Fig. 5. Schematic diagram of the two-circuit control system $(T, p) \rightarrow F(l, n)$
a extruder, *b* drive unit, *c* thrust bearing of screw, *d* actual value recorder, *e* adjustment for set value, *f* comparison of set and actual values, *g* computer, *h* amplifier, *i* positioner with moderator (positioning speed selector)

Fig. 6. Single-circuit system for the autogenous control of stock temperature by means of a rotating dissipator sleeve with a fixed axial position. Set condition: speed of rotation, n', of the sleeve
a torpedo head, *b* sleeve

Fig. 7. Single-circuit system for the autogenous control of stock temperature by means of a (non-rotating) dissipator sleeve capable of axial movement (rheological-thermodynamic differential). Set condition: length of gap l, or the gap length ratio, l''/l' for constant $l' + l''$
a torpedo head, *b* sleeve, *c* mandrel, *e* average axial length of the annular gap between *b* and *a* or between *b* and *c*

Fig. 8. Schematic diagram of the single-circuit control system $T \rightarrow f(n')$ or $T \rightarrow f(l')$
a extruder, *b* actual value recorder, *c* set value adjustment, *d* comparison of set and actual values, *e* amplifier, *f* positioner with moderator (positioning speed selector)

Fig. 9. Extruder with "autostatic system" for maintaining the stock temperature T_s constant. Optimum setting of T_1 and s $dT_s/dT_1 \rightarrow 0$
heater/cooler, *b* thermal insulation

Fig. 10. Calculation of the mean viscosity in the autogenous zone of the autostatic system

Fig. 11. Autogenous temperature stabilization for a plastic with the characteristic $l/\beta = 69$ ($T_s - T_1 = 113$ °C): rise in temperature ΔTn of the autogenous zone and final temperature, T_s, as functions of the initial temperature, T_1 with the gap setting, s, of the orifice as parameter.

The Behaviour of Household Refuse Containing PVC in Incinerators

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NOTE: For figures see German text; translations of captions are at the end of this article

A great deal has been said and written recently on the subject of refuse and refuse disposal. This has led in some cases to a misrepresentation of the facts and even, regrettably, to deliberate attacks on certain classes of material in the popular press, often presented in a sensational manner. It is now being realised, however, that these diatribes are frequently unfounded, particularly where plastics are concerned.

The present paper will discuss the results of systematic trials in which a rotary furnace was used to incinerate municipal refuse to which predetermined amounts of plastics had been added in concentrations rising to higher levels than are ever reached in practice.

Municipal refuse, which consists chiefly of household refuse, is a very heterogeneous mixture whose composition can only be modified to a limited extent. Incineration therefore results in a large number of combustion products of which the gaseous components are discharged into the atmosphere.

As a result of continuous analyses conducted in individual towns, the average composition of household refuse is known and incinerators can therefore be designed in such a way as to reduce environmental pollution as far as possible. High chimneys and flue gas filters are also helpful in this respect.

The household refuse of most Western European countries currently contains an average of between 2% and 3% by weight of plastics. It is estimated that the average proportion in 1980 will be 4.3% in West Germany [1] and about 4% in Great Britain [2], and that the unceasing increase in the use of plastics will lead to a further rise by 1990. If this rise is accelerated, e. g. by the introduction of non-returnable plastics bottles, the proportion of plastics in household refuse will obviously increase very considerably.

The current disposal method most likely to establish itself is incineration, although the other two accepted methods — controlled dumping and composting — show no signs as yet that they will be adversely affected by the presence of a somewhat higher plastics content than is customary at present [3, 4]. As a gradual increase in the proportion of plastics may be expected, however, we felt that it would be in the public interest to investigate the consequences of incinerating refuse containing plastics.

A Prototype Refuse Incinerator

We used a rotary furnace of the type manufactured by the Österreichische Alpine Montan Gesellschaft, Zeltweg, which is superior to most conventional grate type furnaces in that the temperature of the combustion chamber can be kept within precise limits and relatively easily regulated even when dealing with refuse of widely varying composition which may contain large quantities of plastics [5]. Furthermore, there are no grates to be blocked by dripping thermoplastics. This plant, whose capacity ranges from 1 to 2.8 tonnes of refuse per hour depending on the calorific value, was developed for communities of 20000 to 60000 inhabitants. The capacity of the system can be increased as required by installing a number of such rotary furnaces.

[1] For literature references please see German text

Conduct of the Trials and Monitoring of the Flue Gases

The gaseous combustion products of most plastics are CO_2 and H_2O, together with CO if little oxygen is available. Nitrogen compounds, SO_2 and HCl may also be liberated. We are primarily concerned with the composition of the flue gases evolved on the combustion of refuse containing the most important plastics in terms of weight, Fig. 1 [6]. We selected polyethylene (PE) as representative of hydrocarbon polymers and polyvinyl chloride (PVC) as representative of chlorinated hydrocarbon polymers. Subsequent experiments will be conducted on specific plastics and other combustion systems which will not be discussed here, so that the overall picture can be assessed in the light of experiences to date.

The following conditions were laid down to allow for the heterogeneity of the refuse:

a) The experiments would only involve refuse with a predetermined plastics content. This would necessitate determining the basic plastics content of household refuse and the controlled addition of further plastics materials, in this case polyethylene and PVC.
b) The composition of the household refuse employed in the tests must be analysed in order to obtain reproducible results.
c) In order to have homogeneous refuse for part of the experiments we used pine chips of the kind obtained as scrap in the bark stripping plants of sawmills.

With these prerequisites in mind we analysed the flue gases evolved on the combustion of household refuse and the special refuse listed in Table 1, using the experimental set-up illustrated in Fig. 2.

Table 1. Composition of the refuse samples tested

Type of refuse	PE content [%]	PVC content [%]
Household refuse from Zeltweg	0	0
	5	0
	10	0
	0	2.5
	0	5
	0	6[1])
Bark chips	0	0
	1	0
	5	0
	10	0
	0	1
	0	3
	5	1

1 PVC pipe

Gas analysis was carried out with a Multi Gas Detector manufactured by the Drägerwerk Lübeck. The HCl concentration in the flue gases was determined on part of the effluent by the method illustrated in Fig. 3. 30 to 120 litres of the flue gases were pumped per hour through the wash bottles *W* and the gas meter *Z* by means of the pump *P*.

The chlorine content of the absorption liquids in the wash bottles (H_2O and 0.1 n caustic soda solution) was determined by a modified version of Mohr's titration method so that the solubility of AgCl

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could be compensated for by adding an adequate known amount of chloride before carrying out the determination itself. The chloride additive was an aqueous solution of NaCl and K_2CrO_4 which was such that exactly 5 ml of 0.00564 n $AgNO_3$ solution were required for the reddish-brown silver chromate to appear. The consumption of 0.00564 n-$AgNO_3$ solution in excess of this indicates the true chlorine content [7].

The total amount of flue gas evolved was determined with a Prandtl tube. The slag and flue dust were subjected to quantitative analysis by methods which need not be discussed here. Provisional analyses were carried out at three points in the immediate neighbourhood of the incinerating plant to establish the extent of dust immission and the concentration of SO_2, HCl and nitric oxides.

The refuse was sorted as follows: A fairly large batch was carefully mixed and then quartered to obtain a representative sample which was then sorted by hand. A decimal balance was used to determine the amounts of the individual plastics present in the refuse as well as the amount of plastics material added.

Results

Composition of the Refuse

The results of analysing the refuse on each day of the experiment are given in Table 2, which shows the composition of the refuse in the absence of additives, without specifying the individual plastics present. The amount of plastics varied between 1.0% and 5.9% with an arithmetical mean of 3.1% over the 8 days. An examination of household refuse in Hamburg [8] revealed that the proportion of PVC, for example, was 0.2 to 0.6% by weight in that particular town.

Table 2. Results of sorting household refuse (proportions in % by weight)

Date of experiment (1971)	4. March	1. April	14. April	20. May	3. May	11. June	14. June	28. June
Vegetable waste	2.9	7.8	1.9	2.2	4.1	6.9	56.0	14.0
Textiles, leather, rubber	2.4	3.0	4.3	2.5	5.8	5.1	4.5	4.3
Paper, board, wood	25.6	7.0	20.9	27.3	19.3	12.8	20.5	24.3
Plastics	2.6	1.9	2.3	4.4	2.8	5.9	1.0	4.2
Mineral constituents	60.7	71.7	65.7	58.4	63.6	55.6	0	43.9
Metals	3.3	3.0	1.9	2.9	2.8	5.9	4.0	3.2
Gluss	2.5	5.6	3.0	2.3	1.6	7.7	14.0	4.3

Composition of the Flue Gases

The flue gas constituents revealed by the Dräger gas detector were CO, SO_2, HCl and ($NO + NO_2$). We also tested for other gaseous compounds such as NO_2, CO_2, O_2, hydrocarbons (KW), steam, formaldehyde, Cl_2, HF and phosgene in some cases. The results are presented in Table 3.

Table 3. Analysis of flue gases obtained on incinerating Zeltweg household refuse and "homogeneous" refuse

Type of refuse	Temperature of flue gases [° C]	CO_2 [%]	CO [%]	SO_2 [ppm]	HCl [ppm]	NO + NO_2 [ppm]	KW [ppm]	H_2O [mg/l]
Household refuse	850	10	0.009	50	n.n.	35		
Household refuse + 5% PE	880	9	0.016	2	n.n.	35		
Household refuse + 10% PE	870	13	0,050	30	n.n.	30		
Household refuse + 5% PVC	720	8	0.021	80	1—5	28		
Household refuse + 6% PVC	820	9	0.011	20	3.5	25		
Bark	840	11	0.020	n.n.	n.n.	100	n.n.	27
Bark + 1% PE	760	9	0.005	n.n.	n.n.	100	n.n.	17
Bark + 5% PE	810	10	0.010	n.n.	n.n.	60	n.n.	21
Bark + 10% PE	835	9.5	0.005	n.n.	n.n.	50	n.n.	30
Bark + 1% PVC	820	8	0.004	n.n.	n.n.	100	n.n.	41
Bark + 3% PVC	800	8.5	0.007	n.n.	0.1	90	n.n.	16
Bark + 5% PE + 1% PVC	860	6.5	0.006	n.n.	n.n.	60	n.n.	21

(ppm = parts per million; n.n. not detectable)

Chlorine, phosgene, hydrogen fluoride, formaldehyde and hydrocarbons were never detected. The nitric oxide content diminished in proportion as the refuse was "diluted" with plastics. The HCl concentrations of the flue gases are particularly interesting. In view of the presence of PVC in the refuse and the total amount of gas emitted — about 6000 m^3 per hour — the flue gases should theoretically contain up to 1000 ppm of HCl. In point of fact, the maximum amount detected during the tests was 5 ppm. The HCl initially evolved from the PVC obviously reacted immediately with alkaline constituents of the refuse, as a result of which most of it was combined. It must therefore be present as chlorides in the ash and flue dust. An analysis conducted during the last experiment referred to in Table 3 revealed that the chlorine content of the ash was 1.45% and that of the flue dust 0.24%.

The Emission of Hydrogen Chloride

Enquiries at various refuse incinerating plants in West Germany and other Western European countries revealed that the PVC currently present in refuse could be incinerated in existing plant without causing corrosion, since most of the HCl evolved during incineration was combined, presumably by the ash already present in the refuse or formed on combustion.

Serious difficulties are likely to arise, however, if the PVC content of refuse appreciably increases. Generally speaking, a PVC content of 1 to 2% is regarded as harmless [9]. This accords with the most widely held view in the technical press [10 to 13]. In any case it is entirely wrong to attribute the whole of the HCl evolved by a refuse incineration plant to the PVC present in the refuse [14, 15].

If the amount of harmful material emitted from incineration plants were to increase, it would be necessary to install gas scrubbers. This presents no problems as far as HCl absorption is concerned [16]. The experiments described in this paper, however, gave such astonishingly low figures for the HCl concentration of the flue gases that even refuse with a PVC content that is exceptionally high by present standards could obviously be efficiently incinerated in this plant without noticeably affecting the environment.

Table 4. HCl contents in the flue gases of PVC-containing refuse samples

Nr.	Date of experiment	Type of refuse	HCl content of flue gases mg/m^3	HCl content of flue gases ppm
1	23.8.71	Zeltweg household refuse of average composition	2.8	2.0
2	23.8.71	Ditto + 2.5% PVC	6,5	4.6
3	24.8.71	Ditto + 5% PVC	6.5	4.6
6	24.8.71	Ditto + 5% PVC	7.2	5.1
5	25.8.71	Ditto + 5% PVC	10.9	7.2
6	25.8.71	Ditto + 6% PVC pipe	4.9	3.5

The analytical method was used in experiments 1 to 6 and Dräger tubes in experiment 6

Admittedly the scientific value of such experiments depends on the extent to which they are reproducible. The results of the volumetric determination of chlorine by the titration method described earlier are summarised in Table 4. It should be noted that the average degree of absorption was 0.90 [cf. 17]. The calculation was carried out as follows:

$$\frac{\text{HCl content in the first wash bottle}}{\text{HCl content in the first and second wash bottles}}$$

The gas inlet pipe to the absorption vessels was not heated. The results are of the same order of magnitude as those obtained with the Dräger gas detector. The plastic material was mixed with the refuse by hand in the appropriate quantities. In the experiment with a 5% PVC content, 1000 kg of refuse containing 50 kg of PVC (Hostalit® powder) was burnt per hour and an average of 100 litres of flue gas per hour was passed through the absorption liquids. A simple calculation shows that with a total of 6000 Nm^3/h of flue gas an average HCl content of 2500 to 2800 ppm might have been expected. Since some 25 kg of HCl cannot vanish without trace, it must be present in the slag or flue dust in the form of chlorides. The results of analysing the slag and flue dust of Zeltweg household refuse are presented in Table 5. Chloride could not be detected qualitatively with $AgNO_3$ in nitric acid solution.

Chlorine determinations on several samples of slag retrieved during the incineration of refuse containing PVC gave values of between 1.49% and 2.9%. A sample of flue dust taken during the incineration of household refuse containing 5% PVC had a chlorine content of 2.0%.

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Table 5. Composition of the incineration residues of household refuse (without additional PVC)

	Slag [%]	Flue dust (from electrostatic precipitator) [%]
SiO_2	47.91	28.50
Al_2O_3	12.28	19.00
Fe_2O_3	5.81	11.84
Mn_3O_4	0.21	0.14 (MnO)
CaO	9.74	12.80
MgO	3.68	2.61
P_2O_5	0.84	0.53
TiO_2	2.83	1.84
$Na_2O + K_2O$	5.17	2.98
C	6.12	4.58
SO_3	—	8.09
Loss on ignition	3.85	6.65

Observation of the combustion process itself is perhaps just as important and informative as the results of analysing the flue gases and combustion residues. We found that the addition of further plastics materials to the refuse did not adversely affect the combustion process in any of our experiments. With plastics concentrations of about 3% upwards, in fact, we were able to save fuel oil by periodically switching off the heating system. A general inspection of the plant at the end of our experiments revealed no signs of corrosion by the flue gases.

Immission Measurements[1])

To obtain some idea of whether dangerous concentrations of harmful materials were likely to form in the atmosphere, measurements with Dräger tubes were carried out at three points in the immediate neighbourhood of the incinerating plant. The limits of detection of the tubes were 0.1 ppm for SO_2, HCl and ($NO + NO_2$) and 1.0 ppm for CO. Not one of these gases was detected in any instance.

Dust measurements by the conimetric method were carried out at the same time. With one exception all the results were below 2 mg/m³. The dust concentrations were therefore within the conventional average limits for this test.

Discussion of the Results

These results show that even larger amounts of plastics than are generally expected to be present by 1980 can be disposed of safely, effectively and without complications or risk to the environment by means of the refuse incinerating plant for small to medium communities used in our experiments, Fig. 4.

The initially surprising discovery that the HCl content of the flue gases evolved when PVC-containing refuse is incinerated is well below the theoretically probable concentration may be primarily attributed to the design and method of operation of the rotary furnace. As a result of the controllable rotary movement of the furnace and the design of its interior the material to be incinerated is continuously circulated for an average of 30 minutes. This results in optimum contact with the furnace air, virtually complete combustion and sterile slag. The continuous rotation and the helical path followed by the air of combustion cause a powerful eddying movement of the powdery refuse at the feed side and, in due course, the glowing particles and the alkaline ash. The completely odourless ash contains an average of 4 to 6% C in the form of low temperature coke or charcoal.

The flue gases containing gaseous decomposition products pass through these eddying particles as though they were a filter, during which process HCl, for example, is combined by the coke or charcoal particles which behave in the same way as active carbon, and/or is neutralised by Ca and Mg compounds in the ash. Materials such as $CaCl_2$ are highly stable at the temperatures prevailing in these furnaces which do not greatly exceed 700 to 800 °C, however [18]. The HCl liberated on the combustion of PVC therefore appears in the ash in an adsorbed or chemically combined form and can therefore be largely discounted as an atmospheric pollutant, thus eliminating the need for a scrubber. These findings differ fundamentally from those of the model experiments conducted in the laboratory in which neither the material to be incinerated nor the air of combustion were circulated and the HCl content of only small amounts of PVC reappeared almost quantitatively in the flue gases.

The limit for adsorptive and chemical combination of the isolated HCl by the ash is about 5% PVC in the incinerating plant we used, a level we are unlikely to reach even by the year 2000 whatever other changes may have taken place in the composition of household refuse by then. As preliminary experiments have shown, the emission of HCl increases markedly at higher PVC concentrations than this. Temperature control is probably an important factor here, however. We propose to extend our experiments to other plastics, e. g. the nitrogen-containing polymers such as polyamides. Here again, accurate measurement of the immission concentrations is essential.

We can confirm the widely held theory that the combustion of polyolefines, polystyrene and other hydrocarbon plastics does not constitute an emission hazard and that on the contrary such materials are advantageous from the standpoint of their calorific value. Assuming that they are properly mixed with the rest of the refuse, the permissible upper limit in rotary tube furnaces will be of the order of 20 to 25% [19]. Plastics waste can be incinerated in rotary tubular furnaces even without the admixture of other fuels provided allowance is made for their high calorific value and, in the case of PVC (and plastics containing Cl, F or S) certain other prerequisites are fulfilled as regards corrosion protection and scrubbing the exhaust gases.

Translation of captions to figures and tables in German text (cf. pp. 53/56)

Fig. 1. The relative proportions of the various materials used in the packaging field in West Germany in 1970 were: paper and board 49%, glass 25%, wood 10%, all kinds of metals 10% and plastics 6%. This graph shows the breakdown of the latter item into individual plastics

Fig. 2. Experimental set-up used for incinerating refuse
a Introduction of the weighed amount of refuse; *b* Introduction of additional plastics materials, *c* Blower, *d* Rotary tubular furnace at an inclination of 2%, *e* Combustion, *f* Post-combustion chamber, *g* Slag, *h* Flue dust, *i* Determining the amount and temperature of the flue gases, *k* Cooler, *l* electrostatic precipitator, *m* Determination of the composition of the flue gases, *n* To chimney

Fig. 3. System for determining the HCl content of the flue gases
a Flue gases from refuse, *b* Sampling probe, *c* Flue gas duct, *d* Wash bottles; *e* Gas meter; *f* Pump

Fig. 4. Refuse incineration plant at Zeltweg, Austria

1 By "immission" we mean all harmful substances introduced into the atmosphere that affect animate and inanimate nature.

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