (in the boiler) is outside of the scope of balancing. When studying the auxiliary chemicals used in Section 8, however, consumption of ammonia for NO_x-removal will be taken into account. For this reason the SNCR system will be considered as well.

6.2 Substances Balanced

In thermal waste treatment, a very large number of chemical compounds and elements can be detected in the materials flows of the plant, contrary to chemical production processes. Moreover, the individual elements form various compounds.

For the comparison of materials flows being as clear as possible, chemical elements are balanced rather than their compounds. To limit the calculation expenditure, it is required to restrict to a few chemical elements only. Balancing shall first focus on those elements, for which emission limits have been specified in the legal regulations. Due to the numerous limits contained in the regulations, however, a selection of the elements listed there has to be made.

As the present study shall also cover the use of auxiliary chemicals and amounts of residues generated, the elements of chlorine and sulfur are selected. Chlorine and sulfur are balanced, as they make up the largest fraction of “acid pollutants” in the raw gas and determine the use of auxiliary chemicals. In addition, balancing of toxic heavy metals is of interest. Mercury, cadmium, and lead are chosen as representative substances. TABLE 9 contains information on the elements balanced in the present study and their major compounds.

TABLE 9 Balanced elements and their compounds

element	possible compounds		appearance
chlorine (Cl)	HCl	hydrogen chloride	flue gas
	Cl^-	chloride salts	(bottom ash), fly ash, flue gas
sulphur (S)	SO_2	sulphate dioxide	flue gas
	SO_3^{2-}	sulphite salts	(bottom ash), fly ash
	SO_4^{2-}	sulphate salts	(bottom ash), fly ash
mercury (Hg)	Hg	mercury	flue gas,
	Hg_2Cl_2	mercury (I) chloride	flue gas (bottom ash)
	$HgCl_2$	mercury (II) chloride	flue gas (bottom ash)
	other salts		flue gas (bottom ash),
cadmium (Cd)	$CdCl_2$,	cadmium chloride	(bottom ash), fly ash
	$CdSO_4$,	cadmium sulphate	(bottom ash), fly ash
	CdO,	cadmium oxide	(bottom ash), fly ash
	other salts		(bottom ash), fly ash
lead (Pb)	Pb	lead	(bottom ash), fly ash
	$PbCl_2$	lead chloride	(bottom ash), fly ash
	$PbSO_4$	lead sulphate	(bottom ash), fly ash
	PbO	lead oxide	(bottom ash), fly ash
	other salts		(bottom ash), fly ash

At the boiler outlet, the element chlorine (Cl) mainly exists in the form of gaseous hydrogen chloride (HCl). Furthermore, chlorine in the form of metal chlorides is contained in the fly ash.

In boiler ash and fly ash, sulfur (S) mainly exists as sulfate ion bound in salts (SO_4^{2-}). In the flue gas, it has the form of gaseous sulfur dioxide SO_2.

In the flue gas, mercury (Hg) mainly exists as volatile mercury chloride in the gas phase. In the metal form it is also contained in flue gas. The fly ash contains very small amounts of mercury only.

Cadmium (Cd) is volatized as chloride. In the flue gas leaving the boiler, it is nearly completely bound to the filter dust [IAWG]. Lead (Pb) exists in the form of oxides or salts in dusts (and also in the slag).

When analyzing the amounts of auxiliary chemicals used, consumption of ammonia for the SCR and SNCR processes will be calculated as well. However, balancing of ammonia or NO_x is not performed. Hence, the formation of ammonia salts in the flue gas cleaning system, which results from the use of ammonia, and the slip of ammonia into the clean gas are not taken into account.

Another topic related to flue gas cleaning, which is frequently discussed by the public, is the dioxin problem. It was found out at an early point of this study already that dioxin concentrations existing in the flue gas do not have any influence on the use of auxiliary chemicals. The use of coke – on which the dioxins are separated – is determined by other pollutants, in particular mercury, and technical aspects. As a consequence, compliance with the dioxin emission limits is assumed to be ensured. For these reasons, the dioxin problem is not dealt with in detail by the balances.

6.3 Sources of the Data Used for Materials Balancing

Balancing is based on data from very different sources. Above all, information from literature is used. It is verified and complemented by inquiries made to plant constructors and operators. In addition, current data measured in large-scale waste incineration plants are taken into account.

In some cases, design data are available for these plants. However, they can be used with certain limitations only, as the design of new plants sometimes is based on “worst-case” states. Under normal operation conditions, such states are not reached at all or reached for a short term only. These “worst-case” states are not representative of normal operation and, hence, not suited for balancing.

6.4 Procedure

The method used within the framework of the present study is based on an analysis of the individual process steps of flue gas cleaning, which are combined. First, the separation efficiencies regarding the elements to be balanced are determined for each process step. Then, the individual process steps are added up to a total balance. For this, the following information must be available on the elements to be balanced:

- Loads in the dedusted raw gas downstream the boiler
- Loads in the fly dust
- Total amount of dust separated in the dust separator of the flue gas cleaning system
- Separation efficiencies of the flue gas cleaning stages, e.g. scrubber systems, fine cleaning, etc., regarding the balanced elements
- Specific amounts of auxiliary chemicals used and the stoichiometric factor applied for the addition of neutralization agents

Total load of the raw gas, including the dust downstream the boiler, is obtained by adding the load in the gas phase to the load of the fly dust. The resulting raw gas and dust loads are evident from TABLE 6.

As will be explained in the following Sections when specifying the separation efficiencies of the individual cleaning stages, it is not always possible to derive reliable values. For fine cleaning, for example, it must be proceeded in the opposite manner: Starting from plausible clean gas values for the model flue gas cleaning systems selected, separation efficiency of fine cleaning can be calculated by subtraction from the values prior to fine cleaning.

When specifying the individual separation efficiencies and clean gas values, a gradation is made by the authors to account for the separation efficiencies of the individual units and the entire model plant. In the following Sections, basic data and their boundary conditions as well as system assumptions shall be defined and discussed.

6.4.1 Fly Ash Separation

As specified in Section 5, either electric or fabric filters are applied in the model systems selected. Separation efficiency of a dedusting unit is influenced decisively by the particle size distribution of the dust. Fig. 15 shows the particle size distribution of filter dusts from electrostatic precipitators.

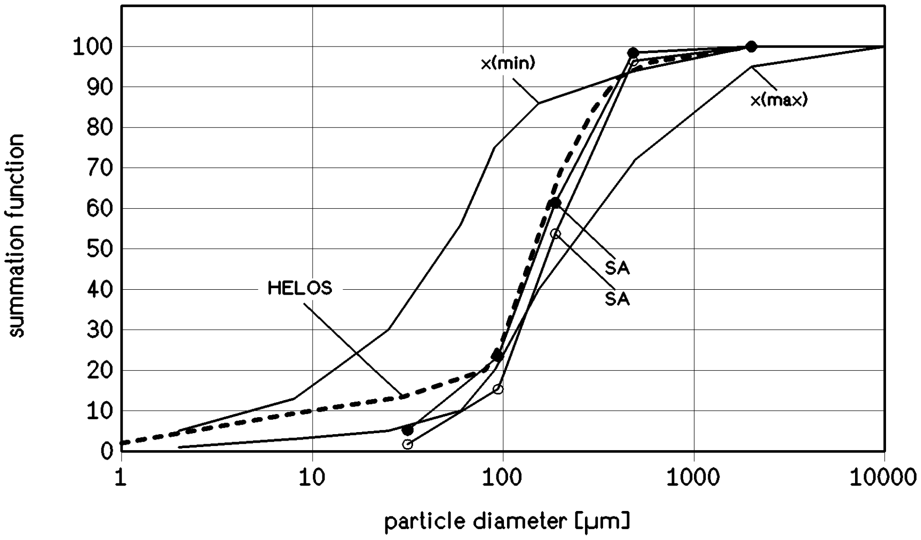

Fig. 15 Particle size distributions of fly ashes from electrostatic precipitators [Birnbaum-4] (see text).

In Fig. 15, x(min) and x(max) denote the lower and upper limit of the particle size distributions, respectively [Hartlen]. In addition, data measured in a large-scale waste incineration plant by screening analysis (SA) and laser diffraction spectroscopy (HELOS) are indicated [Birnbaum-4].

It must be noted that the data measured do not necessarily correspond to the real particle size distributions in the flue gas, because the distribution may be shifted to somewhat larger particle diameters due to agglomeration.

No information is available on particle distributions of dusts from fabric filters. Still, it is evident from Fig. 15 that fine dusts below 20 µm, for which the filter possesses better separation efficiencies, represent a small fraction of the total amount of fly dust only. It may therefore be assumed that particle distributions of fabric filter dusts are very similar to those of electrostatic precipitator dusts. And it may be doubted, whether the expected shift of particle size distribution towards smaller particle diameters can be measured for fabric filter dusts.

The small fraction of fine dust also is reflected by the separation efficiencies given in literature. For instance, values of 99.9 % and 99.2 % are given for fabric filters and electrostatic precipitators, respectively [TNO]. This means that the efficiency of the fabric filter is higher by less than 1 %. Differences between electric and fabric filters will even be further reduced by novel electrostatic precipitators that are equipped with three fields for dust separation.

It is now important to find out, whether these small differences might affect the balances. For this, typical compositions of fly dusts have to be studied, which are listed in TABLE 10 [Birnbaum-4]. In addition to literature data, TABLE 10 also presents data measured in a large-scale waste incineration plant over a period of eleven weeks.

TABLE 10 Concentrations of elements in filter dusts as given in literature and measured in a large-scale waste incineration plant [Birnbaum-4] (see text)

element	literature [ppm]	MSWI I [ppm]
Al	25000-120000	n.a.
As	40-200	150-1420
Ca	40000-340000	130000-170000
Cd	100-1400	270-550
Cl	30000-200000	44200-87000
Cr	300-2000	470-1000
Cu	50-5000	860-1900
F	100-3000	n.a.
Fe	10000-60000	17600-23000
Hg	1-10	n.a.
K	30000-160000	34700-63300
Mg	10000-20000	n.a.
Mn	400-4000	920-1430
Na	15000-80000	n.a.
Ni	100-1000	180-430
Pb	2500-25000	4500-18455
S	10000-50000	27900-47300
Sb	150-2500	580-1430
Si	40000-200000	n.a.
Sn	500-6000	1020-2150
Ti	3000-20000	6690-10200
Zn	5000-100000	18800-32200

According to TABLE 10, chemical composition varies considerably, such that the somewhat improved separation efficiencies of the fabric filter can hardly be measured in a large-scale plant.

Having this in mind, the separation efficiencies of the individual elements are specified for the individual process steps of dedusting. Based on the information available from large-scale plants, the values given in TABLE 11 result. They will be used for the calculations within the framework of this study.

TABLE 11 Separation efficiencies for the elements balanced, related to raw gas with dust

chlorine	ESP fabric filter	12,2 % 12,2 %
sulphur	ESP fabric filter	44,2 % 44,2 %
mercury	ESP without coke fabric filter with coke	3,2 % 90,0 %
cadmium	ESP fabric filter	97,2 % 99,0 %
lead	ESP fabric filter	97,7 % 97,7 %

In the case of chlorine and sulfur, separation efficiencies of the fabric filter are assumed to correspond to those of the electrostatic precipitator. Mercury separation efficiency of the electrostatic precipitator is based on data from the MSWI of Bamberg [Reimann-2], [Achternbosch-1]. When using a fabric filter with an upstream addition of coke, separation is not determined by filter technology, but by the addition of coke. With the addition of coke, a separation efficiency of 90 % can be assumed.

As cadmium is mainly bound in the fine fraction of the fly dust, it may be assumed that a fabric filter reaches a somewhat higher separation efficiency than an electrostatic precipitator. For this reason, a cadmium separation efficiency of 99 % is specified for the fabric filter.

The data available for lead do not allow any clear conclusions to be drawn with regard to an increased separation efficiency of the fabric filter [Reimann-6]. For this reason, the same separation efficiency is used for both filter systems.

To limit the balancing expenditure, it is also assumed that the heavy metals passing the electrostatic precipitator are separated as dust in the downstream scrubbers. This assumption seems to be justified, as the dust concentrations downstream of the scrubbers do not depend on the type of separator used in modern plants. This means that the heavy metal flows downstream of the scrubbers are identical in flue gas cleaning systems with fabric filters and electrostatic precipitators.

To calculate materials flows for the process of dedusting, it is also required to specify the composition of the filter dust. In addition to the data given in TABLE 10, further data from literature [Reimann-2], [Reimann-5], [ASTRA] are taken into account. The concentration data selected are listed in TABLE 12.

TABLE 12 Used fly ash concentrations

element	fly ash concentration
Cl	45000 [mg/kg]
S	35000 [mg/kg]
Hg	3.5 [mg/kg]
Cd	350 [mg/kg]
Pb	8000 [mg/kg]

With these concentration values, the total fly dust amount given in Section 5, and the separation efficiencies, the loads separated during dedusting can be calculated.

6.4.2 Wet Flue Gas Cleaning

Balancing covers ten different flue gas cleaning systems, six of which are equipped with a wet flue gas cleaning unit. In wet flue gas cleaning, the first scrubber stage mainly allows for the removal of HCl and mercury at pH = 1. In the second scrubber stage, SO_2 is taken up by the scrubbing liquid at pH = 7. Moreover, part of the residual dust that has passed the dust separator and remained in the flue gas is separated.

To simplify the calculations, no multi-component constructions with a preliminary separator (quencher) and a main separator are considered for the first scrubber stage. Such a combination has no influence on the balance of the flue gas cleaning system, as the absorption liquids from both separators are discharged together. The SO_2 scrubber also is considered to be an entire separation unit without internal circuits.

For the separation efficiencies regarding the elements to be balanced, data of the MSWI of Bamberg [Reimann-2] are used. They are in very good agreement with information on other large-scale plants [Achternbosch-1]. The separation efficiencies of both scrubber stages are given in the following table.

TABLE 13 Separation efficiencies of the scrubber stages with regard to the elements balanced, related to an electrostatic precipitator as dust separator

element	**Separation efficiency HCl-Scrubber**	**Separation efficiency SO_2-Scrubber**
chlorine	88,2 %	97,8 %
sulphur	10,0 %	98,5 %
mercury	83,5 %	32,9 %
cadmium	70,8 %	90,7 %
lead	87,3 %	47,7 %

Separation efficiencies of the scrubber systems apply to all elements balanced, except for cadmium, irrespective of whether an electrostatic precipitator or a fabric filter is used for dedusting. As specified in Section 6.4.1, cadmium concentrations downstream of the scrubbers are identical for flue gas cleaning systems with an electrostatic precipitator and fabric filter. Due to the assumed improved separation efficiency of the fabric filter for fine dust, cadmium separation efficiency of the scrubber systems has to be modified. For this, the difference between the cadmium load downstream of the fabric filter and the load downstream of the SO_2 scrubber is distributed to the individual scrubbers in a plausible manner.

For balancing the wet flue gas cleaning systems, it is assumed that the use of a spray dryer does affect neither the separation efficiencies of the flue gas cleaning system nor the use of auxiliary chemicals. Hence, materials flows leaving the plant are not changed.

External processing of the effluents comprises neutralization and subsequent evaporation. Here, production of hydrochloric acid and gypsum, which is practiced in some large-scale plants, is not balanced.

Balances of the wet flue gas cleaning systems are based on sewage-free combinations exclusively. Additional consideration of sewage-generating flue gas cleaning systems would by far exceed the scope of the present study. Moreover, the limitation made here accounts for the current licensing practice and expected modifications of German regulations.

The varying materials flows of sewage-generating and sewage-free flue gas cleaning systems are obvious from literature [Achternbosch-1], [Achternbosch-2].

The consumption of auxiliary chemicals and clean gas data for the various model plants shall be explained in Sections 6.4.5 and 6.4.7.

6.4.3 Semi Wet Flue Gas Cleaning

The semi wet flue gas cleaning system considered in the present study consists of a spray absorber and a downstream fabric filter for the separation of flue gas cleaning products and fly dust.

The information available for balancing includes the consumption of auxiliary chemicals, the achievable clean gas concentrations. In some cases the respective raw gas data, which are not consistent. For the balancing of semi wet flue gas cleaning systems, no concrete values are available with respect to the separation efficiencies reached for the balanced elements of Cl, S, Hg, Cd, and Pb.

As information on the separation efficiencies is lacking, balancing must be based on clean gas values. Using the raw gas data available, the separation efficiencies are calculated.

Separation efficiency of a semi wet flue gas cleaning system decisively depends on the type and amount of auxiliary chemicals used. Due to the complex processes taking place in the spray absorber, separation efficiency is not only affected by the chemical composition of the auxiliary chemical, but also by its physical properties, e.g. specific surface area and porosity. For this reason, the amount of auxiliary chemicals required for pollutant separation exceeds the stoichiometrically necessary amount. Especially in older plants, a high stoichiometric factor is required for the clean gas values to be far below the limits given in the 17th Federal Emission Control Ordinance.

The stoichiometric factors and clean gas data of plants with semi wet flue gas cleaning systems shall be covered in Sections 6.4.5 and 6.4.7.

6.4.4 Semi Dry Flue Gas Cleaning

The semi dry model systems consist of an evaporation cooler, a nozzle for the injection of the neutralization agent, and a fabric filter.

Balancing is based on extensive information from measurement campaigns in a large-scale plant as well as on design data supplied by a plant constructor. Separation efficiencies of the semi dry system are assumed to be the same as those of semi wet systems, which seems to be plausible judging from the information available.

The stoichiometric factors and clean gas data of semi dry flue gas cleaning systems shall be described in Sections 6.4.5 and 6.4.7.

6.4.5 Stoichiometric Ratio

The stoichiometric ratio is defined as the ratio between equivalents of the neutralization agents supplied to the flue gas cleaning system and equivalents of acid pollutants in the flue gas. The major acid pollutants are HCl, SO_2, and HF. To neutralize these pollutants, above all $Ca(OH)_2$ and NaOH are used. As an example, the reaction of SO_2 and NaOH may be described by the following simplified reaction equation:

$$SO_2 + 2\ Na\ OH \quad \Leftrightarrow \quad Na_2SO_3 + H_2O \qquad \text{eq. 6.1}$$

While calculating, it must be taken into account that two equivalents of sodium hydroxide are required to neutralize one equivalent of sulfur. Moreover, two equivalents of chlorine are neutralized by one equivalent of calcium hydroxide in the reaction of HCl with $Ca(OH)_2$.

A stoichiometric ratio in excess of 1 describes an excess of the neutralization agent. A ratio of 1.5 means an excess of neutralization agent of 50 %. This excess of neutralization agents enters the flue gas cleaning product arising and needs to be disposed of. Hence, a minimum excess is to be ensured.

Due to the varying separation mechanisms, stoichiometric ratios of wet, semi wet, and semi dry systems differ significantly. The stoichiometric ratio affects the pollutant separation efficiency in particular of semi wet and semi dry systems. The stoichiometric factors encountered in large-scale plants are shown in TABLE 14.

TABLE 14 Stöchiometrische Faktoren

flue gas cleaning	Stoichiometric ration used for calculation	range in literature
wet	1.1	1.1 bis 1.4
semi wet	2.5	2.2 bis 3.0
semi dry	2.8	2.4 bis >3

In wet processes the factor amounts to 1.1 to 1.4, depending on the flue gas volumes and pollutant concentrations desired downstream of the scrubbers. For the calculations within the framework of the present study, a stoichiometric factor of 1.1 is specified.

For semi wet systems, the stoichiometric factors given in literature also are below 2 [Reimann-7]. However, these data probably refer to the outdated requirements made by the TA Luft (Clean Air Regulations). Interviews of plant operators made within the framework of the present study revealed that a stoichiometric factor of 3 is not rare. This study is based on a stoichiometric factor of 2.5. It is to be assumed that the limits indicated in the 17th Federal Emission Control Ordinance can be complied with reliably. To remain far below these limits, higher stoichiometric factors are required.

Compared to wet and semi wet systems, dry systems require larger stoichiometric ratios. In various sources, values ranging from 2.4 to larger than 3 were found for the stoichiometric ratio of dry processes. Balancing here is based on a stoichiometric factor of 2.8. As in case of semi wet systems, emissions can be further reduced by a higher factor.

During calculation, it must be noted that varying separation efficiencies may result from various neutralization agents, even if their chemical composition and stoichiometric factors are the same. Neutralization agents of varying activities are offered on the market. This allows for smaller stoichiometric factors with the same emission values being reached and especially applies to semi dry and dry conditioned flue gas cleaning systems. Therefore, calculated results may differ from the operation data of large-scale plants.

6.4.6 Other Separation Units – Fine Cleaning

Fine-cleaning stages installed in large-scale waste incineration plants are carbon adsorbers or entrained flow reactors. They are installed mainly in wet flue gas cleaning systems between the scrubber and the stack.

As explained in Section 4, a mixture of calcium oxide and lignite coke is applied in the **entrained flow reactor** for separating pollutants. The CaO/lignite coke mass ratio is in the range of 10 : 1 to 4 : 1 [Stegemann]. In large-scale plants, between 2 kg/t_{waste} and 3 kg/t_{waste} of CaO/lignite coke are used [Nethe] (see Section 4.5.2).

Due to uncertainties of the measurements caused by the strong concentration variations and low concentration values, it is difficult to specify separation efficiencies for fine cleaning. In literature, a value of about 80 % is given for entrained flow reactor entrainment with regard to the pollutants HCl, SO_2, and Cd [TNO]. For mercury, a separation efficiency ranging from 80 to 90 % may be concluded [TNO], [Böhmke], [Reimann-6], [Herbig].

TABLE 15 presents the clean gas data of a system prior to and following backfitting with a entrained flow reactor . It has turned out to be impossible to determine a concrete value for the individual separation efficiencies on the basis of operation data.

TABLE 15 Clean gas data of a MSWI

	without entrained flow reactor	**with entrained flow reactor**
HCl [mg/Nm³]	0,8 - 6,5	1 -2
SO_2 [mg/Nm³]	2,4 - 29,5	2 -3
Hg [mg/Nm³]	0,029 - 0,049	< 0,0026 - 0,0045
Cd [mg/Nm³]	<0,0008 - 0,0033	< 0,0006 - 0,0034
Pb [mg/Nm³]	0,0059 - 0,070	< 0,0017 - 0,071

Due to the uncertainties of the separation efficiencies determined, balancing of fine cleaning is based on plausible clean gas values which are given in Section 6.4.7. Separation efficiencies can only be determined by calculation. Furthermore, a consumption of auxiliary chemicals of 2500 g/t_{waste} CaO/lignite coke (ratio 90 : 10) is assumed in the study.

If the fine-cleaning stage consists of a carbon adsrober, coke consumption is not determined by the pollutant concentrations in the flue gas, but by technical process parameters. In case of the carbon adsorber, pressure loss is decisive.

Literature information and data on existing plants allow to conclude that carbon adsorbers reach somewhat better separation efficiencies than entrained flow reactors [Stegemann], [Rheinbraun-1], [Rheinbraun-2], [Cleve], [Grodten]. For this reason, it must be distinguished between carbon adsorbers and entrained flow reactorrs when balancing the ***acid pollutants***.

Separation efficiencies of a carbon adsorber with respect to the individual pollutants cannot be determined reliably on the basis of literature and operation data. In analogy to the entrained flow reactor, plausible clean gas values are derived first on the basis of the information available. Then, the separation efficiencies are determined by calculation.

For flue gas cleaning systems equipped with a carbon adsorber, coke consumption must be specified. Within the framework of the present study, a coke consumption of 1 kg/t_{waste} is assumed for the carbon adsorber based on the data given in TABLE 4.

In wet flue gas cleaning systems, only very small concentrations of ***heavy metals*** are encountered downstream of the second scrubber stage. They already are in the range of the limits given in the 17th Federal Emission Control Ordinance. During further fine cleaning of the flue gases, very small concentration values are reached, such that the differences to be expected between a carbon adsorber and an entrained flow reactor cannot be measured. Cadmium concentrations downstream of the second scrubber stage are so small that the separation efficiency can be given neither for the carbon adsorber nor for the entraind flow reactor. For this reason, balancing is performed assuming that lead is removed by fine cleaning, while cadmium is not.

The loaded coke from the carbon adsorber is fed back into the furnace within the framework of balancing. The resulting consequences on the materials balances, however, are neglected. Judging from the absolute loads in the dust-containing raw gas, which result from the waste input, and in the returned coke, effect on the total loads is negligible.

6.4.7 Clean Gas Data

In view of the situation described above, the clean gas values have to be specified in accordance with the separation efficiencies expected for a complete balancing of the various flue gas systems.

As far as separation efficiency is concerned, wet systems differ from semi wet and semi dry sytems. Due to the fabric filter used and the specified stoichiometric factors, however, clean gas data of semi wet and semi dry systems hardly differ.

As far as the wet processes are concerned, systems with fine cleaning (wet 1 to wet 4) differ from processes without fine cleaning (wet 5 and wet 6) in terms of the clean gas data for HCl and SO_2. Plants with a downstream carbon adsorber adsorber produce the lowest clean gas values. As far as heavy metals are concerned, the extremely small concentrations and large variations do not allow any differences of the systems to be detected.

Based on the data and information available on the different flue gas cleaning systems, the clean gas data presented in TABLE 16 are specified.

TABLE 16 Clean gas data to be used for the materials balances of the model flue gas cleaning systems. The volume data refer to the standard dry state (11 vol.% O2)

model plant	flue gas cleaning	HCl [mg/Nm³]	SO_2 [mg/Nm³]	Hg [mg/Nm³]	Cd [mg/Nm³]	Pb [mg/Nm³]
wet 1	ESP / scrubber-scrubber / SCR / entrained flow reactor	2	4	0,004	0,001	0,02
wet 2	ESP / scrubber-scrubber /SCR/ carbon adsorber	1,5	2	0,004	0,001	0,02
wet 3	ESP / spray dryer / ESP / scrub scrubber /SCR/ entrained f reactor	2	4	0,004	0,001	0,02
wet 4	ESP / spray dryer / ESP / scrubber-scrubber / SCR / carbon adsorber .	1,5	2	0,004	0,001	0,02
wet 5	spray dryer / fabric filter / scrubber-scrubber /SCR	3	6	0,004	0,001	0,02
wet 6	SNCR / fabric filter / scrubber-scrubber	3	6	0,004	0,001	0,02
semi wet 1	SNCR / spray absorber / fabric filter	5	10	0,004	0,001	0,02
semi wet 2	spray absorber / fabric filter / SCR	5	10	0,004	0,001	0,02
semi dry 1	SNCR / fabric filter	5	10	0,004	0,001	0,02
semi dry 2	fabric filter /SCR	5	10	0,004	0,001	0,02

7 Balances of the Flue Gas Cleaning Systems

In the present Section, the flue gas cleaning systems selected shall be presented briefly. In addition, the materials balances calculated for the elements of chlorine, sulfur, mercury, cadmium, and lead shall be explained. Before covering the individual balances in detail, some general remarks shall be made with regard to the representations of the flue gas cleaning systems and the Sankey charts for the balances.

The representations of the flue gas cleaning systems are restricted to the components indispensable for cleaning. For reasons of clarity, the flue gas cooler, heat transfer systems, flues, etc. are not represented.

The balances, given in the form of Sankey charts for the individual flue gas cleaning systems, are based on calculations made using the basic data and system assumptions outlined in Sections 5 and 6. There, a survey of the technical parameters and boundary conditions of the individual flue gas cleaning components is given. In this Section, no basic information will be given.

The procedure selected, i.e. balancing by model calculations, leads to detailed values that are plotted in Sankey charts. It must be noted that these detailed values represent typical mean values of large-scale plants.

Real data measured in large-scale waste incineration plants may deviate more or less strongly from the values given in the Sankey charts. This is due to the waste input or technical factors.

7.1 Model Plant "wet 1"

In this plant, the flue gas cleaning system of which is represented in Fig. 16, the raw gas is dedusted by an electrostatic precipitator downstream of the boiler. The dedusted raw gas enters the HCl scrubber, where hydrogen halogenides and mercury are removed. In the second scrubber, SO_2 is absorbed in a solution of sodium hydroxide. Following the SCR process, the flue gas is passed to fine cleaning by means of an entrained flow reactor. A finely grained mixture of a calcium compound and coke is injected into the flue gas upstream of the fabric filter. The residue arising in the fabric filter is disposed of.

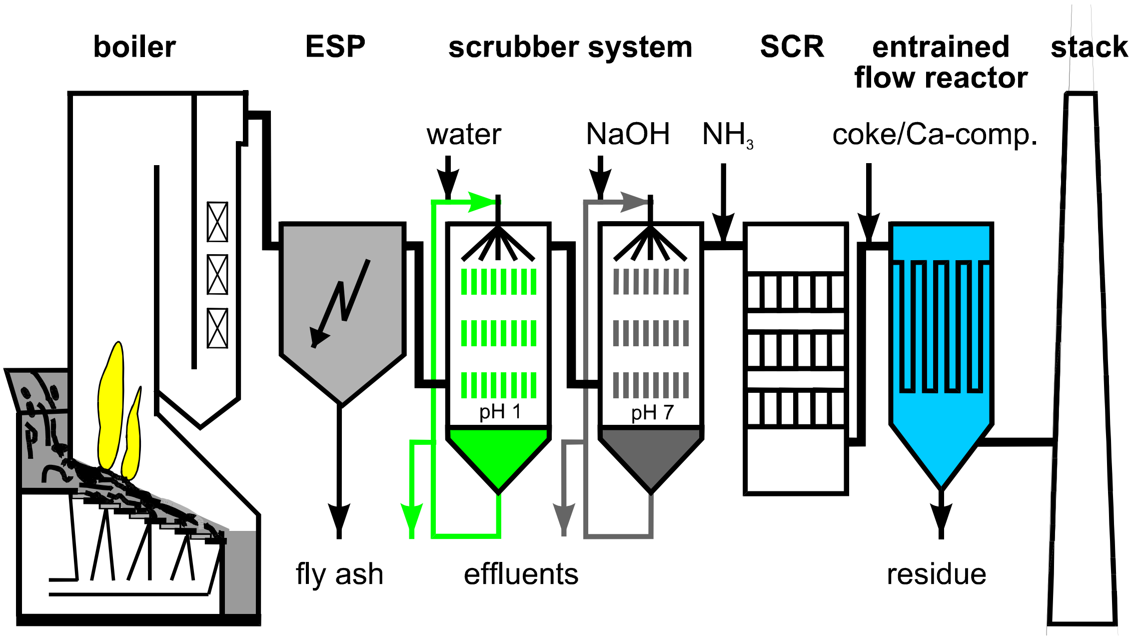

Fig. 16 **Scheme of model plant "wet 1"**

The scrubber effluents are neutralized and processed externally. The various external processing options are outside of the scope of balancing. The materials balances of plant "wet 1" shall be explained below.

Fig. 17 shows the ***chlorine balance*** of the plant. The dust-containing raw gas contains 5890 g/t_{waste} of chlorine according to the system parameters defined. Of this amount, 720 g/t_{waste} are separated as chlorides in the electrostatic precipitator dust. The remaining chlorine load, mainly gaseous HCl, is absorbed in the HCl scrubber (4587 g/t_{waste}). The SO_2 scrubber takes up 569 g/t_{waste} of chlorine only. The scrubber solutions are then transferred to external processing.

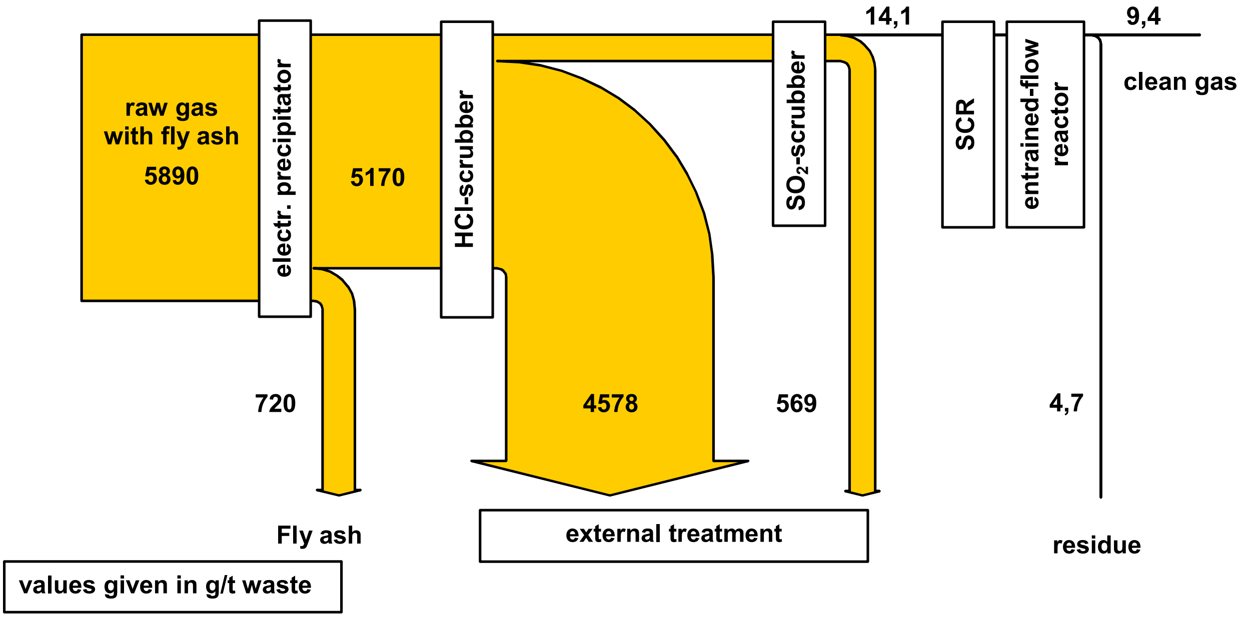

Fig. 17 **Chlorine balance of model plant "wet 1"**

Downstream of the catalytic NO_x-removal which does not affect the chlorine load of the flue gas, 14.1 g/t_{waste} of chlorine remain in the flue gas. In the last flue gas cleaning stage, the chlorine load is reduced again by a factor that depends on the type and amount of lime and coke chemicals used and other parameters.

Due to the small concentration values and variations, it is impossible to calculate an exact separation efficiency. It is assumed by the authors that a clean gas value of about 9 – 10 g/t_{waste} of chlorine can be achieved. According to TABLE 16, this corresponds to a clean gas concentration of 2 mg/Nm^3 HCl. Based on this assumption, the carbon entrainment adsorber residue contains about 5 g/t_{waste} of chlorine.

The Sankey diagram oof ***sulfur*** is shown in Fig. 18.

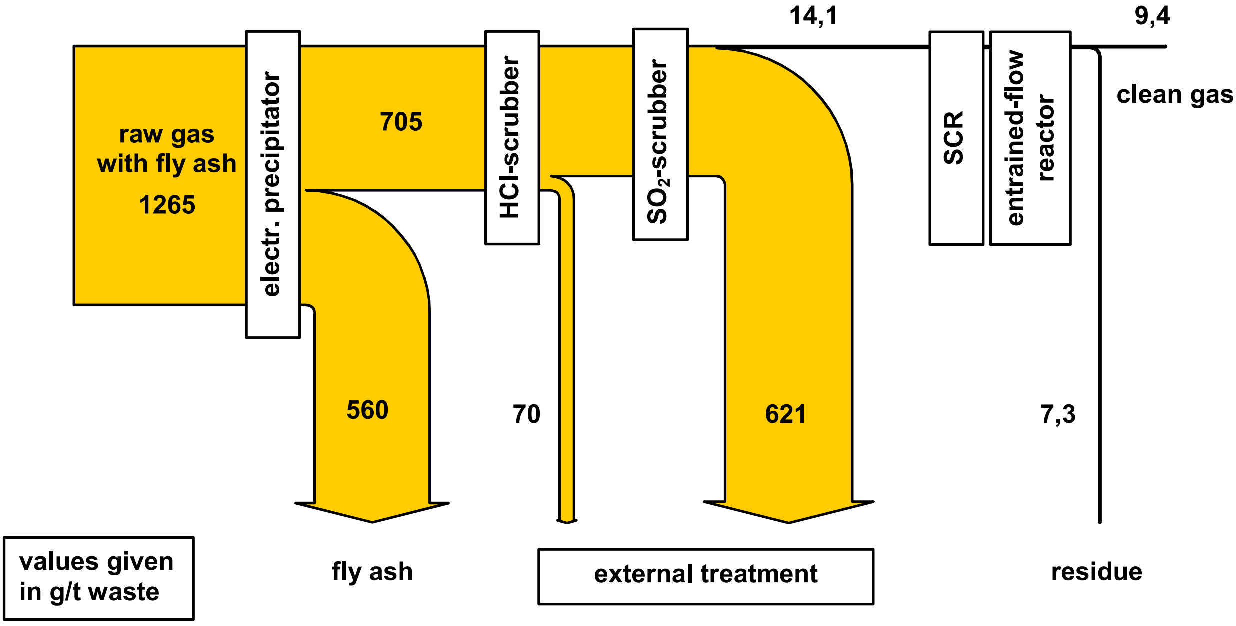

Fig. 18 Sulfur balance of model plant "wet 1"

Calculation of the sulfur load of the raw gas containing a fly dust fraction yields a value of 1265 g/t_{waste} of sulfur. As obvious from Fig. 18, distribution of sulfur in the flue gas cleaning system differs from that of chlorine. By the electrostatic precipitator, 560 g/t_{waste}, i.e. about 44 %, of sulfur are removed from the dust-containing raw gas. Only a small amount of sulfur, namely 70 g/t_{waste}, is separated in the HCl scrubber. The largest amount of sulfur of 621 g/t_{waste} is removed from the flue gas in the SO_2 scrubber.

According to further calculations, the flue gas downstream of the SO_2 scrubber still contains about 14 g/t_{waste} of sulfur. The SCR catalyst is of no relevance to the sulfur balance, but the carbon entrainment adsorber reduces the sulfur load of the flue gas by the injection of CaO and coke. As for chlorine, sulfur separation efficiency is rather difficult to estimate due to the small concentrations and variations. A clean gas value of about 9 – 10 g/t_{waste} can be complied with easily by this flue gas cleaning system. This means that about 7 g/t_{waste} remain in the residue of the carbon entrainment adsorber.

Fig. 19 shows the expected distribution of ***mercury*** in the flue gas cleaning system of "wet 1".

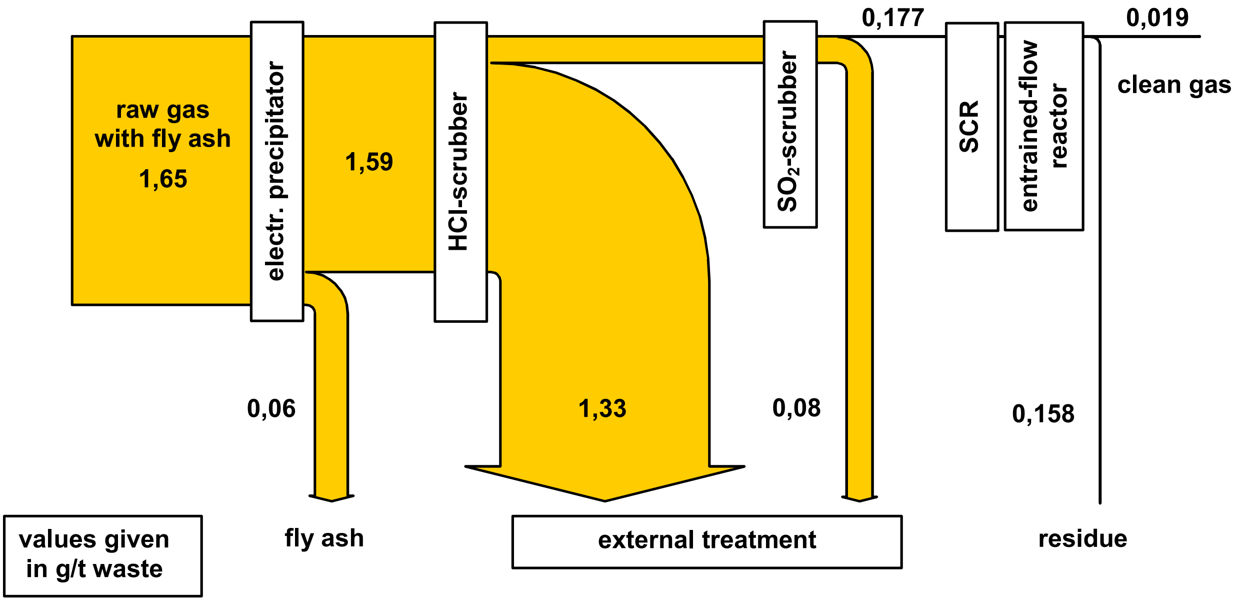

Fig. 19 **Mercury balance of model plant "wet 1"**

According to the basic data specified, the raw gas with the dust contains a mercury load of 1.65 g/t_{waste}. A very small fraction of 0.06 g/t_{waste} only is contained in the fly dust and separated by the electrostatic precipitator. The largest fraction of mercury in the dedusted raw gas of 1.33 g/t_{waste} is absorbed from the gas phase by the scrubbing liquid of the HCl scrubber. In the SO_2 scrubber, small amounts (0.083 g/t_{waste}) are retained by the NaOH solution.

According to calculations, 0.177 g/t_{waste} of mercury remain in the flue gas leaving the SO_2 scrubber. By means of the carbon entrainment process, this load again is reduced considerably by adsorption on the coke injected. For the clean gas, a value of 0.019 g/t_{waste} of mercury is assumed. According to TABLE 16, this corresponds to a clean gas concentration of 0.004 mg/Nm^3 Hg. The residue generated by the carbon entrainment process then contains 0.158 g/t_{waste} of mercury.

As obvious from Fig. 20, 5.76 g/t_{waste} of ***cadmium*** are contained in the raw gas in accordance with the values specified in Sections 5 and 6. This amount also includes the fly dust fraction.

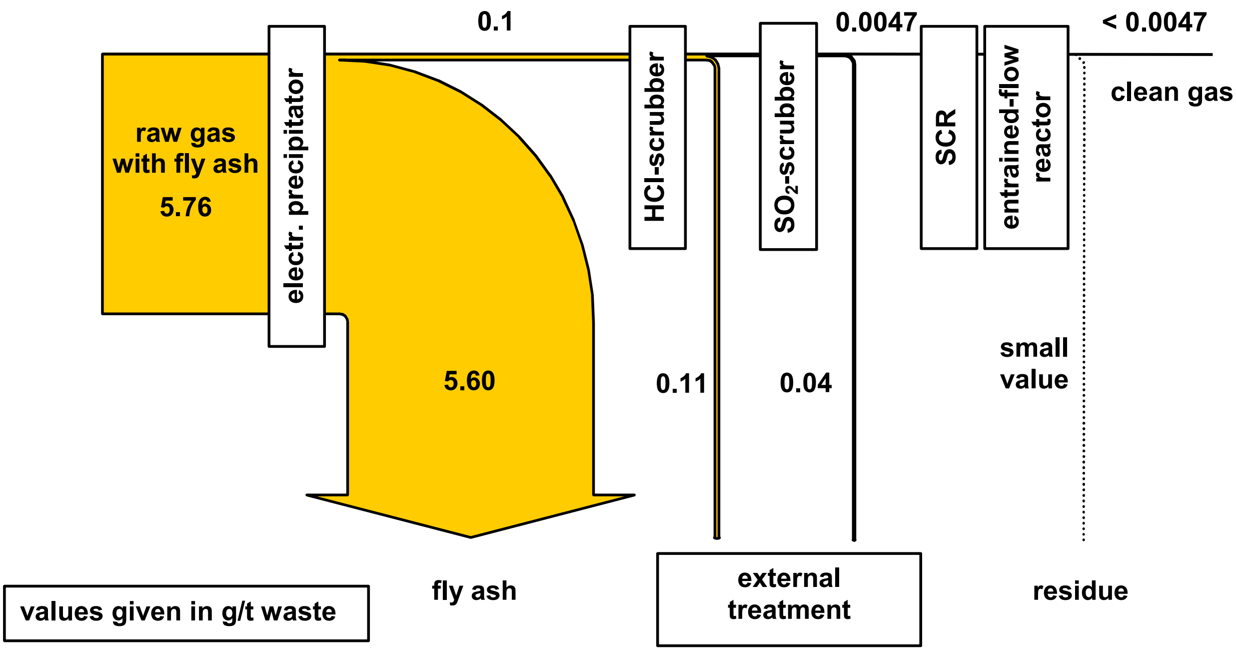

Fig. 20 **Cadmium balance of model plant "wet 1"**

Together with the fly dust, cadmium is nearly completely (about 98 %) removed from the raw gas by the electrostatic precipitator. Very small amounts of 0.16 g/t_{waste} of cadmium only remain in the dedusted raw gas. Of this, a large fraction (0.11 g/t_{waste}) is absorbed by the aqueous phase in the HCl scrubber. The remaining amount (about 0.04 g/t_{waste}) is taken up nearly completely by the NaOH solution in the SO_2 scrubber. Very small amounts (0.0047 g/t_{waste}) of cadmium remain in the flue gas leaving the scrubber system.

The downstream SCR catalyst is of no relevance to cadmium. As shown in Fig. 20, cadmium load is not assumed to be changed in the carbon entrainment adsorber. Due to the very small concentration values in the flue gas and the observed variations of the values measured, separation efficiency cannot be calculated. For the load of the clean gas, a value smaller than 0.0047 g/t_{waste} of cadmium is assumed. According to TABLE 16, this corresponds to a clean gas concentration of less than 0.001 mg/Nm^3 cadmium.

Distribution of ***lead*** in the different materials flows is similar to that of cadmium. Fig. 21 shows the flow of lead in the flue gas cleaning system of "wet 1" studied.

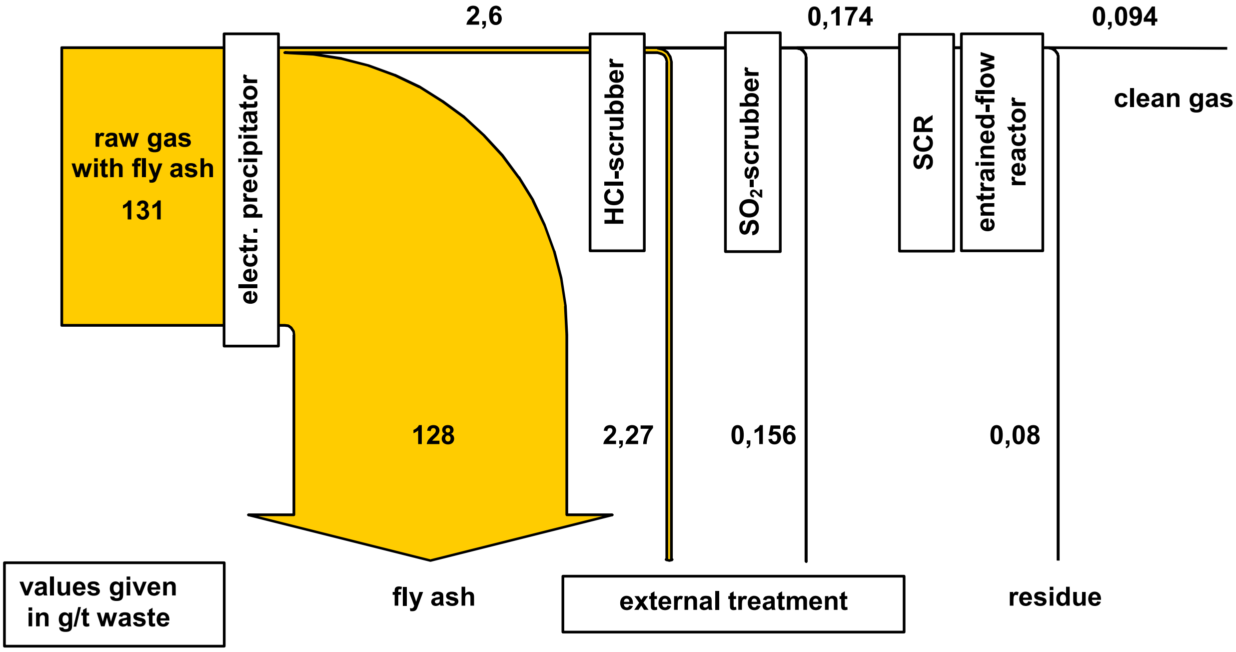

Fig. 21 Lead balance of model plant "wet 1"

Nearly the complete lead load of the raw gas is separated by the electrostatic precipitator in the form of dust. Of the 131 g/t_{waste} of lead in the dust-bearing raw gas, about 98 % are contained in the fly dust. The lead remaining in the dedusted raw gas is mainly (2.27 g/t_{waste}) separated in the HCl scrubber. Following absorption of about 0.156 g/t_{waste} of lead in the second scrubber, about 0.17 g/t_{waste} of lead remain in the flue gas passing the SCR catalyst. Contrary to cadmium, for which no separation efficiency of the carbon entrainment absorber could be given due to the very small concentrations in the flue gas, a lead separation efficiency can be calculated, as concentration is much higher. In the clean gas, the lead load is assumed to be about 0.095 g/t_{waste}, i.e. about 0.08 g/t_{waste} of lead are contained in the fabric filter residue. According to TABLE 16, this corresponds to a clean gas concentration of 0.02 mg/Nm^3 lead.

7.2 Model Plant "wet 2"

The first stage of the flue gas cleaning system of model plant "wet 2"is an electrostatic precipitator for dust removal. It is followed by a multi-stage scrubber system for the absorption of acid pollutants. This scrubber system consists of an HCl scrubber and an SO_2 scrubber. Removal of NO_X of the flue gases is accomplished by the SCR process. The last stage consists of fine cleaning by means of a carbon adsorber. As shown in Fig. 22, the setup of model plant "wet 2" is identical to that of model plant "wet 1", except for fine cleaning.

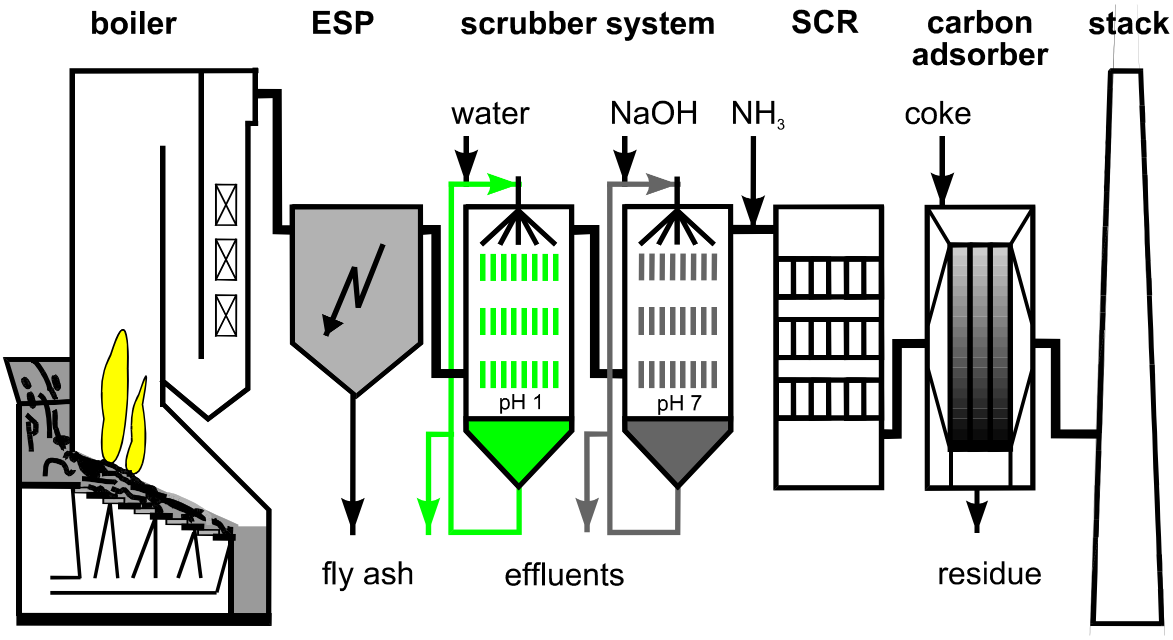

Fig. 22 **Scheme of Model Plant "wet 2"**

Materials balances of the plant "wet 2" largely correspond to the balances of plant "wet 1". The only difference is fine cleaning, as somewhat improved separation efficiencies regarding acid pollutants are assumed for the carbon adsorber.

Heavy metal balances of the plants "wet 1" and "wet 2" are identical. Due to the small concentrations in the flue gas and large variations, no significant differences of the separation efficiencies of the various fine-cleaning stages can be determined.

Up to the flue gas upstream of the carbon adsorber, the ***chlorine balance*** corresponds to that of "wet 1". The exact data are shown in Fig. 23.

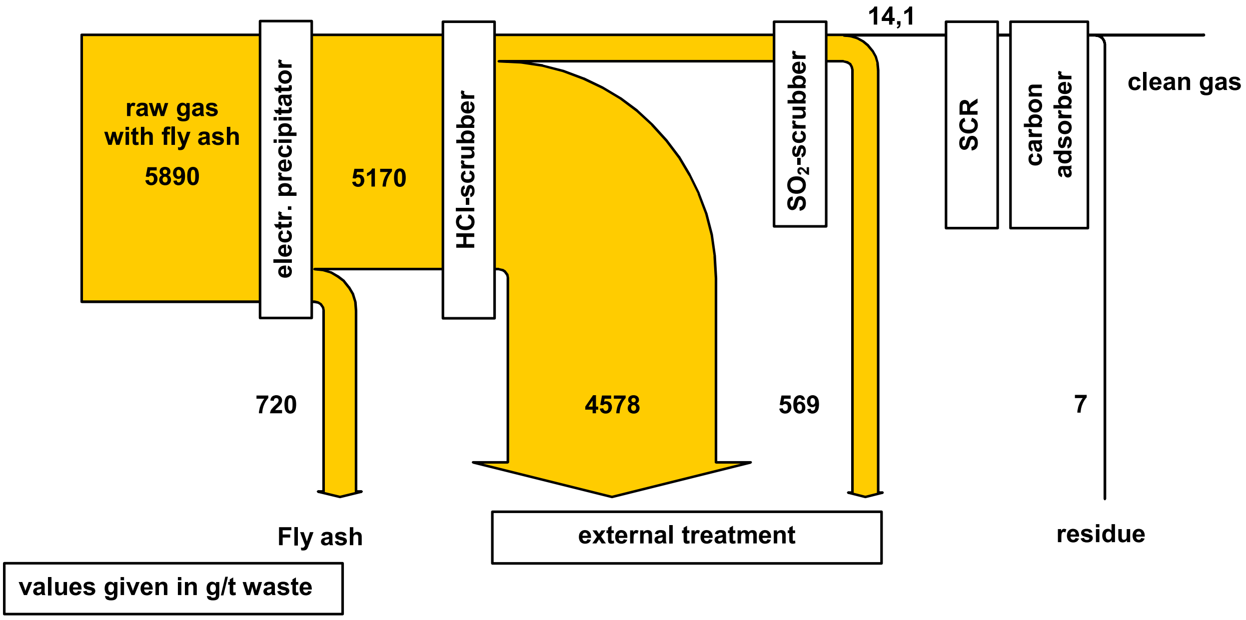

Fig. 23 **Chlorine Balance of Model Plant "wet 2"**

Starting from 5890 g/t_{waste} of chlorine in the raw gas and dust, the electrostatic precipitator separates 720 g/t_{waste}. The largest amount of chlorine of 4587 g/t_{waste} is separated from the flue gas in the HCl scrubber. Only a small amount of chlorine (569 g/t_{waste}) is absorbed by the alkaline scrubbing liquid of the SO_2 scrubber. 14.1 g/t_{waste} of chlorine remain in the flue gas leaving the second scrubber. Chlorine is assumed to be separated also by fine cleaning with a carbon adsorber, such that a clean gas value of 7 g/t_{waste} of chlorine results. About the same amount of chlorine is taken up by the coke.

Fig. 24 shows the Sankey chart for the sulphur balance. Sulphur distribution corresponds to that of plant "wet 1" except for fine cleaning.

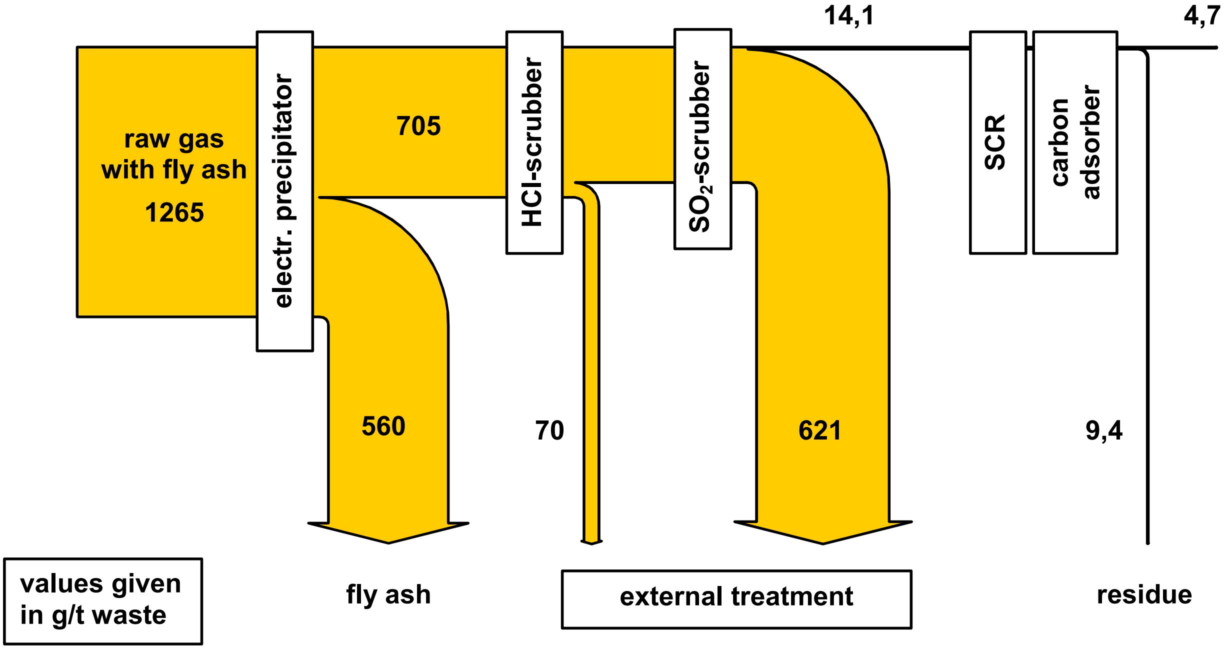

Fig. 24 **Sulphur Balance of Model Plant "wet 2"**

Of the 1265 g/t_{waste} of sulfur in the raw gas and dust, 705 g/t_{waste} of sulfur remain in the dust-free raw gas following dedusting. About 44 % of the sulfur, corresponding to 560 g/t_{waste}, are contained in the electrostatic precipitator dust. According to calculations, only small amounts, i.e. 70 g/t_{waste}, of sulfur are absorbed by the hydrochloric-acid aqueous phase in the first scrubber. Major sulfur separation of about 50 % of the load of the dust-containing raw gas takes place in the SO_2 scrubber. Downstream of the scrubbers, 14.1 g/t_{waste} of sulfur are contained in the flue gas. The SCR catalyst has no influence on the distribution of sulfur in the flue gas cleaning system. The last cleaning stage consists of a carbon adsorber, by means of which the sulfur load of the flue gas is reduced considerably. According to the calculations performed, about 5 g/t_{waste} of sulfur remain in the clean gas. The sulfur-loaded coke is fed back into the furnace.

The mercury, cadmium, and lead balances are shown in Fig. 25, Fig. 26 and Fig. 27, respectively. As explained above, heavy metal distributions in plant "wet 2" are identical with those of plant "wet 1". The carbon adsorber was assumed to have the same separation efficiencies as the carbon entrainment adsorber of plant "wet 1".

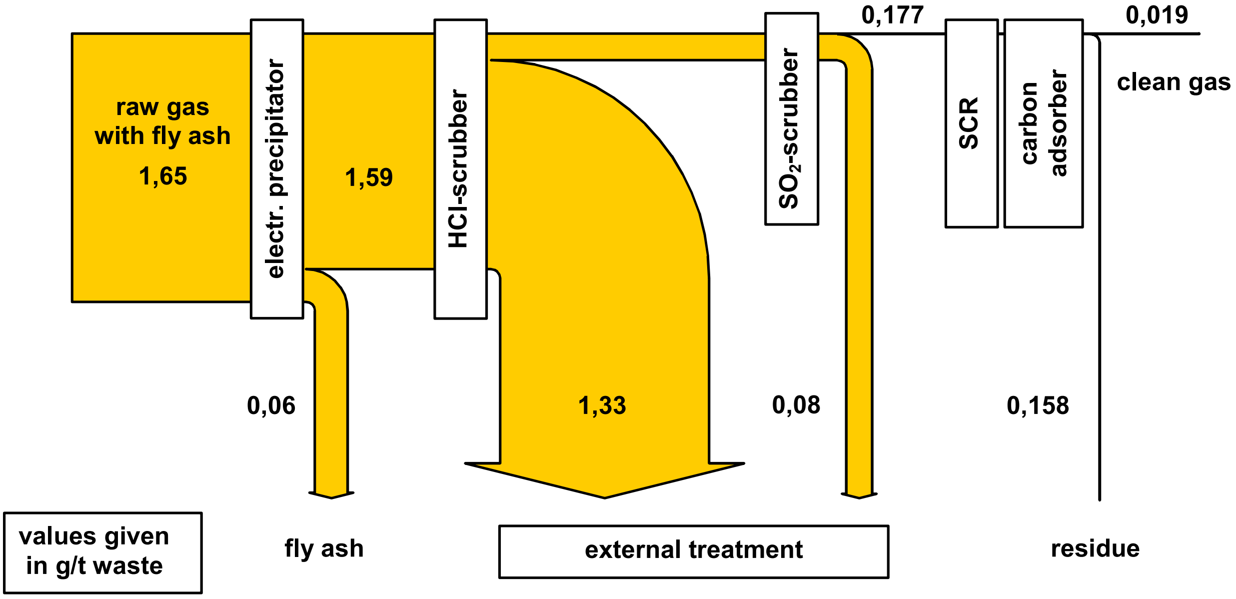

Fig. 25 Mercury Balance of Model Plant "wet 2"

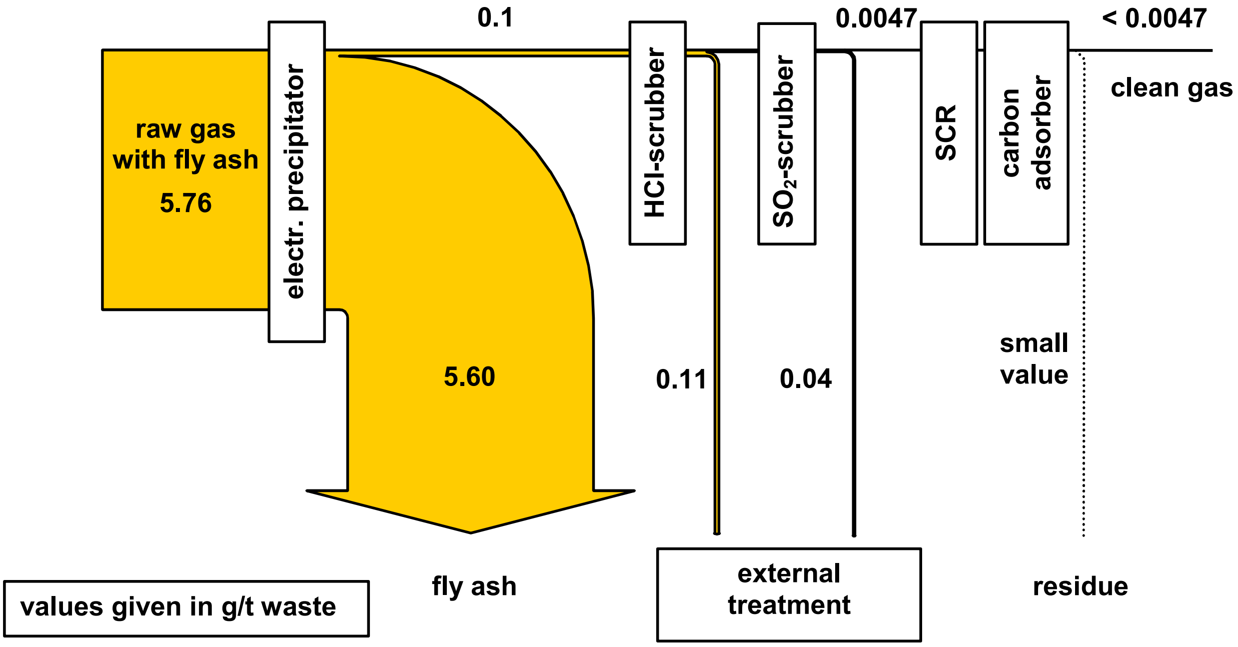

Fig. 26 Cadmium Balance of Model Plant "wet 2"

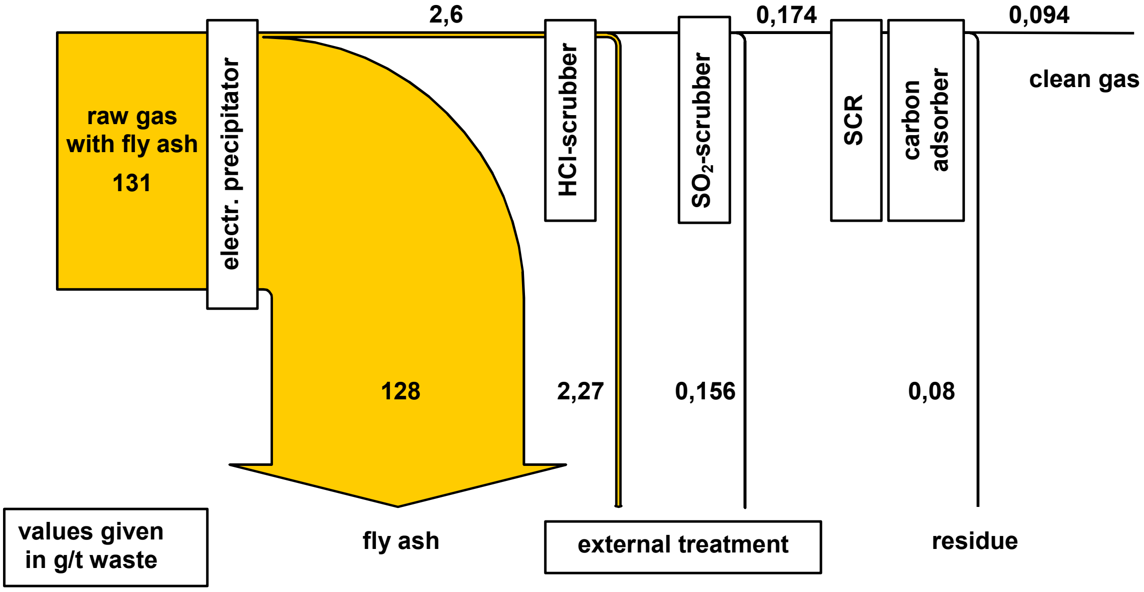

Fig. 27 Lead Balance of Model Plant "wet 2"

7.3 Model Plant "wet 3"

As evident from Fig. 28, the flue gas cleaning system consists of an electrostatic precipitator , a spray dryer, second electrostatic precipitator, an HCl scrubber, an SO_2 scrubber, an SCR catalyst, and a carbon entrainment adsorber. Hence, plant "wet 3" differs from the plants "wet 1" and !wet 2" by the spray dryer and electrostatic precipitator installed between the first electrostatic precipitator and the HCl scrubber. Due to internal evaporation, external processing of the effluents is not required. The plant is designed such that the materials flows leaving the scrubber are passed on to the spray dryer and discharged as solids.

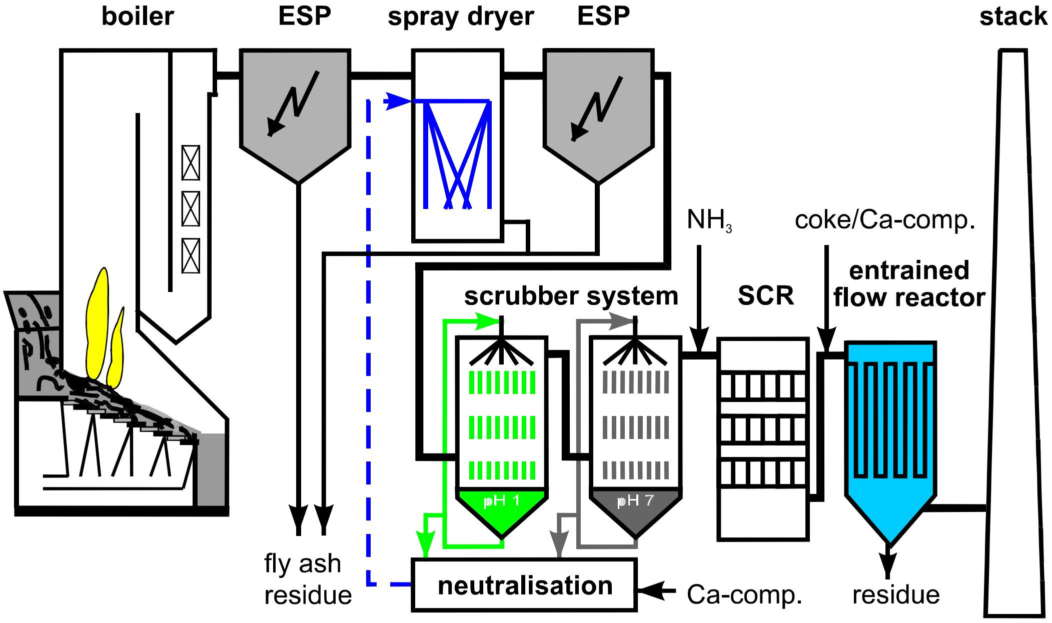

Fig. 28 Scheme of Model Plant "wet 3"

Dedusting of the raw gas is accomplished by the first electrostatic precipitator downstream of the boiler. The next system component is the spray dryer, where the neutralized scrubber solutions from the scrubber system are evaporated by approximately the about 200 °C hot, dedusted flue gases. Downstream of the spray dryer, the flue gas contains large fractions of the flue gas cleaning product, which are then separated in the second electrostatic precipitator.

As in plants "wet 1" and "wet 2", mainly HCl, mercury, and SO_2 are absorbed by the aqueous solutions in the downstream scrubbers. In the second scrubber, sodium hydroxide is applied for pH control. The loaded scrubber solutions are fed to the neutralization stage, where they are transformed into gypsum and other salts using calcium hydroxide. The suspension obtained is passed on to the spray dryer.

For further flue gas cleaning, an SCR catalyst and a carbon entrainment system are installed. Here, the pollutant content remaining in the flue gas is reduced again using a mixture of a calcium compound and coke.

The materials balances of plant "wet 3" shall be presented in detail below. Fig. 29 shows the chlorine balance.

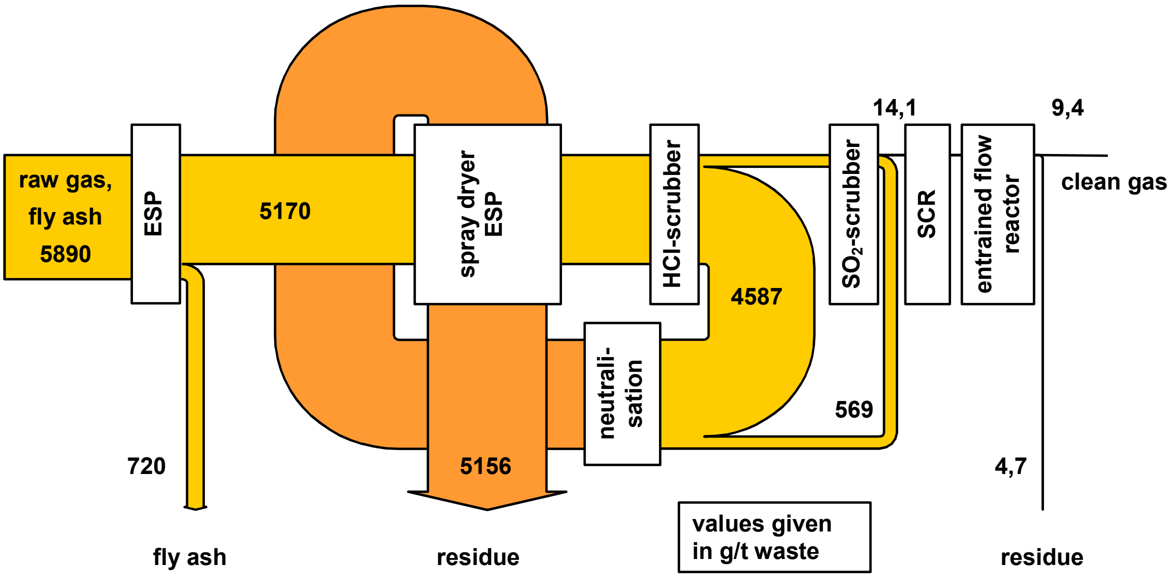

Fig. 29 **Chlorine Balance of Model Plant "wet 3"**

Balancing is based on a chlorine load of the dust-containing raw gas of 5890 g/t_{waste}. As in the model plants "wet 1" and "wet 2", 720 g/t_{waste} are removed by the electrostatic precipitator. The dedusted raw gas is then passed on to the spray dryer, where no chlorine is assumed to be separated from the flue gas.

Main chlorine separation takes place in the first scrubber (4587 g/t_{waste}). In the second scrubber, only small amounts of chlorine (569 g/t_{waste}) are absorbed by the scrubbing liquid. The scrubber effluents which contain a total of 5156 g/t_{waste} of chlorine are neutralized in the neutralization stage using $Ca(OH)_2$. The generated solution with sodium and calcium chlorides is returned to the spray dryer. The residue arising here contains 5156 g/t_{waste} of chloride.

Downstream of the SCR catalyst which does not affect the chlorine load of the flue gas, the chlorine load of the flue gas is further reduced in the carbon entrainment adsorber using a lime/coke mixture. Due to the very small concentrations and variations, a clean gas value can only be estimated. According to TABLE 16, a clean gas value of 9 g/t$_{waste}$ is assumed. This means that about 5 g/t$_{waste}$ of chlorine are separated by the carbon entrainment adsorber.

According to Fig. 30, the sulfur load of the raw gas and dust is 1265 g/t$_{waste}$. By means of the first electrostatic precipitator, 560 g/t$_{waste}$ of sulfur contained in the filter dust are separated from the flue gas. About 705 g/t$_{waste}$ sulfur remain in the dedusted raw gas. As for chlorine, it is again assumed in first approximation that no direct separation of sulfur from the dedusted raw gas takes place in the spray dryer. Hence, the sulfur load of the dust-free flue gas leaving the first electrostatic precipitator corresponds to the load upstream of the HCl scrubber.

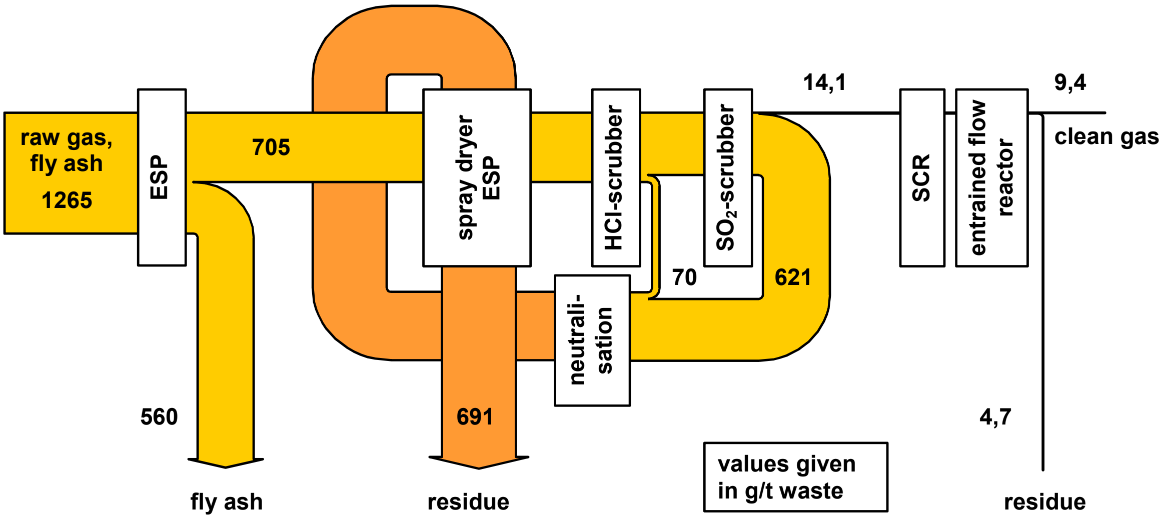

Fig. 30 Sulfur Balance of Model Plant "wet 3"

Small amounts of sulfur (70 g/t$_{waste}$) are absorbed in the HCl scrubber at pH 0 – 1. In contrast to this, the SO_2 scrubber removes the largest sulfur fraction (621 g/t$_{waste}$). A small residual amount of 14.1 g/t$_{waste}$ of sulfur remains in the flue gas downstream of the scrubbers. This corresponds to 0.8 % of the raw gas load, including dust fraction. According to the calculations, this amount enters the carbon entrainment adsorber together with the flue gas. As in the other model plants, separation efficiencies of this fine-cleaning stage can only be estimated. The concentration values given in TABLE 16 result in a clean gas load downstream of the carbon entrainment adsorber of 9.4 g/t$_{waste}$. Hence, about 5 g/t$_{waste}$ of sulfur are separated by the adsorber.

The ***mercury balance*** is represented in Fig. 31. Of the 1.65 g/t$_{waste}$ of mercury contained in the raw gas and dust fraction, 0.06 g/t$_{waste}$ are separated in the electrostatic precipitator. 1.59 g/t$_{waste}$ of mercury remain in the dedusted raw gas. This flue gas load is the same downstream of the spray dryer. The increased concentration downstream of the spray dryer, which is observed in some large-scale plants, is neglected here. These increased mercury concentrations are attributed to the thermal instability of the mercury complexes existing in the scrubber effluents [Albert] as well as to the volatility of mercury chloride.

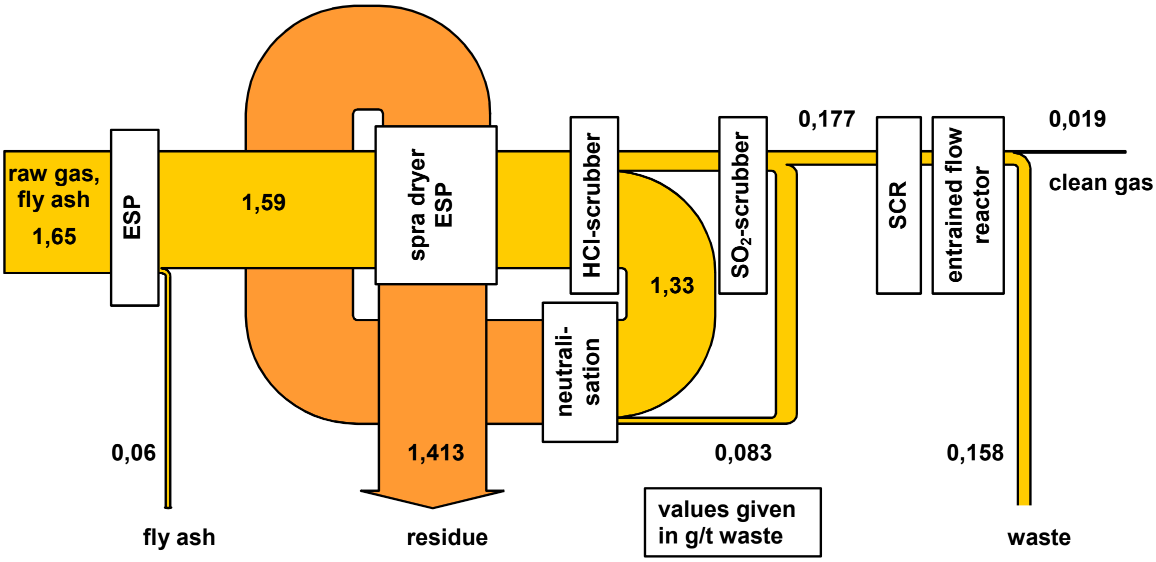

Fig. 31 Mercury Balance of Model Plant "wet 3"

In the downstream HCl scrubber, main mercury separation from the gas phase takes place. 1.33 g/t_{waste} of mercury are absorbed by the HCl-acid scrubber liquid. Small fractions of mercury (0.08 g/t_{waste}) are taken up by the sodium hydroxide solution of the SO_2 scrubber.

The mercury separated in the scrubbers enters the neutralization stage together with the scrubber effluents. There, calcium hydroxide for neutralization and TMT-15™ of the Degussa company as heavy-metal precipitating agent ant are added. By means of this precipitating agenat, about 99 % of the mercury dissolved in the aqueous solution are precipitated [Achternbosch-1]. Following the evaporation of the effluents in the spray dryer, 1.41 g/t_{waste} mercury are contained in the residue that is discharged from the plant near the second electrostatic precipitator. This residue needs to be disposed of.

The SCR catalyst is of no relevance to balancing. Upstream and downstream of SCR unit, 0.177 g/t_{waste} of mercury are contained in the flue gas. As for all fine-cleaning stages, a clean gas value has to be assumed for the separation of mercury in the carbon entrainment adsorber. Assuming a clean gas value of 0.019 g/t_{waste} of mercury, 0.158 g/t_{waste} of mercury leave the system together with the carbon entrainment residue. According to TABLE 16, this corresponds to a clean gas concentration of 0.004 mg/Nm^3 of mercury.

For ***cadmium***, a load of 5.76 g/t_{waste} has been specified for the dust-bearing raw gas. Distribution of cadmium in the individual materials flows is obvious from Fig. 32.

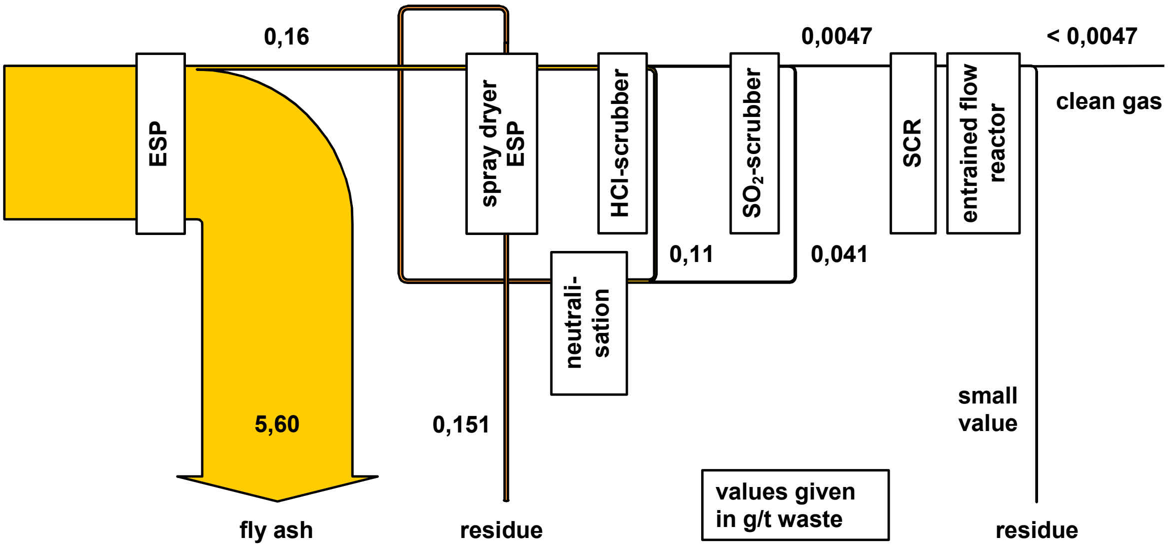

Fig. 32 **Cadmium Balance of Model Plant "wet 3"**

In the first flue gas cleaning component, about 98 % (5.6 g/t_{waste}) of the total cadmium inventory are separated from the flue gas by dedusting. 0.16 g/t_{waste} of cadmium only pass the spray dryer and enter the HCl scrubber, where the largest fraction (0.11 g/t_{waste}) of the load remaining in the dedusted raw gas is separated. According to calculations, 0.045 g/t_{waste} of cadmium are retained by the SO_2 scrubber, such that the flue gas leaving the scrubber systems contains very small amounts of cadmium only.

Based on the concentration given in TABLE 16, it is assumed for the separation by the carbon entrainment adsorber that the clean gas load amounts to about 0.0047 g/t_{waste}. This value is identical for all fine-cleaning stages of the wet model plants. By means of carbon entrainment, cadmium load of the flue gas is about halved.

As evident from Fig. 33, also ***lead*** is nearly completely separated from the raw gas by the electrostatic precipitator.

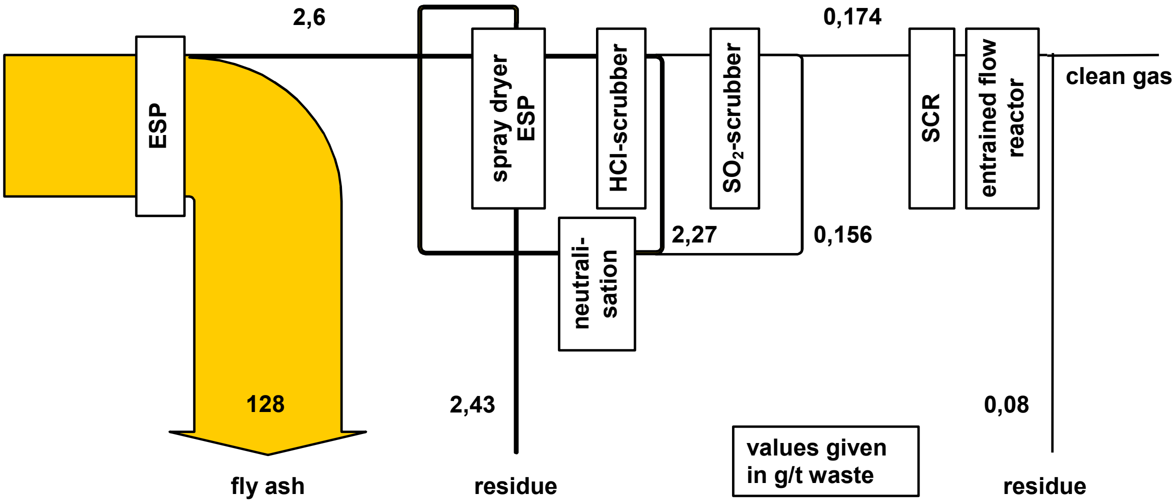

Fig. 33 **Lead Balance of Model Plant "Wet 3"**

Of the 131 g/t_{waste} of lead contained in the raw gas and dust, only 2.6. g/t_{waste} remain in the flue gas following dedusting. This load is the same downstream of the spray dryer. In the downstream HCl scrubber, 2.27 g/t_{waste} of lead are separated. The next SO_2 scrubber absorbs 0.156 g/t_{waste} of lead.

According to calculations, 0.174 g/t_{waste} of lead are contained in the flue gas leaving the scrubber. Without being modified by the SCR catalyst, this heavy metal load reaches the carbon entrainment adsorber. A clean gas value of 0.094 g/t_{waste} of lead is assumed. Hence, 0.08 g/t_{waste} of lead are separated by the adsorber.

7.4 Model Plant "wet 4

Flue gas cleaning of the model plant "wet 4" corresponds to that of "wet 3", except for fine cleaning. Instead of an entrained flow reactor, the last cleaning unit installed in plant "wet 4" is a carbon adsorber. Model plant "wet 4" is shown in Fig. 34.

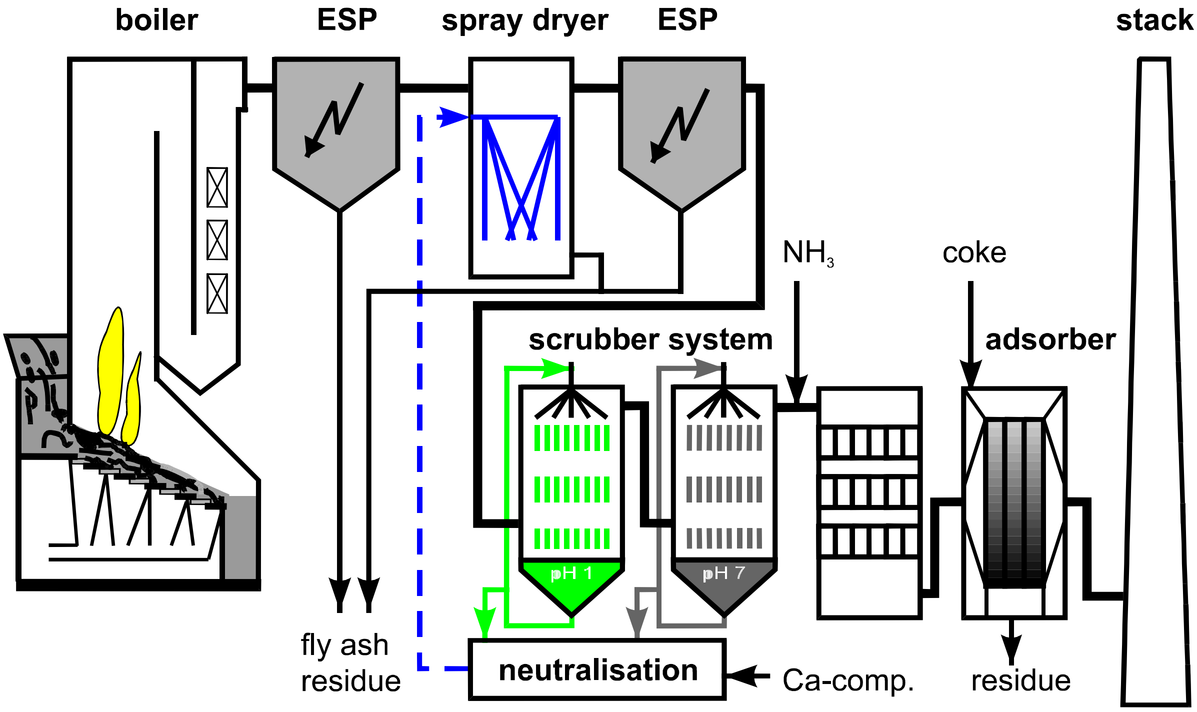

Fig. 34 **Scheme of Model Plant "wet 4"**

First, the raw gas from the boiler is dedusted in an electrostatic precipitator. In the downstream spray dryer, the neutralized scrubber effluents are evaporated using the residual heat of the flue gases. The salt residues arising in the form of dust are separated from the flue gas in the second electrostatic precipitator. Then, the gaseous pollutants are removed from the dust-free flue gas in the 2-stage scrubber system. The effluents produced contain hydrogen halides as aqueous acids (HCl etc.) and SO_2 in the form of salts.

The scrubber effluents are passed on to a neutralization stage, where a heavy-metal precipitant (TMT-15) is added together with calcium hydroxide for neutralization. The suspension arising is returned to the spray dryer for evaporation. Further flue gas cleaning stages installed are a SCR unit and a carbon adsorber for fine cleaning of the flue gases.

In analogy to the model plants studied so far, Fig. 35 first shows the ***chlorine balance***.

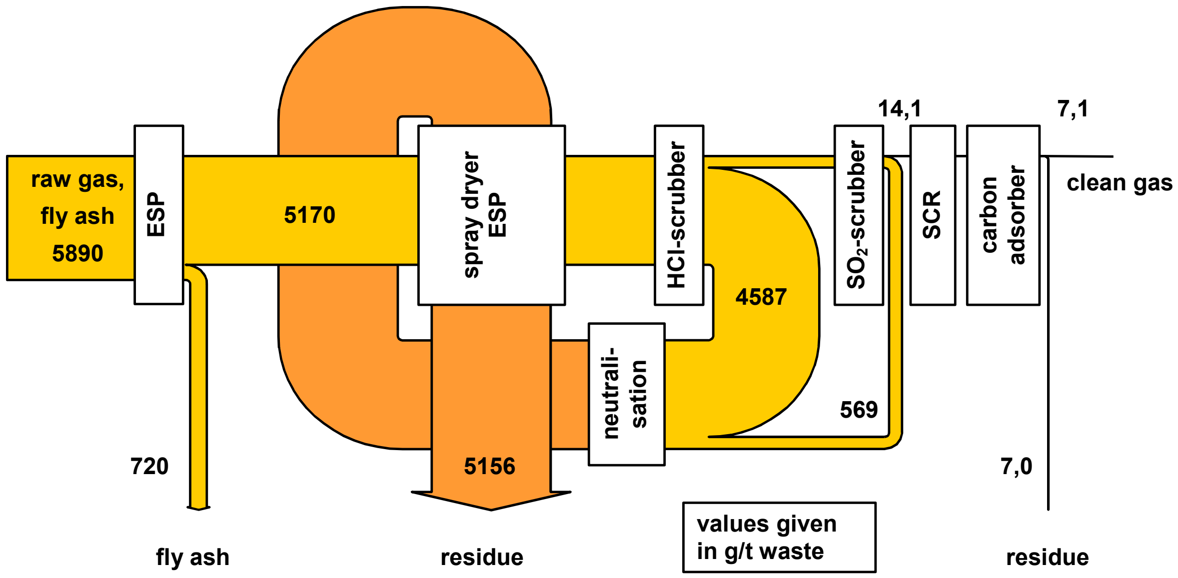

Fig. 35 **Chlorine Balance of Model Plant "wet 4"**

In accordance with the other model plants, 5890 g/t$_{waste}$ of chlorine are contained in the dust-containing raw gas downstream of the boiler of plant "wet 4". The chlorine balance corresponds to that of "wet 3"" up to the carbon adsorber. About 720 g/t$_{waste}$ of chlorine are removed from the raw gas by means of the electrostatic precipitator. Chlorine load of the gas phase is not changed by the spray dryer. 4587 g/t$_{waste}$ and 569 g/t$_{waste}$ of chlorine are then separated in the first and second scrubber, respectively. All scrubber effluents and, hence, the dust-like flue gas cleaning residue from the second electrostatic precipitator contain 5156 g/t$_{waste}$ of chloride.

Following the SCR process which is of no relevance to chlorine balancing, the chlorine load again is reduced significantly in the last flue gas cleaning stage. As explained in Section 6, it is difficult to give a representative chlorine separation efficiency for fine cleaning. Compared to the entrained flow reactor, the carbon adsorber is assumed to have a somewhat higher chlorine separation efficiency. Based on the concentration value given in TABLE 16, a clean gas value of 7.1 g/t$_{waste}$ is obtained. According to calculations, about 7 g/t$_{waste}$ of chlorine are separated by the carbon adsorber.

Sulfur distribution also is identical to that of plant "wet 3" up to the carbon adsorber. This balance is shown in Fig. 36

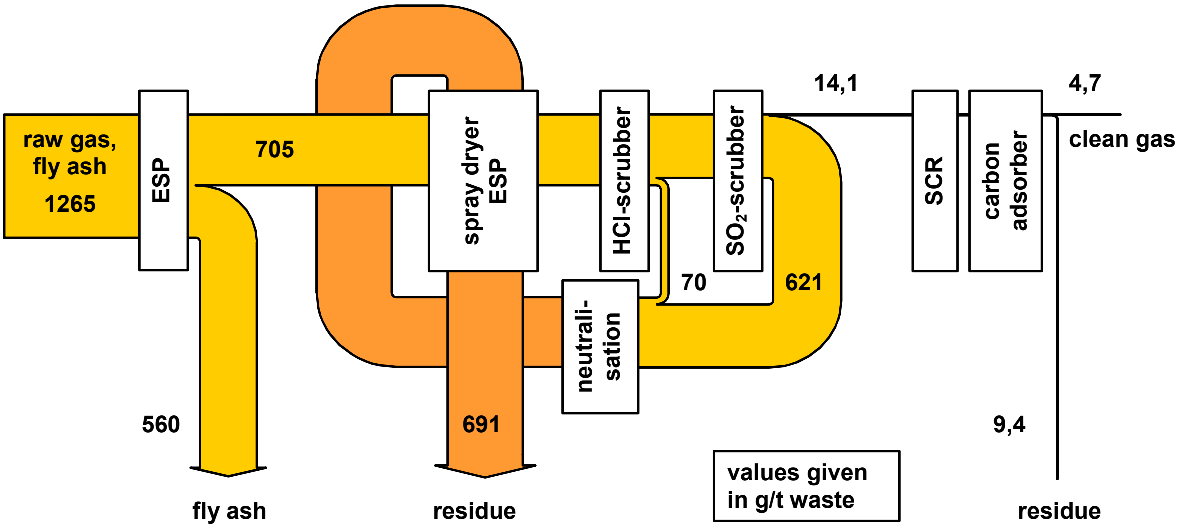

Fig. 36 Sulfur Balance of Model Plant "wet 4"

560 g/t_{waste} of the 1265 g/t_{waste} of sulfur contained in the raw gas and dust are separated by the electrostatic precipitator. The dedusted raw gas passes the spray dryer without the sulfur load being modified. Upstream of the scrubber system, sulfur load amounts to 705 g/t_{waste}. 70 g/t_{waste} of sulfur are retained by the first scrubber.

The main amount of sulfur of 621 g/t_{waste} is separated by the second scrubber. Downstream of the scrubber system, only 14.1 g/t_{waste} of sulfur are contained in the flue gas. This load is not affected by the SCR catalyst. When assuming a clean gas load in the range of 5 g/t_{waste} sulfur based on the concentration value given in TABLE 16, about 9 g/t_{waste} sulfur are removed by the carbon adsorber.

The balances of mercury, cadmium, and lead are shown in Fig. 37, Fig. 38 and Fig. 39, respectively. Due to our system assumptions, the balances are identical with those of plant "wet 3". It is therefore referred to the explanations given in the corresponding Sections.

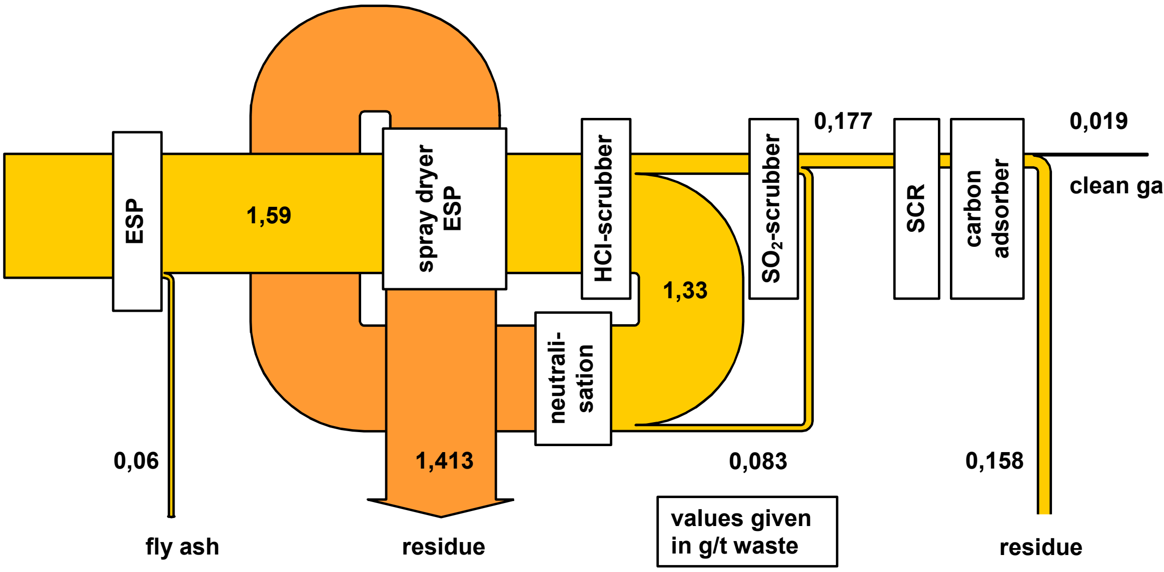

Fig. 37 Mercury Balance of Model Plant "wet 4"

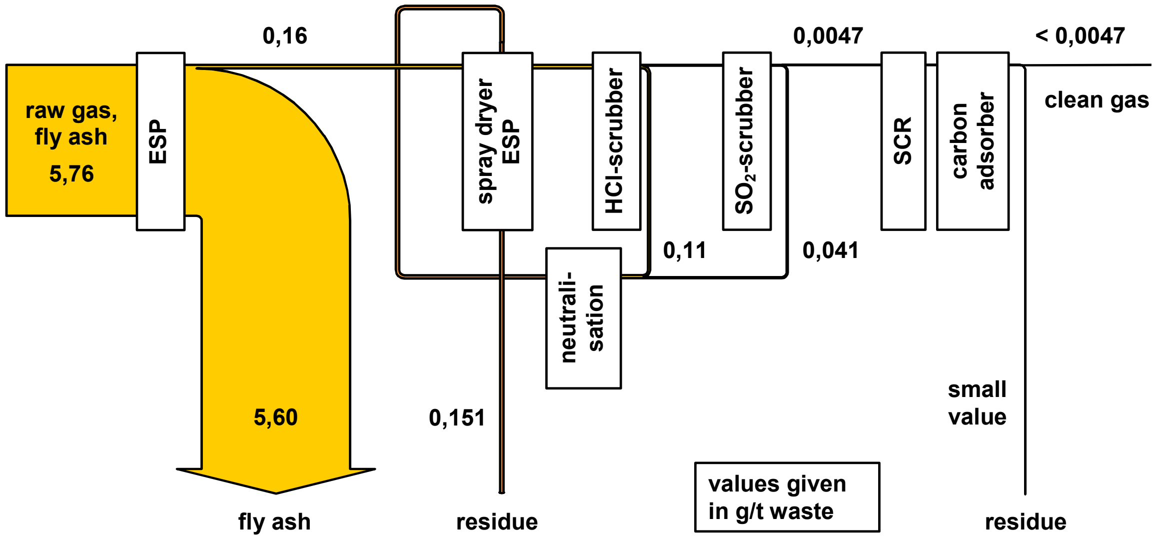

Fig. 38 **Cadmium Balance of Model Plant "wet 4"**

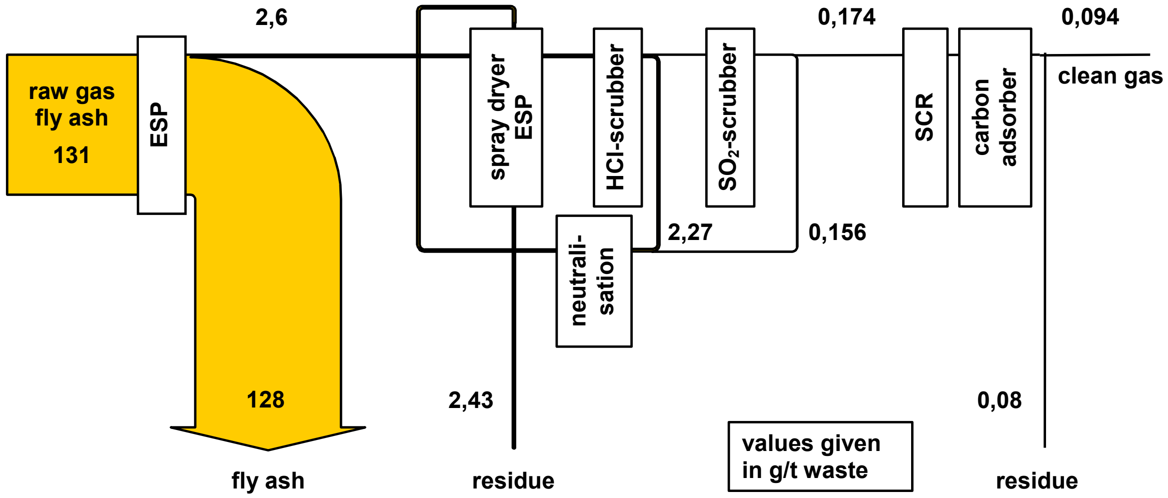

Fig. 39 **Lead Balance of Model Plant "wet 4"**

7.5 Model Plant "wet 5"

The flue gas cleaning system of plant "wet 5", which is shown in Fig. 40, consists of a spray dryer, a fabric filter, a two-stage scrubbing system, and an SCR system. Contrary to the plants discussed above, "wet 5" is not equipped with a fine-cleaning stage upstream of the stack. For compliance with the limit values given in the 17th Federal Emission Control Ordinance, a fabric filter is installed, where coke is injected.

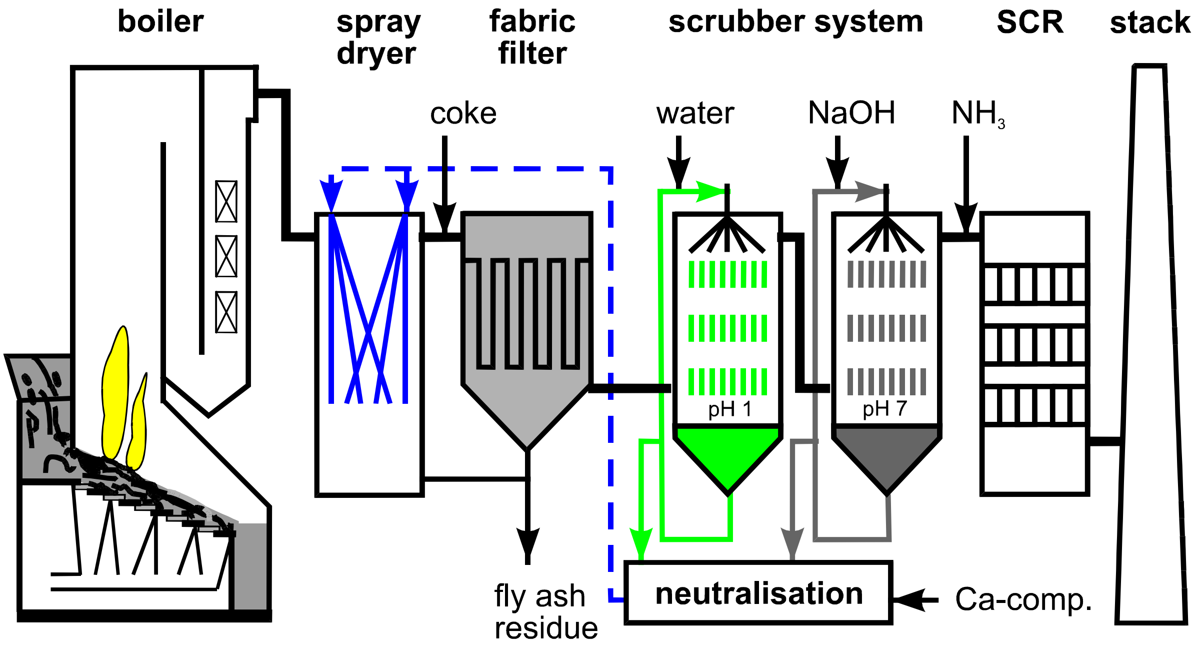

Fig. 40 **Scheme of Model Plant "Wet 5"**

The dust-containing raw gas from the boiler directly enters the spray dryer, where the heat contained in the raw gas is used for the evaporation of the scrubber effluents. Together with the flue gas, fly dust and the major fraction of the evaporated flue gas cleaning residues enter the fabric filter. Coke is injected into the flue gas upstream of the fabric filter for the separation of organic pollutants and heavy metals, in particular mercury.

The acid pollutants and mercury remaining in the raw gas are separated by absorption in the scrubbers. Flue gas cleaning ends with an NO_x reduction using ammonia in the SCR catalyst.

The materials balances shall be presented below. Fig. 41 shows the ***chlorine balance***.

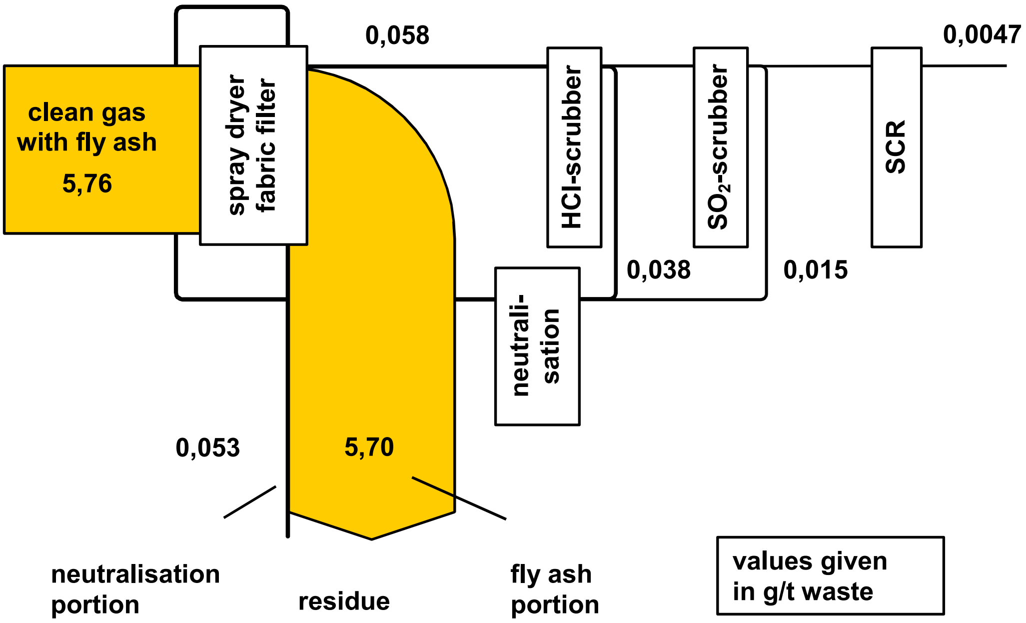

Fig. 41 **Chlorine Balance of Model Plant "wet 5"**

With an initial chlorine load of 5890 g/t_{waste} contained in the raw gas and dust, the flue gas enters the spray dryer, where no separation of chlorine is assumed to take place. In the downstream fabric filter, 720 g/t_{waste} of dust-bound chlorine are separated from the raw gas.

The HCl scrubber absorbs the largest part of the chlorine fraction from the raw gas (4587 g/t_{waste}), while the SO_2 scrubber takes up small amounts only (569 g/t_{waste}). The chloride-loaded scrubber effluents are then neutralized in a neutralization stage with calcium hydroxide and evaporated in the spray dryer. The solid residue arising is separated by the fabric filter together with the fly dust.

According to calculations, the fabric filter residue contains 5876 g/t_{waste} of chlorine. About 5156 g/t_{waste} of this amount originate from the evaporated effluents, 720 g/t_{waste} from the fly dust. As the SCR catalyst does not influence the chlorine load remaining in the flue gas, a clean gas value of about 14.1 g/t_{waste} is obtained for this plant. This load corresponds to a clean gas concentration of 3 mg/Nm^3 HCl. Fig. 42 shows the ***sulfur balance***.

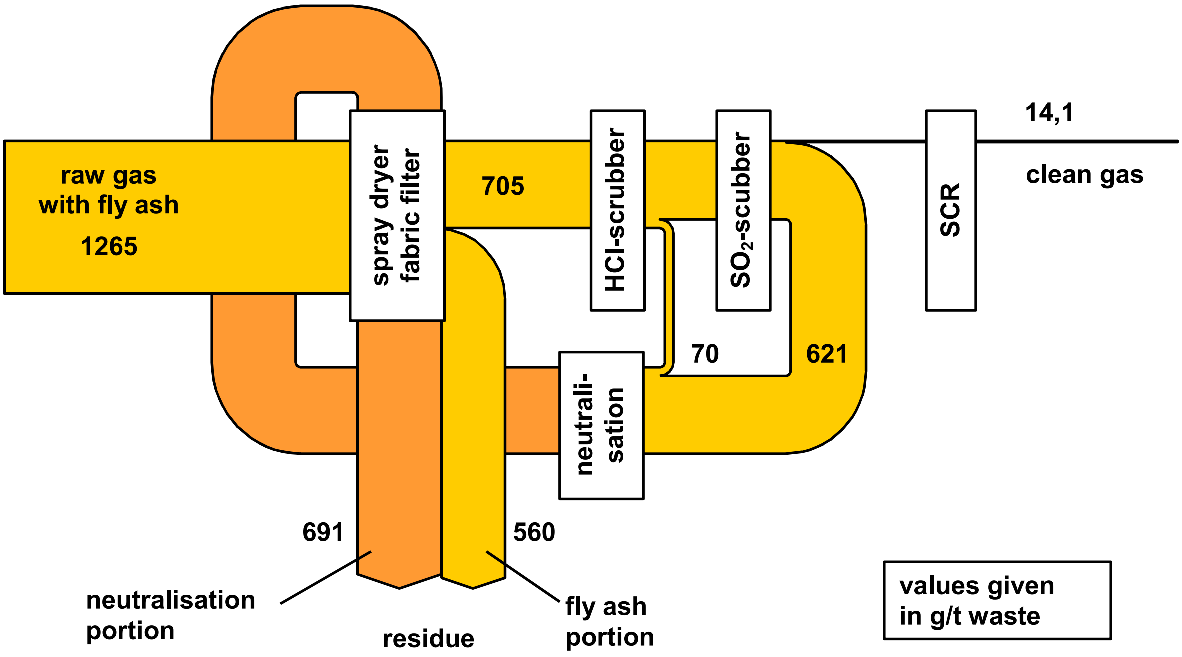

Fig. 42 Sulfur Balance of Model Plant "wet 5"

The raw gas with the dust, which contains 1265 g/t_{waste} of sulfur, is passed through the spray dryer. Here, no separation of sulfur is assumed to take place. In the downstream fabric filter, 560 g/t_{waste} of sulfur contained in the fly dust are separated.

In the scrubbers, 70 g/t_{waste} and 621 g/t_{waste} of sulfur, respectively, are absorbed by the scrubbing liquids. In total, 691 g/t_{waste} of sulfur are transferred to neutralization and converted into gypsum by the addition of calcium hydroxide. The thus generated suspension is evaporated in the spray dryer. The salts are discharged from the fabric filter together with the fly dust. Including fly dust, the fabric filter residue contains 1251 g/t_{waste} of sulfur.

Fig. 43 shows the balance of ***mercury***. The raw gas with the dust contains 1.56 g/t_{waste} of mercury. This concentration enters the spray dryer, where no mercury separation takes place.

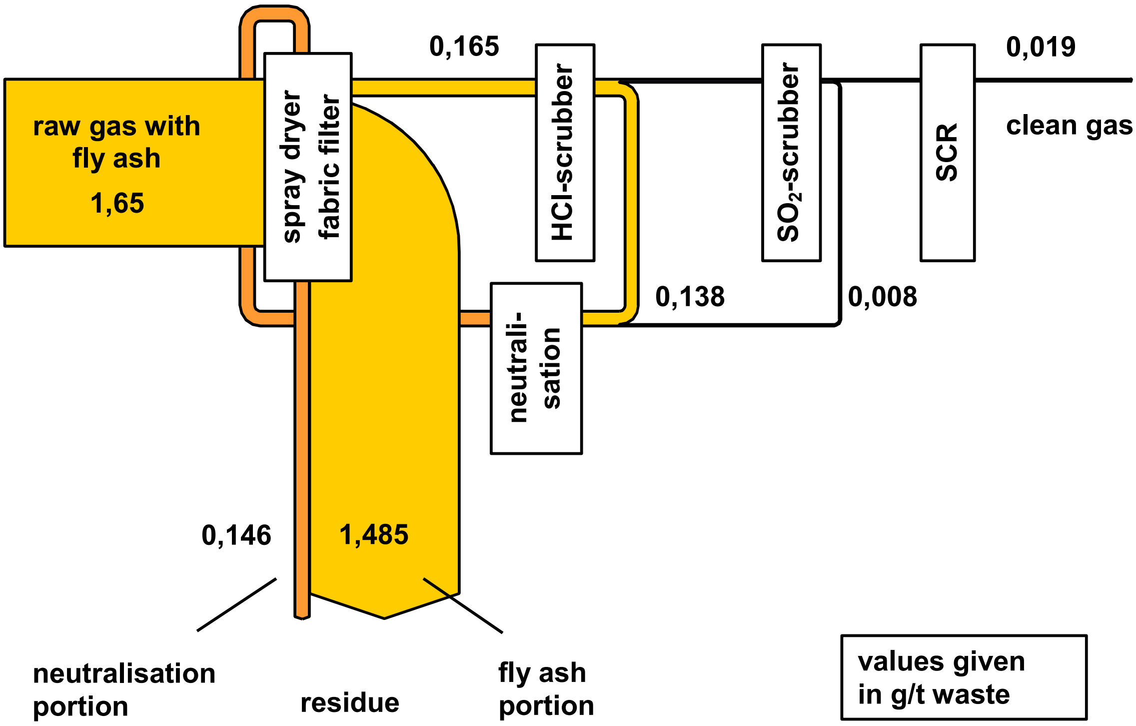

Fig. 43 Mercury Balance of Model Plant "wet 5"

Due to the addition of coke to the flue gas upstream of the fabric filter, about 90 % of mercury are separated. Consequently, 0.165 g/t_{waste} of mercury only remain in the dedusted raw gas. According to calculations, about 0.146 g/t_{waste} of mercury are separated in the two-stage scrubbing system. As in the other model plants, the HCl scrubber provides for the separation of the main fraction (about 0.138 g/t_{waste}).

In the neutralization stage, mercury is precipitated nearly completely using a heavy-metal precipitant (TMT-15^{TM}). Together with the suspension, it is returned to the spray dryer. Following evaporation, a solid flue gas cleaning product arises, which contains 0.146 g/t_{waste} of mercury. Together with the filter dust, the entire concentration discharged from the spray dryer and the fabric filter is about 1.631 g/t_{waste}. Downstream of the scrubber and the SCR catalyst, the clean gas contains 0.019 g/t_{waste} of mercury. This corresponds to a clean gas concentration of 0.004 mg/Nm^3 of mercury.

The ***cadmium balance*** is shown in Fig. 44. Based on the system values specified, the dust-bearing raw gas contains 5.76 g/t_{waste} of cadmium.

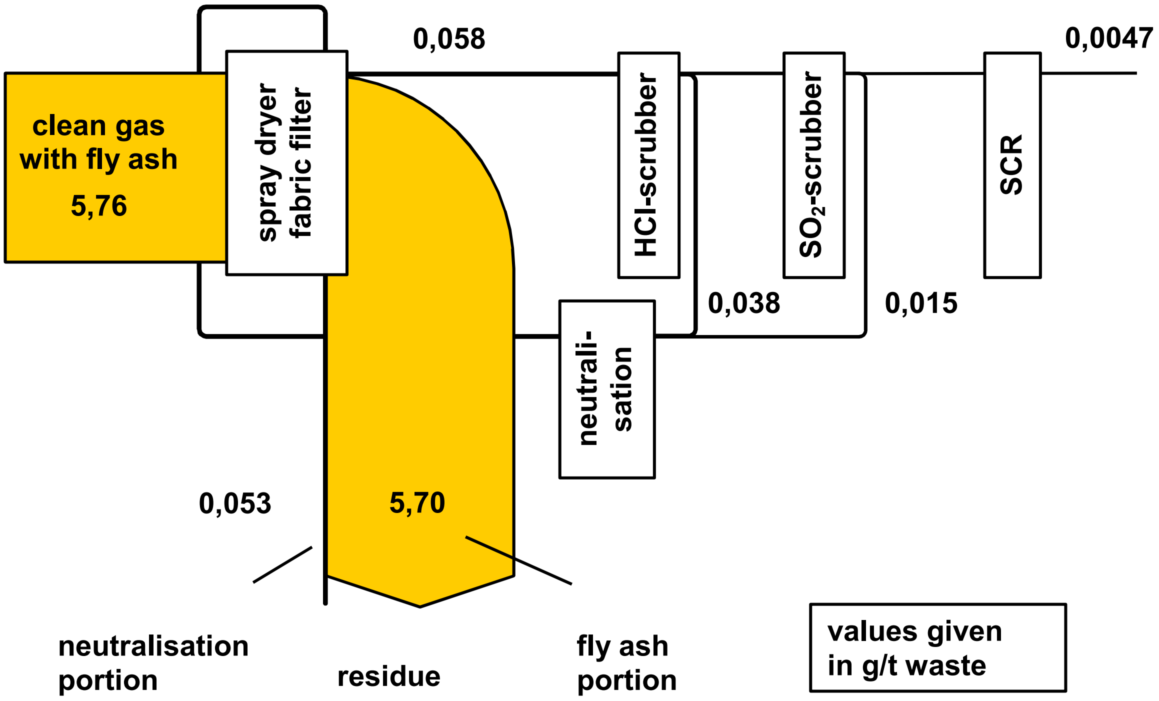

Fig. 44 Cadmium Balance of Model Plant "wet 5"

With this load, the raw gas passes the spray dryer, where no separation takes place. The downstream fabric filter provides for a nearly complete cadmium removal, as cadmium is accumulated in the dust. As explained in Section 6, a separation of about 99 % is assumed.

Still, 0.058 g/t_{waste} of cadmium remain in the flue gas. Of this amount, 0.038 g/t_{waste} and 0.015 g/t_{waste} are absorbed by the HCl scrubber and SO_2 scrubber, respectively. The small amounts separated in the scrubbers as compared to the other model plants result from the installation of a fabric filter with an efficient fine-dust cleaning efficiency upstream of the scrubber system.

In the neutralization stage, the scrubber effluents are processed with calcium hydroxide and a heavy-metal precipitant (TMT-15^{TM}) and returned to the spray dryer. The solid flue gas cleaning product generated contains 0.053 g/t_{waste} of cadmium. The total amount discharged from the spray dryer and fabric filter contains 5.75 g/t_{waste} of cadmium. Hardly any cadmium is contained in the flue gas (0.0047 g/t_{waste}).

The material flows of ***lead*** in the plant "wet 5" are shown in Fig. 45.

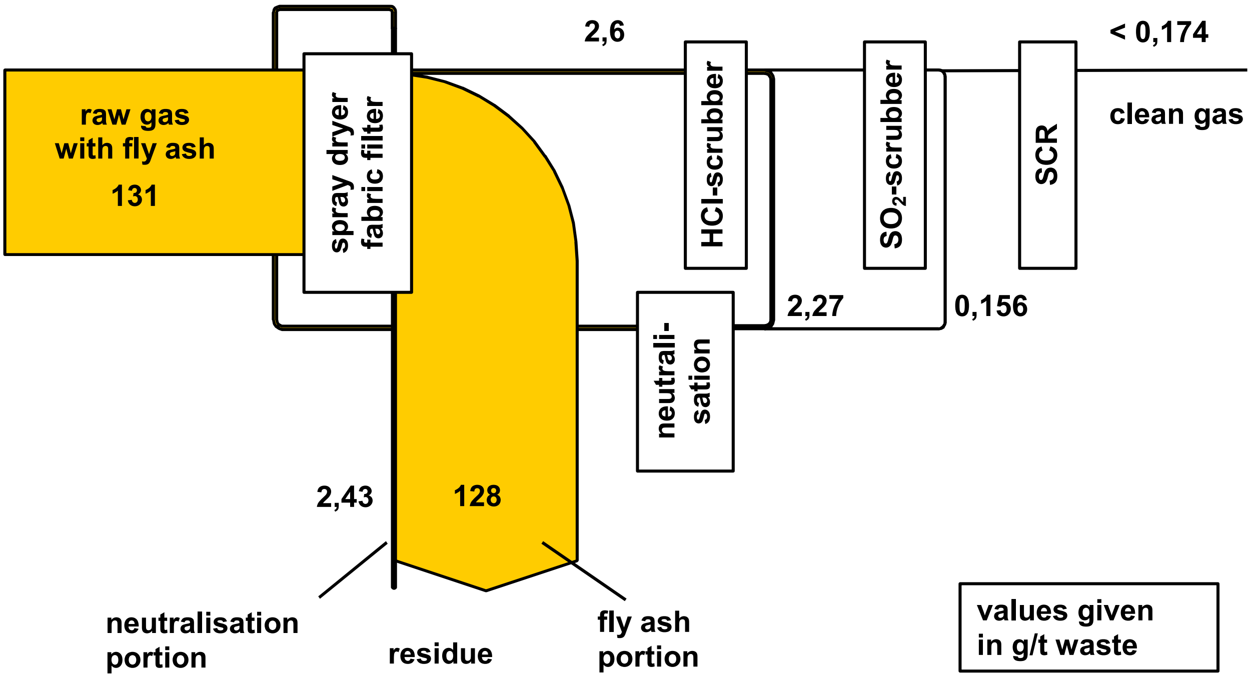

Fig. 45 Lead Balance of Model Plant "wet 5"

When leaving the boiler, the raw gas with the dust contains 131 g/t_{waste} of lead. With this load, the flue gas passes the spray dryer without the concentration being changed. In the downstream fabric filter, lead is separated nearly completely. In first approximation, separation efficiency is assumed to be the same as in an electrostatic precipitator. Hence, 2.6 g/t_{waste} of lead remain in the flue gas according to calculations.

2.27 g/t_{waste} are absorbed by the first scrubber. In the next stage, 0.156 g/t_{waste} are taken up by the scrubber liquid. The scrubber effluents contain a total lead load of about 2.43 g/t_{waste}. It enters the flue gas cleaning product following neutralization and treatment in the spray dryer. The fabric filter residue, consisting of the flue gas cleaning product and fly dust, contains a total of 130.4 g/t_{waste} of lead. According to calculations, lead concentration of the clean gas downstream of the SCR catalyst is below 0.174 g/t_{waste}.

7.6 Model Plant "wet 6”

The flue gas cleaning system of model plant "wet 6" possesses the most simple design of all wet flue gas cleaning systems. According to Fig. 46, a fabric filter and a two-stage scrubber system only are installed downstream of the boiler.

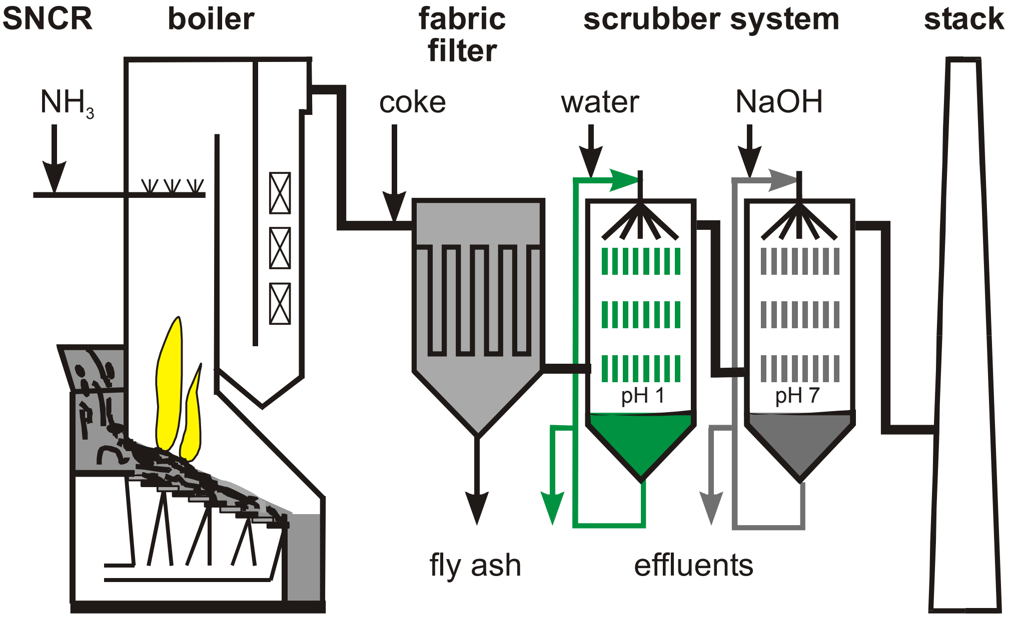

Fig. 46 Scheme of Model Plant "wet 6"

In model plant "wet 6", flue gas cleaning starts with an SNCR process in the boiler already. By the injection of an aqueous NH_3 solution, nitrogen oxides are removed.

Before the flue gases from the boiler enter the fabric filter, coke is injected for the separation of organic pollutants and mercury. The residue arising is separated in the fabric filter together with the fly dust. For the absorption of acid pollutants, the flue gas is passed through a two-stage scrubber system downstream of the fabric filter. The effluents generated are transferred to external processing. Final fine cleaning of the flue gases is not envisaged.

The Hamburg Borsigstraße waste incineration plant, for instance, is equipped with such a flue gas cleaning system. There, however, the final cleaning stage is a wet electrostatic prcipitator, the effects on the emissions of which cannot be measured [Schäfers].

The materials balances are given below. The SNCR process represented by the dashed line in the balances is outside of the scope of balancing defined. It is only shown for completeness of the flue gas cleaning processes of model plant "wet 6" in the Sankey diagram. First, Fig. 47 shows the ***chlorine balance***.

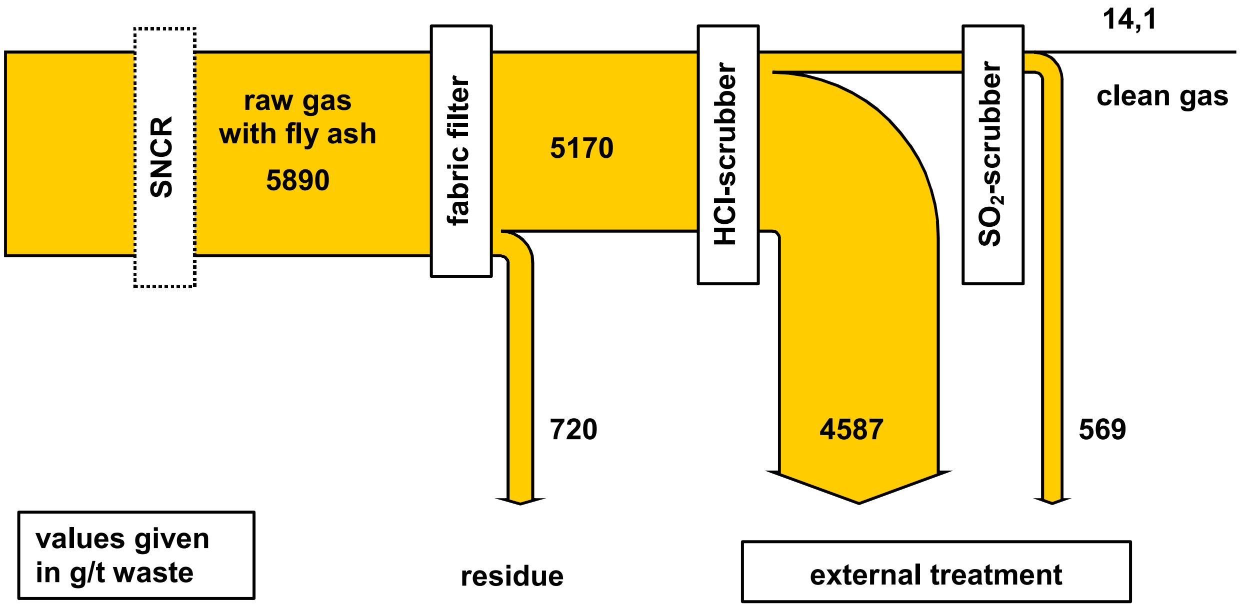

Fig. 47 **Chlorine Balance of Model Plant "wet 6"**

Balancing starts from a chlorine load of the raw gas and dust of 5890 g/t_{waste} downstream of the boiler. Chlorine separation efficiency of the fabric filter is assumed to be the same as of the electrostatic prcipitator. 720 g/t_{waste} of chlorine are separated.

In the HCl scrubber, a very large fraction of chlorine, 4587 g/t_{waste}, is taken up by the scrubber liquid. The second scrubber only provides for 569 g/t_{waste} of chlorine being removed from the flue gas. The chloride-loaded scrubber effluents are transferred to external processing. According to calculations, the chlorine load remaining in the clean gas amounts to 14.1 g/t_{waste}.

Sulfur distribution in plant "wet 6" is obvious from Fig. 48.

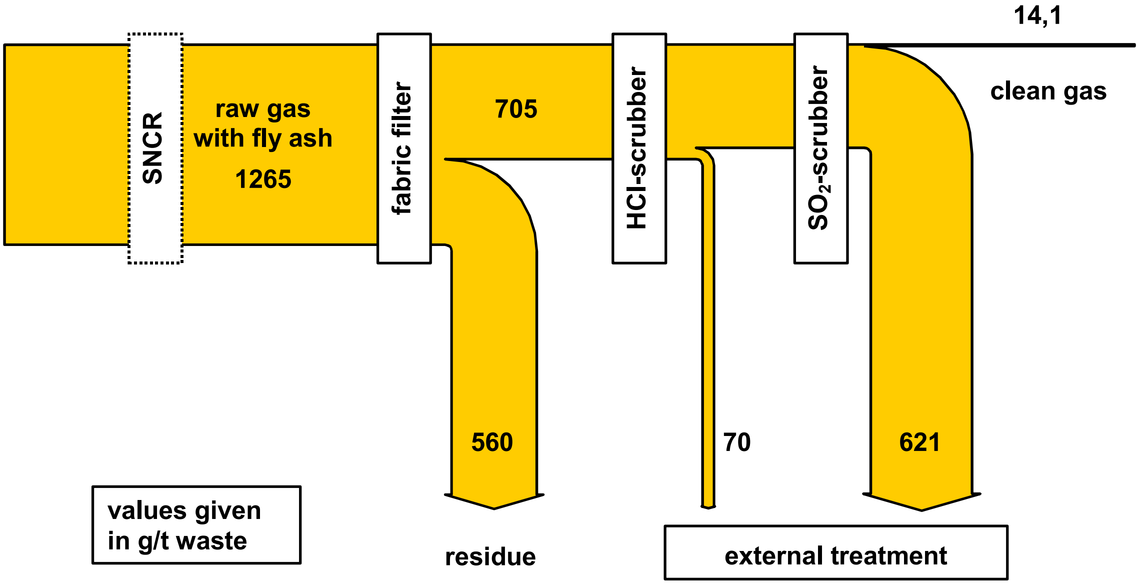

Fig. 48 **Sulfur Balance of Model Plant "wet 6"**

For balancing, sulfur load of the dust-containing raw gas downstream of the boiler is calculated to be 1265 g/t_{waste}, based on the raw gas concentrations specified. As in case of chlorine, sulfur separation efficiency of the fabric filter is assumed to be the same as that of the electrostatic prcipitator. The sulfur load separated by the fabric filter is calculated to be 560 g/t_{waste}.

In the downstream HCl scrubber, only small amounts of sulfur are absorbed. In contrast to this, the SO_2 scrubber provides for a high amount of sulfur of 6.21 g/t_{waste} being removed from the flue gas. The scrubber effluents which contain a total of about 691 g/t_{waste} of sulfur in the form of sulfate are processed externally. The clean gas of plant "wet 6" contains about 14 g/t_{waste} of sulfur. This corresponds to the concentration of 6 mg/Nm^3 SO_2 specified in TABLE 16.

Fig. 49 shows the ***mercury balance***.

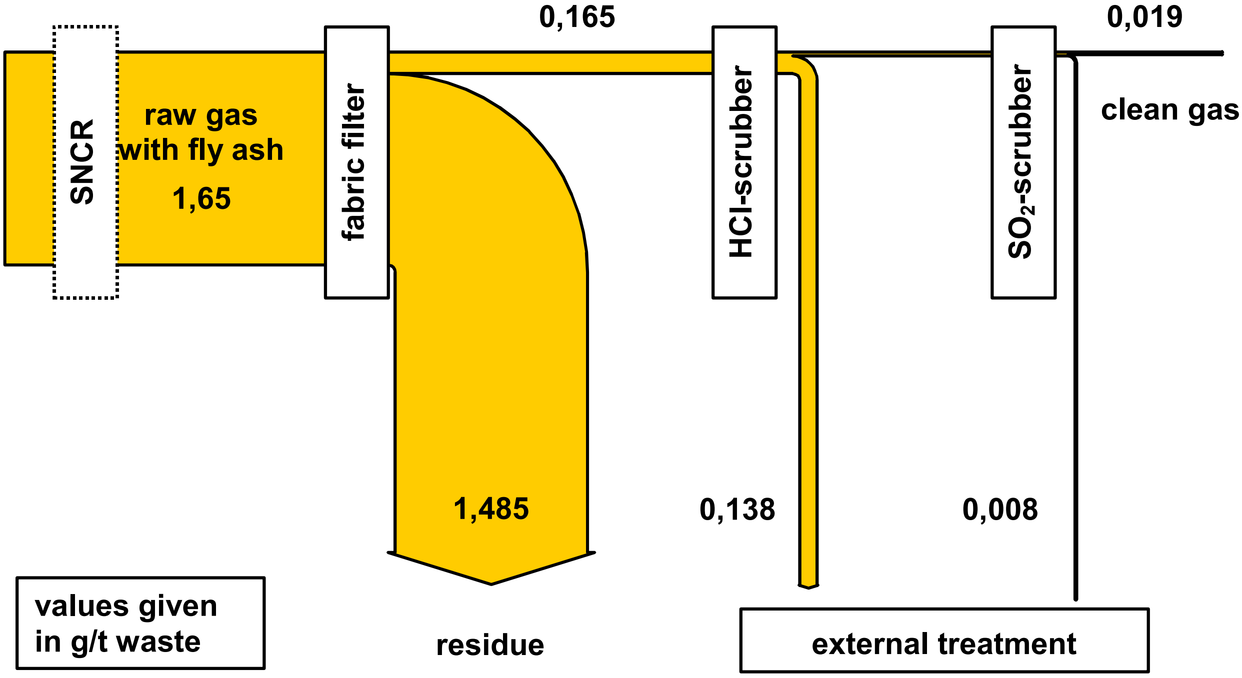

Fig. 49 Mercury Balance of Model Plant "wet 6"

As in all other model plants, the Sankey diagram starts with a mercury load of 1.65 g/t_{waste} in the raw gas leaving the boiler. Coke injection upstream of the filter causes about 90 %, i.e. 1.485 g/t_{waste}, of the mercury to be separated by the fabric filter. Downstream of the fabric filter, 0.165 g/t_{waste} of mercury remain in the flue gas. Of this amount, 0.138 g/t_{waste} and 0.0081 g/t_{waste} are absorbed in the HCl scrubber and second scrubber, respectively. The mercury-containing effluents are fed to external processing. According to calculations, 0.019 g/t_{waste} of mercury remain in the clean gas at the end of the flue gas cleaning line.

In addition to mercury, ***cadmium*** is balanced for this plant. According to Fig. 50, 5.76 g/t_{waste} of cadmium are contained in the raw gas leaving the boiler.

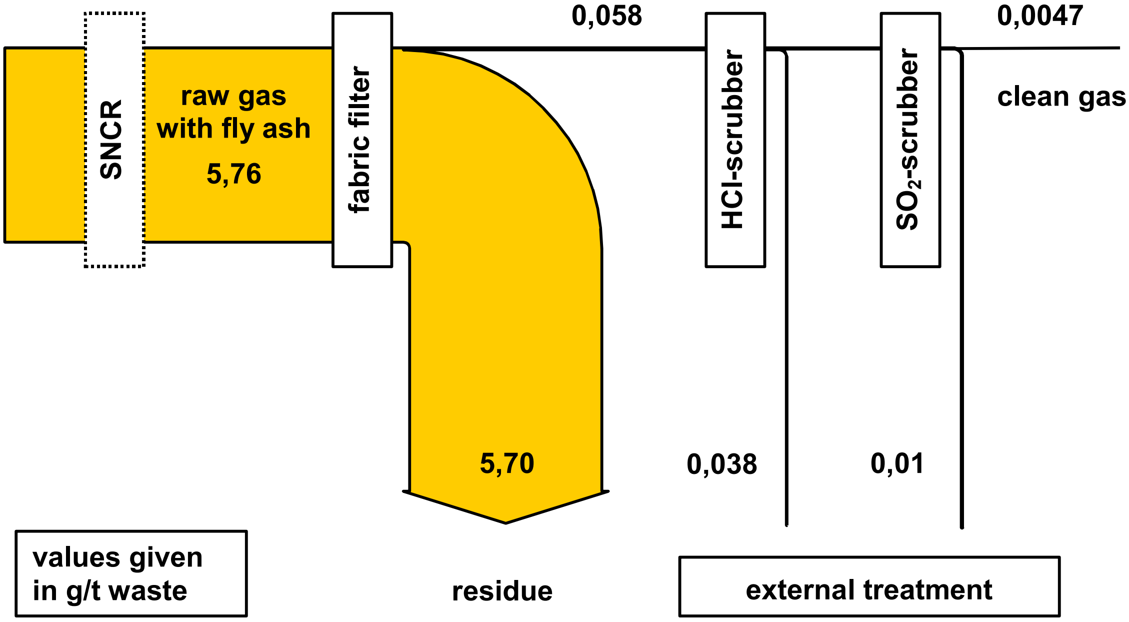

Fig. 50 Cadmium Balance of Model Plant "wet 6"

Cadmium is enriched in the fine dust and nearly completely removed from the raw gas by the fabric filter. A separation efficiency of about 99 % is assumed, such that only small amounts of 0.058 g/t_{waste} of cadmium remain in the flue gas downstream of the fabric filter.

In the HCl scrubber, 0.038 g/t_{waste} of cadmium are separated. Absorption of cadmium in the SO_2 scrubber is 0.015 g/t_{waste}. The scrubber effluents of plant "wet 6" are transferred to external processing. A very small load of 0.0047 g/t_{waste} remains in the clean gas.

The ***lead balance*** is shown in Fig. 51. It starts from 131 g/t_{waste} of lead in the raw gas leaving the boiler.

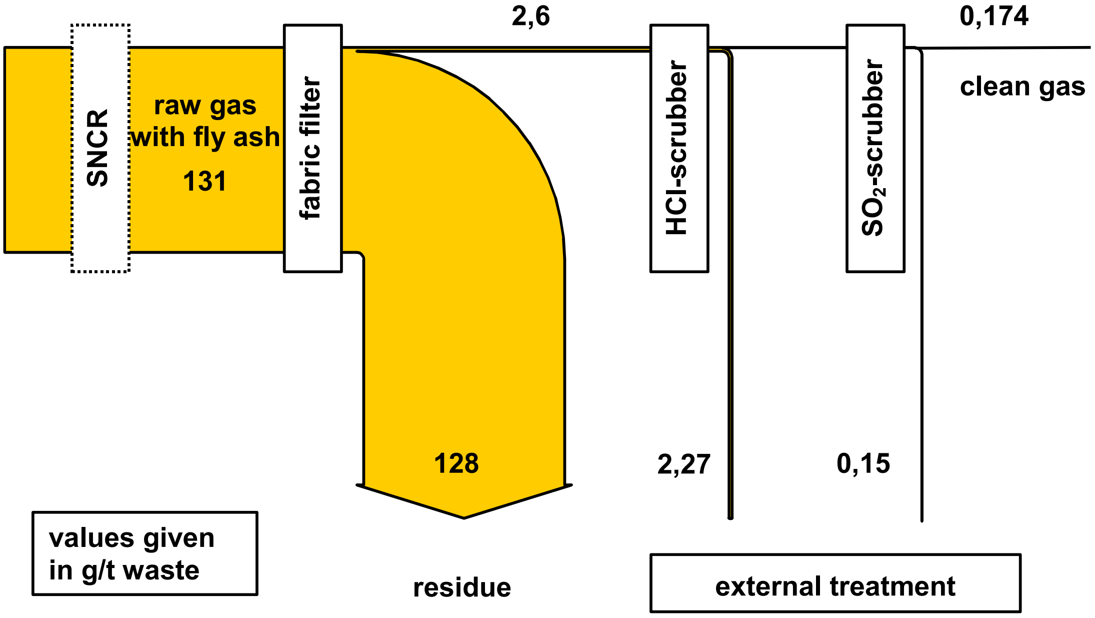

Fig. 51 Lead Balance of Model Plant "wet 6"

Separation efficiency of the fabric filter is assumed to correspond to that of the electrostatic prcipitator. Hence, 128 g/t_{waste} of lead are assumed to be separated from the raw gas. 2.6 g/t_{waste} of lead remain in the dedusted raw gas. In the downstream HCl scrubber, most of it (2.27 g/t_{waste}) is separated from the flue gas. Only small amounts of lead are absorbed in the last scrubber stage (SO_2 scrubber). The scrubber effluents which contain a total of about 2.43 g/t_{waste} are processed externally. The clean gas load amounts to about 0.174 g/t_{waste}.

7.7 Model Plant "semi wet 1"

Contrary to the wet flue gas cleaning systems, a semi wet system is based on another principle, as a spray absorber is used for separating acid pollutants. The schematic setup of the flue gas cleaning system is shown in Fig. 52.

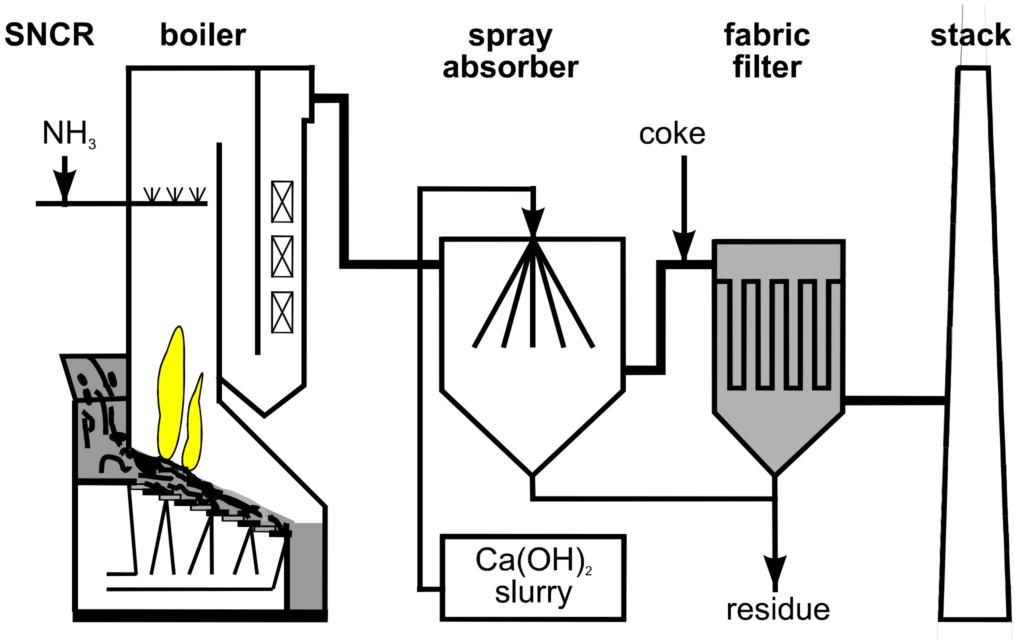

Fig. 52 Scheme of Model Plant "semi wet 1"

As the first flue gas cleaning component, a SNCR unit is installed in the furnace. After leaving the boiler, the dust-containing raw gas enters the spray dryer. It mainly serves for the separation of the acid pollutants HCl and SO_2 from the flue gas. A calcium hydroxide solution is injected into the hot flue gas, as a result of which its water fraction evaporates. At the same time, the acid pollutants react with the calcium hydroxide, forming the corresponding calcium salts. A solid flue gas cleaning product is produced, a small part of which leaves the spray dryer. In the form of dust, it is transferred to the downstream fabric filter together with the flue gas. There, the flue gas cleaning product is separated from the flue gas together with the fly dust.

For the separation of organic pollutants and heavy metals, above all dioxins, furans, and mercury, coke is required as another auxiliary chemical. By the injection of coke upstream of the fabric filter, the pollutants mentioned are separated nearly completely in the fabric filter by adsorption in the filter layer. Instead of feeding coke upstream the fabric filter as shown in Fig. 52, coke can be fed together with the calcium hydroxide slurry. This does not affect the materials balances presented below.

The SNCR process represented in the Sankey diagram of the plant "semi wet 1" is outside of the balancing scope specified and shown only to represent all flue gas cleaning stages of the plant.

At first, the chlorine balance is presented in Fig. 53.

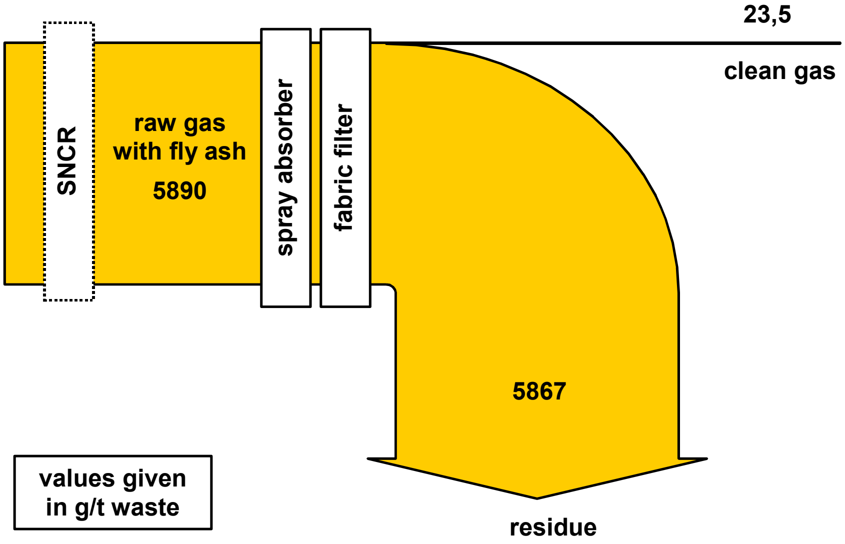

Fig. 53 **Chlorine Balance of Model Plant "semi wet 1"**

Balancing starts with the raw gas leaving the boiler, which contains 5890 g/t_{waste} of chlorine according to the initial data specified. With this load, the flue gas enters the spray absorber, where chlorine in the form of HCl reacts with the calcium hydroxide solution. The generated flue gas cleaning product is discharged partly from the spray absorber and mainly from the downstream fabric filter. The individual paths cannot be balanced in terms of quantities. For simplification, the total amount discharged is assigned to the fabric filter in the Sankey diagram.

The fly dust containing chlorine in the form of chloride is separated by the fabric filter together with the flue gas cleaning product. In total, the spray dryer and fabric filter provide for 5867 g/t_{waste} of chlorine being separated in the form of a solid mixture that has to be disposed of. According to calculations, the clean gas contains 23.5 g/t_{waste} of chlorine.

The principle of semi wet flue gas cleaning results in the Sankey diagram for sulfur being practically identical to that of chlorine. The sulfur flows are shown in Fig. 54.

The dust-containing raw gas leaves the boiler with a sulfur load of 1265 g/t_{waste}. By the injection of calcium hydroxide solution into the hot flue gas, sulfur in the form of SO_2 is separated from the gas phase. Chemical reactions result in the formation of the corresponding calcium salts. They are discharged partly from the spray absorber and mainly from the downstream fabric filter. As the exact amounts discharged from the spray absorber and fabric filter cannot be determined, the total amount discharged is assigned to the fabric filter in the Sankey diagram.

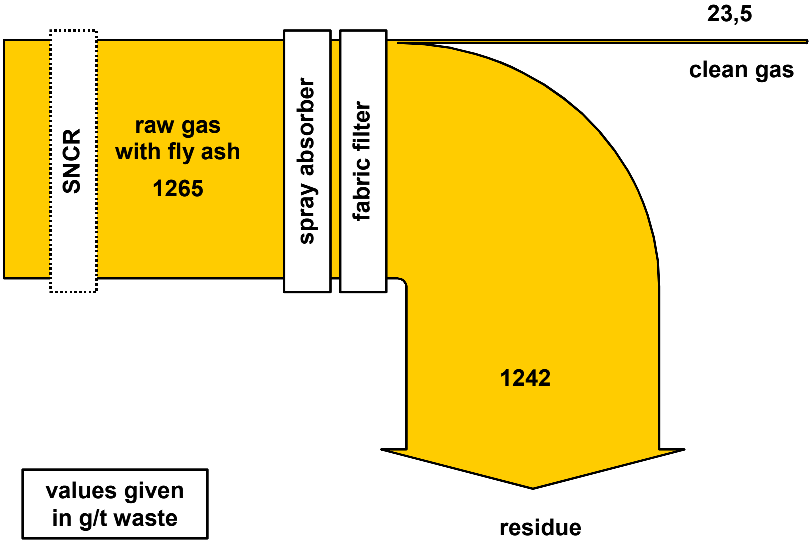

Fig. 54 **Sulfur Balance of Model Plant "semi wet 1"**

The fly dust which contains sulfur in the form of sulfate is separated by the fabric filter together with the flue gas cleaning product. In total, 1242 g/t_{waste} of sulfur are separated from the flue gas by the fabric filter. According to calculations, 23.5 g/t_{waste} of sulfur remain in the clean gas.

The paths of mercury as indicated by the Sankey diagram of Fig. 55 correspond to those of chlorine and sulfur discussed above. However, this distribution is based on other separation mechanisms.

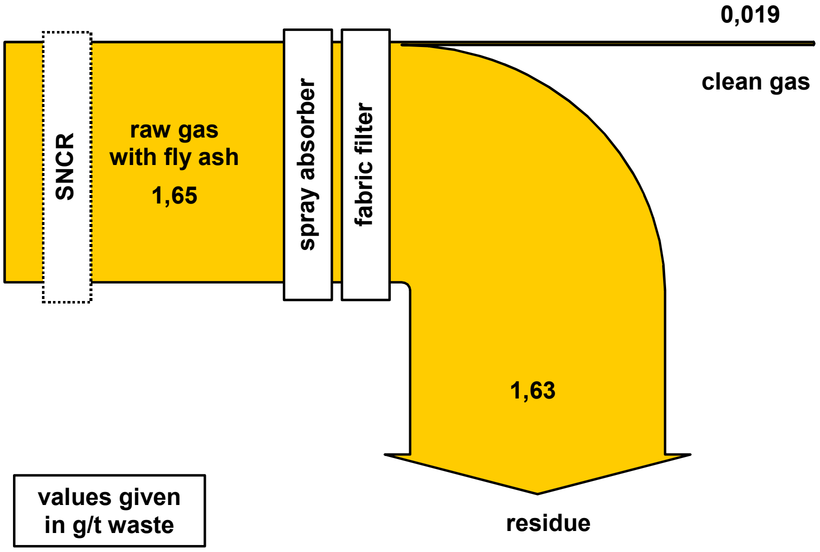

Fig. 55 **Mercury Balance of Model Plant "semi wet 1"**

The raw gas that contains mercury mainly in the gaseous form leaves the boiler with a mercury load of 1.65 g/t_{waste}. In the first flue gas cleaning component, the spray absorber, no significant separation of mercury is reached by the addition of calcium hydroxide. It is only the addition of coke upstream of the fabric filter, which leads to the mercury being separated.

Mercury is adsorbed on coke. Adsorption takes place mainly in the filter cake passed by the flue gas. By recleaning the filter surfaces, the mercury-loaded coke enters the flue gas cleaning residue.

As obvious from Fig. 56 and Fig. 57, also ***cadmium*** and ***lead*** are nearly completely removed from the raw gas.

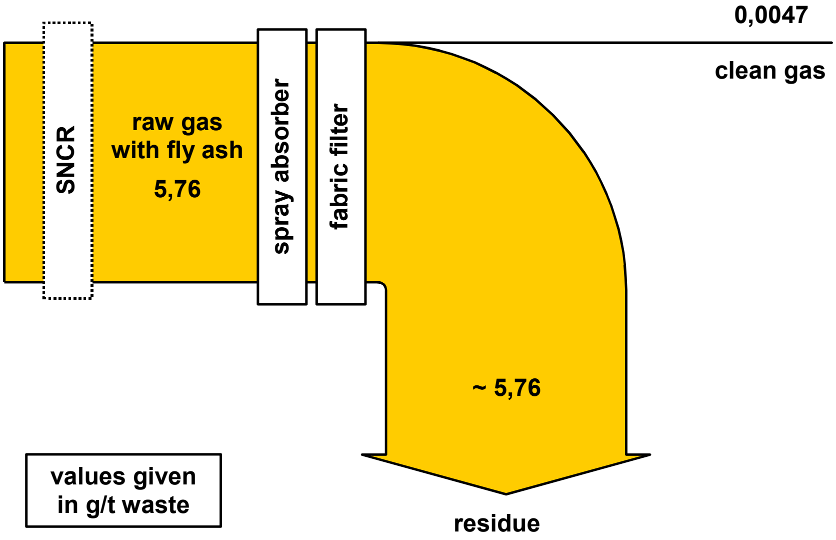

Fig. 56 Cadmium Balance of Model Plant "semi wet 1"

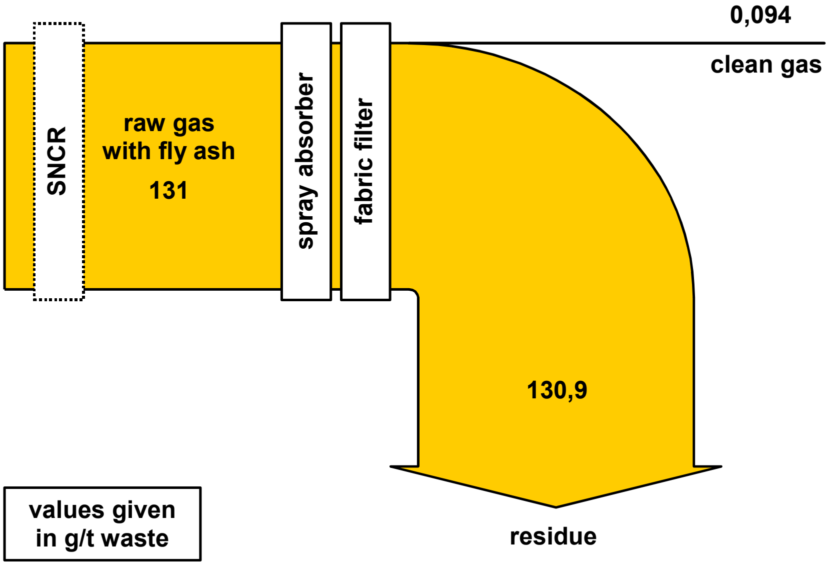

Fig. 57 Lead Balance of Model Plant "semi wet 1"

The paths of cadmium and lead correspond to those of mercury in plant "semi wet 1". Contrary to mercury, however, it is not the coke that is responsible for the good separation of cadmium and lead. The metals of cadmium and lead are contained in the fly dust and separated by the fabric filter.

7.8 Model Plant "semi wet 2"

Model plant "semi wet 2" differs from the plant "semi wet 1" presented above by the process applied for the NO_X-removal of the flue gases only. While in "semi wet 1", an SNCR process is applied in the furnace, model plant "semi wet 2" is equipped with an SCR catalyst upstream of the stack. As shown in Fig. 58, the flue gas cleaning system consists of a spray absorber, a fabric filter, and an SCR catalyst.

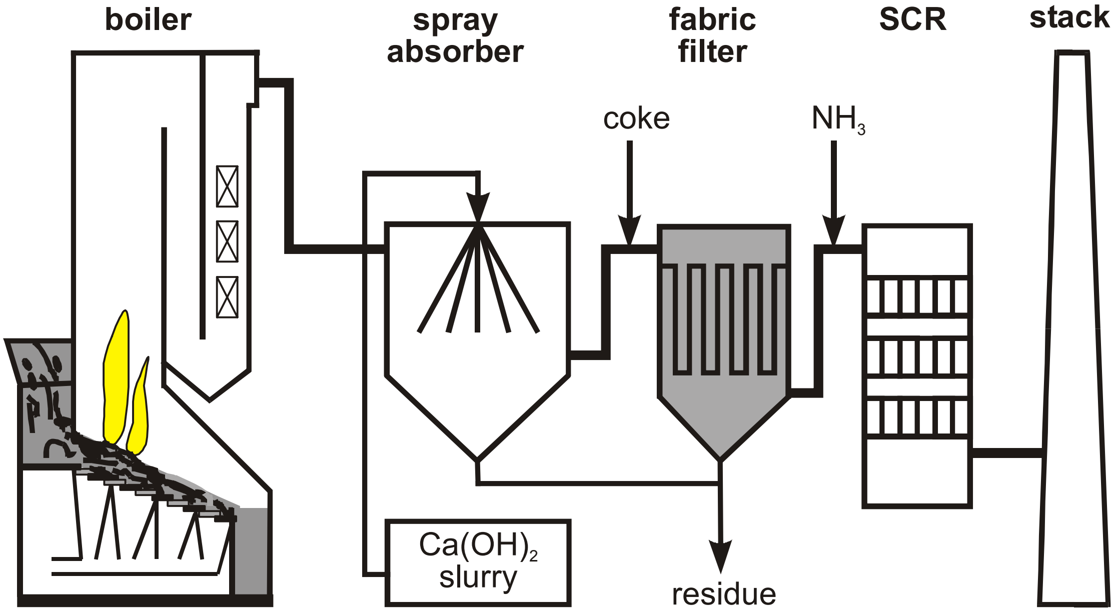

Fig. 58 Scheme of Model Plant "semi wet 2"

In the spray dryer, mainly gaseous HCl and SO_2 are separated from the flue gas by the injection of a calcium hydroxide solution. These acid pollutants react with calcium hydroxide to the corresponding calcium salts. At the same time, the water of the solution injected is evaporated by the hot flue gas. A solid flue gas cleaning product is generated, which is mainly separated by the fabric filter. In addition, coke is injected into the flue gas, such that organic pollutants and mercury are also retained by the fabric filter.

The fly dust contained in the raw gas leaving the boiler passes the spray dryer and is also removed from the flue gas by the fabric filter. Residues from the spray absorber and the fabric filter are disposed of jointly.

As the methods used for NO_x reduction – SNCR or SCR– do not decisively affect the balances of the substances studied, balances of the plants "semi wet 2" and "semi wet 1" are identical. The balances of chlorine, sulfur, mercury, cadmium, and lead are shown in the following figures. For the explanation of the Sankey diagrams shown in Fig. 59 through Fig. 63, it is referred to the Section on "semi wet 1".

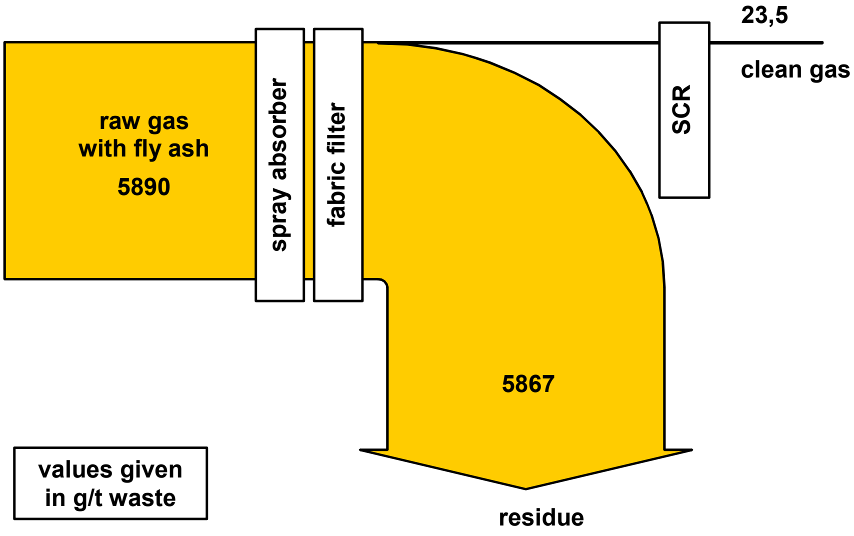

Fig. 59 Chlorine Balance of Model Plant "semi wet 2"

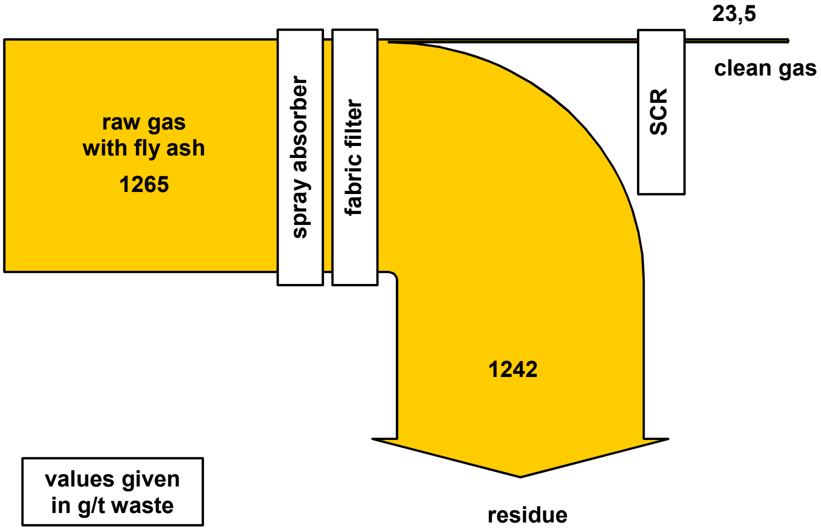

Fig. 60 Sulfur Balance of Model Plant "semi wet 2"

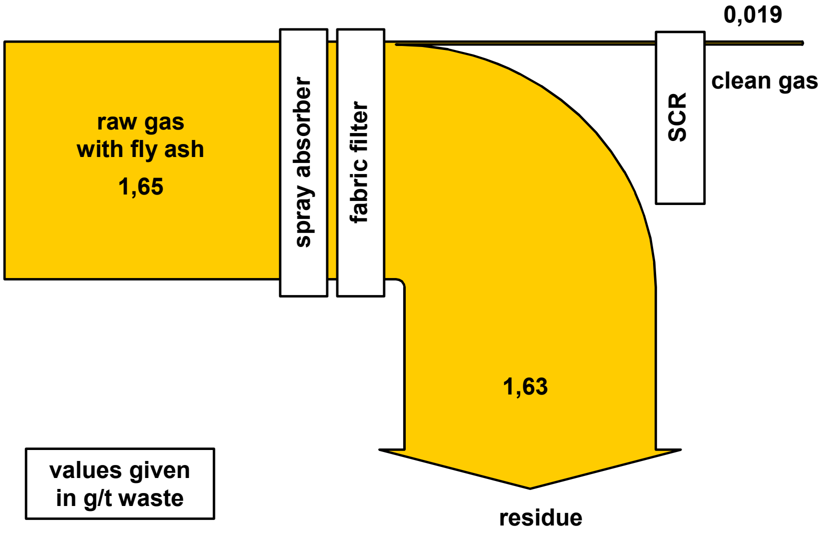

Fig. 61 Mercury Balance of Model Plant "semi wet 2"

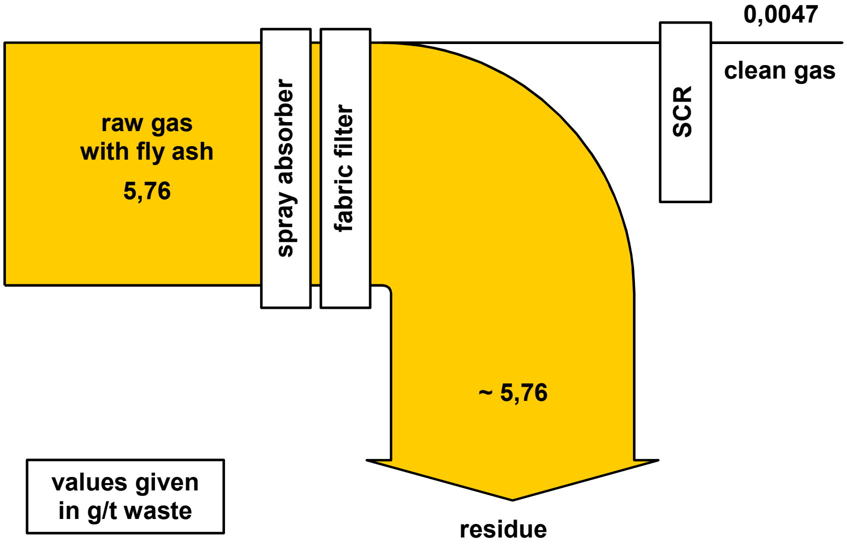

Fig. 62 Cadmium Balance of Model Plant "semi wet 2"

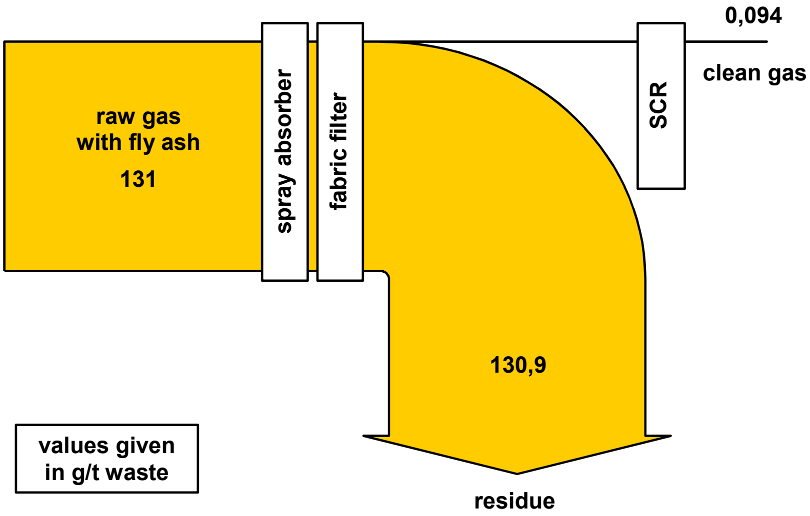

Fig. 63 Lead Balance of Model Plant "semi wet 2"

7.9 Model Plant "semi dry 1"

The flue gas cleaning system of model plant "semi dry 1" is based on a so-called conditioned dry process. According to Fig. 64, the first flue gas cleaning unit is the SNCR unit installed in the boiler. Downstream the boiler, the dusty flue gas with the dust enters the cooler, where optimum conditions for the separation of the pollutants are set by the injection of water. Upstream of the next flue gas cleaning component, a fabric filter, calcium hydroxide and coke are injected into the flue gas flow as finely ground solids.

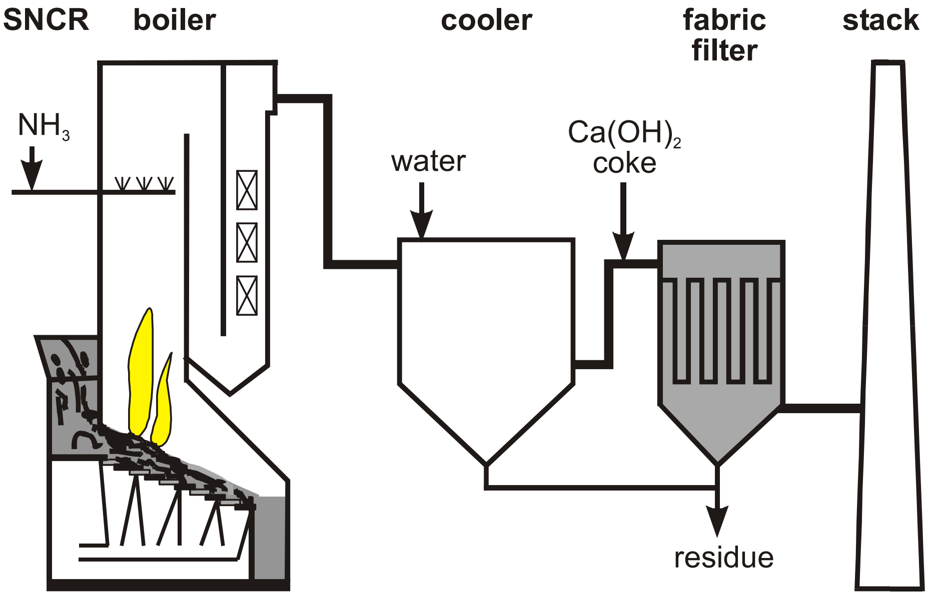

Fig. 64 **Scheme of Model Plant "semi dry 1"**

The gaseous pollutants HCl and SO_2 contained in the flue gas react with the solid calcium hydroxide and form the corresponding salts. These reactions take place both in the flue gas channel and in the filter cake developing on the filter surfaces. By recleaning of the fabric filter, the separated pollutants are removed. Separation of the organic pollutants and mercury is very similar. These substances are adsorbed by the coke which is also separated in the fabric filter.

In addition to the reaction products, fly dust is separated by the fabric filter. Very small amounts only arise in the evaporation cooler. They are disposed of together with the fabric filter residues.

The materials balances of this plant are represented below. For reasons of completeness, the SNCR process is also indicated in the Sankey diagram, although it is outside of the scope of balancing. The ***chlorine balance*** is shown in Fig. 65.

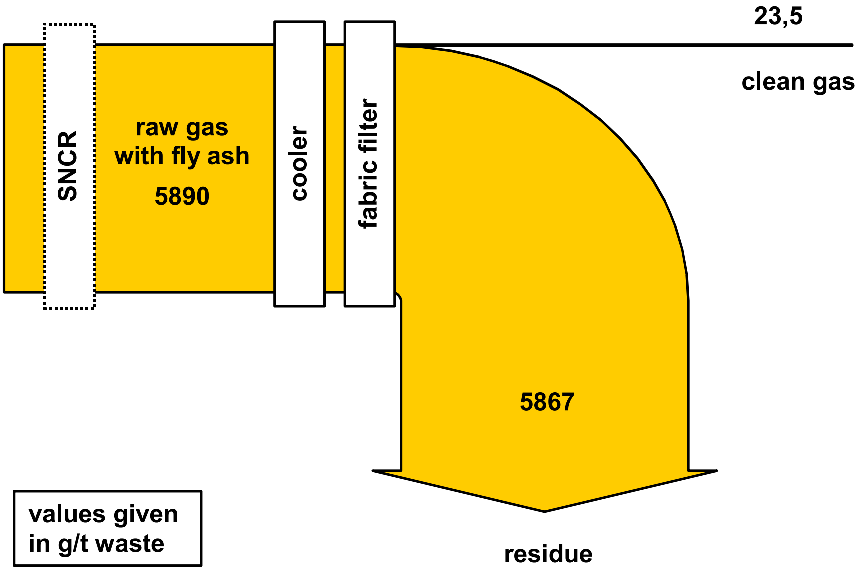

Fig. 65 **Chlorine Balance of Model Plant "semi dry 1"**

Of the 5890 g/t_{waste} of chlorine contained in the dusty raw gas leaving the boiler, 5867 g/t_{waste}

of chlorine are separated in the fabric filter mainly as calcium chloride or fly dust constituent due to injection of the solid calcium compound. The fabric filter residue is disposed of 23.5 g/t_{waste} of chlorine remain in the clean gas.

A similar distribution is obtained for ***sulfur***, as obvious from Fig. 66.

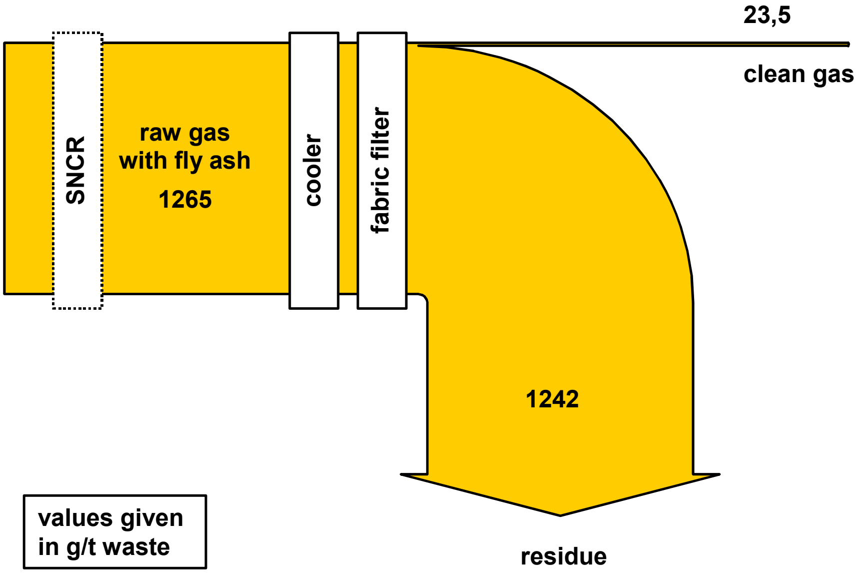

Fig. 66 **Sulfur Balance of Model Plant "semi dry 1"**

Of the 1265 g/t_{waste} of sulfur contained in the flue gas and dust at the boiler outlet, 1242 g/t_{waste} are separated as fly dust or flue gas cleaning product in the downstream fabric filter by the addition of calcium hydroxide. The clean gas leaves the plant with a sulfur load of 23.5 g/t_{waste}. The flue gas cleaning residue is disposed of.

Fig. 67 shows the mercury balance of plant "semi dry 1".

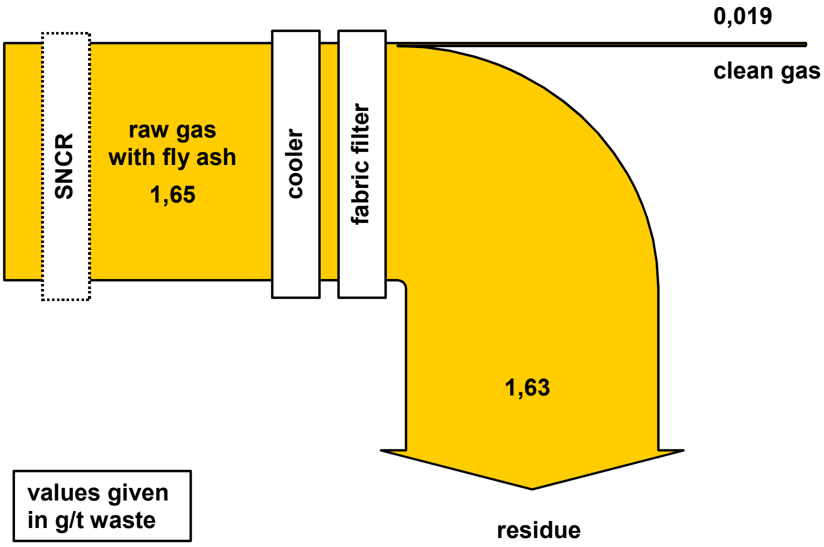

Fig. 67 **Mercury Balance of Model Plant "semi dry 1"**

According to this figure, 1.65 g/t$_{waste}$ of mercury are contained in the non-dedusted raw gas downstream of the boiler. As a large fraction of the mercury exists in the gaseous form, separation in the fabric filter is achieved by adsorption on the coke added. The coke takes up 1.63 g/t$_{waste}$ of mercury and is removed from the flue gas together with the other solids retained by the fabric filter. Mercury load of the clean gas is 0.019 g/t$_{waste}$.

Separation of cadmium and lead from the flue gas is nearly complete. The materials flows are shown in Fig. 68 and Fig. 69.

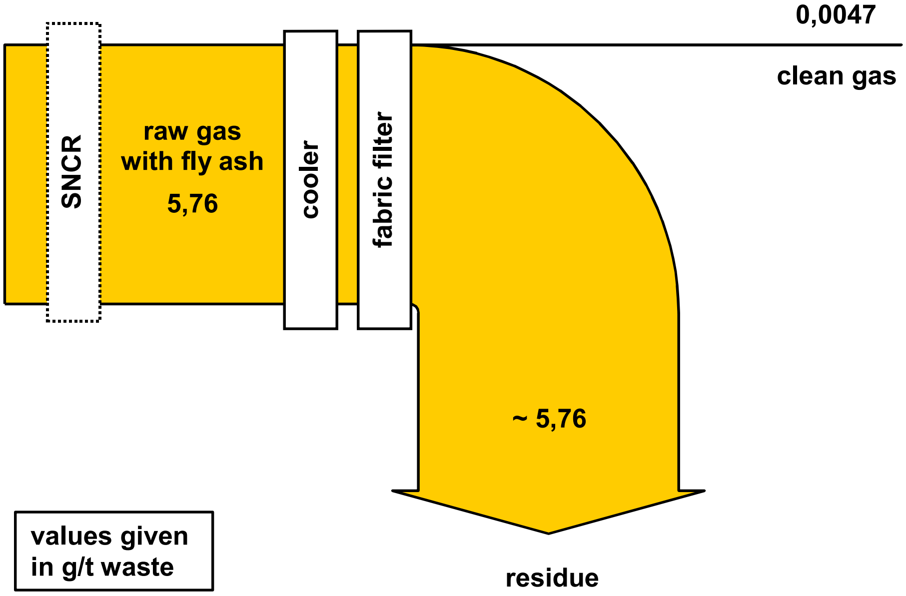

Fig. 68 **Cadmium Balance of Model Plant "semi dry 1"**

Cadmium and lead are contained in the filter dust mainly as salts. Both metals are separated from the flue gas together with the filter dust. Only very small loads (about 0.0047 g/t$_{waste}$ of cadmium and about 0.094 g/t$_{waste}$ of lead) are released into the atmosphere together with the flue gas.

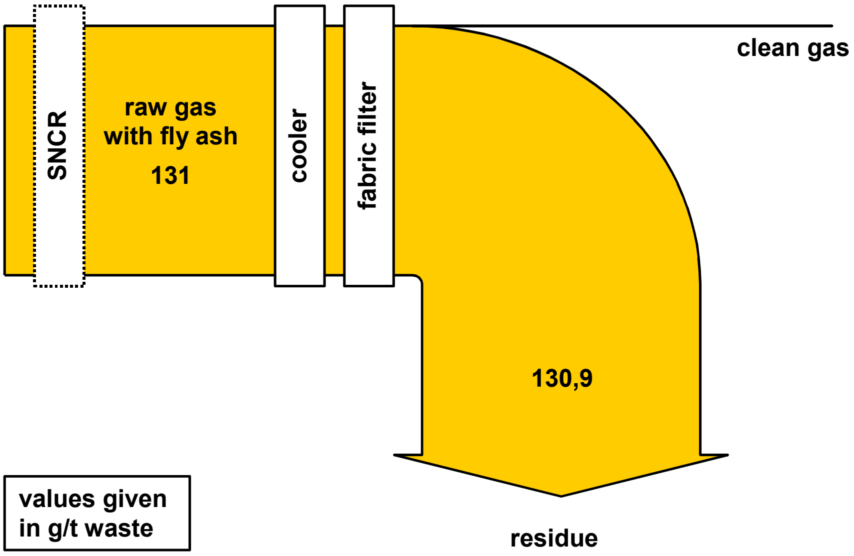

Fig. 69 **Lead Balance of Model Plant "semi dry 1"**

7.10 Model Plant "semi dry 2"

As shown in Fig. 70, the flue gas cleaning system of plant "semi dry 2" consists of an evaporation cooler, a fabric filter, and SCR unit. Hence, it differs from model plant "semi dry 1" by the NO_X-removal process only.

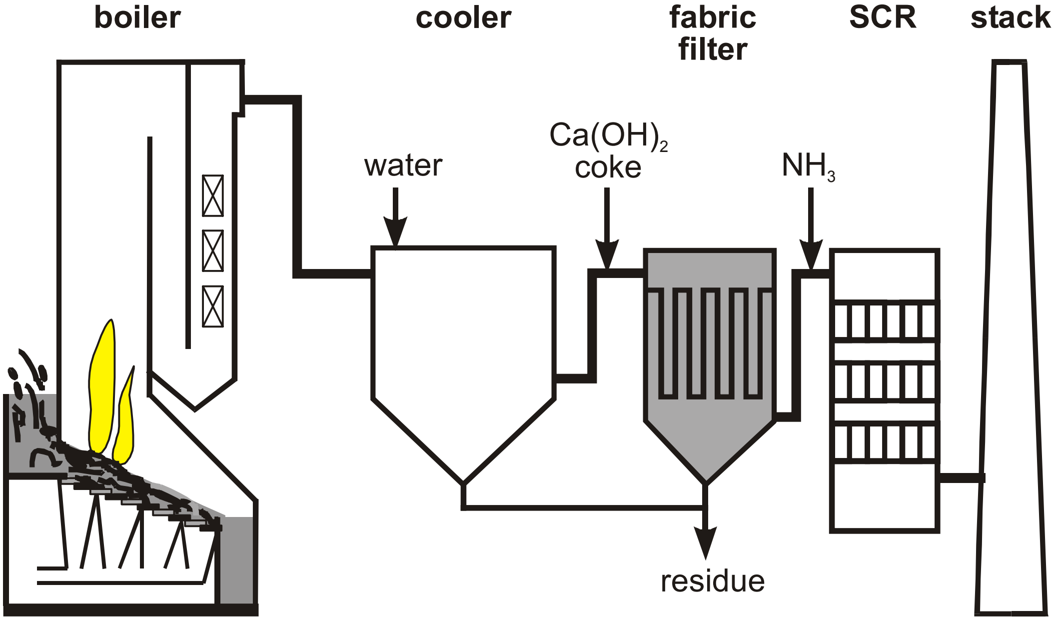

Fig. 70 Scheme of Model Plant "semi dry 2"

To optimize the separation conditions, the hot raw gas and dust leaving the boiler are cooled down and moistened in the evaporation cooler by the injection of water. For the separation of pollutants, a mixture of calcium hydroxide and coke is injected into the flue gas channel upstream of the fabric filter. By chemical reaction or adsorption, HCl, SO_2, organic pollutants, and mercury are removed from the flue gas and discharged from the plant as fabric filter residues. In addition to the reaction product, the fabric filter also provides for a separation of the fly dust. The residue from the fabric filter is disposed of.

Fig. 71 through Fig. 75 show the materials balances of chlorine, sulfur, mercury, cadmium, and lead of the plant "semi dry 2". As plants "semi dry 1" and "semi dry 2" differ in the NO_x reduction method only and the latter has no influence on the balances, the balances are identical for the plants "semi dry 1" and "semi dry 2". For this reason, the Sankey charts of "semi dry 2" will be presented below without any explanation being given. For explanation, it is referred to the Section on "semi dry 1".

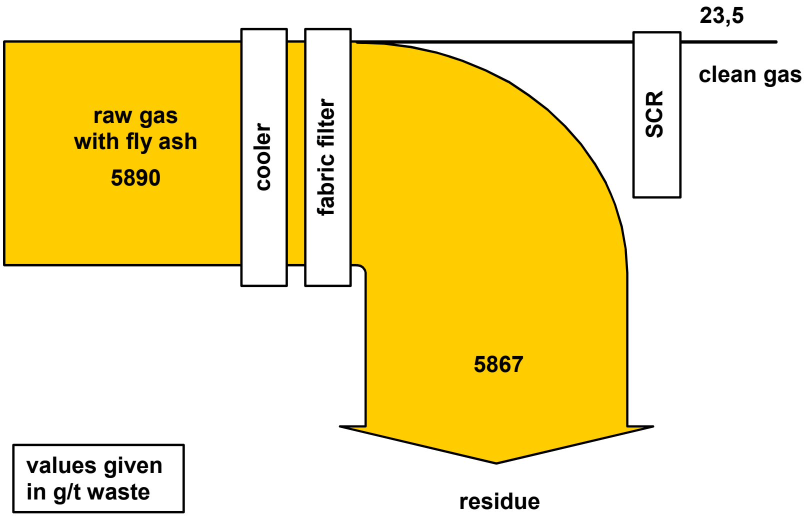

Fig. 71 Chlorine Balance of Model Plant "semi dry 2"

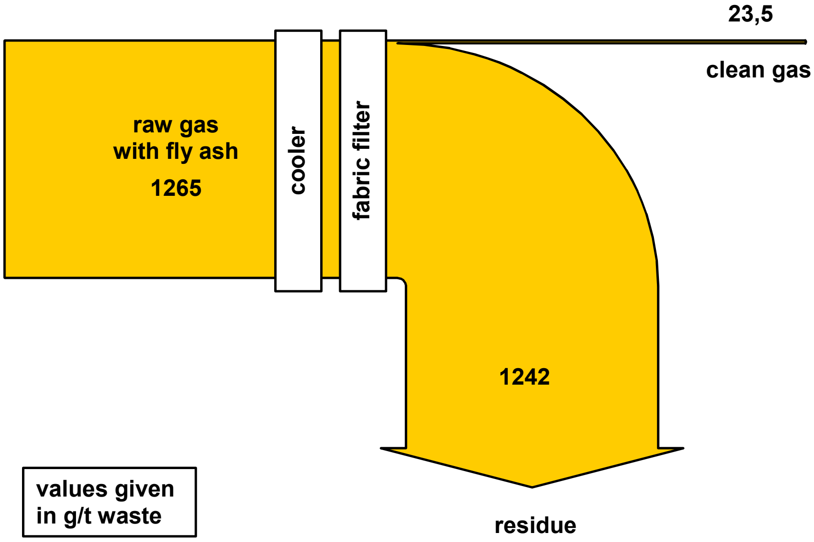

Fig. 72 Sulfur Balance of Model Plant "semi dry 2"

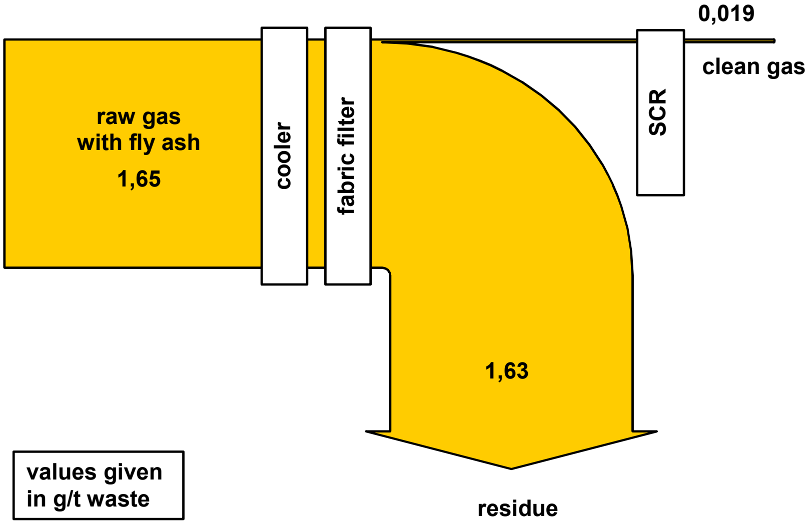

Fig. 73 Mercury Balance of Model Plant "semi dry 2"

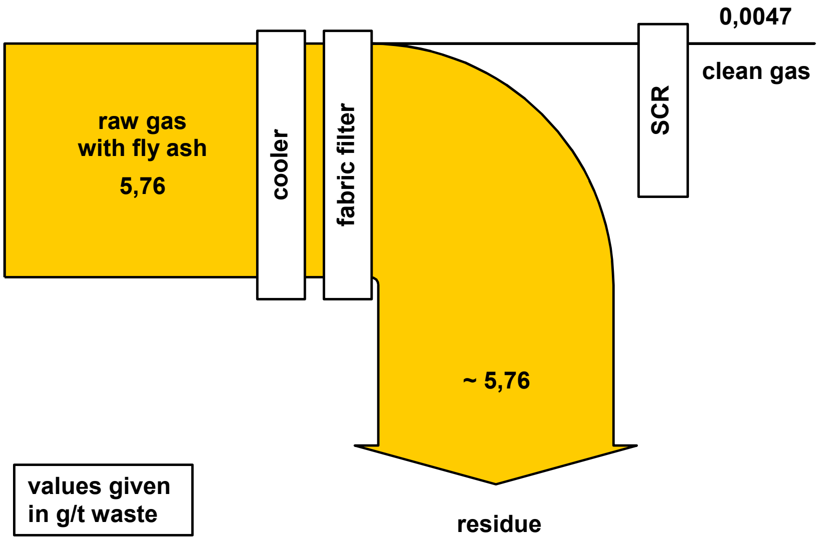

Fig. 74 Cadmium Balance of Model Plant "semi dry 2"

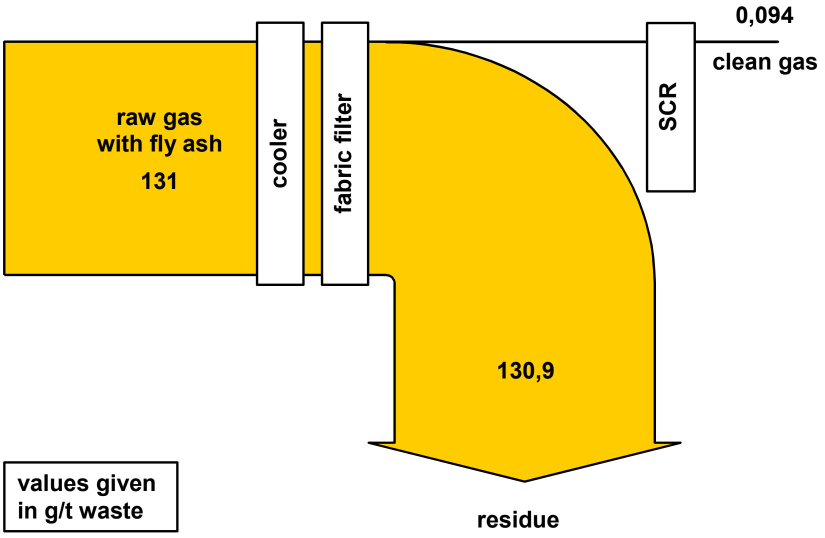

Fig. 75 Lead Balance of Model Plant "semi dry 2"

8 Use of Auxiliary Chemicals in the Model Plants

As mentioned when explaining the respective technologies in Section 4, various auxiliary chemicals are required for separating pollutants from the flue gas in waste incineration plants. In the present Section, the need for auxiliary chemicals in the different model plants shall be calculated taking into account the model parameters described in Section 6.

In detail, the following auxiliary chemicals are needed for the model plants covered by the present study:

- In the wet flue gas cleaning systems, acid pollutants are separated and neutralized using NaOH and $Ca(OH)_2$. In the semi wet and semi dry flue gas cleaning systems, use of $Ca(OH)_2$ only is considered for the removal of acid flue gas constituents.
- Calculations cover the use of coke in the fabric filter, entrained flow reactor, and carbon adsorber. In addition to coke consumption, the need for calcium hydroxide of the entrained flow reactor is calculated.
- The auxiliary chemicals also comprise a precipitant for the separation of heavy metals from scrubber effluents.
- For the various methods of NO_X-removal, the need for a 25 % ammonia solution is taken into account.

As explained in Section 4.5.3, other calcium compounds may be used instead of $Ca(OH)_2$. In addition, activity of the calcium compounds may be improved by special production methods. Improved activity reduces specific consumption, but costs of the more active substances are higher. These high-active substances or auxiliary chemicals rarely used in large plants are not covered by the calculations performed within the framework of the present study.

It must also be noted that calculation is based on “pure” and dry chemicals. Impurities are neglected. This means that a somewhat increased consumption is possible in large-scale plants, depending on the auxiliary chemicals used. This especially applies to calcium hydroxide.

8.1 *The Neutralization Agents NaOH and $Ca(OH)_2$*

The need for neutralization agents is determined decisively by the stoichiometric factor. Based on the chemical neutralization reactions, the stoichiometric factor describes how much neutralization agent is needed in relation to the pollutant concentration. Section 6.4.5 explains the stoichiometric factors used for the calculations made here.

For the model plants "wet 1" through "wet 6", which are equipped with a scrubber system, a chlorine load of the dedusted flue gas of 5170 g/t_{waste} (145.8 mol/t_{waste}) and a sulfur load of 705 g/t_{waste} (22 mol/t_{waste}) were calculated in Section 7. According to Section 6.4.5, the stoichiometric factor of 1.1 is used for wet flue gas cleaning systems. To neutralize the chlorine load, a need for 5942.9 g/t_{waste} of $Ca(OH)_2$ is calculated. To separate the sulfur load, 1935.1 g/t_{waste} of NaOH are needed.

In the sem wet and Semi dry flue gas cleaning systems considered by the present study, chlorine and sulfur loads of the dust-free flue gas are identical with those of the wet model systems. However, neutralization and separation are performed with $Ca(OH)_2$ exclusively. Based on a stoichiometric factor of 2.5, the specific need for $Ca(OH)_2$ is calculated to 17579.6 g/t_{waste} in semi dry processes. The increased stoichiometric factor of 2.8 for the dry flue gas cleaning systems yields a specific $Ca(OH)_2$ consumption of 19689.2 g/t_{waste}.

8.2 Coke-containing Auxiliary Chemicals

Calculations with respect to the auxiliary chemicals also cover the use of coke for the separation of organic substances and mercury during flue gas dedusting with a fabric filter and fine cleaning of the flue gases by an entrained flow reactor. As a rule, a mixture of coke and a calcium compound is applied in the carbon entrainment process. Coke is also required for the operation of a carbon adsorber which is another fine-cleaning method considered by the present study. The consumption values specified are indicated in TABLE 17.

TABLE 17 Consumption of coke and coke-containing auxiliary chemicals

Flue gas cleaning step	auxiliary chemical	amount [g/t_A]
Fabric filter, wet system	coke	1000
Fabric filter, semi wet system	coke	1500
Fabric filter, semi-dry system	coke	2200
carbon adsorber	coke	1000
entrained flow reactor	mixture, lime (90 %), coke (10 %)	2500

8.3 Heavy-metal Precipitant TMT-15^{TM}

Precipitation of heavy metals is achieved by neutralization precipitation (hydroxides) and, in addition, by the use of special heavy-metal precipitants. Use of precipitants mainly focuses on the separation of mercury from scrubber effluents.

Various precipitants are offered on the market. Usually, they contain sulfur. Here, use of the precipitant "TMT-15^{TM}" is considered. It is produced by the Degussa company. TMT-15^{TM} is a solution of the sodium salt of trimercapto-s-triazine (TMT) in water. The structural formula is presented in Fig. 76.

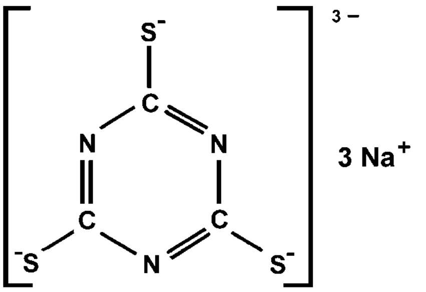

Fig. 76 Sodium salt of trimercapto-s-triazine

As an example, the following reaction equation describes the conversion of mercury using this precipitant.

$3\ HgCl_2 + 2\ Na_3TMT \rightarrow Hg_3TMT_2 + 6\ NaCl$ eq. 8.1

The TMT-15^{TM} consumption considered within the framework of the present study is based on data from large-scale plants [Achternbosch-1] and assumed to be 125 g/t$_{waste}$.

8.4 *Ammonia Solution*

As explained in Section 4, nitrogen oxides (NO_x) generated during waste incineration can be reduced by the SNCR or SCR process using ammonia. Ammonia (NH_3) reacts with nitrogen oxides according to the following simplified equations:

$4\ NO + O_2 + 4\ NH_3 \rightarrow 4\ N_2 + 6\ H_2O$ eq. 8.2

$2\ NO_2 + O_2 + 4\ NH_3 \rightarrow 3\ N_2 + 6\ H_2O$ eq. 8.3

In the flue gas of waste incineration plants, about 95 % of the NO_x compounds are made up of NO, while the remaining 5 % consist of NO_2. However, NO_x contents of the flue gas are given as values referring to NO_2.

As obvious from the technical data specified for the model plant in Section 5, NO_x concentration of the raw gas – calculated as NO_2 – is to amount to 400 mg/Nm^3, while the respective value in the clean gas is to be 170 mg/Nm^3. This clean gas value is to ensure reliable compliance with the 17th Federal Emission Control Ordinance. In addition, calculations are performed for 70 mg/Nm^3 NO_x, as limits of this order of magnitude have been specified for some waste incineration plants.

To calculate the consumption of ammonia solution, the NO_x concentration of 400 mg/Nm^3 referring to NO_2 has to be converted into the actual fractions of NO and NO_2 (see also [Frank]). The following balancing equation is applied:

$c'(NO_2) + c(NO_2) = c(NO_x)$ eq. 8.4

Here, $c'(NO_2)$ denotes the NO_2 concentration calculated from the NO concentration measured c(NO). The term $c(NO_2)$ corresponds to the NO_2 concentration measured. With the molar concentrations n [mol/Nm^3] and the respective molecular rates M [g/mol], the following equations are set up:

$c(NO) = n(NO)\ M(NO)$ M(NO):30.01 g/mol eq. 8.5

$c'(NO_2) = n(NO)\ M(NO_2)$ $M(NO_2)$:46.01 g/mol eq. 8.6

By equating $c(NO)/M(NO) = c'(NO_2)/M(NO_2)$, a new expression for $c'(NO_2)$ is obtained. Eq. 8.4 yields:

$(M(NO_2)/M(NO))\ c(NO) + (NO_2) = c(NO_x)$ eq. 8.7

Taking into account the relations c(NO) = 0.95 c(NO_x) and c(NO_2) = 0.05 c(NO_x), c(NO_x) can be calculated. The values calculated for c(NO_x), c(NO), and c(NO_2) are listed in TABLE 18. As obvious from this table, a raw gas containing 400 mg/Nm^3 NO_x as NO_2 actually contains 252.2 mg/Nm^3 of NO and 13.3 mg/Nm^3 of NO_2.

TABLE 18 NOx concentrations in raw gas

NO_x im raw gas	concentration [mg/Nm^3]
c'(NO_x) in raw gas (calculated as NO_2)	400
c(NO).	252,2
c(NO_2)	13,3
c(NO) + c(NO_2) = c(NO_x)	265,5

With these NO_x concentrations, it is now possible to calculate the amount of ammonia needed and added as 25 % solution in practice. The consumptions of 25 % ammonia solution per ton of waste are given in TABLE 19According to this table, 1880 g/t_{waste} NO_x, as NO_2, have to be reduced by ammonia. For the NO_x concentration in the clean gas being 170 mg/Nm^3 and 70 mg/Nm^3 NO_x, about 1700 g/t_{waste} and 2400 g/t_{waste} of 25 % ammonia solution are required, respectively.

TABLE 19 NOx load of the raw gas and amount of 25 % ammonia solution needed for the SCR process to obtain various NOx clean gas concentrations

flue gas volume		4700 Nm^3/t Waste
m'(NO_x)		1880 g/t Waste
NH_3-amount(25%)	*(NO_x (400 mg) → NO_x (0 mg))*	*2876 g/t Waste*
NH_3-amount(25%)	(NO_x (400 mg) → NO_x (170 mg))	approx. 1700 g/t Waste
NH_3-amount (25%)	(NO_x (400 mg) → NO_x (70 mg))	approx. 2400 g/t Waste

The consumption data given in TABLE 19 apply to the SCR process exclusively. For the SNCR process, much higher values are to be expected. According to the information supplied by a plant constructor, ammonia consumption for the SNCR process is nearly twice as high as for the SCR process in first approximation. Consequently, the consumption of 25 % ammonia solution to obtain a clean gas value of 170 mg/Nm^3 NO_x amounts to about 3300 g/t_{waste}.

8.5 Total Consumption of Auxiliary Chemicals

The consumption values of auxiliary chemicals are summarized in Table 20 for all model plants.

TABLE 20 Consumption of auxiliary chemicals in the model flue gas cleaning systems

model plant	NaOH [g/t_A]	$Ca(OH)_2$ [g/t_A]	lime / coke (90/10 mass-%) [g/t_A]	coke [g/t_A]	NH_3-soluitionLösung (25%) [g/t_A] raw gas 400 mg/Nm³ NO_x clean gas 170 mg/Nm³ NO_x	TMT-15™ [g/t_A]
wet 1	1935,1	5942,9	2500	-	1700	125
wet 2	1935,1	5942,9	-	1000	1700	125
wet 3	1935,1	5942,9	2500	-	1700	125
wet 4	1935,1	5942,9	-	1000	1700	125
wet 5	1935,1	5942,9	-	1000	1700	-
wet 6	1935,1	5942,9	-	1000	3300	-
semi wet 1	-	17579,6	-	1500	3300	-
semi wet 2	-	17579,6	-	1500	1700	-
semi dry 1	-	19689,2	-	2200	3300	-
semi dry 2	-	19689,2	-	2200	1700	-

9 Residues and Effluents Arising in the Model Systems

In internal effluent processing, solid residues are generated in the spray dryer. External processing comprises a separate evaporation facility or process stages for recycling. Recycling is outside of the scope of balancing of the present study.
The amounts of residues generated by flue gas cleaning are determined decisively by the neutralization of the acid pollutants HCl and SO_2 and by the fly dusts. Use of coke is of less importance. As explained in Section 6.4.5, the amount of neutralization agents used depends on the process. Wet, semi wet and semi dry processes require various stoichiometric ratios for the separation of pollutants. The amounts of residues arising increase with an increasing stoichiometric ratio.

In wet processes, it is also important whether internal or external processing of the effluents takes place. In case of external processing, only those amounts of effluents and salt loads contained therein are given, which are identical with the amounts of residues in case of an internal evaporation of effluents.

Determination of the amounts of residues arising in the neutralization of acid pollutants is based on a simplification. The small amounts of HCl and SO_2 remaining in the clean gas are not taken into account by calculation. Due to the very high raw gas concentrations, the small clean gas concentrations, and the excesses of neutralization agents, effects of this simplification on the amounts of residues can be neglected.

9.1 Residues of Wet Processes

To estimate the amounts of residues generated by the evaporation of scrubber effluents, chloride is considered to be calcium chloride and sulfur is deemed to be sodium sulfate. It must be taken into account that one calcium hydroxide molecule neutralizes two “acid” chloride ions. For simplification, the hydrate water contents are neglected, as the salts may have varying hydrate water contents. This especially applies to calcium chloride that crystallizes to hexahydrate in the presence of large amounts of hydrate water, but arises as dihydrate in case of further water removal.

Fluorine (as CaF_2) and all heavy metals (as hydroxides / oxides) are neglected in this calculation, as these substances make up 1 % of the total load to be separated only [Achternbosch-2]. The individual loads of chlorine and sulfur and the resulting total values are listed in the following tables for the individual processes.

TABLE 21 Element and salt loads for calculating the amount of residues generated by neutralization in a wet system. Ex.: Excess of neutralization agent

wet process							
element	**load** [g/t_A]	**calculated as**	[g/t_A]	**$(NaOH)_{Ex.}$** [g/t_A]	**$(Ca(OH)_2)_{Ex.}$** [g/t_A]	**water** [g/t_A]	**total** [g/t_A]
Cl	5170	$CaCl_2$	8093		540.3		8633
S	705	Na_2SO_4	3124	88.0		792.5	4005
							12638

As obvious from TABLE 21, 8093 g/t_{waste} of $CaCl_2$ arise from 5170 g/t_{waste} of chlorine. From 705 g/t_{waste} of sulfur, 3124 g/t_{waste} Na_2SO_4 are generated by neutralization. Taking into account a stoichiometric factor of 1.1 for neutralization, an excess of $Ca(OH)_2$ and NaOH of 540.3 g/t_{waste} and 88.0 g/t_{waste}, respectively, is obtained.

Following neutralization, sulfur exists in the form of gypsum ($CaSO_4$ x 2 H_2O), such that the hydrate water of gypsum needs to be taken into account when calculating the amounts. According to the calculations, this results in a total amount of residues of 12638 g/t_{waste} being produced by neutralization in a wet system with an internal processing stage.

In case of external processing, the effluents arising in the scrubber (about 300 l/t_{waste}) are conditioned in a separate neutralization facility and subsequently evaporated in an evaporator. The residues arising correspond to the amounts of residues generated by internal evaporation in the spray dryer in first approximation.

9.2 Residues of Semi Wet Processes

In semi wet processes, only $Ca(OH)_2$ is applied as neutralization agent. Here, chlorine and sulfur are calculated as calcium chloride and calcium sulfate dihydrate (gypsum). Again, it has to be taken into account that one calcium hydroxide molecule neutralizes two chloride ions. Calculations are based on a stoichiometric factor of 2.5 (see Section 6.4.5). TABLE 22 contains the values calculated for the loads arising from neutralization.

TABLE 22 Element and salt loads for calculating the amount of residues generated by neutralization in a semi wetsystem. Ex.: Excess of neutralization agent

Semi wet process					
element	**load** [g/t_A]	**calculated as**	[g/t_A]	**$(Ca(OH)_2)_{Ex.}$** [g/t_A]	**total** [g/t_A]
Cl	5170	$CaCl_2$	8093	10548	8093
S	705	$CaSO_4 \times 2\ H_2O$	3786		14334
					22427

With 5170 g/t_{waste} of chlorine and 705 g/t_{waste} of sulfur, 8093 g/t_{waste} of calcium chloride and 3786 g/t_{waste} of gypsum are arise during neutralization. Based on a stoichiometric factor of 2.5, the excessive amount of calcium hydroxide $(Ca(OH)_2)_{Ex.}$ is 10548 g/t_{waste}. A total of 22427 g/t_{waste} of residues results from neutralization.

9.3 Residues of Semi Dry Processes

The amounts of residues arising from neutralization in a semi dry system are calculated in the same way. Contrary to the semi dry process, however, calculations are based on a stoichiometric factor of 2.8 (see Section 6.4.5). The results are listed in TABLE 23. The amount of residues generated by the dry process is 24536 g/t_{waste}.

TABLE 23 Element and salt loads for calculating the amount of residues generated by neutralization in a conditioned dry process.
Ex.: Excess of neutralization agent

Element	Fracht	berechnet als		$(Ca(OH)_2)_{Ex.}$	Gesamt
	[g/t_A]		[g/t_A]	[g/t_A]	[g/t_A]
Cl	5170	$CaCl_2$	8093	12657	8093
S	705	$CaSO_4 \times 2\ H_2O$	3786		16443
					24536

9.4 Total Amounts of Residues Arising in the Model Plants

In addition to the amounts of residues generated by the neutralization of acid pollutants, fly dusts and other amounts discharged have to be taken into account. As outlined in Section 6, the calculations performed within the framework of the present study are based on fly dust amounts of 16000 g/t_{waste}. In addition, coke consumption must not be neglected. The total amounts of residues of the model plants are listed in TABLE 24.

TABLE 24 Total amounts of residues of the model plants *: about 300 l/t_{waste} effluents with salt loads

model plant	Residue from neutralisation [g/t_A]	fly ash [g/t_A]	lime / coke or coke [g/t_A]	TMT-15^{TM} [g/t_A]	Residue from external vaporization* [g/t_A]	**total** [g/t_A]
wet 1	external*	16000	2500	18.8	12638	**31156.8**
wet 2	external*	16000	1000	18.8	12638	**29656.8**
wet 3	12638	16000	2500	18.8	**-**	**31156.8**
wet 4	12638	16000	1000	18.8	**-**	**29656.8**
wet 5	12638	16000	1000	-	**-**	**29638**
wet 6	external*	16000	1000	-	12638	**29638**
semi wet 1	22427	16000	1500	-	**-**	**39927**
semi wet 1	22427	16000	1500	-	**-**	**39927**
semi dry1	24536	16000	2200	-	**-**	**42736**
semi dry 2	24536	16000	2200	-	**-**	**42736**

10 Investment Costs

10.1 General Preliminary Remarks

Comparison of various flue gas cleaning systems must not only be based on the distribution of pollutants along the flue gas cleaning line, the amounts of auxiliary chemicals needed, and the residues arising, but also on the costs of the flue gas cleaning systems.

The following cost analysis is restricted to the investment costs of the technical flue gas cleaning components. Specific disposal costs of a ton of waste can hardly be calculated for the model plants discussed, as real waste incineration plants are subject to complex influences by local effects. Moreover, disposal costs are not only determined by thermal waste treatment, but also by other waste management measures.

Even when restricting to the investment costs, cost analysis is complex and difficult. The information obtained from literature and interviews of plant constructors sometimes refers to different years. The investment costs obtained are not calculated for a certain standard year by means of correlation analyses, but represent estimates after the varying values have been harmonized.

Cost comparisons are preferably based on the specific disposal or incineration costs, i.e. costs of the treatment of 1 t waste in a plant for the disposal or reuse of waste. Incineration costs of 1 t waste are mainly influenced by the following factors [Rose], [Wolf], [Teichmann], [Warnecke], [Cavalieri], [Schetter], [Reimann-3]:

- Investment costs of the plant
- Operation costs, such as
  - Debt service of investment costs
  - Use of auxiliary chemicals
  - Management of residues
  - Profits from the use of energy
  - Waste management concept and logistics (transfer station, etc.) in the disposal area
  - Rate of utilization of the plant
  - Other operation costs (personnel, maintenance, etc.)

The ***investment costs*** comprise the planning, buildings, process technology, electric equipment, measurement and control technology, infrastructure (special unloading stations, etc.), and the construction time. The rough shares of these factors in the mean investment costs of a waste incineration plant of 150000 – 250000 t/a incineration capacity are presented in TABLE 25.

TABLE 25 Shares of investment costs

investment costs	[Auksutat]	[Wolf]	[Christmann-2]	[Neukirchen]
process technology	approx. 68 %	approx. 69 %	approx. 68 %	approx. 60 %
buildings	approx. 16 %	approx. 13 %	approx. 16 %	approx. 15 %
infrastructure	approx. 14 %			
measure and control technology			approx. 16 %	approx. 11 %
other investment costs		approx. 18 %		approx. 14 %

Operation costs of the plant mainly include the debt service, expenses for the use of auxiliary chemicals and energy, costs of the disposal of residues or profits from the reuse of products, the supply of energy as well as expenses for personnel and maintenance.

A major factor is the rate of utilization of the plant, which is determined by the amounts of wastes delivered, outage periods, and unplanned outages. In addition, the calorific value may influence the rate of plant utilization.

Costs are also influenced by the location of the waste incineration plant. Locations with a consumer of the process steam or heated steam or the electricity produced being present are rather favorable. In addition, waste transport logistics have to be taken into account. A logistic network of several waste incineration plants or connections to existing logistics systems help to prevent bottlenecks in waste delivery.

10.2 Procedure and Data Sources

It is demonstrated by the statements made above that the specific disposal costs are not only determined by the investment and operation costs of a waste incineration plant. However, effects of the local conditions prevailing at a location can hardly be generalized for calculation. Therefore, these influences have been neglected by cost analyses made in literature.

Reliable calculation of specific disposal costs is additionally aggravated by the lack of specific and reliable data. Plant constructors provide cost estimates only, which represent pure plant costs. These costs include neither construction services nor instrumentation and control systems, such that the costs cannot be equaled to the investment costs incurred when building a new plant.

Hence, specific disposal costs may not be applied in the present study. Therefore, only the ***investment costs of pure plant technology*** are calculated and compared.
In general, it may be assumed that simple flue gas cleaning systems of low investment costs are characterized by a high need for operation agents and larger amounts of residues. Contrary to this, minimum amounts of residues usually require more sophisticated processes of flue gas cleaning, which lead to higher investment costs.

In literature, the share of the flue gas cleaning systems in the total investment costs of new plants is given to be 15 - 35 % [Auksutat], [Christmann-2], [Wolf]. Total investment costs of a waste incineration plant with two lines and a capacity of 200000 t/a amount to about 200 –

600 mio DM [Warnecke], [Auksutat]. These figures, however, refer to the market situation of 1995 to 1996. In the following years, investment costs of flue gas cleaning systems have dropped for various reasons. The extent to which this development affects the share of flue gas cleaning in the total plant investment costs cannot be determined exactly.

In cost analysis, the investment costs of ***individual plant components*** are collected or calculated taking into account the design data. Then, the costs of the individual flue gas cleaning units are added up to a total amount of a specific model plant design. The investment costs of the

- electrostatic prcipitator
- carbon entrainment adsorber
- spray dryer
- SNCR
- SCR
- fabric filter
- coke adsorber
- spray adsorber
- additive injection unit of evaporation cooler
- external evaporation facility

are taken into account. Determination of these investment costs requires an immense expenditure. Hardly any information is available in literature with regard to the investment costs of individual plant components and entire flue gas cleaning systems. Sometimes, information and data supplied by plant constructors and plant operators are used. Extensive information on investment costs of flue gas cleaning system components was obtained from a large-scale waste incineration plant, the design data of which largely correspond to the model incineration plant. Investment costs of dry flue gas cleaning systems were reported by a plant constructor. Thus, investment costs of some of the flue gas cleaning systems and system components covered by the present study could be determined directly. ***All costs indicated below refer to two flue gas cleaning lines.***

The little information provided in literature mainly refers to the investment costs of selected complete flue gas cleaning systems [Schaub], [Thomé-2], [Thomé-1], [Kürzinger]. The plants covered by literature, however, are not identical with the plants selected in the present study. They differ in both the setup of the flue gas cleaning system and plant design. As plant design has an influence on the investment costs, the costs given by Thomé and Kürzinger, which refer to smaller incineration capacities and are based on the cost situation of 1994, appear to be too small for a direct comparison. However, due to the price drop in the following years, costs have equaled to a certain extent.

Again, these costs do not include construction services or instrumentation and control technology. Still, the investment costs of some plant components may be derived indirectly by evaluating the costs given for various flue gas cleaning systems [Schaub], [Thomé-2], [Thomé-1], [Kürzinger].

10.3 Cost Calculation

Investment costs of conditioned dry systems were provided by a plant constructor. According to him, investment costs of the plant "semi dry 1", consisting of SNCR/evaporation cooler/additive injection/fabric filter, are in the order of 24 mio DM for two lines. Investment costs of the plant "semi dry 2" (evaporation cooler/additive injection/fabric filter/SCR) were reported to amount to roundabout 30 mio DM. These figures refer to 1996/1997 and probably take into account electronic devices and measurement and control technology as well. For electrostatic prcipitators (three fields) and fabric filters, evaluation yields investment costs of about 4.8 mio DM and 4.5 mio DM, respectively. Investment costs of SCR units are in the range of 10 mio DM.

In a next step, these figures were compared with other accessible information. Evaluation of literature sources and adaptation to the above costs of individual plant components only allows figures to be obtained, which are subject to considerable uncertainties. An error of 10 – 20 % cannot be excluded. Still, the order of the costs might be correct.

Schaub compared various basic concepts of flue gas cleaning, including the estimated investment costs [Schaub]. His data refer to a model plant with three lines of 110000 t/a of waste each. The cost estimates do not include any construction services or costs of instrumentation and control. In first approximation, the costs given were multiplied by 2/3 for obtaining the corresponding values for two lines of 110000 t/a.

Doing this, an investment volume of about 30 mio DM results for a semi dry flue gas cleaning system, consisting of spray adsorber/fabric filter/SCR. As the investment costs of semi dry and semi wet systems should be of the same order, this figure is in good agreement with the figure given above for the plant with the evaporation cooler/additive injection/fabric filter/SCR ("semi dry 2", 30 mio DM).

Based on the information supplied by Schaub for NOx-removal from the flue gas, investment costs of an SCR unit may be derived. The difference between the investment costs of a semi wet system with SCR and without SCR results in an investment volume of about 9 mio DM for two incineration lines. This value is in good agreement with the 10 mio DM given above.

To determine the investment costs of other plant components, the comparisons of investment costs of selected flue gas cleaning systems as published by Thomé and Kürzinger were evaluated [Thomé-1], [Thomé-2], [Kürzinger]. The cost analyses performed by them refer to an incineration plant with two lines having a total annual capacity of 150,000 tons. Also here, construction services or costs of instrumentation or control are excluded.

For a carbon entrainment adsorber, Thomé and Kürzinger give a value in the range of 3.6 to 4.9 mio DM. Hence, these costs are of the same order as the 4.5 mio DM given above for a fabric filter.

TABLE 26 presents the investment costs of some of the flue gas cleaning systems assessed by Thomé and Kürzinger. Comparison of the costs given by Thomé with the integral value of the costs of individual plant components presented above shows that the investment costs given by Thomé are of the same order. As pointed out in TABLE 26, a cost volume of about 26.7 mio DM for the two-line dry sorption system “electrostatic prcipitator/fabric filter I/fabric filter II/SCR” results according to Thomé [Thomé-1]. The integral value of the data given at the beginning of the present Section is 23.8 mio DM, i.e., the value differs by about 11 %.

TABLE 26 Investment costs of selected flue gas cleaning systems according to [Thomé-1] for two lines and investment costs according to other sources

flue gas cleaning system	investment costs [Thomé] [Mio DM]	revised investment costs according other sources [Mio DM]
Electrostatic precipitator /Fabric filter I/Fabric filter II/SCR	26,7	23,8
Electrostatic precipitator /Spray absorber/Fabric filter I/Fabric filter II/SCR	29,7	26,5
Electrostatic precipitator /Spray dryer/Fabric filter/2-stufiger Scrubber/SCR	35,7	31,8
Electrostatic precipitator /Spray dryer/Fabric filter/3-stufiger Scrubber/SCR	39,6	35,3
Electrostatic precipitator /Fabric filter/3-stufiger Scrubber/SCR/external vaporization	40	35,7

For further proceeding, the data given by Thomé and Kürzinger are corrected by these 11 %. This results in the investment costs given in the right column of TABLE 26. Based on these data, the investment costs are estimated for various plant components. The results are presented in the following table.

TABLE 27 Estimated investment costs of selected components of flue gas

separation unit	investment costs [Mio DM related to two incinerators]
two step scrubber	ca. 10
three step scrubber	ca. 14
external vaporization	3 - 4
spray absorber	(ca. 3)

The value of about 3 mio DM for the ***spray absorber*** is uncertain and considered to be too small. As no better information was obtained, however, this value is used for further calculation and estimation of the costs of other plant components.

The costs of a ***spray dryer*** are assumed to be below 3 mio DM. According to a plant constructor, investment costs are in the order of about 2 mio DM.

Accordingly, investment costs of about 10 mio DM may be assumed for a two-stage scrubber, while a value increased by about 70 % results for a three-stage scrubber. Investment costs of an external facility for the evaporation of scrubber effluents to a residue to be disposed of amount to about 3 to 4 mio DM.

Comparison of investment costs of ***semi dry systems*** [Thomé-2] and ***semi wet systems*** [Thomé-1] reveals that the costs of the latter exceed those of the former by 4 mio DM. This is plausible, as the technical expenditure of the semi dry process is higher than that of the semi dry process.

No concrete information is available with regard to the investment costs of the ***coke adsorber***. According to the information supplied by plant constructors, the investment costs are of the same order as those of the carbon entrainment adsorber when referring to plants without the necessary additional equipment. If the additional equipment is taken into account, the coek adsorber is far more expensive due to the necessary safety systems and the downstream filter.

10.4 Survey of Costs

In a next step, the evaluation of all data available with regard to the investment costs of the individual system components was discussed with various plant constructors. It turned out that the investment costs had been estimated relatively well. The error of the investment costs determined is supposed to be below 15 %. The resulting values are given in TABLE 28.

TABLE 28 Investment costs of individual flue gas cleaning system components, related to two incineration lines and an incineration capacity of 200000 t/a

separation unit	invesment costs [Mio DM related fto two incinerators]
electrostatic precipitator (3 fields)	4,4
electrostatic precipitator (2 fields)	3,1
fabric filter	4,3
spray dryer	ca. 2
two step scrubber	9
three step scrubber	13
entrained flow reactor	4,5
coke adsorber	4,5
external vapourisation (no reuse of the residues)	< 4
SNCR	2
SCR	8,5

The investment costs of a conditioned dry system "semi dry 1" (SNCR/evaporation cooler/additive injection/fabric filter) and "semi dry 2" (evaporation cooler/additive injection/fabric filter/SCR) of 24 mio DM and 30 mio DM, respectively, as reported by a plant constructor in 1997, are supposed to be too high judging from present information. Due to the price drop, the authors assume lower values. Adaption yields costs of about 14 mio DM and 20 mio DM for "semi dry 1" and "semi dry 2", respectively. These adapted values were confirmed by a plant constructor.

Based on the results presented in the previous Section, the investment costs of the individual system components can now be added up to total investment costs of the systems. In TABLE 29, the estimated investment costs are listed.

TABLE 29 Estimated investment costs of the model systems without construction services, electronics, and measurement and control technology.

model plant	flue gas cleaning system	[Mio DM/ related to two incinerators]
wet 1	ESP / scrubber-scrubber / SCR / entrained flow reactor (external treatment)	29
wet 2	ESP / scrubber-scrubber /SCR/ carbon adsorber (external treatment)	29
wet 3	ESP / spray dryer / ESP / scrubber-scrubber /SCR/ entrained flow reactor	30
wet 4	ESP / spray dryer / ESP / scrubber-scrubber / SCR / carbon adsorber .	30
wet 5	spray dryer / fabric filter / scrubber-scrubber /SCR	24
wet 6	SNCR / fabric filter / scrubber-scrubber (external treatment)	19
semi wet 1	SNCR / spray absorber / fabric filter	16
semi wet 2	spray absorber / fabric filter / SCR	22
semi dry 1	SNCR / fabric filter	14
semi dry 2	fabric filter /SCR	20

According to this table, investment costs of the 10 model plants vary by a factor of about 2. The cheapest systems are those based on a conditioned dry process ("semi dry 1", "semi dry 2"). The system using SNCR ("semi dry 1") requires the lowest investment costs. The semi wet systems ("semi wet 1", "semi wet 2") are of the same order as far as investment costs are concerned, but more expensive due to the somewhat larger process expenditure expected. The only wet system of comparable investment costs is "wet 6" which consists of a few plant components only. It must be noted, however, that this plant is not equipped with a fine-cleaning stage. Wet processes with fine cleaning are the most cost-intensive of the 10 model plants.

11 Summary of Results

The present study was aimed at comparing various flue gas cleaning systems of waste incineration plants based on materials flow analyses and a complementary evaluation of investment costs. Work focused on the relationship between the setup of various flue gas cleaning systems and the respective materials flows. Furthermore, effects of the flue gas cleaning system on the need for auxiliary chemicals, the amounts of residues generated, and the investment costs were demonstrated.

Materials flow analyses were performed by means of model calculations, because large-scale plants mostly do not possess the data set required for reliable flow analyses to be made. In addition, materials flows are considerably influenced by the mode of operation of the flue gas cleaning systems.

Model calculations for the materials balances of the individual flue gas cleaning systems were based on a model plant with an annual incineration capacity of 200000 t waste. This plant consisted of two incineration lines with grate incineration and separate flue gas cleaning systems. Based on the experience gained from large-scale grate incineration plants, the flue gas volume and pollutant concentrations were specified for this model plant.

Then, 10 flue gas cleaning systems were selected for calculating the materials flows. Of these flue gas cleaning systems selected, 6 were wet flue gas cleaning systems with four of them having a very complex setup and a downstream fine-cleaning stage. In addition, two semi wet and semi dry flue gas cleaning systems were considered each. The semi dry flue gas cleaning systems covered by the present study were dry conditioned systems. By additional moistening, conversion of the auxiliary chemicals required for neutralization was improved and, hence, their consumption reduced.

In wet flue gas cleaning, various variants are possible for converting the scrubber effluents into solid residues – which is required according to the law. Of the 6 wet flue gas cleaning systems selected, three systems were equipped with an internal spray dryer for evaporation of scrubber effluents. In the remaining three systems, the scrubber effluents were transferred to external processing. By external processing, solid residues or reusable materials, such as gypsum and hydrochloric acid, can be generated. Production of reusable materials was not considered in detail by the present study, as the future of this recycling method significantly depends on the costs and sufficiently reliable information for balancing was lacking.

The scope of balancing comprised the entire flue gas cleaning system, starting downstream of the boiler and ending with the stack. Consequently, boiler and grate ashes produced by incineration were not covered. In contrast to this, auxiliary materials used in the system as well as the residues arising were taken into consideration by the balances.

In addition to the scope of balancing, the substances to be balanced had to be specified. Due to the waste properties, a large number of chemical elements or compounds could be balanced. To limit the expenditure required, an acceptable selection had to be made. Within the framework of the present study, the elements of chlorine (Cl), sulfur (S), mercury (Hg), cadmium (Cd), and lead (Pb) were balanced.

Balancing was accomplished by model calculations that were largely based on data of large-scale plants. For each plant stage, separation efficiency with respect to a pollutant had to be determined.

Many new large-scale plants are equipped with a wet process, as this allows the flue gas cleaning products to be recycled from the scrubber effluents in principle. Relatively good data are available for the scrubber stages. In wet systems, fine-cleaning stages are often installed downstream of the scrubbers. In literature, no information is given with regard to the separation efficiencies of the fine-cleaning stages backfitted for compliance with the 17th Federal Emission Control Ordinance. In the present study, these separation efficiencies were calculated by comparing old data without fine cleaning with actual clean gas data measured in a backfitted fine-cleaning system.

Data on semi wet flue gas cleaning systems in Germany are insufficient for reliable balancing. Data are available on the clean gas and the stoichiometric factors used only. The reason is that new large-scale plants are mainly equipped with wet or dry flue gas cleaning systems. Moreover, existing semi wet flue gas cleaning systems often represent backfitted old facilities which use an electrostatic prcipitator for dust separation. No information was available on foreign plants. In addition, their boundary conditions are completely different. For compliance with the current emission limits, a NOx-removal system and carbon entrainment were considered. For reasons of costs, however, new plants are not planned to be equipped with such a combination.

Compared to the semi wet systems, much more data are available on the semi dry flue gas cleaning systems, as large-scale plants are equipped with them.

Evaluation of the design data of a large-scale waste incineration plant revealed, however, that these data are based on worst-case situations. Hence, design data are suited for the calculation of materials flows with certain limitations only.

Data taken from literature were found to be outdated partly. This especially applied to data on the stoichiometric factors of semi wet and semi dry flue gas cleaning systems. Compared to the literature values, stoichiometric factors reported by the operators sometimes were much larger. In some cases, literature data are only sufficient for compliance with the old requirements made in the Clean Air Regulations, but not with the far smaller limit values indicated in the 17th Federal Emission Control Ordinance.

When evaluating the clean gas data of various plants and processes, emissions from the stack were not found to differ significantly. Due to the very small concentrations encountered, no clean gas values could be calculated. For balancing, they had to be specified according to the expectations. The emission values achieved by semi wet and semi dry flue gas cleaning processes are influenced by the type and amount of auxiliary chemicals used. In some cases, a large excess of neutralization agents is used in large-scale semi dry or semi wet flue gas cleaning systems in order to remain far below the requirements made in the 17th Federal Emission Control Ordinance.

The results may be summarized as follows:

Materials Balances and Emissions

- It is shown by the balances that the requirements made in the 17th Federal Emission Control Ordinance are complied with reliably by all flue gas cleaning systems selected. This applies to all elements studied.
- However, the individual processes differ for the elements of ***chlorine*** and ***sulfur***. For the elements Cl and S, wet flue gas cleaning systems with a downstream fine-cleaning stage reach the lowest emissions. Compared to this, emissions of semi dry and semi wet flue gas cleaning systems are on a higher level.
- Using larger amounts of auxiliary chemicals, also semi wet and semi dry flue gas cleaning systems can reach the emission values achieved by wet flue gas cleaning. This means that the mode of operation of a semi wet or semi dry flue gas cleaning system has a considerable influence on the materials balances and emissions.
- In semi dry and semi wet flue gas cleaning systems, materials flows and emissions may be influenced without technical modifications being required. In wet processes, materials flows and emissions can only be influenced when modifying the fine-cleaning technology.
- A reliable differentiation between the various flue gas cleaning systems cannot be made for the other elements balanced (***heavy metals***). The concentrations of the metals studied are very small such that a dependence on the flue gas cleaning system can no longer be detected.

Auxiliary Chemicals

- The amounts of auxiliary chemicals needed were calculated on the basis of the stoichiometric factors specified. For determining the stoichiometric consumptions, information gained in relatively new plants was used for wet and conditioned dry processes (see TABLE 14).
- As no new plants equipped with a semi wet flue gas cleaning system exist, information from older plants had to be used. There, the stoichiometric consumptions are very high in some cases. For optimized new plants, smaller consumptions are to be assumed, especially when taking into consideration optimized physical properties of neutralization agents. However, no data were available on this. The stoichiometric consumptions used within the framework of the present study were based on values for the use of conventional neutralization agents and specified to be smaller than applied in many large-scale plants for compliance with the values indicated in the licenses. Still, they did not represent the optimum.
- Use of auxiliary chemicals for the separation of acid pollutants is influenced by the process applied. As expected, the calculations revealed a gradation. Semi dry processes require more auxiliary chemicals than semi wet processes, and the latter require more than wet processes. Consumptions amount to:

wet:	1.9 kg NaOH/t_{waste} and about 5.9 kg $Ca(OH)_2/t_{waste}$,
semi wet:	17.6 kg $Ca(OH)_2/t_{waste}$,
semi dry:	19.7 kg $Ca(OH)_2/t_{waste}$

- Sometimes, the amount of auxiliary chemicals needed is due to process technology. Coke consumption of the carbon adsorber is determined by the pressure loss and not by the pollutant load of the coke layer.

Residues

- The amounts of residues generated by the individual flue gas cleaning systems are determined by the auxiliary chemicals used. Here, the stoichiometric factor is of decisive importance. The amounts of residues arising are:

wet:	29.6 – 31.2 kg/t_{waste},
semi wet:	39.9 kg/t_{waste},
semi dry:	42.7 kg/t_{waste}.

- The individual fractions of the residues, such as dust, neutralization residues, etc., are obvious from TABLE 24.
- The use of coke in the fine-cleaning components does not have any considerable influence on the amounts of residues generated.
- The auxiliary chemicals used for fine cleaning do not always have to be disposed of as waste. The loaded coke from the carbon adsorber may be incinerated in the furnace. This may be considered an advantage of the carbon adsorber as compared to the entrained flow reactor.

Costs

Analysis of the costs turned out to be rather complex and difficult. The data determined are restricted to partial costs of the investments made. These costs only include the plant components, but no construction services, electronic equipment, measurement and control technology, etc.

- In the past years, investment costs of plants have dropped.
- Depending on the design data, investment costs of individual flue gas cleaning system components range between 0.5 and 7 mio DM (see TABLE 28).
- Depending on the design data, investment costs of entire flue gas cleaning systems range from 14 to 30 mio DM (see TABLE 29).
- Costs of semi dry and semi wet flue gas cleaning systems hardly differ. These systems require the lowest investment costs.
- Investment costs of wet flue gas cleaning systems vary largely. A relatively simple wet flue gas cleaning system, e.g. Borsigstraße, hardly is more expensive than a semi wet flue gas cleaning system.

12 Conclusions

Analyses of the data available confirm that very small pollutant fractions only are released into the atmosphere by the flue gas cleaning systems of modern waste incineration plants, irrespective of the technology selected. In general, a separation efficiency in excess of 98 % is achieved. It is obvious from the materials balances that pollutants are separated by the flue gas cleaning system and discharged from the plant together with the residues arising. An assessment of the various flue gas cleaning processes in terms of emissions is impossible due to the very small differences in large-scale plants. For the present study, the clean gas values of the individual flue gas cleaning processes had to be defined in line with the expectations. Values achievable in large-scale plants might be below the values assumed. In view of this situation and the procedure selected, the model calculations do not allow any conclusions to be drawn or evaluations to be made with respect to emissions.

Comparison of the balanced flue gas cleaning systems shows that the semi wet processes represent favorable alternatives. These processes are characterized by low investment costs with still acceptable amounts of residues produced. An interesting alternative to semi wet processes is simple wet flue gas cleaning with a fabric filter and a two-stage scrubber system only. Investment costs of this wet flue gas cleaning system may be somewhat higher, but the amounts of residues generated are far smaller.

A final recommendation cannot be made, as data on semi dry flue gas cleaning systems in Germany are insufficient. This especially applies to the stoichiometric factor, i.e. to the amounts of auxiliary chemicals used and the amounts of residues generated, both of which do not seem to be optimized.

In this respect, it is also necessary to take the future development of the legal boundary conditions into consideration. It is not sure, whether the transfer of residues from flue gas cleaning to mines will continue to be an accepted recycling path as it was in the past. If this recycling option will no longer be accepted due to new legal regulations or political decisions, a wet flue gas cleaning system will probably be favored.
Analysis of the individual flue gas cleaning systems shows that it is still possible to optimize both new and existing plants. For instance, residues from the entrained flow reactor could be used in the neutralization of scrubber effluents.

A new development that may gain importance in the future is the installation of the SCR unit in the boiler range upstream of the economizer. In this case, it is not required to reheat the flue gases. Alternative primary measures to further reduce nitrogen oxides in the flue gas may also become more relevant.

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