

# LARGE SCALE DEMONSTRATION OF THE TREATMENT OF ELECTRICAL AND ELECTRONIC SHREDDER RESIDUE

*by co-incineration in the Würzburg  
Municipal Solid Waste Incinerator*

January 2006



*Prepared by :*

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A Technical Report  
produced by:

**PlasticsEurope**  
Association of Plastics Manufacturers

## List of Abbreviations

ASR	Shredder Residue from mainly Automobiles and White Goods
CVV	German Chemical Banning Ordinance
DEC	Destruction Efficiency Coefficient
ESR	Shredder Residue from Electrical and Electronic Equipment
E+E	Electrical and Electronic Market Sector
MSWI	Municipal Solid Waste Incinerator
PCBs	Polychlorinated Biphenyls
PBDE	Polychlorinated Bi phenyl ethers
PCDD/Fs	Polychlorinated Dioxins / Furans
PBDD/Fs	Polybrominated Dioxins / Furans
PXDD/Fs	Polybrominated/chlorinated Dioxins / Furans
SR	Shredder Residue from a mixture of ASR and ESR
WEEE	Waste of Electrical and Electronic Equipment
WEEP	End of life Plastics from E+E sector

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## Abstract

The use of a modern municipal incinerator for solid waste, such as that at Würzburg, in Germany, has been shown to be suitable for the safe treatment of shredder residue obtained from waste electric and electronic equipment (ESR), provided the concentration of PCBs allows the waste to be classified as non-hazardous. A large scale trial has demonstrated the successful addition of up to 26 wt% of ESR as well as the addition of shredder residue (SR) with a high metal content to the normal municipal waste stream. Despite the high heat content of the shredder residue, there was no blocking of the grate, which was operated at close to 90% of capacity. Along with ensuring the recovery of energy, there is the option of metal recovery in a subsequent operation from the resultant grate ash. The results also highlight the positive role of municipal incinerators in destroying dangerous organic compounds such as halogenated dioxins and furans.

## Summary

The co-incineration of shredder residue derived from electrical and electronic waste together with solid municipal waste is an efficient and practical option for the safe treatment of such waste with the recovery of energy. A controlled test campaign has been conducted by a broad consortium of stakeholders to evaluate the effects of residues from electrical and electronic end of life goods treatment on the performance of the large scale energy recovery incinerator in Würzburg, Germany (MHKW).

The test conditions included a base case of solid municipal waste without additional electrical and electronic shredder residue (ESR), addition of 11 wt% ESR containing waste electrical and electronic plastics (WEEP), and addition of 26 wt% ESR with WEEP as well as the addition of a high metal content shredder residue (SR) mixture to investigate potential metal recovery from the grate ash.

Representatives from the local authorities as well as the Bavarian Environmental Protection Agency (LfU) were present at these large scale trials. As well as attending a formal pre-meeting, the representatives were able to review the feeding and the sampling points.

The fact that a certain amount of WEEE is already present in the mixed municipal solid waste feed made the testing important for the MHKW operator as well as for the environmental protection authorities. Depending on the PCB level, electrical and electronic waste may be categorized as hazardous waste and consequently has to be reported to the local environmental agencies.

The tests were successfully completed on Line Nr. 2 without any undue operational delays. The operation of the water cooled grate did not show any mechanical blocking during the test in spite of the high heat value of 23 GJ/t of shredder residue. The grate was operated close to 90 % of capacity throughput, equivalent to 26 t/h steam generation. (It should be noted that the selected Line Nr. 2 was at the end of its operational time and close to a planned shut-down for maintenance.)

The 103 t of shredder residue (ESR) supplied by Electrocyling in Germany was derived from 650 t of a typical mixture of electrical and electronic waste from information technology equipment, consumer electronics, small household appliances and other applications. During the test condition to produce a metal rich grate ash no gas sampling was carried out.

An analysis of the results of the trial show the following:

- Clean gas concentrations of the chlorinated dioxins/furans were all well below the 0.1 ng ITE/m<sup>3</sup> level.
- Raw gas HCl and HBr concentrations were in the range expected, namely 1000 - 2000 mg/m<sup>3</sup> and 50 - 200 mg/m<sup>3</sup> respectively. Currently there are no HBr emission limit values mentioned either in the EU Waste incineration directive (WID) nor the German equivalent 17th BImSchV. The conditioned dry lime addition system worked perfectly for a feed concentration of 11 wt% WEEP to 26 wt% WEEP. The clean gas HCl concentrations could be kept below the limits of the permit in compliance with the WID.
- It has been shown that higher WEEP feed can be handled with the standard equipment.
- The heavy metals raw gas concentration was in line with what can be expected from the typical metal and heavy metal volatility behaviour. Most heavy metal raw gas concentrations were lower than those during the test conducted in 1997 (4) with automotive and appliance shredder residue (ASR).
- The decomposition of micro organics such as PCBs and halogenated dioxins and furans as well as flame retardants of the PBDE structure has been shown by individual mass flow analysis to be sufficiently efficient to ensure almost complete destruction of these organic compounds. This calculation was based on known measured concentrations in the feed and residual concentrations in the solids as well as the emission concentrations in the clean gas.
- The leaching of the grate ash has been assessed with positive outcomes according to the European, German, Dutch and US procedures. The effect from ESR co-incineration is minor and only few significantly increased leachate concentrations were measured. The limits for Germany on heavy metal leaching are not exceeded if grate ash is matured for 3 month as recommended. If fresh grate ash is tested the lead leachate concentration is higher than the limit, regardless of whether the feed is with or without ESR addition. Leachate concentrations are below European non hazardous landfill limits but higher than the ones for the inert landfill class. The leaching results of the TCLP test required in the United States for regulated metals were all within the specified limits.



# Introduction

National legislation is being enacted in all European countries to ensure compliance with the European Waste Electrical and Electronic Equipment (WEEE) Directive (1) as well as the Restriction of Hazardous Substance Directive (ROHS) (2). This legislation requires equipment manufacturers to meet high reuse and recycling quota. The total recovery target in 2006 limits the energy recovery portion to a minimum of 5 and a maximum 50 % depending on the category of the equipment.

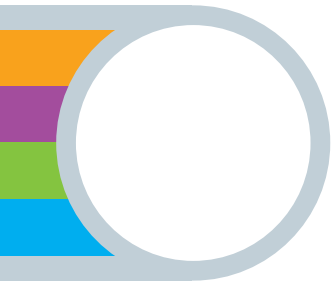
The plastics industry is supporting efforts to establish environmentally sound and economically efficient approaches to deal with WEEE, as has been described in previous publications (3, 4). Large scale shredding of the waste electrical and electronic equipment and recovery of the resulting shredder residue (ESR) is encouraged by *PlasticsEurope* (formerly APME) due to the high eco-efficiency of such a recovery route. Energy recovery of the ESR in raw or refined form is in fact needed to achieve the target. The use of ESR in a municipal solid waste incinerator (MSWI) is in principle a highly attractive option to contribute towards the compliance with the WEEE Directive in various European countries. As a result of this *PlasticsEurope* decided to support a large scale demonstration trial at the MSWI in Würzburg Germany (MHKW). At this installation demonstration trials have been successfully carried out previously with packaging waste and automotive shredder residue (ASR) (5,6).

A joint stakeholder consortium was formed to conduct and oversee the programme, and establish the technical feasibility of such a co-incineration route. This consisted of the MHKW incinerator owner (ZVW) and the operator (STW), the plastics producing industry associations in Europe (*PlasticsEurope*) and North America (American Plastics Council), the Institute for Technical Chemistry / Thermal Waste Treatment Division of the Forschungszentrum Karlsruhe GmbH, Germany (ITC), the recycling company Electrorecycling, Germany, and the Non – Ferrous Metal Producer Boliden from Sweden. Earlier technical programmes of the plastics industry (APME) with the ITC (7, 8) helped prepare the ground for the large scale testing through extended incineration tests in the Tamara pilot plant.

Co-incineration of ESR is not practiced very widely in Europe on a large scale, primarily as a result of the unfavourable economics compared to landfill. Nevertheless, in many European countries and regions co-incineration is a politically acceptable solution although the capacity and number of municipal incinerators (MSWI) will not be sufficient once the EU Landfill Directive (Council Directive 1999/31/EC) will be enacted in all EU countries. This will finally result in a severe landfill restriction on biodegradable waste (as is the case already in Germany since 1.6.2005). As regards co-combustion in new plants, this will be regulated after 2005 according to the Waste Incineration Directive (Directive 2000/76/EU of the European Parliament and the Council). In Germany the MSWI has to comply with the 17th Federal Emission Control Ordinance (Bundesimmissionsschutzverordnung, BImSchV).

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# 1. Electrical and Electronic Shredder Residues (ESR)

Electrical and Electronic shredder residue (ESR) which is almost all landfilled today, is not produced to meet any particular specification except that for leaching. The properties of the ESR are in practice specific to the feed used by the operator, the plant operation equipment and the mode of operation. However, there are certain countries which have set regulatory limits for specified parameters that determine the type of landfill in which ESR can be disposed.

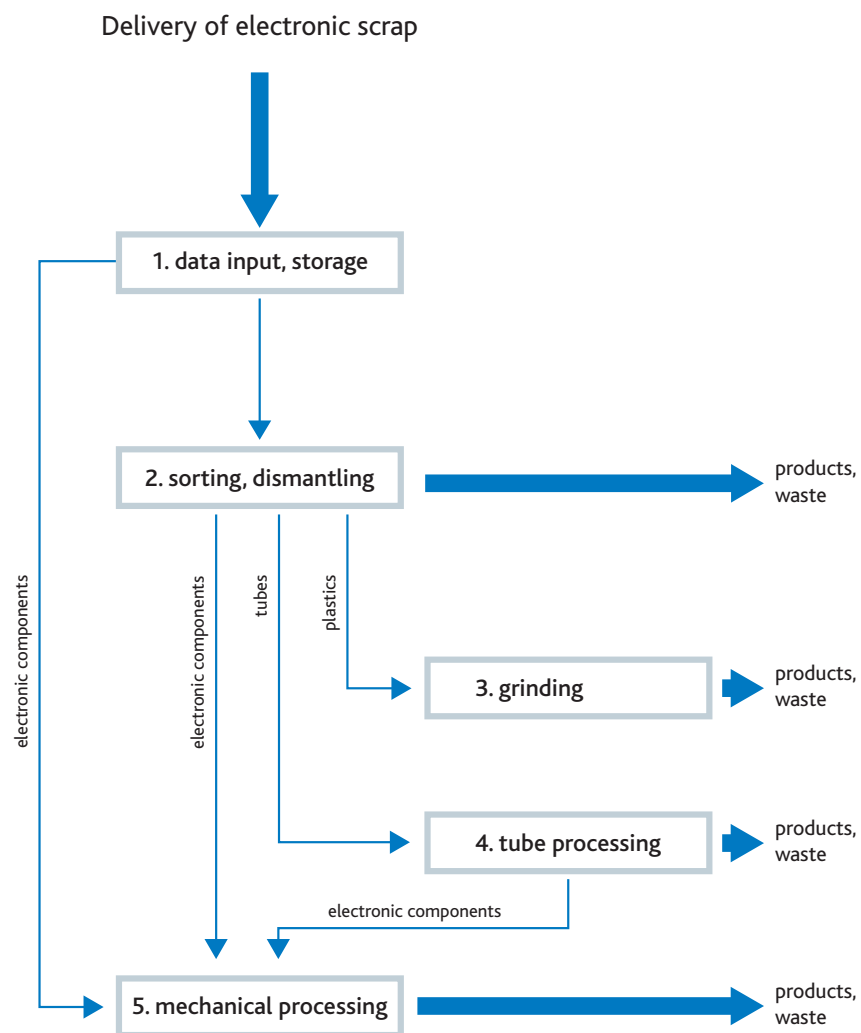
The wide compositional variation of ESR is described in the literature (10, 9) and is due to a number of factors. These include the input feed stream of WEEE which is affected by the collection (household, commercial or industrial), country of production, extent of dismantling and de-pollution, type of shredding equipment, the extent of metals recovery practised and the nature and volume of metals sent to off-site locations for further processing.

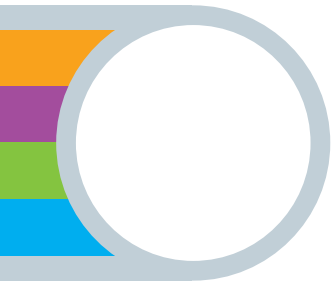
There is quite a broad range of understanding regarding the general term shredder residue (SR). Many literature sources include ESR also under the term SR. In this report the term ESR is used to describe the feed that has been identified to be only from waste electrical and electronic equipment (WEEE). SR residues in general originate mostly from mixed shredding of automotive and white household goods. In Europe, this is usually without refrigeration equipment because ozone depleting substances have to be first recovered in accordance with the European Ozone Directive and special handling of the equipment is required.

## 2. WEEE Treatment Operations / Shredder plant

The WEEE processing plant (Fig. 1) used in these demonstration trials consists of five subsections: incoming material/storage, preliminary dismantling, picture tube processing, plastic shredding, and mechanical processing. These process units are all located in a single building. The entire operation is dry except the refining of the ESR fines fraction, which is covered later.

FIGURE 1: Basic Flow Sheet Electrocycling





The appliances are fed directly from storage to different manual dismantling lines: a dismantling line for light appliances (up to approx. 5 kg), another for appliances of medium size (up to approx. 50 kg), display screens (TV/computer) and a third for heavy appliances (up to 200 kg). Manual dismantling as the first process entity stage comprises three main tasks:

- (1) Removal of useful components and or assemblies containing hazardous materials,
- (2) Disassembly and removal of components or severing parts of housings,
- (3) Removing reusable components as spare parts.

The processing layout contains a 3-stage liberation using a shredder to produce maximum piece sizes of 1000 x 800 x 800 mm and also two hammer mills for feed piece sizes from 60 to 200 mm and 5 mm respectively. Iron is separated out using overhead magnets. The concept for non-ferrous metals (NF) separation includes the use of eddy current separation. The mixed plastics and the filter dust generated during the mechanical treatment are normally sent to incineration plants for energy recovery or to a gasification plant for raw material recovery (feedstock recycling). The split of coarse to fines fraction is currently approximately 50:50 on a weight basis. The ESR coarse and fine fractions were sent separately to the MHKW incinerator in big bags having a weight between 600 and 800 kg. The coarse fraction is the residue stream of the dry mechanical refining part. The fines fraction is the residue from the wet refining part.

The total feed to the Electrocyling plant for the test was 650 t consisting of 240 t industrial sourced materials with the balance being consumer type materials. Both material sources comprised a number of individual fractions. The description used below is according to the categories in the EU WEEE Directive.

## 3. WEEE Description Categories

2	Household appliances (small)
3	Information and Telecommunication
4	Consumer electronics
6	Electrical and electronic tools
7	Games, sporting and leisure goods
8	Medical equipment

The categories taken into the plant were 2,3,4,6,7 and 8. The main share of the 650 t came from categories 2, 3 and 4. An additional third of the feed consisted of 6 and a small amount of category 7. Category 8 was contained in the 240 t of industrial equipment. The total amount delivered to the MHKW incinerator from Electrocyling was 50 t of REST1 and 53 t of REST2, the terms REST1 and REST2 being used by Electrocyling for the coarse and the fines fraction respectively.

The second type of WEEE residue coming from the local shredder company Preuer was derived from:

2	Household appliances (small)
3	Telecommunication
4	Consumer electronics: Radios, Tape recorders, etc;

The total amount of 10 t input for the test condition D was collected in the region of the Main-Tauber county and has been pretreated by a local company to remove contaminants as required by the WEEE Directive.

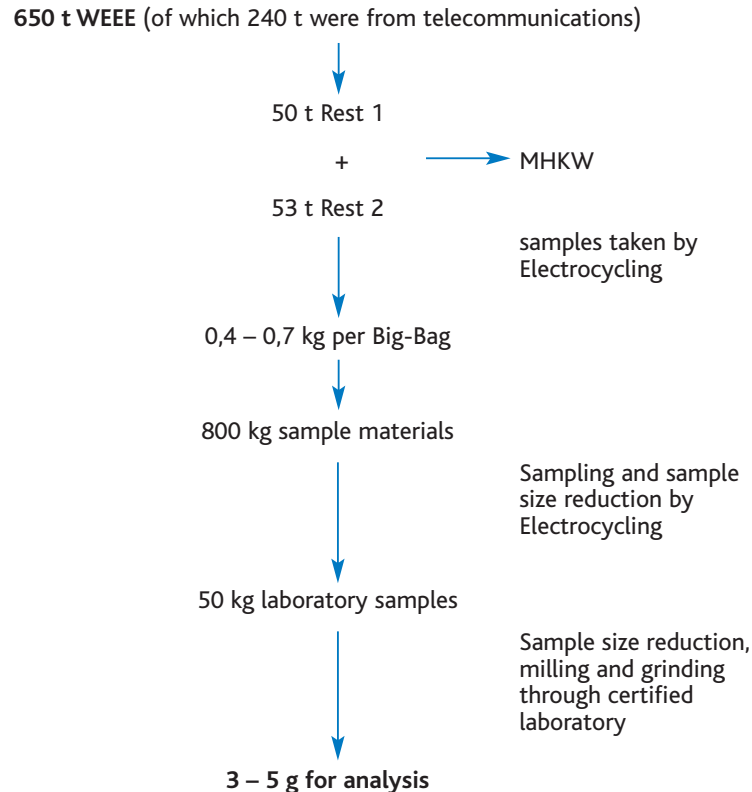




## 4. ESR Characteristics

Sampling was considered extremely important due to the large variability of the feed as shown above and the heterogeneous character of ESR with large variations of heavy metal concentrations. The representative sample of the 50 kg ESR shipped to a contracted analytical laboratory for further material separation and analysis was prepared in the following way. From each big bag shipped a 400 to 700 gr. sample of ESR was taken with a special 2 meter long lance. All representative samples collected in a big bag of 800 kg were then size reduced at the Electrocyling sampling facility by piling the sub sample up on the floor and taking a quarter from the total material. This procedure was done twice and resulted in 50 kg which were shipped to a contracted analytical laboratory for further material separation and for analysis.

**FIGURE 2: Overview of the total materials flow input and the samples used for the analysis**



**ESR Mixture Coarse / Fines:** The data for the ESR coarse and fine fraction, a calculation for the 50:50 mixture as well as a comparison of published ESR literature is shown below in Table 1. The mean value of the literature range given in the right column is based on existing literature values and our own internal data.

**TABLE 1: ESR compositional results and comparison with ESR literature range**

		Coarse	Fine	Mixture	Typical
		REST1	REST2	REST1/2	ESR Range for comparison
		2004	2004	50/50	Literature data
<b>Combustion parameters</b>		<b>Calculated</b>			
lower Hu	GJ/t	26	20.3	<b>23.1</b>	9 to 20
LOI	at T,C % wt	82.2	<b>77.6</b>	<b>79.8</b>	15 to 80
Carbon	% wt	65	49.5	57.2	20 to 40
Hydrogen	% wt	5.74	5.6	<b>5.67</b>	2 to 6
<b>Inert content</b>					
Ash	% wt	19.4	22.4	<b>21.2</b>	28 - 61
Moisture	% wt	3	-	-	2 to 5
<b>Halogen content</b>					
Br	% wt	<b>2.66</b>	5.5	<b>4.08</b>	0.5 - 6
Cl	% wt	<b>1.62</b>	1.6	<b>1.61</b>	0.5 - 6
F	% wt	0.05	0.11	<b>0.08</b>	0.01 - 0.08
<b>Heavy Metals</b>					
Hg	mg/kg	<b>0.24</b>	1.9	<b>1.07</b>	1 - 49
Cd	mg/kg	<b>53.8</b>	62	<b>58</b>	2 - 85
Tl	mg/kg	0.29	0.9	<b>0.6</b>	n.a.
Sb	mg/kg	<b>251</b>	<b>87</b>	<b>169</b>	<b>50 - 10000</b>
As	mg/kg	4.4	8.3	<b>6.4</b>	20 - 50
Pb	mg/kg	<b>564</b>	<b>1300</b>	<b>932</b>	<b>1100 - 11000</b>
Cr	mg/kg	45	140	<b>93</b>	1000 - 1800
Co	mg/kg	1.9	36	<b>18.9</b>	13 - 33
Cu	mg/kg	<b>547</b>	<b>24000</b>	<b>12274</b>	3700 - 26300
Mn	mg/kg	33	260	<b>147</b>	360 - 1100
Ni	mg/kg	53	200	<b>127</b>	400 - 1500
V	mg/kg	1	4	<b>2.6</b>	20 - 150
Sn	mg/kg	22	30	<b>26</b>	130 - 400
<b>Sum (Sb to Sn)</b>	mg/kg	<b>1351</b>	<b>26130</b>	<b>13854</b>	n.a.
Zn	mg/kg	529	1400	<b>964</b>	4600 - 20000





The ESR specific heavy metals concentration for Hg, Cd, Sb, Pb and Cu show significantly higher values compared to the equivalent shredder residue data of a typical ASR. The levels of Br and Cl are also much higher in ESR than in the ASR (6).

The table suggests that the PCB concentration of the REST2 fraction can exceed the German limits set by three ordinances, the Ordinance on Hazardous Substances (Gefahrstoff-Verordnung), the Chemicals Ban Ordinance (Chemikalienverbots-Verordnung (CVV)) and the Ordinance on the Ban of PCB and PCT (PCB/PCT-Abfallverordnung), which both are aimed at protecting the consumer, and the Dangerous Goods Ordinance Road and Rail (Gefahrgutverordnung Straße und Eisenbahn - GGVSE) for transportation of hazardous materials by road and rail. Plastics-rich residue fractions are sometimes removed from ESR at selected recyclers. REST 1 fraction has been gravity separated into 3 parts to show differences.

**TABLE 2: Organics and Micro Organic analytical results from ESR test samples**

2004 samples		REST 1			REST 2	mixture		Law
		coarse			finer			
		Lights 1.0-1.12	Medium 1.12-1.22	Heavies 1.22-1.44		calculated *50/50	Regulation	Limit value
PCB	mg/kg	n. a.	12.3	23.8	39.1	<b>22,8</b>	PCB-Directive	<b>50</b>
PentaBDE		n. a.	2.1	30.8	153	<b>79,3</b>	Directive	<b>1000</b>
OctaBDE		n. a.	585	1070	303	<b>299</b>	2003/11/EC	<b>1000</b>
Penta-Octa-BDE	"	n. a.	1509	2733	971	<b>863</b>		
DecaBDE	"	n. a.	906	1330	1400	<b>901</b>	n.a.	
PBDE (Tri-Deca)	"	n. a.	3170	5093	2932	<b>2206</b>	RoHS	<b>n.a.</b>
PBrDD/F (Sum Tetra-Octa)	"	n. a.	1.78	3.66	2.51	<b>1.74</b>		
PBrDD/Fs 4 Congeners 2378	µg/kg	n. a.	1.29	2.55	4.39	<b>2.54</b>	CVV	<b>1</b>
PBrDD/Fs 8 Congeners 2378	µg/kg	n. a.	1.58	4.84	5.6	<b>3.36</b>	CVV	<b>5</b>

Note: The calculation assumes that there are zero micro-organics in fraction 1.0 - 1.12 which are regulated by the European Directives covered in the above table. PCB Directive is the Council Directive 96/59/EC on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT), RoHS (Restriction of Hazardous Substances) is the Directive which will enter into force on July 1, 2006 and CVV is the PCB/PCT-Abfallverordnung. \*\* if not analyzed, 50 % of detection limit should be used (this should be justified by the average figures found in the analyzed samples). The light fraction of the coarse material was not measured due to cost reasons. It is assumed that there is a low concentration of restricted substances. The lower concentration of halogen elements does support this. The abbreviation n.a. means not available.

## 5. ESR/MSW Mixing

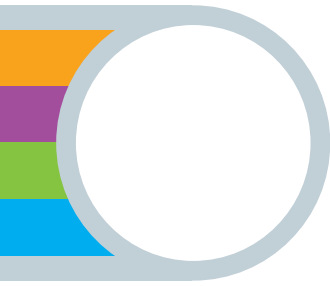
The type of in-line mixing of loose municipal waste (MSW) and ESR done this time represented real life operation and characterizes the worst mixing of MSW and ESR. Handling of the ESR big bags required more personal and is thus neither desirable nor necessary for a normal operation. Big bags with ESR fines did not flow as well as the coarse material. The crane operator did assist the mixing of MSW and ESR through placement of the ESR big bag. Mixing of MSW and ESR did take place in the feeding hopper on the way down into the furnace, mainly along the side of the walls.

ESR/MSW is pushed automatically from the chute on top of the grate. The amount of MSW/ESR moved onto the grate through the funnel is determined by the plant steam load and is controlled automatically by the plant control system. This means that steam flow was maintained at constant level of approximately 24 to 28 tons of steam per hour. An increase in heating value will automatically reduce the total feed to the grate according to the plant operating diagram.

## 6. Co-Combustion Tests of ESR and MSW

The specific incinerator plant site was selected for the same reasons as for doing the plastics packaging co-combustion test in 1993/94 and the ASR testing in 1997: cost efficient operation, reliable dry scrubbing system, long residence time furnace leading to good burn out in the gas phase, proven grate and boiler design leading to excellent residue characteristics and well documented emissions. In addition to these important features, the know-how of the plant personnel and the results from the ASR co-combustion at the MHKW were the decisive factors to do the test here.





## 6.1. MHKW Incinerator Facility Description

The MSW incinerator design and operation has been extensively described elsewhere, both by *PlasticsEurope* (5,6) and other public literature (see [www.zvaws.de](http://www.zvaws.de)). The significant changes since 1997 are on the input side.

FIGURE 3: Basic flow sheet MHKW with sampling points

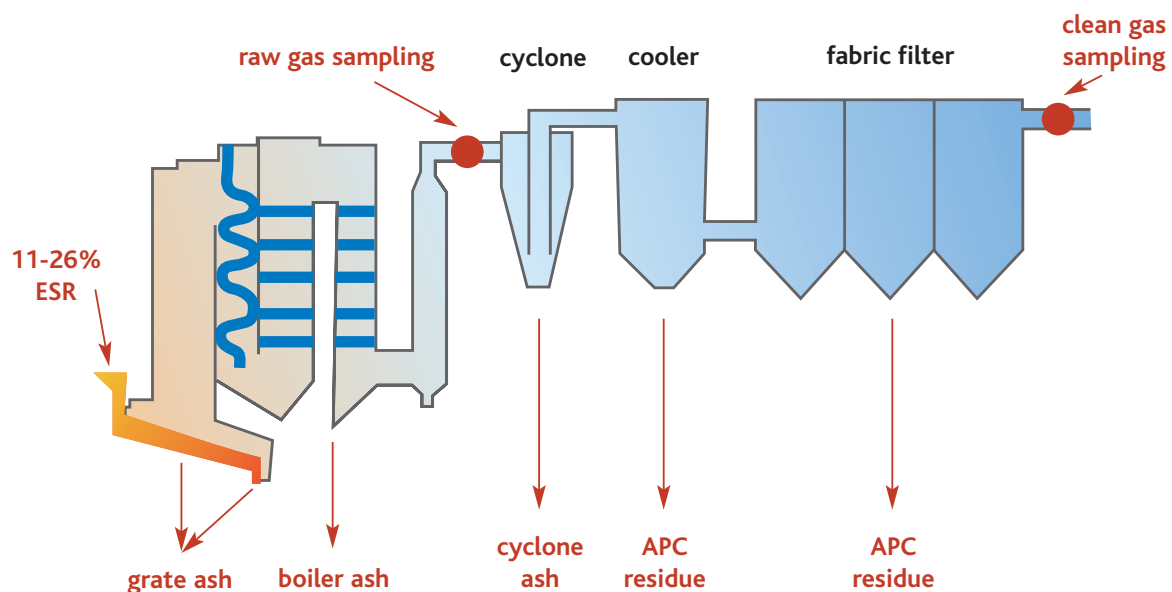
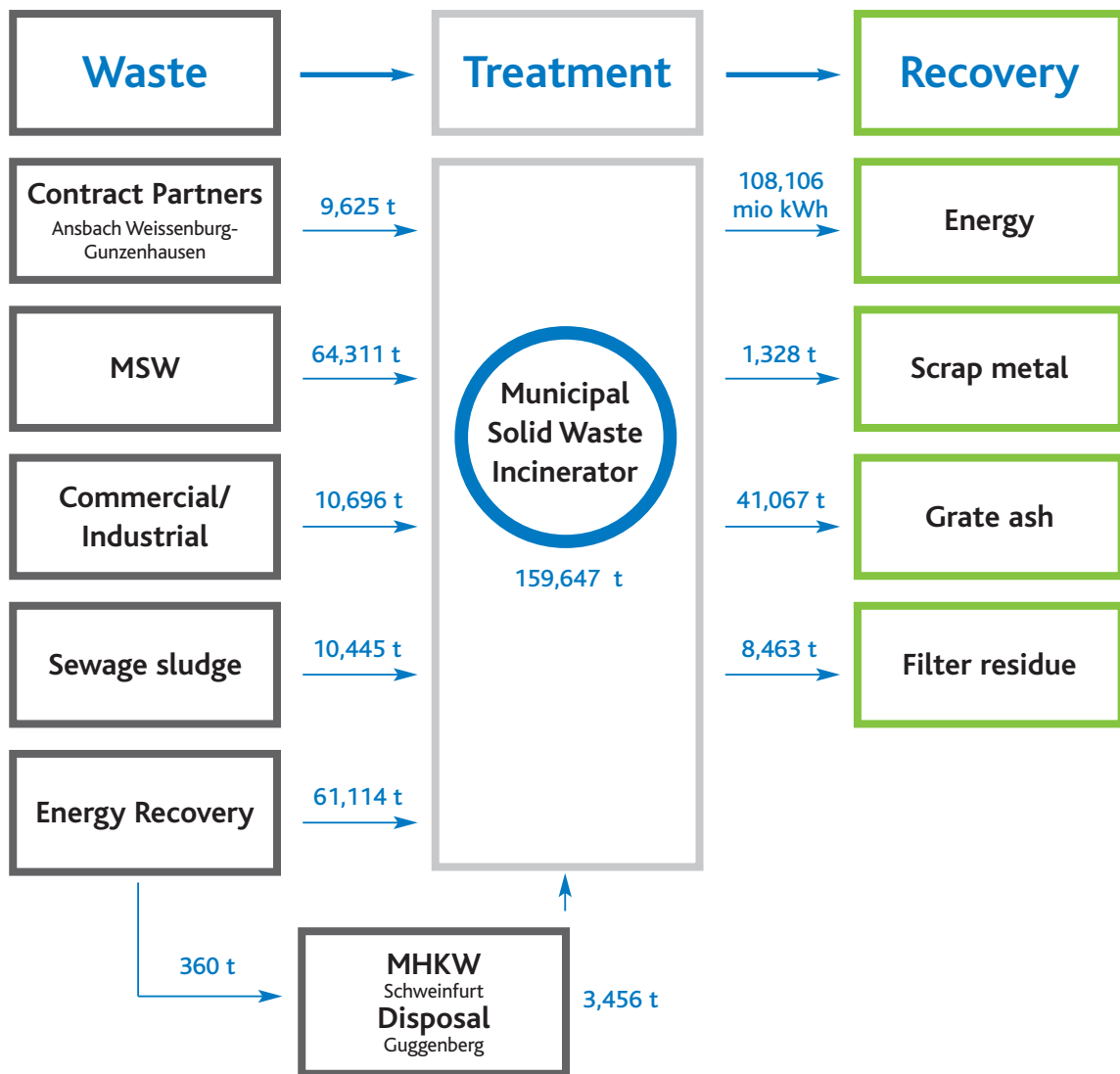


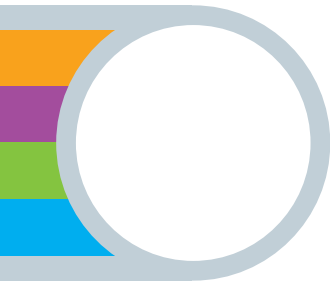
Figure 4 shows the mass and the ratios of the different streams entering the MHKW installation. The extent to which waste streams in the MHKW are officially recognized as waste for energy recovery by the German authorities has grown and is significant. This type of waste is mostly commercial waste more than half of which originates from external customers not belonging to the ZVAWs region. The amount of sewage sludge has stayed constant. The hardware changes since the earlier testing in 1993/94 were significant:

- raw gas conditioning including a cooler,
- separate activated carbon addition /  $\text{Ca}(\text{OH})_2$  and
- catalytic  $\text{NO}_x$  reduction.

The measured emission data since the start of the new emissions control system of the plant shows it is performing well and documents a globally well operated plant. The modifications allow the plant to achieve lower HCl,  $\text{SO}_x$ ,  $\text{NO}_x$  emissions and have a reduced consumption of lime/active carbon as well as a smaller amount of hazardous filter ash material to be landfilled, which saves considerable cost.

FIGURE 4: Mass Input Output Streams.  
 Recovery Balance of MHKW Würzburg 2003





## 6.2. MHKW Operation

The programme consisted of a one week testing period whereby the test conditions represented a boiler operation at the very end of the cycle before a regular maintenance shut down. The line Nr. 2 was chosen to benefit as much as possible from comparative data of the earlier tests carried out in 1993/94 and 97. The conditions are coded as follows:

- A base case with A1,
- B medium level of 11 wt% ESR addition,
- C higher level of ESR addition was intended, but  $\text{Ca}(\text{OH})_2$  feed was blocked,
- D addition of a high metal containing mixture from various fractions to achieve a grate ash which may have some economic value for Non-ferrous (NF) metal recycling,
- E higher level of 26 wt% ESR addition (repeat of condition C).

The operation of the plant was maintained constant as much as possible and conditions kept close to normal operation. This situation applies completely to the control of the air management, the furnace, the boiler and the air emission control section.

Solid residue sampling was carried out on the following streams:

- grate ash, taken from the ash discharging belt downstream of the grate ash water quench tank,
- fly ashes from the fourth flue of the boiler and the air cooler, taken from a discharge silo,
- cyclone ash taken out of a port at the bottom of the cyclone, and
- fabric filter ash taken out of the ash conveyor.

The sampling was done by ITC according to the recommendation of the International Ash Working Group. Spot samples from the 5 th boiler section were taken as well. Grate ash for condition D was separated from the rest and magnetic metal removal was running continuously.

Gas sampling was carried out by an external contractor having a proven record in emission, with four people sampling and recording:

- clean gas upstream of the chimney, and
- raw gas at the end of the emergency cooler.

No major time delays compared to the sampling plan were encountered. Sampling frequency for HCl and HBr was increased to 28 raw/clean gas samples to get as many samples as possible during the B and C test period.

## 6.3. Halogen Emissions

The clean gas emission of HCl indicated by the plant on-line monitoring equipment during the condition E with 26 wt% ESR could meet the emission standards very easily. During the condition C with a lower ESR feed, the HCl clean gas concentration exceeded the WID for the ½ hr limit because of a valve feeding the Ca(OH)<sub>2</sub> was blocked. During this period the feed rate of MSW/WEEP was stopped. Results from the ½ h gas sampling analyzed by the contractor agreed well with the plant on-line clean gas results for B1/B2. The batch ½ hr gas samples ranged between 40 and 500 mg of HCl /m<sup>3</sup> with an average of about 140 mg HCl for the ½ hr results. HBr levels in the clean gas during the conditions B1/B2 were significantly below 5 mg/m<sup>3</sup>. During the 8 hour measuring campaign of condition C1/C2 the HBr exceeded this value only during 15 % of the time.

**TABLE 3: HCl and HBr Raw Gas and Clean gas average data from 1/2 samples**

Raw Gas	A1	B1	B2	C1	C2	E	Emission Limit
HCl, mg/m <sup>3</sup> (MHKW)	1366	1480	1482	1310	1254	1790	n.r.
HBr, mg/m <sup>3</sup> (contractor)	9	143	176	120	104	283	n.r.
<b>Clean Gas</b>							
HCl, mg/m <sup>3</sup> Contractor	8	13	7	184/87*	99	7	10**
HBr, "	0	1	3	5.3*	3	4	6.37**

*Note: \* There was a lower Ca(OH)<sub>2</sub> addition during the conditions E, C1, C2 which was not high enough to achieve the necessary neutralization. \*\* The yearly 2003 HCl emission value was reported as 6.37 mg/m<sup>3</sup>, n.a. means not applicable, n.r. not relevant*

The above results of HCl and HBr concentrations are averages of 6 half-hourly samples. The range of HCl and HBr concentration varied +/- 20-30 % around the average value. The HBr raw gas values varied to a lesser degree. The standard deviation of the clean gas figures shows a higher variability due to the low concentration values. The analytical error affects the results very much in that range.





## 6.4. Test Programme and Conditions

The sampling and on-line analysis was started Tuesday the 27th August 2004 with a duration of six hours for the gas phase and 8 hours for the solid phase. The sampling finished up at 4 p.m. Test duration for the conditions during the other weeks was at least the same time length. In order to get a simultaneous sampling of solid and gas, a time difference of 2 hours between solid and gas sampling was chosen since the solids leave the system 1-2 h later than the gas.

	Tuesday	Wednesday	Thursday	Friday
Week 31 <sup>st</sup> 2004	A1	B1, 2	C1, 2	D
Week 32 <sup>nd</sup> 2004	A2			
Week 11 <sup>th</sup> 2005		E	E	

## 6.5. Online Analysis

The operation of the MHKW incinerator is fully automatic and uses a process support system. A data logger was used to document on-line data on different interval sizes: raw data, averaged for 10, 300 and 900 seconds. The plant online data are compared below from a total averaged data for the 8 or 4 hours of sampling. The average values were calculated one hour after the feed had been introduced to the funnel.

**TABLE 4.1: MHKW Online Boiler Results***n.u. : not used*

Boiler		A1	B1	B2	C1	C2	A2	D	E
Steam	t/h	28.6	25.5	29	24.5	25.3	24.4	18.7	28.8
Feed water	°C	27.7	27	27	26	26	26.3	21.6	n.u.
T Furnace	°C	894	883	868	666	895	864	851	n.u.
Oil burner	Nr.	12364	2364	2365	2369	2370	2337	2380	n.u.
Oil burner	Nr.	22392	2392	2392	2396	2397	2253	2407	n.u.
O2 Furnace	vol%	8.9	8.5	8.8	10.3	7.9	9.4	10.7	7.2
MSW	t/h	8.7	9.5	7.4	6.3	7	11	6.3	7.9

**TABLE 4.2: MHKW Online Raw Gas Results**

Raw Gas		A1	B1	B2	C1	C2	A2	D
HCl	mg/m <sup>3</sup>	1366	1480	1053	1310	1254	698	755
SO <sub>2</sub>	mg/m <sup>3</sup>	422	299	143	62.7	267	227	185
NO <sub>x</sub>	mg/m <sup>3</sup>	378	336	372	335	366	455	429
H <sub>2</sub> O	mg/m <sup>3</sup>	13	13.2	13.2	12.5	14.7	16.8	13.1
T Boiler end	°C	259	256	263.2	264	253	196	253
CO	mg/m <sup>3</sup>	8.5	8.2	8.44	7.8	9.2	8.9	7.1
V	Nm <sup>3</sup> /h	54598	54026	54145	53344	47466	44086	49156
H <sub>2</sub> O	m <sup>3</sup> /h	3.7	4	3.6	3.8	3.5	1.7	3.3

No effect of ESR combustion can be seen on the basis of the clean gas analytical results. Variations in the concentrations of NO<sub>x</sub>, dust, temperature and moisture are not significant. The Hg results from the plant on-line measurements are less accurate and the contractor data are more reliable. There is hence no negative influence of ESR on the gas emission side which could increase the environmental impact.





**TABLE 4.3: MHKW Online Clean Gas Results**

Note: \* There was a lower  $\text{Ca}(\text{OH})_2$  addition during the conditions E, C1, C2 which was not sufficient to achieve the necessary neutralization.

		A1	B1	B2	C1	C2	A2	D	E
<b>Clean Gas</b>									
Hg	$\mu\text{g}/\text{m}^3$	0.6	1	n.a.	1.48	3.9	0.6	2.3	9.
O <sub>2</sub>	vol%	9.3	9.2	9.3	10.1	8.5	8.6	10.7	8.1
NH <sub>3</sub>	$\text{mg}/\text{m}^3$	1.11	0.62	1.26	0.16	0	0.8	0.08	3.75
HCl	$\text{mg}/\text{m}^3$	9.2	13.4	5.63	17.2	16.8	6.4	16	8.6
CO	$\text{mg}/\text{m}^3$	25.4	48.6	23.6	47	75.5	40.1	16.7	19.9
C (TOC)	$\text{mg}/\text{m}^3$	0.68	1.65	0.57	1.14	2.32	<1	5.9	0.63
SO <sub>2</sub>	$\text{mg}/\text{m}^3$	4	8	3	78*	103*	12	72*	4
NO <sub>x</sub>	$\text{mg}/\text{m}^3$	118	118	84.2	358	365	62	403	425
H <sub>2</sub> O	$\text{mg}/\text{m}^3$	17.3	17.4	16.4	16.1	18.4	16.4	13.6	18.5
Dust	$\text{mg}/\text{m}^3$	3.1	3.5	4.2	6.4	3	0.06	11.6	0.3
T chimney	°C	156.3	153.7	166	152	146	153	138	249
V	Nm <sup>3</sup> /h	54202	54305	54352	53770	47492	44151	50929	51869
p	mbar	988.7	990	988	986	985	980	988	n.a.

The data from the contractor were measured at the same location as in the 1993/94 testing programme for comparison reasons. The plant on-line measurement does not detect HBr and the HCl reading seemed not as reliable in the low HCl concentration and hence the halogen batch measurements from the contractor have been used for further efficiency calculations.

## 6.6. Efficient Raw Gas Cleaning by Emission Control

The emission control as described above performed in an excellent way which is confirmed by the clean gas data. The addition of lime was controlled as described above and the excess lime ratio during the testing varied between two and three. This ratio is quite acceptable and representative for typical MSW incineration plants. The stoichiometric excess is defined as the ratio of the molar equivalent of the actual lime injected to the stoichiometric amounts needed as calculated from the raw gas concentration of the HCl and the SO<sub>2</sub>.

The typical stoichiometric ratio for the neutralization was around 2-2.5 times the theoretical value and in extreme cases up to 3.2. The raw materials used in the air pollution control section were of typical quality. For the conditions of C1 and C2 the necessary dosing of  $\text{Ca}(\text{OH})_2$  was not possible due to a momentary mechanical defect in the  $\text{Ca}(\text{OH})_2$  feeding line.

## 6.7. Grate Ash Characteristics

Grate ashes were analyzed according to the German standardized procedures for disposal and utilization of grate ash from MSW incinerators as laid down in the LAGA memorandum (14), a code of practice which is an official guideline for operators in Germany.

The grate ash quality from the MHKW installation is rather good for an older plant due to the high burnout and the metal removal from the grate ash. Some metal is also already removed prior to combustion during the sorting of commercial waste.

**TABLE 5: Solid Residue Heavy Metal Composition**

<b>Grate ash</b>															
	units	Tl	V	Cr	Mn	Co	Ni	Cu	Zn	As	Cd	Sn	Sb	Hg	Pb
A1	mg/Kg	7570	148	910	1720	1500	751	5680	5070	14.2	< 4	227	283	<0.01	2140
B1/B2	mg/Kg	7230	91.1	589	880	696	471	7190	3350	49.8	17.2	268	1030	<0.01	1260
C1/C2	mg/Kg	8540	178	1000	2200	1690	601	6640	3060	18.6	< 4	285	553	0.04	4330
A2	mg/Kg	6800	155	678	1070	731	518	3570	2850	18.5	< 4	236	167	0.01	1090
<b>boiler 4. flue</b>															
A1	mg/Kg	11000	141	679	1460	527	391	1490	14600	24.6	127	366	662	0.79	3220
B1/B2	mg/Kg	16000	188	527	1450	333	636	3150	6780	22.7	44.6	249	1940	0.09	1000
C1/C2	mg/Kg	12500	133	725	1610	751	486	2750	9420	20.6	46.1	288	1550	0.05	1750
A2	mg/Kg	9860	144	269	1120	231	251	1120	6930	24.0	55.5	199	309	0.25	901
<b>cyclone</b>															
A1	mg/Kg	13200	168	364	1320	222	256	2240	19500	38.7	156	593	1140	0.71	3960
B1/B2	mg/Kg	14400	136	351	1000	180	251	2900	11700	36.0	180	523	4510	0.91	2360
C1/C2	mg/Kg	13200	153	646	1180	400	352	2590	17100	39.8	176	577	3650	1.95	4430
A2	mg/Kg	19100	229	411	1490	231	275	1570	15600	26.9	103	319	567	1.08	1820
<b>APC residue</b>															
A1	mg/Kg	796	<20	89.8	248	< 50	27.7	980	16200	26.0	240	739	1110	6.58	7690
B1/B2	mg/Kg	1485	<20	160	252	< 50	78.1	2040	12000	15.6	288	532	3280	5.57	5560
C1/C2	mg/Kg	1109	<20	70.9	191	< 50	41.9	1520	10700	45.7	333	844	4660	8.47	5900
A2	mg/Kg	794	<20	100	251	25	36.0	1040	18200	31.1	287	653	980	12.6	7420





## 7. Summary of Leaching Tests

The leaching tests applied differ in their purpose and therefore in the procedure employed. Table 6 gives the main characteristics of the tests. The German and the European tests are quite similar with the main differences in the liquid to solid ratio (L:S) and the maximum grain size of the samples. Their results have to be compared with legal regulatory limits depending on the nature of the intended disposal.

The results from the Dutch tests reveal the long term leaching behaviour of the heavy metals in a worst case simulation in the availability test and the increasing liquid to solid ratio during the column test.

The comparison of the data from the U.S. TCLP test with regulatory standards allows an assignment of the ashes as hazardous or non-hazardous wastes. This test is carried out on a mixture of all solid residues, i.e. grate ashes, cyclone ashes, APC residues, etc. due to the co-disposal of such ashes that is practised in the United States.

**TABLE 6: Overview of leaching tests**

	Germany	Europe	Netherlands		U.S.A.
	DIN EN 38414-4	EN 12457-1	NEN 7341 Availability	NEN 7341 Column Test	TCLP method 1311
Material	Grate ash fresh or stored	Grate ash fresh or stored	Grate ash fresh or stored	Grate ash fresh or stored	Grate ash and mixed APC residues
Grain size	< 40 mm	< 4 mm	< 0.125 mm	< 4 mm	< 9.6 mm
Steps	1	1	2	7	1
L:S	10	2	50 + 50	0.1, 0.1, 0.3, 0.5, 1, 3, 5	20
Eluent	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O + HNO <sub>3</sub>	H <sub>2</sub> O acidified with HNO <sub>3</sub> (pH 4)	H <sub>2</sub> O acidified with CH <sub>3</sub> CH <sub>2</sub> OOH (pH 2.88)
End pH	Not controlled	Not controlled	7 and 4	Not controlled	Not controlled
Time	24 h	24 h	3 h + 3 h	About 3 weeks	16 h

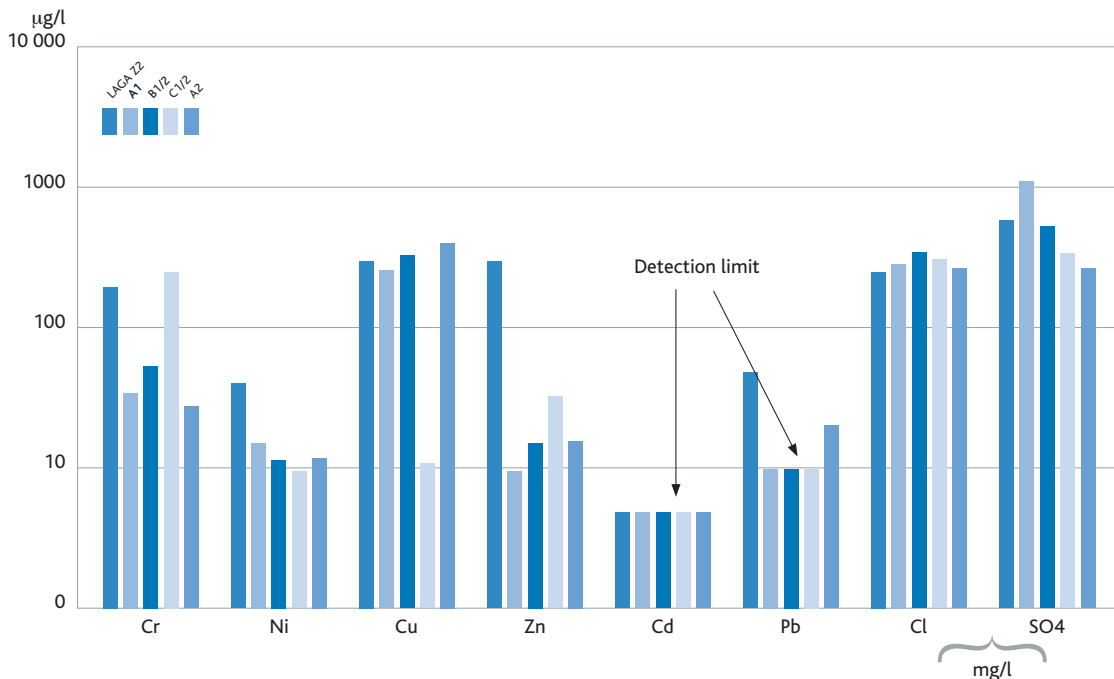
## 7.1. German DIN 38414-4 Test

According to the German LAGA memorandum, grate ashes can be used as material for applications such as road construction after three month storage, known as ageing, if their leaching results stay below the so called Z2 limit. This storage causes a reduction of the pH of the ashes by CO<sub>2</sub> uptake from the air and reduces the leachability of heavy metals, especially of amphoteric ones such as lead. The ageing in this trial took place in small piles at ITC. To simulate rainfall the ash piles were sprinkled regularly with water.

In Germany fresh ashes can be disposed of in landfills. In this case the results of the DIN leaching test define the landfill class. Most of the leaching values of heavy metals from the fresh ashes were within the limits. Only the lead solubility was too high in all samples due to the high pH value in the leachates. As mentioned above, the ageing lowered the pH in the ashes and stabilized the lead in the stored ashes, but the solubility of copper from the grate ashes of C1/2 and A2 were still too high to meet the LAGA Z2 limit. Z2 is the limit value for the usage of residues for defined and specific use, e.g. road construction, to avoid environmental damage.

The lack of a drainage system in the storage facility explains why the chlorine levels in the leachates remained at a high level.

FIGURE 5: Leaching tests data DIN 38414-4 on aged ashes



The differences between the reference tests A1 and A2 and the co-feeding tests are not significant and it is clear that the quality of the grate ashes is not influenced by the co-combustion of the ESR material.



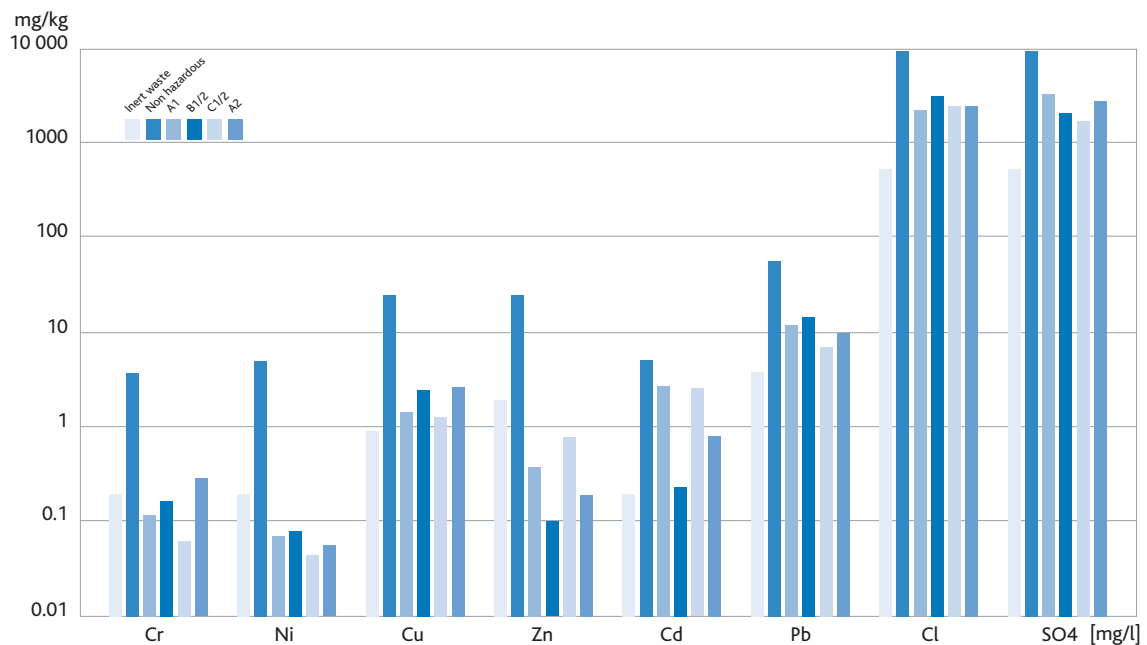


## 7.2. European EN 12457-1 Test

The EN 12457 test offers four options. The fourth option is quite similar to the German DIN 38414-4 so for this study the first option was chosen with a different liquid to solid ratio. The landfill acceptance criteria (2003/33/EC) which should be applied by the European member states by 16 July 2005 provide limits for different landfill classes depending on which leaching test is performed.

Figure 6 shows a comparison of the above mentioned landfill criteria for inert waste landfills and non hazardous waste landfills and the results of the EN 12457-1 leaching test on fresh grate ashes for selected elements. This criterion requires a calculation at the liquid to solid ratio in mg/kg dry substance.

**FIGURE 6: Leaching tests data EN 12457-1 on fresh ashes**



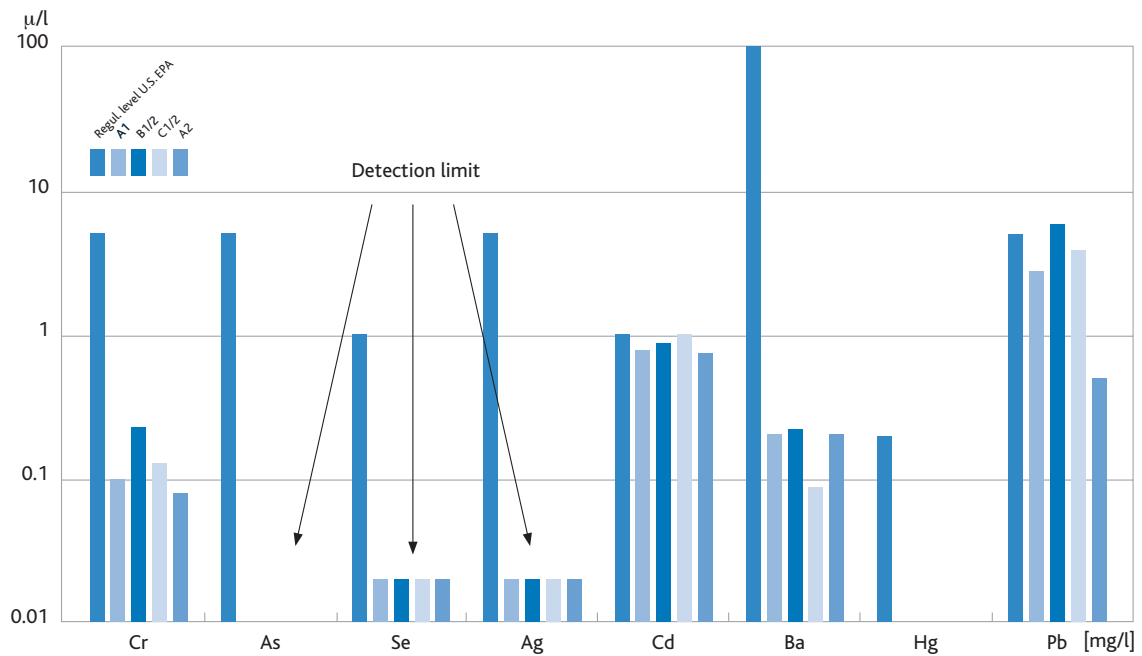
The concentration of some elements and anions in the leachates are higher than the limit for inert waste landfills but for all measured components they are well below the limits of the non-hazardous landfill class. Again it can be noticed that the influence of the co-incineration on the grate ash quality can be neglected.

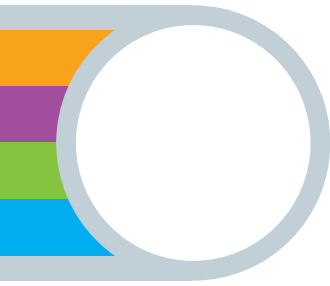
### 7.3. U.S. TCLP Test

In the United States grate ashes are disposed of together with fly ashes and other wastes. Therefore in this study a mixture of all solid residues sampled was produced for each test run. The portion of each ash was calculated on the basis of their yearly amount in the facility. The purpose of the TCLP test is to classify a waste as hazardous or non-hazardous. The results are shown in comparison with the regulatory levels in Figure 7. An increased concentration in the leachates due to the co-incineration of the ESR- Material can only be observed for copper, which is not regulated by the EPA, and for lead.. The lead value of mixture B1/2 is slightly higher than the regulatory value.

This testing method is not practiced or required in Europe and has a completely different background compared with the European leaching test procedures.

FIGURE 7: Leaching test data U.S. EPA TCLP method 1311 on mixed ashes

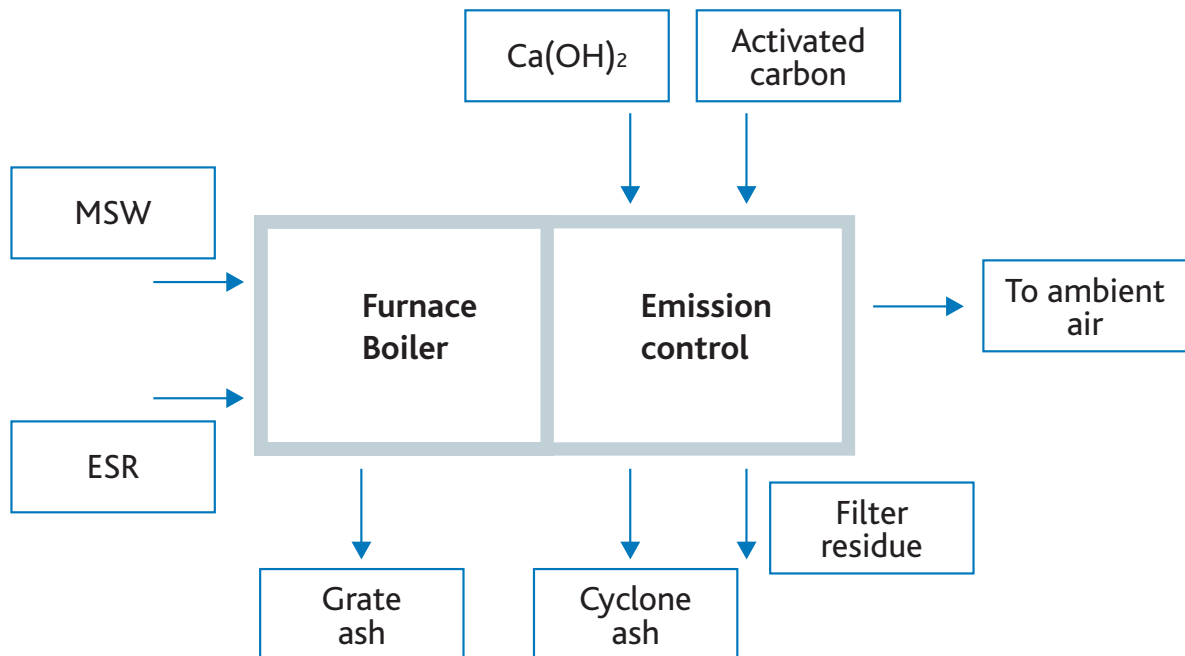




## 7.4. Mass Balance

The total mass balance is shown schematically Fig. 8. The feed stream input data have been taken from the weigh cell of the crane Nr.2. Calibration of the crane weighing cell was established for two conditions as in previous trials. The accuracy estimate of the comparison from the indicated and the calibrated weight is less than 5 % error in the low range for both cranes and 1-2 % error for Nr.1 and <10 % for Nr.2 crane in the 1.2 t region.

FIGURE 8: Schematic Diagram for mass flux calculations and destruction efficiency calculations



## 7.5. Energy Balance / Boiler Efficiency

The energy balance for the MHKW was done according to a straightforward engineering calculation which combines the mass and the energy balance calculations. The results of the efficiency calculation range around 74 % with a minimum of 71 and a maximum of 75 %. The differences of the lower heating values  $H_u$  for the different conditions vary starting from 11.7 for A1 with the highest value of 13.4 for C1 and the lowest value of 9.6 for B1. These changes of the total  $H_u$  feed value are due to the normal changes of heat values experienced with MSW of different composition delivered during the test.

## 7.6. Gas Analysis: Raw Gas

### 7.6.1. Dioxins/Furans

The gas sampling for metal and PCDD/PCDF analysis was very close together, inserted into one opening. The height level was the same as for the on-line sampling, but about two meters apart. Typical 6 hours sampling time was applied for A1 and 4 hours sampling time for the other conditions B and C.

Previous raw gas PCDD/F concentrations measured in 1993/4 were in the range 2.75 - 4.58 ng ITE/m<sup>3</sup> in the 1993 campaign and 1.29 - 6.53 ng ITE/m<sup>3</sup> in the second campaign in 1994. During these tests no significant difference was measured for the case with and without additional plastics. As seen below, there was no detectable concentration of PBDEs found in the raw gas. This supports confirmation of a very high destruction efficiency, as obtained from the PBDE destruction calculation.

**TABLE 9: PCDD/F concentrations in the raw gas in ng/m<sup>3</sup> at 11 vol % O<sub>2</sub>**

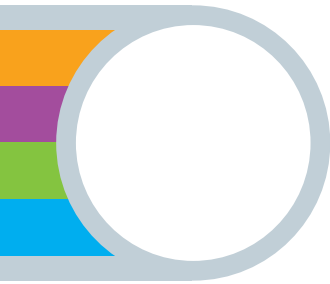
(NB: n.a. = not analyzed, n.d. not detected, n.m. not measurable as not sampled).

\* means potential influence from auxiliary oil burner used during conditions C1, C2.

Condition	A	B1/B2	C1/C2
PCB ng/m <sup>3</sup>	n. m.	n. m.	n. m.
PBDE ng/m <sup>3</sup>	n.a.	n.d.	n.d.
PCDD/F ng/m <sup>3</sup>	<b>697</b>	<b>977</b>	<b>1500, 11310</b>
PBrCDD	n. m.	180	180, 185
PBrCDF	n. m.	733	733, 633
Sum PBCDD/F	<b>n. m.</b>	<b>1481</b>	<b>914 , 819</b>
PCDD/Fs ITE	15.3	14.7	22.1*, 24.7*

From a comparison of all results from 1997 back to 1993 it can be concluded that there is also no significant difference in the data. The operating window of the MHKW plant for the raw gas PCDD/F concentration ranges from the low to the highest value. The fact that line Nr. 2 was at the end of the operational time before maintenance is more important. The amount of dust accumulated in the boiler section causes the raw gas concentration of PXDD/F in general to increase. The level of PCDD/F is about two to three times higher than in previous campaigns for A1. The raw gas concentrations for the condition B1, B2 with ESR, addition during the incineration does not change the level at all. At higher addition in condition C1, C2 an increase by a factor of two has been measured. But the fact that the clean gas emission concentration and the residue concentration for the PXDD/F did not change significantly is more important. It demonstrates that good combustion control with high combustion efficiency was achieved.





### 7.6.2. Heavy Metals

The effect of heavy metals, especially those specific to ESR, is of particular interest due to their higher occurrence in the ESR and their potentially increased level in the raw gas depending on their volatility. This summary report describes only the raw data and does not deal with any further analysis.

**TABLE 10: Heavy Metals concentrations in the raw gas**

Condition: 2004 ESR	zero	11 %	11 %	> 15 %	>15 %
in mg/m <sup>3</sup>					
Cd, Tl	0.076	0.33	n.a.	0.35	0.62
Hg	0.0063	0.0046	n.a.	0.080	0.031
Sb to Sn	12.82	15.5	n.a.	14.22	15.14
Zn	44.4	23.1	n.a.	22.1	35.0

Condition ASR	zero, average 1997	24 % 1997	31 % 1997	31 % 1997	zero ranges 1993	
in mg/m <sup>3</sup>					min	max
Cd, Tl	0.73	1.7	2.14	2.1	0.3	1.3
Hg	0.21	0.45	0.21	0.19	0.10	1.59
Sb to Sn	25.2	73.6	67.2	53.6	5.4	21.5
Zn	56.0	344	341	263	4.0	20.7

The heavy metals have been combined into four classes: Cd/Tl, Hg, Sb to Sn and Zn in order to obtain a somewhat simplified and easier to understand picture. The metals included in the sum Sb to Sn are the following heavy metals: Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V and Sn normally requested for emission measurements under the German 17th BImSchV and the European Waste Incineration Directive (WID).

The addition of ESR to the MSW did not increase the level of Zn in the raw gas significantly compared to the ASR case. This is due to the fact that the concentration of Zn in ESR is only 1/20 of that in automotive shredder residue (ASR). The very volatile heavy metals Hg, Cd and Tl also increased as expected from the feed characteristics. The raw gas concentration is in a significantly lower range when compared to the ASR level. The same observation and conclusion holds true for the sum of the heavy metals Sb to Sn. The concentration levels of the individual heavy metals in ESR and ASR are very different and a case by case comparison has to be made. The concentrations for the base case in 2004 can be very well compared to the previous heavy metal concentrations in the raw gas from 1993 and 1997. In summary it can be stated that while there is an increase of heavy metals from the addition of ESR, the increase is measurably lower than in the case of ASR. This is related to the presence of higher concentrations of many metals in ASR (compare Table 1) and the lower addition of 11 % ESR (compared to 31 % of ASR).

The dust levels in the raw gas were measured during approximately a half-hour time period three times for each condition during both weeks. The half-hour results differ quite widely from 0.65 to a maximum of 1.6 g/m<sup>3</sup> which is normal during typical MSW incineration. The levels of dust were lower compared to the ASR co-incineration tests in 1997 which ranged from 3.0 to 5.4 g/m<sup>3</sup>. This general lower dust concentration has an influence on the concentration of the heavy metals in the raw gas. In light of the large but expected variations of the half hour dust levels, no significant difference can be confirmed between the base line and the co-combustion testing.

## 7.7. Clean Gas

### 7.7.1. Dioxins/Furans

The level of clean gas emissions is, as expected, extremely low. The limit of 0.1 ng ITE /m<sup>3</sup> specified in Germany and most other countries is always safely met.

This can be understood by the two principle reduction mechanisms namely by the addition of activated carbon and by a final abatement in the SCR unit. The results from the one week of testing as well as previously measured emission results in 2002 to 2004 have been included for comparative reasons and are shown in the table below.





**TABLE 11: Organo-halogen compounds in the clean gas**

*NB: n.a. means not analyzed, n.d. not detected, DL mean detection limit*

Condition 2004 PCDD/F, ng ITE/m <sup>3</sup> (ITE is NATO/CCMS)	A1	B1, B2	C1, C2	A, 1997
excl.DL	0.0019	0.0020, 0.0056	0.0038, 0.019	0.0024, 0.0049
incl. DL	0.0023	0.0023, 0.0059	0.0041, 0.021	0.025, 0.0081

Condition 2004 ng/m <sup>3</sup>	A1	B1/B2	C1/C2	A, 1997
PCB incl. DL	0.60	0.78	0.98, 0.86	n.a.
PBDE	n.a.	n.d.	n.a.	n.a.
PBCDD/F	n.a.	0.55	n.a.	n.a.

It needs to be kept in mind that the value of 0.55 ng/m<sup>3</sup> for PBCDD/F is the actual concentration and not a TEQ value which does not exist for mixed halogenated congeners. The level of clean gas measured for base condition A and the ESR addition are similar to the results obtained for the addition of ASR. There is no effect of ESR co-combustion on the clean gas emissions and the environmental performance of the scrubbing unit was very satisfactory. The non detectable concentration of PBDEs in the clean gas is easily understood from their absence in the raw gas and again confirms the overall high PBDE destruction efficiency in a well operated MSWI.

### 7.7.2. Heavy Metals

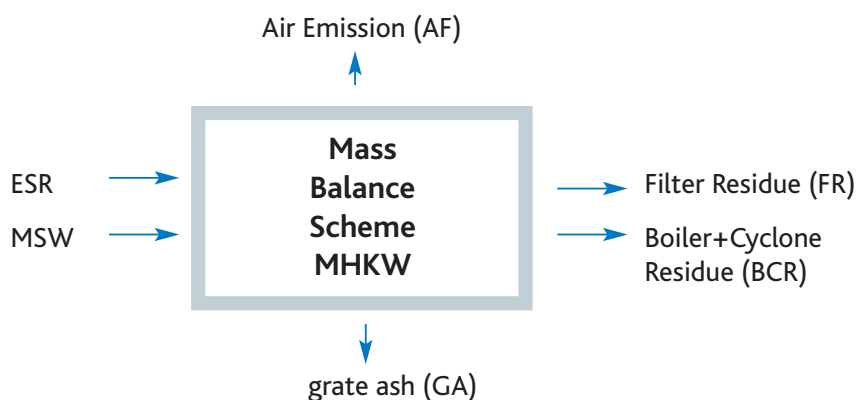
The level and range of heavy metals within the clean gas is extremely low and for many elements close to the detection limits. The levels of all elements are all safely below the specified limits according to the German 17<sup>th</sup> BImSchV and WID in Europe.

The raw gas concentration of the heavy metals during the ESR testing was significantly lower than in the ASR trials and as a result, no higher heavy metal clean gas concentrations could have been expected. For that and reasons of cost savings no clean gas analyses were done. The heavy metal concentration results from 1997 provide the assurance that the air pollution control unit achieves the required emission limits of the Waste Incineration Directive (WID) and hence only selected collected clean gas samples were analyzed. The measured concentrations were all well within the limit values.

## 7.8. Destruction Efficiency

The destruction of potentially hazardous organic compounds such as PCBs and PXDDFs has been calculated in the following way (see Fig.9) to prove the dioxin/furan sink principle of the MHKW in general. In addition the destruction of regulated polybrominated diphenyl ethers (PBDE or micro organics contained in the ESR is estimated below).

**FIGURE 9: Micro organic destruction analysis** (Destruction efficiency coefficient (DEC)= out g/h/ in g/h)



example for DEC PCB  

$$= \frac{FR \text{ (kg/h* micro g/kg)} + BCR \text{ (kg/h* micro g/kg)} + AF \text{ (m}^3\text{/h* ng/m}^3\text{)} + GA \text{ (kg/h* micro g/kg)}}{(ESR \text{ (kg/h* micro g/kg)} + MSW \text{ (kg/h* micro g/kg)})}$$

The degree of destruction is similarly high as experienced in 1994 and previously shown for MSW co-incinerated with packaging plastics (5). In the cases calculated literature data for PCB concentrations in MSW with 77 µg/kg and for PCDD/F in MSW of 64 ng ITE/kg have been assumed (12). The destruction efficiencies all were sufficient to reach satisfactory levels of more than 95 % which is enough to ensure that one can definitely confirm the sink function of a municipal incinerator.

**TABLE 12: Degree of Micro Organic Destruction**

	Degree of Destruction, %
PCBs, incl.	> 99.5
PBDEs (Penta-Octa) incl. DL	> 99.99
PBDD/Fs (Tetra-Octa) excl. DL	> 99.7
PBDD/Fs (Tetra-Octa) incl. DL	> 99.0
PCDD/Fs for incl. DL	> 90
PXDD/Fs for incl. DL	> 94





The destruction calculations shown above have been done using data from external sources, for example PCB and PCDD/Fs concentration in municipal solid waste certain assumptions such as (1) MSW is similar to commercial and industrial waste which have been co-fed to the MSW, (2) there are no mixed halogen PBCDD/F concentrations in the MSW, (3) the amount of PBDD/Fs in the MSW can be calculated from its Br content, which is related to the Fr-Br content and with that to the PBDE content.

The fact that the PCB and PCDD/F content from the MSW in Würzburg is not known for that particular day and can only be assumed to be in the range of the mean literature data published by LfU (Bavarian EPA Authority) makes the destruction efficiency calculation results relative and not absolute. But in spite of this limitation, which is always used for such calculation, the results show clearly that the overall destruction coefficient for the sum of the halogenated dioxin and furan is greater than 94 %. The same statement holds true for the destruction of PBDEs where a very satisfactory overall destruction coefficient for all penta to deca PBDEs of almost 100 % has been documented. The relatively low destruction coefficient for the PCBs can hence be understood that the calculation accuracy is low due to the low PCB input concentration used for the MSW. The high destruction efficiency for the PXDD/Fs and the PBDEs leads to the conclusion that higher and similar > 95 % PCB destruction efficiency is achieved in other MSW incinerators. The fact that de novo synthesis of dioxins/furans has been demonstrated to occur in MSW incinerators (5) leads to the conclusion that the total practical destruction efficiency is even higher than the one measured and shown in table Nr.12.

## 7.9. Metal Recovery from the Grate Ash

During the test of condition D the project team wanted to achieve a metal rich grate ash. The following exercise highlights the potential of metal recovery from such a grate ash. The sources and feed streams are known by compositional analyses. The example calculation to determine the copper concentration in the grate ash based on our own analysis and known data of suppliers resulted into 3 wt% Cu. The MSW/ESR mix was done on 1:1 weight ratio of MSW as mixed in the bunker.

The summary analytical results from Boliden on the grate ash were as follows:

Au 1,3 g/t, Ag 99 g/t, Cu 1,09 %, Pt <1 g/t, Pd <1 g/t, Ni 0,8 %, Zn 0,61 %, Pb 0,34 %, Sb 0,033 %, Fe 8,4 % and Cl 0,91 %. The x-ray analysis result of 1.0 to 0.5 wt % of CuO from a contract laboratory confirms the Cu content in the grate ash as found by Boliden. Although the result from Boliden is double the concentration of the contract laboratory. The explanation for the obvious difference between the expected calculated Cu concentration of about 3 and the analytical determined one of about 1 wt % reflects difficulty in obtaining a representative grate ash sample from the bunker. This seems to indicate that the handpicked sample of 30 kg during the discharge of grate ash from the bunker was in fact not representative.

## 8. Conclusions

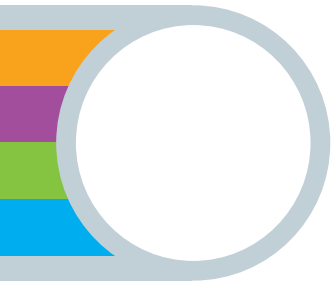
The electrical and electronic shredder residue (ESR) co-combusted during the tests at the MHKW incinerator had characteristics which are typical of commercial shredder operations and was relatively consistent and representative for that kind of heterogeneous material. The test was done using a feed material which is typical of that expected in the future for waste incinerators like the MHKW. The conditions during the test were very realistic and simulated the time in Germany and other countries in 2006 when MSW incinerators may have to deal with that kind of concentrated feed material (SR) consisting also of residues from WEEE treatment.

The effect of the ESR co-combustion on the firing of the waste to energy plant is similar to other co-combustion tests done in 1993/4 with packaging plastics and in those carried out in 1997 with automotive shredder residue (ASR). The combustion efficiency in the gaseous phase has been shown to be similar to normal conditions as evidenced by the CO and O<sub>2</sub> concentrations remaining the same during the ESR co-combustion tests. The highly volatile plastics portion in the ESR should favour an early ignition and an improved burn-out of the grate ash as indicated by lower TOC found earlier in the Tamara pilot incinerator in Karlsruhe Germany. Large scale real life testing did not in fact bring out this relation as found in the Tamara pilot plant testing.

The effects produced by the addition of 7 to 10 % wt of total SR derived from the automotive and the electrical and electronic sector are within the operating range of a MSW incinerator. It does not lead to any operational difficulties if there is sufficient mixing by the crane operator. The grate ash leaching and the general characteristics such as heavy metal content is not negatively changed and the beneficial use of the residue product is also not affected.

The increased raw gas concentrations of heavy metals are directly linked to the amount of ESR combusted. Concentrations of elements such as Pb, Sn and Zn which are specific to ESR are increased and to a large part carried in the fly ashes. This is also valid for more volatile heavy metals like Cd, which should be found more in the gaseous phase. The higher amount of particle born heavy metals can be linked to a slightly higher amount of dust in the raw gas. The acidic gases HCl and SO<sub>x</sub> in the raw gas are reduced to the typical low levels in the clean gas through the dry lime addition system. The neutralization efficiency compared to earlier testing was of the same magnitude and no difference between HBr and HCl was detected.





The PCB content in the ESR fines fraction was high and close to the 50 mg/kg value. In the mixture, coarse and fines together gave a value lower than the limit value. The thermal destruction of PCBs was demonstrated on a large scale to reach a sufficiently high value of greater than 95%. The fact that PCBs are precursors to dioxin and furan-like molecules is dealt with below. Due to the historical nature of the ESR waste, which could contain penta - and octa - PBDE, it was important to show that a high degree of destruction (> 99.99 %) could be demonstrated on a large incineration scale. Other Br containing flame retardant compounds will go through the same process conditions, namely high temperature (> 850 degrees C), long residence time (> 2 seconds) etc. resulting in a similar high destruction efficiency. The experience made during this concentrated ESR co-incineration test does suggest that similar or even higher destruction efficiencies are achieved under normal incinerator conditions. High destruction efficiencies (> 94 %) through co-incineration have also been demonstrated for PXDD/Fs.

The European WEEE Directive requires a minimum amount of collected WEEE of 4 kg per person and year. In Germany, as an example, this equates to a minimum amount of collected material of 320 000 tons. While it is expected that the collected amount will surpass the legal minimum amount, the total shredder residue from WEEE treatment for Germany is estimated at minimum of 50 000 t. Such a quantity could be handled safely in the existing MSWI facilities.

Such considerations indicate that municipal incinerators can play an important and eco-efficient role in the implementation of the EU WEEE Directive.

## 9. Acknowledgements

This work would have been not possible without the support of the various company stakeholders involved in this cooperative venture.

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In: Müll-Handbuch (Hösel, G., Schenkel, W. & Schnurer, H., ed.) Berlin: Erich Schmidt Verlag, Kennzahl 7055, Lfg. 4/94



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