

# Co-Combustion of End of Life Plastics in MSW Combustors

*APME's Technical & Environmental Centre Work 1992-98*

*A Summary Overview*

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## SUMMARY

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This report summarises a series of studies commissioned by the Association of Plastics Manufacturers in Europe (APME) on the co-combustion of end of life plastics in Municipal Solid Waste Combustion (MSWC) plants. The studies have focused on plastics waste arising from 4 different market sectors: packaging, automotive, electrical & electronic and building & construction.

The addition of packaging plastics waste to MSWC can be beneficial to the combustion process. Depending on the quantity added there can be an improvement in combustion efficiency together with an overall improvement in combustion stability. There is no increase in PCDD/F concentrations in the raw gases, even with the inclusion of 8-10 wt% of PVC, the European market average. By means of addition of lime containing active carbon to the scrubbing system, PCDD/F clean gas concentrations can be kept to only 10% of the permitted limit.

Automotive Shredder Residues (ASR) can also be beneficial to the MSWC process. As evidenced by a reduced level of Total Organic Carbon (TOC), grate combustion efficiency is improved and no detrimental effects are observed in the clean gas waste stream. The leaching characteristics of the grate ash are not impacted, with the results for some parameters actually improved. Consequently, while differences in regulations on a country by country basis must be taken into account, the potential either to use grate ashes beneficially or for their disposal in approved landfills is not impacted.

Pilot trials with Electrical and Electronic (E+E) plastics waste support co-combustion with MSW as an environmentally and economically sound recovery route for medium to high amounts (3-12 wt%). Provided the E+E waste fractions are treated for efficient metal extraction prior to combustion, their high heat value has a beneficial effect on the required inert character of the grate ash residue. Clean gas emissions comfortably achieve regulatory limits for PCDD/F's, with controlled MSW combustion demonstrating that it is an effective "dioxin sink" with a destruction efficiency of >90%.

Polyurethane and polystyrene based building and insulation foams can present special challenges for waste management because of the presence of chlorofluorocarbons (CFC's) used at one time as blowing agents, and of flame retardants based on bromine, chlorine and phosphorus. Trials have demonstrated that co-combustion with MSW is an environmentally recommended option for these foams. This strategy is simple, makes full use of the energy of the plastic material, and offers an overall environmental benefit compared with other disposal options.

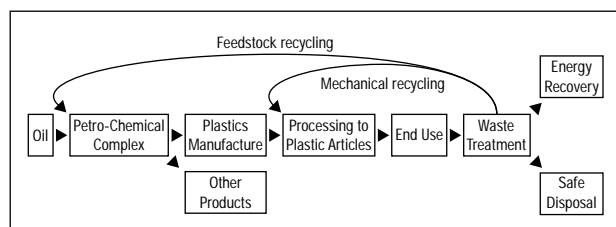
## 1. INTRODUCTION

### 1.1 OPTIONS FOR PLASTICS WASTE RECOVERY

The objective of waste recovery is to conserve resources and protect the environment at the minimum cost to consumers. Almost all plastics are derived from oil. Although accounting for only 4% of current oil consumption, this represents a valuable resource. After serving their useful life in numerous applications, plastics can be recovered in a variety of ways which contribute to the needs of sustainable development while maintaining a high level of environmental protection.

The available recovery options for end of life plastics are illustrated in the following diagram:

**Figure 1.1**  
**RECOVERY OPTIONS FOR END OF LIFE PLASTICS**



### 1.2 INTEGRATED WASTE MANAGEMENT

Choosing the best option for a given waste stream depends on a combination of several factors such as suitability of the material for a particular type of treatment, location, transport infrastructure and availability of end markets. The option selected should achieve the maximum value with the minimum environmental impact. The environmental impact of the overall recycling operations, including such things as preparation and transport, must not exceed the environmental benefit gained from recycling the product. Similarly, if there is no market for the finished product, mechanical recycling may increase the environmental burden. In some cases a mixed approach may be taken, for example with some products removed from the waste stream for mechanical recycling, and the remainder recovered as energy.

### 1.3 ENERGY RECOVERY

When energy recovery is the best choice, a further range of options is available, such as monocombustion in fluidised bed facilities and co-combustion in power stations, cement kilns and Municipal Solid Waste Combustion (MSWC) plants. The Association of Plastics Manufacturers in Europe (APME) conducts wide ranging research programmes to investigate optimum recycling and recovery technologies. This report summarises a series of projects commissioned by APME to study energy recovery from a variety of plastics waste streams by means of co-combustion in MSWC plants (See references 1-8).

While the majority of disposed polymeric materials currently ends up in landfills, about 25%, mostly from packaging and distribution, are directed to MSWC. Europe had approx. 500 MSWC plants in 1992, mostly of the so-called mass burning type. The characteristics of these units are rather diversified with respect to grate type, size, age, extent of energy recovery and the different air pollution control devices used throughout Europe. The growth of MSWC as a waste disposal method has been moderate in recent years, considering the upcoming stricter landfill regulations in many European countries. The role MSWC will play in energy recovery from end-of-life plastics is therefore expected to become more significant.

## 2. END OF LIFE PLASTICS

The consumption of plastics in Western Europe, including non-plastics applications like adhesive coatings, etc., was 32 million tons in 1995. The total amount of typical thermoplastics was 26.5 million tons. The major applications are shown below

Packaging	41 %
Building & Construction	20 %
Distribution and Large Industry	15 %
Electrical & Electronic	9 %
Automotive	7 %
Agricultural	2 %
Other	6 %

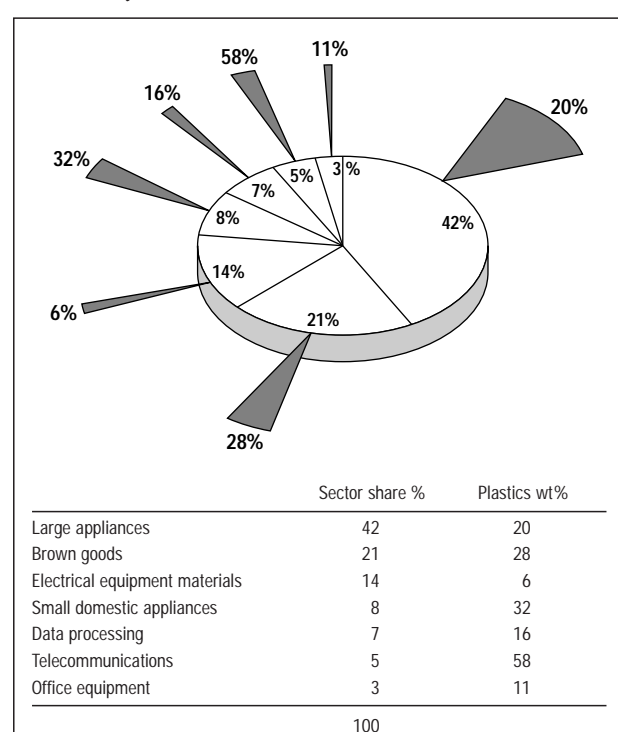
## END OF LIFE PLASTICS

The consumption pattern of the different plastics in these sectors does not allow a conclusion to be drawn on the distribution of the various compositions and qualities in waste plastics. The lifetime of plastics in these sectors is rather different. Market know-how and an understanding of the lifetime, taking inventory into account, enable estimates to be made on typical compositions for the above sectors.

But in addition to good market research data, sampling and analysis of typical waste plastic streams is both useful and necessary to get accurate and reliable compositional data.

This overview of APME's activity in four sectors: packaging, automotive, electrical & electronic and building & construction, covers this important aspect of fuel or waste composition. The compositional aspect of the different plastics used in packaging, automotive and building & construction has already been described in several APME reports (see references for further reading). As an example of a typical and very fragmented durable goods market sector, the electrical and electronic (E+E) one is described below in detail.

**Figure 2.1**  
**E+E EQUIPMENT AND PLASTICS CONSUMPTION**



### 2.1 E+E MARKET INFORMATION: CONSUMPTION

The E+E waste sector can be sub-divided into consumer, industrial and commercial goods. Within the consumer sector, a further division is commonly made into brown and white goods. The white goods sector contains refrigerators, freezers, washing machines etc., which were not part of APME's study. These are usually collected in separate schemes from other consumer equipment.

The examples below illustrate the very different types of equipment which are considered:

<b>Consumer</b>	<ul style="list-style-type: none"> <li>• Small appliances e.g. hairdryers, toasters, heaters, irons, toothbrushes</li> <li>• Medium sized appliances e.g. VCR's, coffee &amp; kitchen machines, vacuum cleaners</li> <li>• Larger sized units e.g. PC's, TV's, Hi-fi equipment</li> </ul>
<b>Commercial</b>	<ul style="list-style-type: none"> <li>• Medium sized electronic equipment e.g. PC's, fax machines</li> </ul>
<b>Industrial</b>	<ul style="list-style-type: none"> <li>• Electrical switchgear equipment</li> <li>• Electronic instrumentation and control systems.</li> </ul>

#### 2.2.1 SOURCE SEPARATED E+E MATERIALS

Electrical and electronic equipment is sometimes collected by local authorities, but information on E+E waste categories is rather scarce. Similarly, the number of pilot projects to collect E+E waste in Europe is also limited. Very little is known about the polymer composition in different types of equipment. Nevertheless, the total amount of source separated E+E equipment waste is growing rapidly, although as yet the amounts are still unclear. For the trials in TAMARA, the test plant of the Forschungszentrum Karlsruhe Institut für Technische Chemie Bereich Thermische Abfallbehandlung (FZK) in Karlsruhe, it was therefore necessary to get E+E waste from large-scale commercial operations. A very detailed identification and classification of the different E+E articles has been made for several countries: for Germany by the Zentralverband Electrotechnik-und Elektronikindustrie e.V. (ZVEI) and for France by the Fédération des Industries Electriques et

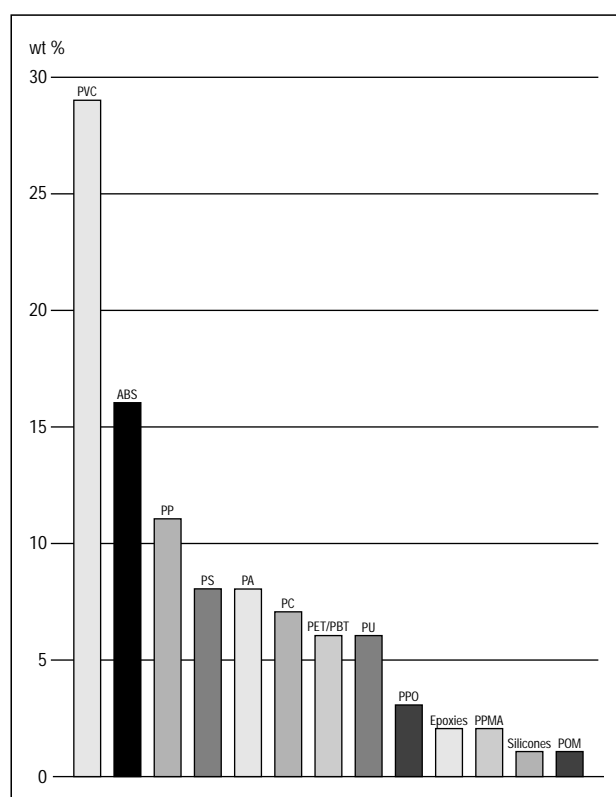
Electroniques (FIEE). Reports on material stream identification by article have come from the Institut für Umwelttechnologie und Umweltanalytik e.V. (IUTA) and the company Schleswag.

Three medium size suppliers of E+E plastics waste streams in Germany were asked to provide pretreated E+E waste. Shredders of recycling operators do not commonly mix the shredding residues of white goods with those of brown goods (TV's, videos and audio equipment). For an accurate comparison of ESR (electrical shredder residue) compositions, a clear understanding of the source of the waste was needed.

### 2.2.2 PLASTIC MATERIALS FROM TODAY'S E+E EQUIPMENT

A simulation of types and quantities of plastics materials used in current E+E equipment was made to approximate the composition of future waste streams arising from the

**Figure 2.2**  
**POLYMER COMPOSITION OF TODAY'S E+E EQUIPMENT**



disposal of such equipment. The composition of an average E+E polymer mixture in Europe supplied by APME members was simulated by blending together materials typical of those sold in the market today. The materials can be separated into two categories according to their burning characteristics: horizontal burning or flame retarded burning. The ratio between these two classes is 66% to 34% respectively.

## 3. CO-COMBUSTION OF PACKAGING PLASTICS

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### 3.1. OBJECTIVES OF INVESTIGATIONS

APME's research is directed to define the role and quantify the influence of plastics on the combustion process and its residues. The number of papers published on these topics is very limited, especially for large-scale tests.

The search for an appropriate site for the commercial test programme involved visits and assessments of 13 combustors throughout Europe. Eventually, the MSWC plant in Würzburg, Germany was selected. It fulfilled the criteria of the project team by providing:

- A modern plant, operating the widely used Reverse Acting Grate, developed by Martin
- Previous expertise in hosting large scale trials with other plastics types
- Excellent documentation of the combustion operation, together with statistically significant data
- An economic emission control system (dry scrubbing process)
- A sufficiently long residence time in the furnace to achieve complete combustion
- Energy recovery for electricity and district heating schemes.

## CO-COMBUSTION OF PACKAGING PLASTICS

The plant has two identical lines, with a design throughput of 12.5 mt/h at 8.4 GJ/mt. The total thermal input is a maximum 100 GJ/h. All test runs were made on line number two. The line was operated at full capacity producing 30mt/h steam at 43 bar and 400 °C.

### 3.2 PLANNING AND EXECUTION OF THE TEST

The full scale commercial testing programme carried out at the MSWC plant in Würzburg Germany (MHK Würzburg), was developed over a three year period from a desk study to first tests. These pilot tests were carried out during 1992 at the TAMARA mass burn combustor, operated by FZK. The large scale test was performed jointly with official environmental authorities and the partners shown in the table below. The project was managed by APME, with other interested parties having the responsibilities indicated.

**Table 3.1**  
**PARTNERS IN THE WÜRZBURG TEST**

TASK	RESPONSIBLE PARTY
Organization	APME
Waste Sorting/Analysis	Joint Waste Authority - MSW Würzburg, Germany. Fachhochschule Würzburg-Schweinfurt, Germany.
MPW Analysis	APME
MSW Analysis	P. Töpfer, Germany.
Combustion	MARTIN GmbH, München, Germany (furnace manufacturer).
Emission Control	NOELL GmbH, Würzburg, Germany (plant construction).
System Sampling/Analysis	Gesellschaft für Arbeitsplatz Umweltanalytik GmbH Münster-Roxel, Germany.
Technical Operations	MHK Würzburg, Germany.

### Tasks and Responsibilities in the Würzburg Trials

Each series of tests extended over a four-week period. They were carried out during October 1993 and January 1994. During the first phase, standard lime was added as a neutralisation additive. An active-carbon/lime mixture was applied for emission control to ensure low concentrations of chloro-organics in the clean gas. The mixture, containing 3 to 5 wt% active-carbon on the basis of lignite, was added upstream of the cyclone.

### 3.3 TEST CONDITIONS

The test conditions aimed to replicate the effects of plastics in a real operating environment. Most MSWC's operate at the full heat load capacity of the boiler - an operation commonly known as heat removal limited case. This meant that during the addition of plastics with an average calorific value three times higher than that of standard MSW, the total throughput had to be reduced according to the energy inventory of the feed.

During the tests, three different feed condition scenarios were established as follows:

A = normal MSW with a MPW content of 8.5 to 12 wt%	Base case
B = MSW + 7.5 % by weight mixed plastics.	Medium polymer case: 16 to 19.5 wt% MPW*.
C = MSW + 15 % by weight mixed plastics.	High polymer case: 23.5 to 27 wt% MPW*.

*\*(a typical so-called mixed plastic fraction from the DSD, Germany, was added to the normal MSW which contained between 8.5 to 12 wt% plastics).*

Due to the changing conditions found within a furnace and boiler during combustion, the first test campaign was based on the following sequence of feed streams, using lime as a neutralising additive: A1, A2, C1, C2, A3, A4, B1, A5, A6.

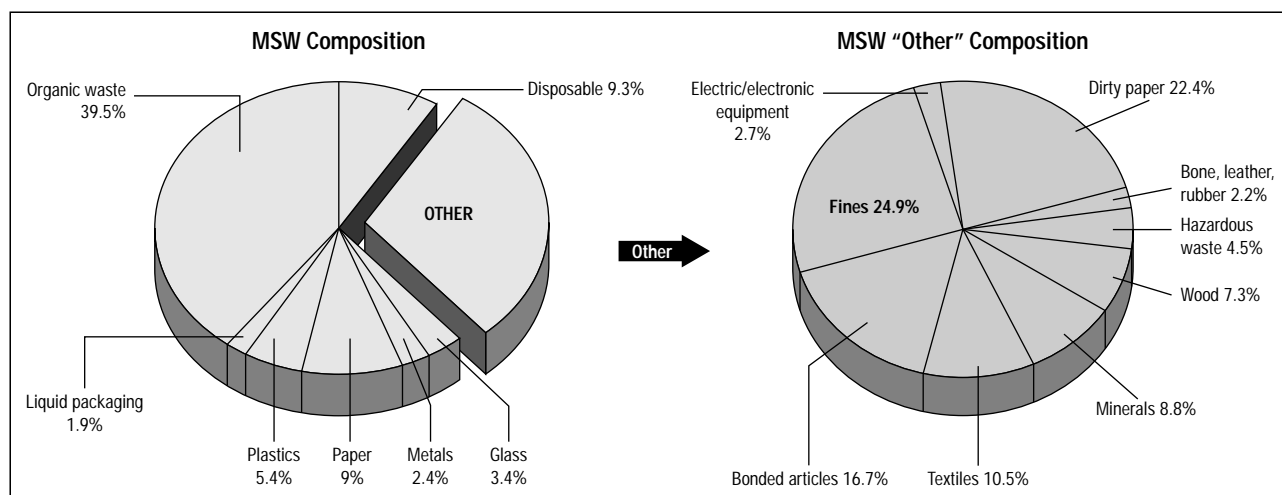
The second campaign, using a lime and active-carbon mixture, followed the sequence: A, A, B, C. During these tests, A to B to C, the mean heat value increased from 11 to 12.8 to 14.7 GJ/t feed.

The MSW used during these combustion runs was carefully analysed according to the official classes from the German EPA (UBA). 14 representative samples with a total weight of 12 t were manually sorted.

Previous MSW waste sorting studies have concentrated largely on total polymer articles like bottles. It was hence of interest to extend the number of polymer containing categories to four.



**Figure 3.1**  
**MSW COMPOSITION IN THE WÜRZBURG AREA**



**Table 3.2**  
**IDENTIFIED AND SORTED POLYMER FAMILIES**

Category	Description	Estimated Polymer content - wt %
I	Complete polymer articles e.g. films, bottles, blister packs, foams	100
II	Laminated packaging materials mainly drink containers	15
III	Technical articles, consumer items	50
IV	Disposable items e.g. nappies	25

### 3.4 DSD MIXED WASTE PLASTICS COMPOSITION

Analysis of the mixed plastic waste fraction used as fuel in the test programme was undertaken by the Fachhochschule Würzburg (technical department of Würzburg University). Three 230 kilogram bale samples of representative mixed waste were hand sorted and classified according to polymer type. Use of identification codes on sample items showed the split by polymer.

**Table 3.3**  
**POLYMER TYPES IN DSD MIXED PLASTICS**

Material	Content wt%
Polyethylene	64
Polystyrene	6
Polyethyleneterephthalate	2
Polyvinylchloride	4
Residue, paper, etc.	18
Non-identifiable plastics	6

For a full understanding of the above results it is important to note that the so-called DSD mixed fraction does not represent the total mixed plastic waste, as bottles and films are separated for material recycling. APME estimates the European average content of PVC in MSW to be approximately 10 % by weight. The PVC content was therefore increased by adding post-use articles such as PVC pipes and flooring products.

Extensive analysis was also carried out to establish the halogens, heavy metals and trace elements content, and that of dioxins and furans, found in the mixed waste plastics. Concentrations of sulphur, fluorine and bromine were very low, at around 400, 20 and 15mg/kg, respectively. Several typical polymer fractions were also measured to establish their content of dioxins and furans. All samples contained less than 10% of the minimum limit specified by the German Act on hazardous material handling, with a limit of 5 µg of dioxins and furans/kg of total MPW.

Heavy metal concentrations ranged between 0.6 and 1.2 g/kg with a broad spread of results, depending on product and polymer type.

### 3.5 TEST RESULTS

#### Influence on Emission

The effects of plastics on the composition of incineration flue gases were assessed over a three-month period, and averages

## CO-COMBUSTION OF PACKAGING PLASTICS

from eight six-hour periods of measurement were obtained. Gas emission levels measured on gases from typical MSW (base case) (A), and on those from MSW containing medium (B) and high levels (C) of polymer appear in the Table below.

**Table 3.4**  
**CLEAN GAS EMISSIONS DURING PACKAGING**  
**CO-COMBUSTION**

	Base Case A	Medium Polymer B	High Polymer C
CO [mg/m <sup>3</sup> ]	19	18	7
HCl [mg/m <sup>3</sup> ]	23.5	22.4	21.4
SO <sub>2</sub> [mg/m <sup>3</sup> ]	19	9.0	<5.0
NO <sub>2</sub> [mg/m <sup>3</sup> ]	405	385	410
Dust [mg/m <sup>3</sup> ]	2.4	<2.0	2.4
Furnace temp.[°C]	890	892	894

In the high polymer level case CO concentration was actually reduced from 19 to less than 7 mg/m<sup>3</sup>, demonstrating the excellent burn out achieved in the gas phase. This is in line with the generally improved stability of combustion achieved by adding waste plastics.

Other indicators, like steam production variation, or the decreasing number of CO peaks measured in the furnace, underline this enhanced combustion stability. A CCD endoscope video camera was used to observe changes exhibited by fire on the grate. The grate combustion zone was seen to shift toward the direction of the feeder, and become shorter, causing a more intense fire.

### Hetero Atom Content

HCl concentrations in the flue gas rose as expected because of the addition of PVC along with the waste plastics, but were subsequently reduced by the emission control system to amounts found in normal clean gas.

SO<sub>2</sub> concentrations recorded in clean gas were rather low compared to other MSWC operations. The feed dilution effect from the non sulphur-containing waste plastics also caused this concentration to drop still further. NO<sub>x</sub> levels did not change significantly as the combustion temperature of the furnace was kept constant at around 890°C, independent of the polymer addition levels. This was achieved by the constant heat removal technique, and the change in air distribution for combustion control.

### Chloro-Organics in Gas Phase

The main objective of this test programme was the analysis of chloro-organic compounds like polychlorinated dibenzo (p) dioxins and dibenzofurans (PCDD/F). The values are expressed in toxic equivalents (TE) of the German health ministry (BGA) to facilitate the comparison with existing data.

The measured raw gas concentrations of PCDD/F, expressed in toxic equivalents as 2.7 to 4.4 ng TE/m<sup>3</sup> (BGA), were placed in the lower operating range of the European MSWC industry at that time. The mean values found in this study range from 10 to 12 ng/m<sup>3</sup> TE. This finding is indicative of a well-designed and operated furnace, which provides a sufficiently long residence time. The raw gas values in new plants are considerably lower with about 1.0 ng/m<sup>3</sup>. No correlation between polymer content and occurrence of PCDD/F's can be derived from the results of these tests.

The only correlation found in the data is an increased raw gas PCDD/F concentration at increasing oxygen levels, which is typically found in waste combustion, and can be explained by the de-novo synthesis formation mechanism of PCDD/F.

This shows that for the wide range of Cl concentrations in the feed of 6.2 to 10.7 g/kg total MSW, the PCDD/F concentration did not increase. The HCl raw gas concentrations were measured on-line and the mean values ranged from 400 to 1200 mg/m<sup>3</sup> over the 6-hour measuring period. Peaks in raw gas concentrations were only two to three times the normal value with 300 to 4500 mg HCl/m<sup>3</sup> for a 30-minute measuring batch sample.

### 3.6 RESIDUES : QUALITY OF MSWC OPERATION

All properties of the residues: burn out, heavy metals content, elution behavior and the content of micro pollutants like chloro-organics, need to be considered and judged in a balanced ecological way. The level of unburned carbon in the residues and the gas phase is the primary criterion and indicates the quality of the combustion operation. If the level of the total carbon is relatively high, the degree of combustion is insufficient.

## 3.7 RESIDUES: ORGANIC CARBON CONTENT

The total carbon (TC) content was measured as the sum of the inorganic (TIC) and the organic content (TOC) in the residues.

**Figure 3.3**  
**INFLUENCE ON RESIDUE BURN OUT**

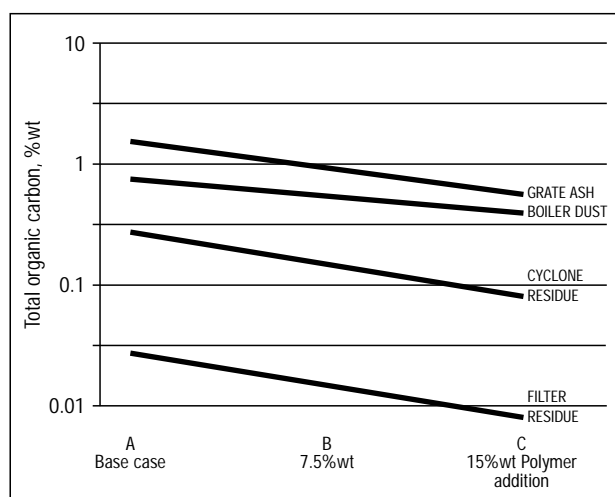


Figure 3.3 shows the effect of the addition of plastics on the grate ash quality. The TOC values are averages of many runs. The reduction of TOC from 1.4% by weight to 0.7% by weight in grate ash was achieved by the addition of 15% by weight plastic in the feed.

This improvement of grate ash quality by about 50% TOC reduction can be explained by the difference in combustion behavior. A higher polymer concentration increases the volatility of the fuel leading to a more homogeneous combustion behavior. A shorter combustion zone is the result.

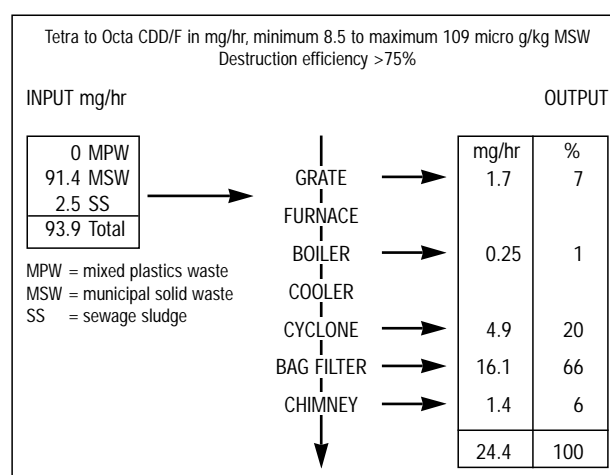
## 3.8 DIOXIN/FURAN BALANCE

The current discussion about MSWC acting as a “dioxin sink” continues. In the trials at Würzburg it was possible to balance the dioxin and furan components within the emission control section. A rigorous mathematical component balance was carried out and documented by the Gesellschaft für Arbeitsplatz und Umweltanalytik in Munster. The analytical results from this investigation enable a proper dioxin and furan balance around the total MSW combustor to be achieved, using an estimate of the dioxin and furan content in the MSW.

Dioxin and furan analyses were also carried out on the sewage sludge and on representative mixed waste polymer samples. The results confirmed that the content of dioxins and furans in mixed plastics is extremely low, with values ranging from 0.5 to 6 µg/kg total tetra- to octa- CDD/F. The analytical results from the sewage sludge were similarly low compared with the MSW.

No analysis of the MSW from the Würzburg area was made due to its complexity and the fact that limited standardisation has been achieved on the preparation of MSW samples. For the component calculation, the recent furans and dioxin figures from ITU were used. MSW total tetra- to octa- CDD/F concentration ranges from 8.5 to 109 µg/kg MSW. For the component balancing, the lowest value of 8.5 mg CDD/F found in this study has been assumed. Calculating the destruction efficiency in this way guarantees a conservative result. Higher values for the dioxin destruction efficiency can be expected for higher input values of PCDD/F in the feed. APME's technical report summarizes the large-scale trials details of the MSW feed. The MSW was typical of today's MSW found in Germany.

**Figure 3.4**  
**PCDD/F BALANCE BASE CASE**  
**WITHOUT ADDITIONAL PLASTICS**

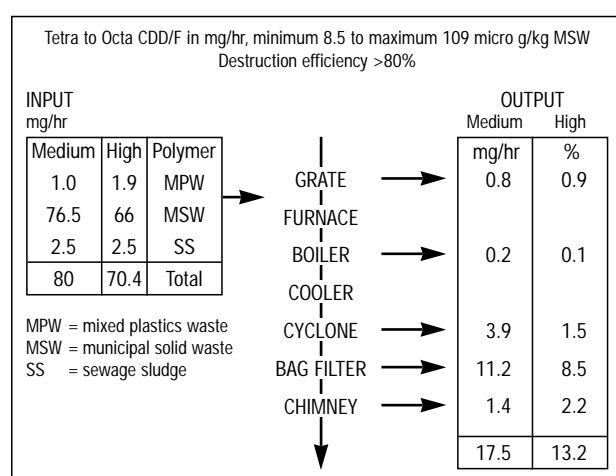


These data fit well with other official literature referenced by the German EPA. From the mass balancing scheme as outlined in Figure 3.4 and using six-hour mean data on the concentration of tetra- to octa- CDD/F, the flux of these components expressed in mg/h can be calculated. In the

## CO-COMBUSTION OF PACKAGING PLASTICS

base case (A) without polymer addition, the total of PCDD/F in input streams was 94 mg/h, whereas 24 mg/h of tetra- to octa- CDD/F were found in the output streams. The distribution of outgoing components can be given as: 7, 1, 20, 66, and 6% for the residues from the grate, boiler/cooler, cyclone, filter and the clean gases emissions.

**Figure 3.5**  
**PCDD/F BALANCE WITH ADDITIONAL PLASTICS**



This balance demonstrates a minimum destruction efficiency for dioxins of 75% under normal operating conditions (see Figure 3.4). The contribution of the streams: clean gas and grate ash, to the environment is less than 13% of the total out-going mass and represents only 4% of the initial content in the feed. Residues from the filter and the cyclone are today safely disposed of in special classified landfills or deep mines and do not contribute to pollution.

The amount of dioxins and furans not destroyed in the combustor is less than 25% of the input. From these, 87% are safely disposed of. Addition of plastics did not diminish the very favourable high destruction efficiency of 75%. In fact an increased destruction capability of the combustor could be demonstrated for the runs with plastics addition (B) and (C). The average results of the high and medium polymer addition case are shown in Figure 3.5.

Higher combustion efficiency, as confirmed through better burn out of the residues and the gas phase, supports this increased dioxin and furan destruction efficiency.

### 3.9 CONCLUSIONS

Large scale testing in a typical public MSW combustor has proven the positive effect of plastics on the burn out of the various residues from the grate, boiler, cyclone and filter as well as in the gas phase. The ash quality can be improved through further reduction of heavy metals content. Low elution values facilitate the marketability of the grate ash.

The raw gas data for the chloro-organics demonstrate that addition of plastics does not increase the PCDD/F concentration. This statement also applies to the incineration of waste plastics containing 8 to 10 wt% of PVC, the European norm.

Increased hetero atoms content was found only for Cl. Peak raw gas concentration during the test series was 4.7 g/m<sup>3</sup>, up to five times the normal value of 1 - 1.5 g/m<sup>3</sup> for a typical MSWC. No increased PCDD/F formation in the raw gas was found.

PCDD/F clean gas concentrations depend on the neutralisation additive used in the dry scrubbing system. The addition of a 5 wt% active-carbon containing lime guarantees a very low emission level. The actual measured concentrations were only 10% of the 0.1 ng TE/m<sup>3</sup> limit of the German 17. BlmSchV.

## 4. CO-COMBUSTION OF PLASTICS IN AUTOMOBILES

### 4.1 SITE SELECTION

A number of MSWC facility operators believe that co-combustion of Automotive Shredder Residue (ASR) and MSW would be problematic. Therefore, it was preferable, but not essential, to identify a site that presently was co-combusting ASR or had successfully done so in the past. The MSWC plant in Würzburg, Germany is one of several modern, well-operated MSWCs in Europe that co-combust ASR on a regular basis. Over the past five years, the facility has burned ASR at average annual substitution levels of about 4-8% on a weight basis. There was a very

significant additional advantage from selecting the Würzburg site. APME had conducted the mixed plastics demonstration programme described in Section 3 at the same plant in October 1993 and January 1994.

## 4.2 SHREDDING FACILITY

The Johann Preuer shredding facility, which is located adjacent to the river Main in Würzburg, has a capacity of 350 t/day. The feedstock consists of a mixture of approximately 50% automobiles and 50% light iron. The latter materials are obtained from municipal recycling operations as well as from commercial and private deliveries. Generally, all metals that are less than 6 mm thick are shredded. Approximately 80% of the vehicles shredded are processed with engines still in place after all of the fluids have been drained. Preuer's standard practice is to alternate charges of one automobile followed by an equal volume of light iron into the horizontal hammer mill. A more detailed description of the shredding operation can be found in (7).

**Table 4.1  
ASR CHARACTERISTICS<sup>a</sup>**

Parameter	Units	Coarse ASR	ASR Fines	ASR Mixture <sup>b</sup>	Typical Range
Heating Value H <sub>u</sub>	GJ/t	14.1	6.0	10.9	9-20
Moisture	%	3.8	3.8	3.8	2-5
Ash Content <sup>c</sup>	%	39.1	71.9	52.2	28-61
Metals (Hand Separated)	%	4.6	0.0	2.8	n.a
Chlorine	%	1.22	0.42	0.90	0.5-2
PCBs	mg/kg	63.0	n.a	n.a	n.a
<b>Main Metals</b>					
Aluminium	%	2.8	0.5	1.9	0.7-3
Iron	%	10.3	15.4	12.4	3.3-18
Magnesium	%	0.3	0.4	0.3	0.05-0.8
<b>Heavy Metals</b>					
Cadmium	mg/kg	51	60	55	2-85
Thallium	mg/kg	<0.4	<0.4	<0.4	n.a
Mercury	mg/kg	2.8	7	4	1-49
Antimony	mg/kg	410	147	304	180-3/200
Arsenic	mg/kg	46	47	46	20-50
Lead	mg/kg	2,582	8,425	4,919	1,100-11,000
Chromium (Total)	mg/kg	321	445	370	1,000-1,800
Cobalt	mg/kg	45	62	52	13-33
Copper	mg/kg	17,612	7,780	13,679	3,700-26,300
Manganese	mg/kg	569	1,378	893	360-1,100
Nickel	mg/kg	523	332	446	400-1,500
Vanadium	mg/kg	22	36	27	20-150
Tin	mg/kg	192	380	267	130-400
Zinc	mg/kg	10,827	33,300	19,816	4,600-20,000

<sup>a</sup> As received basis.

<sup>b</sup> As calculated using 60/40 coarse/fines split.

<sup>c</sup> Includes hand-separated metals.

## 4.3 ASR COMPOSITION

The characteristics of the ASR produced by the shredding facility were established in four phases. The method of sampling, sorting and characterisation was very similar to a study done by the Interkantonaes Technikum Ingenieur Schule (ITR) in Switzerland. ASR compositional analysis results for the various fractions: plastics, rubbers, textiles etc., compare very favourably with the results from Switzerland. The average results of the analyses for the three ASR samples taken during the trials are presented in Table 4.1. The net heats of combustion, H<sub>u</sub>, for the coarse and fine fractions were determined by three laboratories. The average of the nine coarse ASR analyses was 14.1 GJ/t, and the average of the three fine fraction samples was 5.95 GJ/t. Using a 60/40 split for mixed ASR, the resultant heating value would be about 10.9 GJ/t. Although this value is at the lower end of the 9 to 20 GJ/t range presented in the literature, it is comparable to the heating value of MSW, which was previously determined to be 11 GJ/t.

## 4.4 TEST CONDITIONS

The principal programme objectives were to demonstrate that ASR can be co-combusted in a modern MSWC with no adverse operational or environmental impacts and to develop the supporting documentation required to permit long term co-combustion projects at other MSWCs. In order to convincingly achieve these objectives, and thereby fulfil the third objective of public acceptance, it was decided that the ASR substitution levels should be as high as reasonably possible. The higher substitution levels would facilitate detection of heavy metals and other components of concern that might exist in the combustion gases or solid residues at relatively low concentrations.

After carefully reviewing all of the pre-trial sampling results, the decision was made to set one of the mixed ASR substitution levels at approximately 20% and the other at 30%. For a third test, it was decided to co-fire only the coarse ASR at about a 30% substitution level. The test conditions for the four trials were therefore established as follows:

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**Table 4.2**  
**TEST CONDITIONS OF THE 4 TRIALS.**

Trial	ASR Type	Planned ASR substitution level	ASR substitution level recorded
A		Nil (Base Case)	0
B	Mixed	20%	24%
C	Mixed	30%	31%
D	Coarse	30%	31%

It is important to note that all substitution levels were made on a weight basis. Thus, on a boiler heat input basis, the substitution levels for Trials B and C would be slightly higher than reported here, and Trial D would be about 36%. The test programme was conducted during two four-day periods (Tuesday to Friday) within calendar weeks 25 and 27 in 1997. All testing was performed on the Müllheizkraftwerk Würzburg (MHKW) Line 2. During the first week one baseline test (case A) was performed while feeding only MSW. This was followed by three days of feeding the previously prepared Trial B, C and D ASR/MSW mixtures; one full day was dedicated to each mixture. During the second test week four additional one-day baseline tests were conducted combusting only MSW.

### 4.5 FUEL PREPARATION, STORAGE AND FEEDING

The Preuer shredding facility generates two ASR streams, the coarse and fine fractions, and typically delivers them separately to the MHKW facility. The coarse fraction often includes “pockets” of non-metallic heavies rejects from Preuer’s non-ferrous enhancement system. These are discharged periodically into roll-off containers as the coarse fraction is produced. The pockets contain elastomers, heavy plastics, wood and some glass. Thus, the first steps in the MSW/ASR mixing process were to thoroughly mix the coarse ASR and then recombine the two ASR fractions back to the 60/40 ratio in which they were produced. The re-combined ASR was then mixed with MSW in the new storage pit of the MSWC plant and stored for the test.

### 4.6 MONITORING, SAMPLING AND ANALYSES

The monitoring, sampling and analysis portions of the programme were carefully conceived to provide an appropriate foundation upon which the impact of co-combusting ASR with MSW could be fully evaluated. The planning efforts

were facilitated by the experiences from an earlier APME study at Würzburg in 1993/1994. Extensive analysis was done on all solid residues from the process: grate, boiler, cyclone and filter ash. Boiler ash is taken from the energy recovery section. The cyclone is part of the neutralisation system for the acid gases. The fabric filter removes solid fly ash, excess lime and salts.

### 4.7 RAW AND CLEAN GASES

The gas sampling programme targeted both raw and clean flue gases and employed a combination of manual sampling trains and continuous emission monitoring systems (CEMS). The sampling protocols remained the same for each of the eight days of testing. The raw flue gases were sampled using continuous emission monitoring equipment installed in a mobile unit brought to the site. The sampling location was the vertical duct directly upstream of the cyclone. The on-line system was operated between 08:00 and 14:00 each day of the test and the following components and parameters were sampled and recorded:

Carbon monoxide	Carbon dioxide	Nitrogen oxides
Sulfur dioxide	Oxygen	Total organic carbon
Flue gas temperature	Flue gas flow rate	

The clean gas was also sampled on a daily basis using a manual sampling train. The sampling port for these tests was located in the stack. Each day during week 25, a six-hour sample was obtained and analysed for PCDD/F and a 4½ hour sample was obtained and analysed for particulates and heavy metals. In week 27, the same samples were obtained, but only one additional baseline clean gas sample was analysed. A daily gas moisture content was also recorded.

#### 4.7.1 RAW GASES

The results of the on-line sampling and the manual sampling train for raw gases are summarised in Table 4.3. The results of the analyses for heavy metals in the raw gas downstream of the boiler showed an increase in a number of parameters when combusting ASR. This is to be expected since, as shown in Table 4.1, such metals are present in

ASR. The arsenic, lead and zinc levels experienced the most significant increases - a factor of approximately 6 for Trials B and C. However, the increase factors for Trial D, which was the combustion of coarse ASR only, were only 3.9, 4.3 and 4.7 for arsenic, lead and zinc respectively.

**Table 4.3  
RAW GAS SAMPLING RESULTS**

Parameter	Units	A (Ave)	B	C	D
O <sub>2</sub>	%	8.9	9.4	9.2	9.0
CO <sub>2</sub>	%	9.8	10.1	10.2	9.0
CO	mg/m <sup>3</sup>	21	13	14	9
NO <sub>x</sub>	mg/m <sup>3</sup>	441	489	456	339
SO <sub>2</sub> (on line)	mg/m <sup>3</sup>	130	140	126	95
SO <sub>2</sub> (manual)	mg/m <sup>3</sup>	98	109	87	104
HCl	mg/m <sup>3</sup>	1,076	1,005	1,005	1,076
TOC	mg/m <sup>3</sup>	3.0	<2.0	6.0	19.0
Particulates	mg/m <sup>3</sup>	3,524	4,206	3,991	3,161
PCDD/F	ng(TE)/m <sup>3</sup>	2.92	3.59	6.77	6.22
Temperature	°C	266	263	269	255
Volume	km <sup>3</sup> /hr	50	51	53	58
<b>Heavy Metals</b>					
Cadmium(Cd)	mg/m <sup>3</sup>	0.727	1.714	2.127	2.107
Thallium (Tl)	mg/m <sup>3</sup>	0.006	0.004	0.007	0.005
Subtotal: Cd + Tl	mg/m <sup>3</sup>	0.733	1.718	2.134	2.112
Mercury(Hg)	mg/m <sup>3</sup>	0.210	0.454	0.211	0.194
Antimony(Sb)	mg/m <sup>3</sup>	2.833	6.418	5.577	4.999
Arsenic(As)	mg/m <sup>3</sup>	0.056	0.343	0.301	0.218
Lead(Pb)	mg/m <sup>3</sup>	7.127	44.366	39.632	31.004
Chromium(Cr)	mg/m <sup>3</sup>	0.709	0.781	0.784	0.638
Cobalt(Co)	mg/m <sup>3</sup>	0.058	0.113	0.131	0.084
Copper(Cu)	mg/m <sup>3</sup>	6.161	8.784	8.720	7.502
Manganese(Mn)	mg/m <sup>3</sup>	5.469	5.840	5.456	3.775
Nickel(Ni)	mg/m <sup>3</sup>	0.197	0.521	0.566	0.347
Vanadium (V)	mg/m <sup>3</sup>	0.849	0.588	0.579	0.427
Tin(Sn)	mg/m <sup>3</sup>	1.768	5.849	5.431	4.645
Subtotal: Sb - Sn	mg/m <sup>3</sup>	25.228	73.603	67.177	53.638
Zinc(Zn)	mg/m <sup>3</sup>	55.970	344.001	341.482	263.688

#### 4.7.2 CLEAN GASES

The results of the on-line sampling and the manual sampling train for the clean gases are summarised in Table 4.4. For the manual sampling train, because of cost constraints only the three ASR co-firing trial samples and two of the five baseline trial samples, A0 and A3, were analysed. The results presented in Table 4.4 clearly demonstrate the minimal impact of ASR co-firing on the clean gas emissions.

#### 4.8 SOLID RESIDUES

The daily sampling programme for solid residues from the combustion process began at 10:00, two hours after the gas

**Table 4.4  
CLEAN GAS SAMPLING RESULTS**

Parameter	Units	Regulatory Limit <sup>a</sup>	A (Ave)	B	C	D
O <sub>2</sub>	%		9.8	10.3	10.1	10.0
CO <sub>2</sub>	%		9.8	9.4	9.4	9.0
CO	mg/m <sup>3</sup>	50	23.5	14.3	15.2	11.8
NO <sub>x</sub>	mg/m <sup>3</sup>	200	60.2	60.3	60.2	59.9
SO <sub>2</sub> (on line)	mg/m <sup>3</sup>	50	< 5	<5	<5	<5
HCl	mg/m <sup>3</sup>	10	5.9	8.0	2.6	6.2
Particulates	mg/m <sup>3</sup>	10	1.03	0.81	0.89	0.63
PCDD/F	ng(TE)/m <sup>3</sup>	0.1	0.0047	0.0021	0.0027	0.0024
<b>Heavy Metals</b>						
Cd + Tl <sup>b</sup>	mg/m <sup>3</sup>	0.05	0.0020	c	c	c
Mercury (Manual)	mg/m <sup>3</sup>	0.05	0.0080	0.0040	0.0030	0.0050
Mercury (on line)	mg/m <sup>3</sup>	0.05	0.0005	0.0029	0.0084	0.0041
Sb-Sn <sup>b</sup>	mg/m <sup>3</sup>	0.5	0.0150	0.0040	0.0060	0.0010
Zinc (Zn)	mg/m <sup>3</sup>		0.0100	0.0230	0.0050	0.0190

<sup>a</sup> German limits per 17th BImSchV.

<sup>b</sup> For identification of metals included within these categories, see Table 4.3

<sup>c</sup> Metallic element not detectable

sampling was initiated, and ended at 16:00. The grate ash, which included the grate siftings, was sampled every 30 minutes from the head end of the ash extractor. The boiler ash, which included ash from the economiser pass and from the evaporative cooler, was sampled on an hourly basis. Also sampled hourly were the fly ash from the cyclone and the fly ash from the bag house, which included the recirculated absorbent and activated carbon.

#### Grate Ash

As expected, the co-combustion of ASR, which contains elevated levels of several heavy metals, measurably impacted certain grate ash parameters. In particular, the zinc levels for Trials C and D increased by a factor of four over the 2,322 mg/kg average of the five baseline trials. Copper increased by nearly three times the average baseline level of 1,860 mg/kg. Antimony, cobalt and nickel increased by two to three times their respective average baseline levels of 52, 20 and 139 mg/kg. Because lead is more volatile, the lead levels increased by only 10-30% above the average baseline level of 1.065 mg/kg, and the increases associated with firing ASR were reflected in the raw gas analyses presented.

The grate ash was also tested for leaching characteristics using the following regulatory protocols:

Germany	DEV S4	Switzerland	TVA
Netherlands	NEN 7341	USA	TCLP

## CO-COMBUSTION OF PLASTICS FROM ELECTRICAL/ELECTRONIC APPLIANCES

The DEV S4 test results showed that the co-combustion of ASR and MSW had essentially no adverse impact on the leaching characteristics of the grate ash. In fact, in some cases, the results were notably improved. Chlorides, copper, total chromium, lead and electrical conductivity were all less when ASR was co-fired. Two exceptions were zinc and sulphates. The zinc concentration in the leachate of grate ash from Trial B was more than double the baseline average, but still less than 10% of the LAGA limit of 0.3 mg/kg. The sulphates in Trials C and D were higher too, but still only one third of the 600 mg/kg limit. Leaching tests were also performed on the grate ash using the Swiss TVA standards which employ a more aggressive extraction fluid. As a result, the cadmium, copper and zinc concentrations increased for each of the ASR co-firing trials. When the results were compared to the Swiss limits for residue landfills, the only problems noted were the copper concentrations in the grate ash from the ASR trials. Trial B exceeded the limit by about 10%, Trial C was at the limit and Trial D was about 90% of the limit. The corresponding result for the baseline test for copper was about 30% of the limit. All other parameters when co-firing the ASR/MSW mix were less than 50% of the limits. It is important to note that, unlike in Germany and the Netherlands, most grate ash in Switzerland cannot be beneficially used and must be sent to an approved landfill.

### 5. CO-COMBUSTION OF PLASTICS FROM ELECTRICAL/ELECTRONIC APPLIANCES

End of life electrical and electronic (E+E) equipment contains significant contaminants and harmful substances. A pre-dismantling and removal of these components is desirable before any plastic parts or shredder residue can be used for energy recovery. The demonstration that selected plastic parts, like TV housings or specified mixed plastic streams from collected electrical or electronic end of life goods, can be used for energy recovery in MSWC has been done at the TAMARA pilot plant of the Forschungszentrum Karlsruhe (FZK). This pilot plant has been extensively described and proven to be a valid research and scale-up tool for the industry.

### 5.1 STANDARD FUEL ANALYSIS

End of life plastics from the E+E sector are very different from those from other sectors and are rather unknown with respect to their end of life quality. Analysis of the various E+E plastics wastes was therefore carried out by both FZK and GfA, the Gesellschaft für Arbeitsplatz - und Umweltanalytik mbH in Münster. Some key items of standard fuel characterisation: heat value, ash, etc., are shown in Table 5.1. Aspects more important for E+E plastics waste, such as analysis for metals and for dioxin and furan content, are covered later.

**Table 5.1**  
**E+E WASTE PLASTICS FUEL ANALYSIS**

	Consumer	Commercial	Industrial	Today's polymer market mix
Test series	(1)	(1) (2)	(1) (2)	
Heat Value, Hu GJ/t	35	32	25.5	35
Ash, wt%	3-5	3-5	35-40	6.5
Bromine, wt%	0.4	4.1 1.5	1.3 0.6	0.9
Chlorine, wt%	0.4	2.3 1.1	0.7 0.2	3.5
Antimony, wt%	0.2	1.3 0.2	0.35 0.2	0.3

Special importance was given to the elemental analysis of bromine and chlorine contents. Bromine analysis was performed by four different parties all experienced in this field. The ratio of antimony to bromine is a very good indicator of the accuracy of bromine content analysis. The range of bromine content covered was quite large, from a very low level of around 0.4 wt% up to 4 wt%. The consumer type equipment had a low level of about 0.4 wt%. The commercial material could be assumed to be more representative of commercial/industrial E+E plastics as more flame retardant agent is used.

The ratio of bromine to antimony on a weight for weight basis ranged from about 2 to 7. This is in line with the experience of formulating flame retardant products by addition of bromine plus antimony to gain beneficial synergistic effects. A comparative fuel analysis is shown in Table 5.2 where all the elements in E+E plastics waste are compared to the basic fuel of the TAMARA runs. The results of the analysis are from FZK and may differ slightly from earlier data measured by GfA.



## CO-COMBUSTION OF PLASTICS FROM ELECTRICAL/ELECTRONIC APPLIANCES

**Table 5.2**  
**CONCENTRATIONS OF SELECTED ELEMENTS IN THE**  
**BASIC FEED AND IN THE DIFFERENT E+E MATERIALS**

material	basic fuel	basic fuel	consumer	Today's polymer market mix
test series	1	2	1	2
Cl	5,800 ± 230	6,150 ± 300	3,895	38,550 ± 2,000
K	9,500 ± 500	7,100 ± 800	1,050	22,150 ± 400
Ca	34,000 ± 2500	32,000 ± 5000	1,200	7,000 ± 1,500
Ti	1,120 ± 140	1,420 ± 240	1,730	4,550 ± 620
V	46 ± 18	47 ± 12	36	900 ± 15
Cr	109 ± 12	150 ± 30	63	53 ± 8
Fe	5,800 ± 900	6,400 ± 650	1,700	287 ± 36
Ni	69 ± 13	56 ± 13	88	30 ± 1
Cu	109 ± 22	112 ± 36	1900	137 ± 55
Zn	470 ± 30	430 ± 70	620	292 ± 18
As	17 ± 4	25 ± 11	9	47 ± 2
Br	62 ± 13	34 ± 10	4,290	8,600 ± 1,000
Rb	22 ± 3	17 ± 2	30	20 ± 3
Sr	130 ± 19	108 ± 17	18	79 ± 17
Mo	7 ± 2	7 ± 1	2	4 ± 1
Cd	10 ± 3	9 ± 3	240	41 ± 6
Sn	26 ± 4	24 ± 5	85	18 ± 15
Sb	31 ± 8	26 ± 4	2,000	2,630 ± 110
Ba	410 ± 75	660 ± 320	250	-
Pb	410 ± 40	600 ± 350	146	1,890 ± 50
P	1,880	2,080	250	1,200

In order to judge the destruction efficiency of the TAMARA facility, the levels of brominated flame retardant compounds in the polymer matrix were determined in a similar way to the levels of brominated dioxins and furans. It is important that waste management routes for E+E equipment should particularly address this aspect of complete destruction of all organo-halogen compounds.

### Conclusions from analysis of the E+E waste

A detailed analytical characterisation of the E+E plastics waste has shown that:

- The level of bromine (Br) ranged from as low as 0.4 wt% for the consumer sector materials, to as high as 4% by weight for industrial high voltage applications. Ratios of Br to antimony (Sb) were between 2 and 7, which is in agreement with typical industry formulations for flame retardancy. The chlorine level ranged very widely from as low as 0.2% to several % by weight.
- The bromine level is directly linked to the amount of flame retardant. Analytical work was carried out to determine the level of flame retardant for three com-

mercial compounds sold today namely, PBB, PBDPE and TBBA. In practice, the two latter compounds contribute the majority market share, with PBB being a relatively small contributor along with other brominated flame retardants (Fr-Br) from older products.

- The amounts of micro-organic species such as halogenated dibenzo-p-dioxins and dibenzofurans (PXDD/F) were analysed and compared with the limits of the German ordinances. Although the range of levels found was quite large, the average content value met the German regulations.

### 5.2 TEST PROGRAMME

The TAMARA test programme lasted about two weeks. Two test runs were conducted per day, each lasting four hours. On the first and last days of each week two reference tests were performed which burned only the basic fuel. The test programme is detailed in Table 5.3. During the first week of tests the combustion chamber was in a parallel flow geometry. In the second week a centre flow configuration was installed. The combustion temperature was kept at approximately 900°C in the first and approximately 930°C in the second week.

### 5.3 ELEMENT PARTITIONING

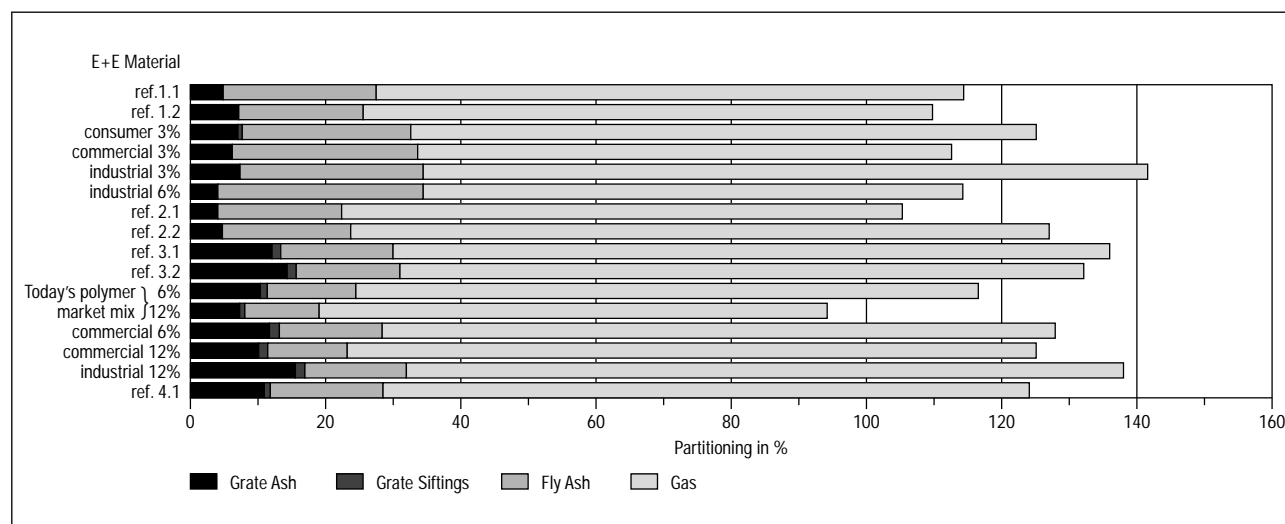
Earlier investigations had shown the distribution of Cl in the various streams to cover a very broad range from as

**Table 5.3**  
**E+E MATERIAL ADDITIONS DURING THE TEST PROGRAMME**

Code	Test Series	E+E Material	Addition in wt%
ref. 1.1	1	-	0
ref. 1.2	1	-	0
E+E 1.1	1	consumer	3
E+E 2.1	1	commercial	3
E+E 3.1	1	industrial	3
E+E 3.2	1	industrial	6
ref. 2.1	1	-	0
ref. 2.2	1	-	0
ref. 3.1	2	-	0
ref. 3.2	2	-	0
E+E 4.1	2	today's polymer market mix	6
E+E 4.2	2	today's polymer market mix	12
E+E 2.2	2	commercial	6
E+E 2.3	2	commercial	12
E+E 3.3	2	industrial	12
ref. 4.1	2	-	0

## CO-COMBUSTION OF PLASTICS FROM ELECTRICAL/ELECTRONIC APPLIANCES

**Figure 5.1**  
PERCENT PARTITIONING OF Cl



low as 0.6 wt% to 3 wt%. Due to the importance of chlorine in the discussion of the formation of dioxins and furans the result from these tests are shown.

The Cl load in the feed varies between approximately 0.6 and 1.2 wt% based on output and input analysis. The comparison of the input numbers to the outputs analysed in the different compartments is shown as a percent partitioning in Figure 5.1.

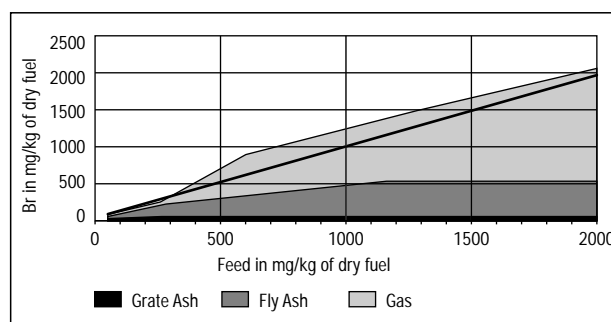
The elemental balances were satisfactory, taking into account the poor homogeneity of some of the feed materials and the analytical error of the various analyses. It is well known, from full-scale incineration plants, that about 70 - 80% of the total Cl inventory is found in the gas phase. This was confirmed by the tests for high Cl and very high Br concentrations.

A more detailed investigation revealed a significant difference in the partitioning depending on the geometry of the combustion chamber. During the first test campaign the fly ashes carried a significantly higher fraction of the Cl inventory than they did in the second campaign. The probable reason was the higher residence time of the acid HCl and the alkaline fly ashes at high temperatures in the parallel flow configuration.

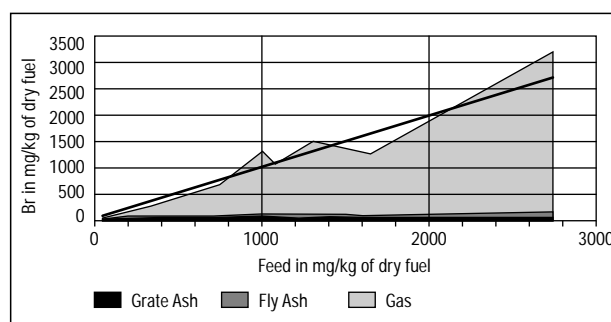
### 5.4 ELEMENT PARTITIONING: Br

The geometrical effect was more easily seen for the Br behaviour (Figures 5.2 and 5.3). Figure 5.2 shows the sum

**Figure 5.2**  
PARTITIONING OF Br IN THE PARALLEL FLOW  
COMBUSTION CONFIGURATION



**Figure 5.3**  
PARTITIONING OF Br IN THE CENTRE FLOW  
COMBUSTION CONFIGURATION



## CO-COMBUSTION OF INSULATION FOAM: EXTRUDED POLYSTYRENE (XPS) AND POLYURETHANE (PU)

of analysed output streams plotted against the sum of analysed input. Dry fuel is in this case the total feed, basic fuel and E+E materials without water. The output data to some extent exceeded the inputs. This fact is presumably due to difficulties in sample preparation and digestion of the organic waste fractions. In general, the agreement of both Br balances can be deemed satisfactory. Figure 5.2 also indicates an increasing incorporation of Br into the fly ashes with increasing Br input. At very high input the curve seems to level off.

### 6. CO-COMBUSTION OF INSULATION FOAM: EXTRUDED POLYSTYRENE (XPS) AND POLYURETHANE (PU)

Insulation foams from the building demolition sector will become waste not today but in years to come. Some waste arises from on-site job fabrication. The plastics producing industry, through their industry associations APME, ISOPA (European Isocyanate Producers Association) and EXIBA (European Extruded Polystyrene Insulation Board Association), undertook this research project in cooperation with FZK in a responsible manner. The primary objective was to ensure that waste insulation foams can be safely recovered in a modern MSWC without operational problems.

#### 6.1. FUEL COMPOSITION

Extensive efforts have been devoted to ensure that typical insulation foams of known composition would be used for this trial. Table 6.1 shows concentrations of the same 19 elements measured in the components of the basic fuel for the three different XPS types: the granulate and the two foams. The F and Cl concentrations in the foams could not be measured directly due to losses during the digestion of the foam. In these cases the (H)CFC content was measured and the respective concentrations of the pure elements were calculated on the basis of these data. The CFC 12 blown foam contained 6 wt% of CFC 12 and 0.3 wt% of C<sub>2</sub>H<sub>5</sub>Cl. The second foam contained 6.3 wt% of HCFC 142b and 3.3 wt% of HCFC 22.

**Table 6.1**  
ANALYSIS OF THE TWO XPS FOAMS, CONTAINING CFC  
AND (H)CFC. ALL DATA IN MG/KG.

Element	Granulate	XPS (CFC 12 blown)	XPS (HCFC 22/142 blown)
F	100 ± 10	18,960 *	38,330 *
S	<100	<100	<100
Cl	43 ± 10	37,900 *	36,750
K	355 ± 25	<300	361 ± 11
Ca	277 ± 95	229 ± 71	215 ± 110
Ti	140 ± 120	340 ± 150	<150
Cr	76 ± 10	85 ± 18	69 ± 15
Mn	29 ± 10	20	43 ± 20
Fe	142 ± 15	173 ± 10	183 ± 33
Ni	58 ± 22	103 ± 15	88 ± 13
Cu	30 ± 4	49 ± 11	53 ± 7
Zn	62 ± 6	45 ± 11	41 ± 13
As	<10	<10	<10
Br	7,800 ± 430	25,050 ± 260	25,560 ± 430
Cd	<5	<5	<5
Sn	<10	<10	<10
Sb	<10	<10	<10
Ba	<100	750 ± 450	450 ± 100
Pb	<10	<10	<10

\*calculated using (H)CFC concentrations in the foams

The above table gives an indication of high additional inputs of F, Cl, and Br if these materials are added to the basic waste stream. The foam in all cases was of a better fuel quality than the base waste fuel.

The next table, Table 6.2, compiles the data for the PU foams as analysed during the experiments in Karlsruhe. It was found that the data on F and Cl did not totally comply with that provided by the raw material supplier. For example, the F figures found in the Karlsruhe analysis are approximately 0.3 wt% lower and for Cl approximately 1 wt% lower. This may be an indication of a loss of blowing agent with time, but a more likely reason for these differences is loss occurring during sampling and dissolution of the foams in Karlsruhe.

**Table 6.2**  
ANALYSIS OF THE TWO PU FOAMS, CONTAINING CFC 11

Element	PU A (2 wt % Br)	PU B (4 wt % Br)
F	7,700 ± 1,000	6,850 ± 1,000
P	7,120 ± 1,000	6,820 ± 1,000
Cl	76,000 ± 5,000	72,000 ± 5,000
K	6,820 ± 600	7,650 ± 600
Ca	375 ± 50	300 ± 60
Ti	8 ± 2	7 ± 2
Fe	30 ± 5	37 ± 5
Ni	2.5 ± 1	2.3 ± 1
Cu	1.5 ± 0.5	1.5 ± 0.5
Zn	8.5 ± 3	9 ± 3
Br	22,200 ± 2,000	41,700 ± 4,000
Pb	2 ± 1	1.9 ± 1

## CO-COMBUSTION OF INSULATION FOAM: EXTRUDED POLYSTYRENE (XPS) AND POLYURETHANE (PU)

**Table 6.3**  
**MAIN COMPONENTS FOR PU FOAM CO-COMBUSTED**  
**IN TAMARA**

Component	PU A (2 wt% Br)	PU B (4 wt% Br)
N	6 wt%	6 wt%
P	0.7 wt%	0.7 wt%
Cl	8.7 wt%	8.0 wt%
Br	2.0 wt%	4.0 wt%

The main components for PU foams co-combusted in TAMARA were analysed by BASF/Elastogran (before PU foam delivery). The results are summarised in Table 6.3. As the results indicate, PU B differs from PU A in its Cl and Br content.

### 6.2. ACID GAS REMOVAL IN THE TWO-STAGE WET SCRUBBER SYSTEM

TAMARA is equipped with a separate quench followed by an acid ( $\text{pH} = 1$ ) scrubber and a neutral ( $\text{pH} = 7$ ) scrubber, both of which are modified Venturi scrubbers. Between the two scrubbers, and downstream from the neutral scrubber, special sampling trains were installed. Test results from these were combined with those from raw gas concentrations derived from the isokinetic sampling system upstream of the fabric filter. The efficiency of the wet system for the different acid gases could then be calculated.

During the entire PU test campaign, the scrubber system was operated in a routine way. No optimisation for the removal of special gas components such as HBr or  $\text{Br}_2$  took place. Due to temporary storage problems, the discharge rate of scrubbing solution from the first scrubber was set very low. It had to be increased slightly in order to avoid salt precipitation. Despite this, for all three of the acid gases: HCl, HF, and HBr, the emission standards required by Germany could easily be met. No scrubber performance was monitored during the XPS test runs.

#### HCl Abatement

The change in concentrations of HCl while the flue gas passed through the scrubbing system reveals that the installation of only an acid scrubber does not guarantee the observance of the emission limit of  $10 \text{ mg/m}^3$  set by the German

17.BlmSchV. However, after passing the second scrubber, measurements far below  $1 \text{ mg/m}^3$  were easily achieved.

#### HF Abatement

Measurements of concentrations of HF were performed the same way as for HCl. It is obvious that the efficiency of the first scrubber was much lower for HF than it was for HCl. Nevertheless, in the clean gas, levels of  $<0.2 \text{ mg/m}^3$  were measured, which is well below the 17.BlmSchV limit of  $1 \text{ mg/m}^3$ .

#### HBr Abatement

Removal of HBr in the first scrubber was better than that of HF but did not reach the quality achieved for HCl. The 17.BlmSchV contains no emission limit for HBr but the German emission regulation issued in 1986, the "TA Luft 86", sets a limit of  $5 \text{ mg/m}^3$ . The HBr level found in the clean gas of TAMARA was well below  $0.2 \text{ mg/m}^3$ .

#### Scrubber Efficiency

The scrubber efficiency is defined as the amount of a component removed by the scrubber, divided by the input, expressed as a percentage. The removal efficiencies of the first and second scrubber for HCl, HF, and HBr are averaged for the different combustion conditions. Approximately 98% of the raw gas HCl was removed in the first scrubber. After having passed the neutral scrubber, almost 100% of the HCl was absorbed. For HF, the removal efficiency in the first scrubber was relatively poor, reaching only 50% in the case of the test runs where the input concentration was low. During the co-combustion trials, when the F feed was increased, approximately 70% removal was calculated. The overall efficiency was at least 98%. For HBr, an efficiency in the order of 90% could be achieved in the first scrubber. With the exception of the reference tests, with their low input, almost 100% could be removed by the entire system.

### 6.3. CFC/(H)CFC's

#### Input Data

Three different (H)CFC's were fed into the incinerator along with the XPS foam. Table 6.4 gives an overview of

the expected levels of (H)CFC with no thermal destruction taking place. For CFC 12 blown foams, a separate experiment of 2 h was performed at a medium temperature in a later TAMARA test run.

**Table 6.4**  
**THEORETICAL (H)CFC CONCENTRATIONS**  
**IN THE FLUE GAS CALCULATED ON THE ASSUMPTION**  
**THAT NO THERMAL DESTRUCTION TOOK PLACE.**

Temperature °C	CFC 12 mg/m <sup>3</sup>	HCFC 22 mg/m <sup>3</sup>	HCFC 142b mg/m <sup>3</sup>
850	312 ± 10	150 ± 8	290 ± 10
880 - 900	350 ± 10		
950	340 ± 10	190 ± 10	360 ± 10

#### **Destruction of CFC 11 and of CFC 12**

In earlier extended experiments in TAMARA, as well as in a full-scale MSW combustor, an almost complete thermal destruction of CFC 11 (in PU foams) was confirmed (12). At temperatures above 800°C no temperature influence could be detected.

Due to its higher chemical stability, a different behaviour in the incinerator could be expected for the CFC 12.

During the reference test runs, the concentration of CFC 12 was approximately constant at both combustion temperatures. An average CFC 12 level of  $2.6 \pm 1.3 \mu\text{g}/\text{m}^3$  was analysed. The actual values range between  $0.8 \mu\text{g}/\text{m}^3$  and  $8 \mu\text{g}/\text{m}^3$ . During the co-combustion experiments a certain influence of the combustion temperature was found on CFC 12 destruction. At the low temperature of approximately 850°C residual concentrations of up to  $1,000 \mu\text{g}/\text{m}^3$  were analysed. At 950°C the levels of CFC remaining were found to be 10 - 20  $\mu\text{g}/\text{m}^3$ . In order to confirm the observed effect of combustion temperature on CFC 12 destruction, an additional TAMARA test campaign was used to run further experiments at temperatures between 870°C and 900°C. The results from these experiments fell mid way between those at the lower and higher temperatures, confirming the effect. The destruction efficiency calculated from the concentrations given above is more than 99.9% at 900°C.

#### **Destruction of HCFC 22 and HCFC 142b**

In contrast to CFC 12, the partially halogenated HCFC 22 and HCFC 142b were below the detection limit of

$3 \mu\text{g}/\text{m}^3$  in the flue gas of TAMARA during all test trials. On the basis of the amounts of these HCFC's fed into the incinerator, minimum destruction yields of 99.9% can be calculated for HCFC 22 and for HCFC 142b. As a consequence, the HCFC blown foams used today can be incinerated in a MSW combustor in an ecologically beneficial way.

#### **6.4 CONCLUSIONS FROM THE TRIALS** **WITH INSULATION FOAM**

The main objectives of these foam combustion trials were to establish information on:

- The thermal destruction of the blowing agents CFC 12, HCFC 22 and HCFC 142b,
- The thermal destruction of flame retardants, and
- The distribution of additional F and Br fed with the foam.

The tested foam materials added substantially to the Br content in the incinerator. An increase by a maximum factor of 6 was attained. The Br levels in the bottom ash stayed almost constant during all experiments and the additional Br load was more or less totally released into the flue gas.

This indicates that the bromine containing flame retardant is first released from the foam and then burned in the gas phase. The formation of HBr and Br concentrations in the fly ash thus shows a strong correlation with the Br in the feed.

During the foam experiments, considerable amounts of F were also introduced into the combustor. This caused an increase in the F content by a factor of about 6 for XPS and 1.5 for PU. The fluorine balance suffered losses, presumably due to reactions with silicate matter. Most of the additional F in the feed was found as HF in the flue gas. This fraction increased with increasing combustion temperature. The fly ash transported only a small percentage of F, even though its concentration in this sample correlated with the F input. F concentration in the bottom ash was little affected.

## CONCLUSION

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The Cl level in the feed was only increased by about 20 to 25% when the CFC 11 blown PU and the (H)CFC blown XPS foams were added. The Cl, nevertheless, promoted the volatilisation of some thermally mobile elements such as K, Cu, An, As, Cd, Sn, and Pb at the higher combustion temperature. At 850°C only minor effects could be observed. The mobilisation of such metals prevents them from forming water soluble compounds in the bottom ashes, which is beneficial to co-combustion in terms of bottom ash quality.

The enhanced levels of acid gases do not challenge a state-of-the-art air pollution control system such as a two-stage wet scrubber. The HCl does not exceed typical raw gas concentrations excessively and the HCl emissions were always  $<2 \text{ mg/m}^3$ . HBr was present in low concentrations, as was HF. The emission values measured for HF were  $<0.2 \text{ mg/m}^3$  and those for HBr  $<0.8 \text{ mg/m}^3$ . All these values comply well with the most stringent air emission regulations and create no pollution problem at all.

## 7. CONCLUSION

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During their production and life cycle plastics achieve a high level of sustainability. For example, within a few years, a small fraction of their expected lifetime of more than 50 years, insulation foams like XPS and PU save more energy than their production process has consumed. Similarly, adding plastics to automobiles to reduce fuel consumption

achieves an environmental payback in energy terms in a similar time period, even though lifetimes of cars are shorter. End-of-life plastic articles like packaging films, pouches, and bottles have, in a similar manner, conserved material and energy through source reduction. The plastics industry has made enormous progress through the development of advanced higher performance polymers and increasingly sophisticated and faster polymer processing equipment. This has significantly enhanced the cost performance ratio, particularly when environmental parameters are taken into account. Energy recovery from end-of-life plastic articles can assist society to achieve an even more sustainable lifestyle. MSWC has a high potential to contribute in an economical and ecological manner.

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