

**Energy Recovery
from Automotive Shredder Residue
through Co-combustion with Municipal Solid Waste**

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Abstract

This project was commissioned by the Association of Plastics Manufacturers in Europe (APME) and the American Plastics Council (APC) to evaluate the operational and environmental impacts associated with the co-combustion of automotive shredder residue (ASR) with municipal solid waste (MSW) in a modern, commercial waste-to-energy plant. This paper describes the shredding and combustion facilities utilized for the program, discusses study protocols and test results, and presents analytical results of ASR characterizations, raw and clean boiler gas sampling and solid residues sampling. The study concludes that co-combustion of ASR and MSW improved burnout, did not adversely impact boiler performance, stack emissions or disposal of the combustion residues (ash) and is, therefore, an environmentally sound method of recovering the energy value in ASR.

INTRODUCTION

Energy recovery from municipal solid waste (MSW) has been practiced for many years. Today's municipal solid waste combustors (MSWC, or MWC in the US) have evolved into well managed, environmentally effective waste processing operations and, simultaneously, into highly efficient producers of steam and electric power. Likewise, the recovery and reuse or recycling of end of life vehicles (ELV) has been practiced for a commensurate period of time. Today's operations, which generally employ shredding after manual dismantling for the recovery of salable parts, are highly efficient and environmentally sound. Residuals from the ELV shredding processes, which are called automotive shredder residue (ASR), are co-combusted with MSW routinely at a few European facilities and sporadically at a number of others throughout Europe and North America. One of the principal impediments to the expansion of this practice appears to have been a perception on the part of MSWC operators, environmental regulators and municipalities that the co-combustion of ASR with MSW would result in operational problems in the MSWC boilers and environmental problems with respect to emissions and combustion residues.

The typical practice to date has been to dispose of ASR in conventional sanitary landfills. However, some countries, such as Switzerland, have banned the landfilling of ASR. Similar ASR landfill bans have been considered elsewhere and may be implemented within the next several years, although near term implementation is not anticipated. There also is significant legislative activity at the EU level and in various European countries that could mandate both landfill phase out and higher levels of automotive recovery and recycling. Enhanced recovery certainly would have a favorable impact on historical increases in the per vehicle ASR generation that resulted primarily from processing more later generation, lighter weight, fuel efficient ELVs. However, when the rate of growth in the total number of ELVs requiring disposal also is taken into consideration, it becomes evident that a supplemental means of ASR recovery is desirable.

The Association of Plastics Manufacturers in Europe (APME) and the American Plastics Council (APC) actively promote resource optimization. This concept is based on minimizing resources used in design, production and use, as well as maximizing environmentally and economically sustainable recovery, reuse and recycling of products that have reached the end of their useful lives. To help ensure implementation of this concept with respect to plastics, APME and APC have developed comprehensive programs of technical, scientific and environmental initiatives in several areas. These programs are intended to improve existing technologies, develop new technologies that are environmentally acceptable and cost effective, identify innovative approaches for technology implementation and demonstrate the successful application of such technologies and approaches.

Energy recovery is one area addressed by APME and APC programs. It is particularly significant as it provides a means of recovering value from the residuals that remain after reuse and conventional recycling have been applied to the maximum practical extent. Thus, implementation of a program that would encourage recovery of the energy value in ASR would be consistent with APME and APC's overall objectives.

Prior to commissioning this program, only a few comprehensive studies related to the co-combustion of ASR with MSW had been undertaken. In November 1993, a co-combustion trial was undertaken at Horgen, Switzerland where ASR was fired at substitution levels of up to 10%. Although this was only a preliminary trial, it concluded that ASR could be co-combusted with MSW at these levels, but recommended additional study.¹ A more comprehensive co-combustion trial was undertaken at the Bazenheid, Switzerland MSWC in September 1994, where ASR was co-combusted at a substitution level of approximately 7.5%. It concluded that there were no adverse impacts on operations or emissions and that none would be expected at substitution levels of less than 10%.² Unfortunately, neither of these studies co-fired ASR at sufficiently high substitution levels to provide convincing evidence regarding the actual impacts of co-combusting ASR with MSW.

Therefore, APME and APC commissioned this energy recovery program to meet the following objectives:

- Convincingly determine the operational and environmental impacts of co-combusting ASR with MSW in a modern municipal solid waste combustor.
- Develop the documentation necessary to support the ASR co-combustion permitting process at other MSWCs.
- Increase public awareness and acceptance of ASR co-combustion with energy recovery as a viable alternative recovery route.

The successful completion of this program is expected to generate more interest in the use of ASR as an environmentally acceptable alternative fuel source.

DEMONSTRATION PROGRAM

Overall Approach

To achieve program objectives, it was essential to clearly identify the impact of co-firing ASR on routine MSW combustion operations. The first step in this process was to determine the MSW and ASR compositions. An appropriate sampling and analysis program was initiated for this purpose. The next step was to determine the baseline operating conditions while combusting routine MSW. Typical furnace and boiler performance parameters, raw gas and clean gas emissions and facility residues were measured and documented to establish the baseline conditions against which the co-combustion test results were compared.

It also was important that known quantities of ASR be introduced into the furnace as a means of establishing the actual substitution levels. This necessitated weighing small volumes of ASR, mixing these volumes with known quantities of MSW, and storing the resultant mixtures for the tests. Care also was required during the actual co-combustion trials to ensure that all previously-measured parameters were sampled, analyzed and documented properly so that reasonable comparisons and conclusions could be drawn. Twice daily co-ordination meetings assisted in this regard.

Site Selection

As noted earlier, a number of MSWC facility operators believe that co-combustion of 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-combusts 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 to selecting the Würzburg site. APME had conducted a similar demonstration program at Würzburg in October 1993 and January 1994.³ Although the earlier program was dedicated to the co-combustion of mixed plastic packaging materials and MSW, some of the data from the study would be directly applicable to the current program. Specifically, the MSW composition already had been established and a number of baseline tests had been performed on raw and clean gas emissions.

FACILITY DESCRIPTIONS

Müllheizkraftwerk Würzburg (MHKW)

MHKW (the Würzburg MSWC) has two identical combustion trains, each with a design throughput of 12.5 t/h at 8.4 GJ/t (7.2×10^6 Btu/T). Both original trains were built in 1984 and utilize Martin® reverse acting grate systems. The total thermal input is a maximum of 100 GJ/h. Incoming MSW is dumped directly into a storage pit from an enclosed tipping hall. Two bridge cranes mix the waste and transport it to the charging hopper of either of the two combustion trains.

A second storage pit and larger enclosed tipping hall constructed earlier in 1997 also were utilized for the demonstration program.

The emissions control system was substantially modified in 1996. The principal changes to each train included the addition of an activated carbon injection system for mercury control, a spray absorber for the removal of acid gases and a NO_x reduction system. These supplemented the previously existing cyclones and bag houses, which were retained as part of the system. NO_x reduction is achieved in a selective catalytic reduction (SCR) system installed downstream of the Conditioned Dry Sorption Process. Ammonia containing water is injected into the gas stream upstream of a two layer, honeycomb-type catalyst that converts the nitrogen oxides to nitrogen and water. A somewhat unique feature of the MHKW emissions control system is that the bag house residue, which contains only partially utilized absorbing agent, is collected and discharged into a recirculation silo. The majority of this partially utilized absorbing agent, which also contains the captured fly ash, then is blown back into the flue gas duct. The remainder is diverted to the residue storage silo.

Johann Preuer Shredding Facility

The Johann Preuer shredding facility, which is located adjacent to the Main River in Würzburg, has a capacity of 350 t/day. The feed stock consists of a mixture of approximately 50% automobiles and 50% light iron. The latter materials are obtained from municipal recycling operations as well as 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 are drained). Preuer's standard practice is to alternate charges of one automobile followed by an equal volume of light iron into the horizontal hammermill.

The shredded ELVs and light iron must pass through 200 mm grates before they can leave the shredding chamber. This material then is fed into the top of a vertical counter-current air flow separator that draws its air from a rotary drum air separator located immediately downstream. The light materials are carried in the air stream, out of the air separators, to a cyclone where they are removed and drop onto a belt conveyor. At this point, the dust from the cyclone in the shredder dust collection system is deposited onto the same belt. The combined stream then is exposed to a cross belt magnet that removes the smaller pieces of ferrous metal entrapped with the light material.

The non-ferrous fraction continues on the belt and is discharged into a rotary trommel screen with 18 mm holes. The undersized fraction, which typically represents about 40% on a weight basis, is the "fines" fraction that was sent to the MHKW facility for the co-combustion trial. The oversize fraction, which constitutes the remaining 60%, represents the majority of the "coarse" fraction used during the trial. Some loads of coarse fraction also included small quantities of the non-metallic fraction from Preuer's non-ferrous metals enhancement system. These non-metallic materials included most of the heavy elastomers, heavy plastics, wood, and some glass.

Returning to the rotary drum air separator, the materials not removed in the counter-current air stream, or the heavy fraction, contain essentially all of the marketable ferrous and non-ferrous metals. These metals are removed during subsequent processing steps that include multiple stages of magnetic separation, screening, and eddy current separation. Preuer also removes a < 15 mm fines fraction that is predominantly glass and dirt, but contains sufficient non-ferrous metals to make it marketable. Although this material is sold at the Preuer facility, most other shredding installations simply add it to the ASR.

FUEL COMPOSITION

MSW Composition

The Würzburg MSWC is owned by ZVAW, the joint waste management authority, and serves a total population of 360,000 people in the City and County of Würzburg and the County of Kitzingen. The MSW stream to the MHKW facility was thoroughly evaluated as part of APME's

mixed plastics packaging/MSW co-combustion trials in 1993/1994. For this reason, no new MSW sampling and compositional analyses were undertaken during the current program.

The predominant MSW deliveries to the MHKW facility are typical household wastes, which generally represent about 60% of the waste stream. Residues from commercial waste sorting facilities, which constitute approximately 25% of the waste stream, are the second largest category followed by scrap wood at about 6%. Approximately 100 metric tons per week of sewage sludge also are delivered to the MHKW facility. The sewage sludge is partially dewatered and then injected into the two furnaces. This practice was continued during the baseline trials as well as the ASR/MSW co-firing trials. Industrial wastes, which tend to be very non-homogeneous and unpredictable, were intentionally excluded from the MSW used during the trials. This was done so that the true impact of co-firing ASR could be determined with some degree of certainty.

The average MSW composition from the prior study is presented in Table 1. Various organic materials, such as food and yard/garden wastes, account for almost 40% of the waste stream; this is followed by paper, which represents about 15%. It is important to note that paper, corrugated box board, glass, steel cans and other ferrous metals and plastic containers and other plastic packaging materials are collected separately for recycling. As a result, the levels of these materials in the MSW feed stream to the MHKW facility are correspondingly lower than in other typical MSW feed streams. The earlier study also showed that the average bulk density of the MSW during collection was 199 kg/m³⁽³⁾ and the lower heating value, H_u, was 11GJ/t.

ASR Composition

The characteristics of the ASR produced by the Johann Preuer shredding facility were established in four phases. In March 1997, four coarse ASR samples were obtained and analyses performed to determine general ASR characteristics. These analyses were followed by more comprehensive pre-trial sampling and analyses of three coarse ASR samples in April 1997 and one ASR fines sample in May. Additional comprehensive sampling of both coarse ASR and ASR fines was performed during the June trials.

The April efforts included hand sorting three large coarse ASR samples, which had a combined weight of 330 kg, into 17 categories. Each category then was subjected to comprehensive analyses; the partial results from one sample are reported in Table 2. The knowledge gained from detailed analyses of this type is important when evaluating possible alternative processing methodologies for ASR quality improvements.

The < 5 mm fraction present in the coarse ASR, which represented 37% of the total sample, was further analyzed in triplicate to determine the metal components. As might be expected, the ferrous content averaged 176,000 mg/kg, followed by zinc at 32,957 mg/kg, copper at 18,440 mg/kg and lead at 4,811 mg/kg. All other previously identified metal components were less than 1,500 mg/kg.

The combined hand sorted metals fraction from each of the three April samples was analyzed for total metals. The results showed that the average ferrous content was approximately 50%, aluminum was about 35% and copper accounted for nearly all of the balance. Small quantities of magnesium, chromium, manganese and zinc also existed at levels of about 0.2% each, and other metals existed in trace amounts.

During the June co-combustion trial, three additional samples of coarse ASR were obtained – one from each day of co-firing ASR and MSW. These samples were designated as ASR Coarse Fractions B, C and D to correspond to the nomenclature used for the co-firing tests. The average results of the analyses for the three samples are presented in Table 3.

One sample of the ASR fine fraction from the B trial was analyzed. These results have been combined with the results of the similar sample taken in May and the average reported in Table 3. Table 3 also presents a column showing a calculated mixed ASR based on Preuer's normal ASR production output of 60% coarse fraction and 40% fines fraction. The final column shows the typical literature range for most of the parameters.

The hand-separated metals from each of the three samples were analyzed in triplicate for the primary metals. Unlike the April sample where ferrous metals constituted the majority, in the June samples, aluminum averaged approximately 45%, ferrous 25%, copper 20% and magnesium < 1%. Such differences are not uncommon when handling a heterogeneous material like ASR, which can be significantly impacted by the characteristics of the materials shredded.

The total metals content of the calculated mixed ASR sample was approximately 15% as shown in Table 3. Although this is consistent with the literature, it does not explain why the metals content is so much higher than expected for the Preuer operation, which employs an extensive metals recovery system.

PCB levels for two of the three coarse ASR samples obtained for this study exceeded the 50 mg/kg limit established in the German regulations. However, it should be noted that, due to the localized nature of PCB contamination during ASR production, several samples from each production lot generally are obtained. Such sampling was beyond the scope of this study. Thus, the PCB results may not be indicative of typical coarse ASR deliveries.

The net heats of combustion, H_u , for the coarse and fine fractions were determined by three laboratories. The average of the nine coarse ASR analyses was about 14.1 GJ/t, and the average of the three fine fraction samples was about 5.95 GJ/t. Using a 60/40 split for mixed ASR, the resultant heating value would be about 10.85 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 previously was determined to be 11 GJ/t.

PROGRAM EXECUTION

Test Conditions

The principal program 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 for permitting long term co-combustion projects at other MSWCs. In order to convincingly achieve these objectives, and thereby fulfill 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 parameters of concern that might exist in the combustion gases or solid residues at relatively low concentrations. Precision analytical methods then would have a greater chance of detecting such parameters. Moreover, operational impacts, such as stability of steam generation, might not be discernable at low substitution levels.

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 the third test, it was decided to co-fire only the coarse ASR at about a 40% substitution level. The actual recorded substitution levels for test conditions B and C (mixed ASR) and D (coarse ASR only) were 24%, 31% and 31% respectively. 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 program was conducted during two four-day periods (Tuesday through Friday) within calendar weeks 25 and 27. All testing was performed on MHKW Line 2. During the first week, one baseline test 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.

Fuel Preparation, Storage and Feeding

The Preuer shredding facility generates two ASR streams, the coarse and fine fractions, and delivers them separately to the MHKW facility. The coarse fraction includes “pockets” of non-

metallic heavies rejects from Preuer's non-ferrous enhancement system. 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.

Coarse ASR was dumped, two loads at a time, onto the enclosed tipping floor and thoroughly mixed using a small, rubber-tired front end loader equipped with quick disconnect pallet forks. Once mixed, the material was spread evenly over the floor. Using the known weight of the two loads of coarse ASR, the appropriate quantity of ASR fines then was spread as evenly as possible over the coarse ASR and the two fractions again thoroughly mixed with the pallet forks. The re-combined ASR was stockpiled for the next phase of the mixing process.

The re-combined ASR then was mixed with MSW in the new storage pit and stored for the test. After some experimentation, the best mixing was achieved by first using the bridge crane to dump a representative grapple load of MSW, which weighed approximately 2.4 t, into the nearly empty pit directly beneath the tipping bay. Then, the required number of buckets of premixed ASR was dumped directly on top of the MSW. The ASR and MSW became well mixed during the normal crane/grapple functions of picking the materials up, carrying them to the designated storage area, dropping them onto the pile below, picking them up again and finally discharging them into the furnace charging hopper. The quantity of MSW and ASR that was mixed and stored was always greater than required for each 24 hour test.

At approximately 16:00 on the day prior to the designated test, the plant began to feed the scheduled MSW/ASR mix into the boiler. This provided ample time for the boiler and air pollution control systems to stabilize before the scheduled 08:00 start of the sampling program. During the 24 hour boiler feeding process for each of the B, C and D trials, test personnel stationed in the crane control room logged the times and weights (from the integral crane weigh scales) of each grapple load of mixed MSW/ASR fed into the charging hopper.

Boiler/Emissions Control System Operations

The overall objective was to maintain the MHKW plant and daily operations as close to normal as possible. However, to help ensure compatibility of the individual tests, special attention was given to keeping the combustion parameters (boiler load set point and O₂ at the boiler outlet) and fuel bed depth on the grate as constant as possible. The boiler feed rate was controlled to maintain a constant steam flow of approximately 28 tons per hour and the O₂ was set to 7% by wet volume.

The combustion air system was adjusted by Martin prior to the trials to accommodate the more volatile, higher heating value MSW/ASR mix, which ignites and burns closer to the ram feeder inlet. The changes included installation of larger underfire air orifices in zones 2 and 3 and adjustment of the control system to increase the maximum opening in zone 1 from 64% to 82%. Martin also wanted to increase the overfire air flow, but the system already was working at its full capacity during normal operations.

The emissions control system was set to run in the fully automated mode for the entire test. The temperatures after the evaporative cooler and before the catalyst, the activated carbon dosing level and the recycle rate all were preset and held constant during the tests.

Monitoring, Sampling and Analyses

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

Raw and Clean Gases

The gas sampling program targeted both raw and clean flue gases and employed a combination of manual sampling trains and continuous emissions 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 emissions monitoring equipment brought to the site in a self-contained van. The sampling location was the vertical duct immediately before the cyclone. The on line system was operated between 08:00 and 14:00 each day of the test and sampled/recorded the following:

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

The plant CEMS also was used to monitor the HCl levels on a continuous basis. The sampling port for the plant HCl system is located at the entrance to the emergency cooler, which is just upstream of the cyclone.

The raw gases also were sampled on a daily basis using a manual sampling train. The sampling period coincided with the on line raw gas sampling and the probe location also was near the inlet to the cyclone. Each day, a six hour sample was obtained and analyzed for the same parameters identified above plus PCDD/F. Three one-half hour samples were obtained daily and analyzed for particulates (dust). These three samples then were combined and analyzed for heavy metals. Separate one-half hour samples were taken daily for HCl and SO_x. A daily gas moisture content also was obtained.

The plant CEMS also was used to continuously monitor and record the clean gases. The parameters were the same as listed above for the raw gases, except that total organic carbon was not included and mercury, particulates and moisture were obtained. The sampling port for the plant CEMS is located in the stack. Although CEMS data was available for the entire day, only the eight-hour period from 08:00 to 16:00 was analyzed.

The clean gases also were sampled on a daily basis using a manual sampling train. The sampling port for these tests also was located in the stack. Each day during week 25, a six hour sample was obtained and analyzed for PCDD/F and a 4 ½ hour sample was obtained and analyzed for particulates and heavy metals. In week 27, the same samples were obtained, but only one additional baseline clean gas sample was analyzed due to cost constraints. A daily gas moisture content also was obtained.

Solid Residues

The daily sampling program for solid residues from the combustion process began at 10:00, two hours after the gas sampling was initiated, and ended at 16:00. The reason for the delay was to accommodate the longer system residence time of the solids. In this manner, the residues and gases generated from the combustion of a specific portion of the MSW/ASR mix would be measured and could be compared at a later time if elevated parameters from one of the streams were noted. The details of the solid residue sampling program have been reported in a separate paper in these proceedings.⁴

Plant Operations

The plant's data logging system was fully operational during the test and plant personnel, Martin and Noell monitored the information on a regular basis.

Video recordings also were made inside the furnace looking down onto the grates. A periscopic camera was introduced at the observation port located 18 m above the grate. The objective of the recordings was to document the flame patterns when burning MSW only and when burning the MSW/ASR mix. Any changes, such as earlier ignition of ASR or flame pattern shifts, then could be evaluated.

TEST RESULTS

Raw Boiler Gases

The results of the on line sampling and manual sampling train are summarized in Table 4. Of particular interest is the significant reduction in CO when burning ASR, particularly the ASR coarse fraction in Trial D, where the CO was less than half the average for the baseline trials. This appears to be attributable to earlier ignition of the ASR and the readily combustible plastics in the ASR. This same trend was observed in the earlier testing at the MHKW with plastics packaging materials.³

Although the particulate loadings in the raw gas stream were higher for Trials B and C than for the average of the baseline trials, the increase was within the normal range of operations. In fact, particulate loading in the first baseline trial, Trial A0, was the highest at 5,360 mg/m³. The particulate results for Trial D (coarse ASR only) were lower than in Trials B and C, which utilized mixed coarse ASR and ASR fines. Although it is possible that the significantly higher ash content of the ASR fines may have been a contributing factor to the higher particulate loadings in Trials B and C, a conclusion cannot be drawn from such limited data.

The results of the raw gas analyses for dioxins/furans (PCDD/Fs) showed an increase from the average baseline level of 2.92 ng (ITE)/m³ when combusting ASR. This was particularly evident at the higher ASR substitutions in Trials C and D where the dioxins/furans levels were 6.77 and 6.22 ng (ITE)/m³ respectively. However, the Trial B level of 3.59 ng/m³ was less than the Trial A0 level of 4.60 ng/m³ and these trials occurred on two successive days. Moreover, the results were within the operative range of the 1993/1994 results at the MHKW plant.

The results of the raw boiler gas analyses for heavy metals showed an increase in a number of parameters when combusting ASR. This is to be expected since, as shown in Tables 2 and 3, 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 increases for Trial D, which was the combustion of coarse ASR only, were only 3.9, 4.3 and 4.7 (respectively). The higher increases for lead and zinc in Trials B and C reflect the fact that the concentration of these materials in the ASR fines, which were present in the mixed ASR, was three times those of the coarse ASR (see Table 3).

The levels of cadmium, antimony, cobalt, copper, nickel and tin also showed increases of varying degrees. Although the mercury level in Trial B was over twice the baseline average of 0.210 mg/m³, the mercury level for baseline Trial A2 was slightly higher than Trial B. Thus, the co-combustion of ASR and MSW was not shown to impact mercury levels beyond normal operational ranges.

Another important observation from Table 4 is that, with the exception of cadmium, which remained the same, the test results for every Trial D heavy metal parameter were less than for Trial C, even though both trials were conducted at ASR substitution levels of 31%. Once again, this highlights the possible impact of ASR fines on the results.

Clean Gases

The results of the on line sampling and manual sampling train for the clean gases are summarized in Table 5. For the manual sampling train, only the three ASR co-firing trial samples and two of the five baseline trial samples, A0 and A3, were analyzed because of cost constraints. The results presented in Table 5 clearly demonstrate the minimal impact of ASR co-firing on the clean gas emissions.

Particulate levels increased slightly during the combustion of the mixed coarse ASR and ASR fines in Trials B and C. However, such increases are within the normal operational fluctuations as evidenced by the fact that the highest particulate level was in baseline Trial A4. With the exception of Trial A4, all particulate results were < 1 mg/m³, which is less than 10% of the 10 mg/m³ allowed under 17.BImSchV. Even Trial A4 was only 2.63 mg/m³, still well below the regulatory limit.

The HCl levels ranged from a six hour average of 3-8 mg/m³, with the highest average during Trial B. However, the results of Trials A1, A3 and A4 ranged from 6-7 mg/m³, and all results were within the regulatory limit of 10 mg/m³(dry). It is important to note that these results were obtained with only typical minor adjustments of the lime dosage. If it had been necessary, which it was not, the dosage could have been increased to facilitate additional removal.

Although the levels of heavy metals in the raw boiler gases when firing ASR showed increases of up to six times the baseline trials, the emissions control system was able to easily accommodate the increases. In fact, with only a few exceptions, the manual sampling train results showed that heavy metal concentrations in the clean gas were less for the ASR trials than for the baseline MSW only trials. All heavy metal sampling results were well within regulatory limits.

The clean gas results for dioxins/furans are similarly impressive. The PCDD/F results for the three ASR/MSW trials were very consistent at 0.0021 to 0.0027 ng/m³, which is less than 3% of the 17.BImSchV limit of 0.1 ng (ITE)/m³. Even Trial A3, which had the highest PCDD/F level, was only about 7% of the regulatory limit.

Solid Residues

The four residue streams, grate ash (bottom ash), boiler ash, cyclone ash and bag house residues, produced during each of the eight days of the trial were sampled and analyzed. It should be noted that the historical MHKW proportions for the solid residue streams are reflected by the following: for each ton of waste burned in 1996, 295 Kg of grate ash, 9.25 Kg of boiler ash, 11.34 Kg of cyclone ash and 29.73 Kg of bag house residue were produced. A detailed discussion of analytical results from the sampling of the solid residue streams has been reported in a separate paper in these proceedings.⁴ Therefore, only some of the highlights will be presented here.

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 for 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. The lead levels increased by only 10-30% above the average baseline level of 1,065 mg/kg, because lead is more volatile, and the increases associated with firing ASR were reflected in the raw gas analyses presented in Table 4. Despite the increases of certain heavy metals when co-firing ASR and MSW, the heavy metal concentrations for all trials were within the German LAGA limits for beneficial ash use.

Although the grate ash burnout at the MHKW facility, as evidenced by the average total organic carbon level of 0.5% for the baseline trials, is excellent, it actually improved significantly (0.1-0.3%) when firing the higher heat value ASR/MSW fuel mix. The same improvements were noted during the 1993/1994 trials with mixed plastic packaging materials.

The dioxins/furans analyses for the grate ash showed very low concentrations of 2-8 ng (ITE)/kg for all of the trials.

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

Germany	DEV S4
Netherlands	NEN 7341
Switzerland	TVA
USA	TCLP

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 less. Chlorides, copper, total chromium, lead and electrical conductivity all were less when ASR was co-fired. Two exceptions were zinc and sulfates. The zinc concentration in Trial B

was more than double the baseline average, but still less than 10% of the LAGA limit of 0.3 mg/L. The sulfates in Trials C and D also were higher, but still only one-third of the 600 mg/L limit.

Leaching tests also were 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 copper result for the baseline test 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.

The grate ash also was tested using the USA Toxicity Characteristics Leaching Procedure (TCLP). Although the TCLP results were somewhat higher when co-firing ASR, they were clearly in compliance with the US regulatory standards. Lead was less than 25% of the 5.0 mg/L limit, cadmium was only 10-20% of the 1.0 mg/L limit and all other regulated metals were less than 10% of their respective limits.

Boiler Ash

The results of the boiler ash analyses show that when co-firing ASR, increases in the concentrations of the ASR-prevalent heavy metals can be significant. In particular, zinc, which averaged 3,100 mg/kg for the baseline trials, increased by a factor of 8 for Trial D to 11 for Trial B. Lead, which was noted at high levels in the raw boiler gases (Table 4), showed increases of 7-8 times the average baseline trial level of 517 mg/kg. In nearly all cases, the concentrations were highest in Trial B (mixed coarse ASR and ASR fines) and lowest in Trial D (coarse ASR only). The only exception was for arsenic, which was just the reverse. Although the lower concentrations in Trial D were not a surprise, the expectation was that Trial C, and not Trial B, would have the highest concentrations. It should be noted that boiler ash, cyclone ash and bag house residues are considered hazardous wastes in Germany and most other European countries and must be disposed accordingly.

Cyclone Ash

The results of the cyclone ash analyses show similar, but even more pronounced increases in the concentrations of heavy metals when co-firing ASR. Lead showed the most significant increases, ranging from about 12 times the average baseline level of 539 mg/kg for Trial D to more than 18 times for Trial B. Zinc increases were 8 times the average baseline level of 4,500 mg/kg for Trial D and over 16 times for Trial B. Nickel, tin and antimony also showed significant increases.

Bag House Residues

The results of the bag house residue analyses are not particularly meaningful because they are significantly influenced by the absorbent recirculation system. Moreover, in Germany, these residues also must be disposed of as hazardous wastes. Only the grate ash (bottom ash) can be beneficially used if it meets the LAGA limits.

Plant Operations

The overall plant operations were not impacted in any unexpected manner as a result of co-firing ASR, even at the high substitution levels employed in these trials. For the boiler operations, a careful evaluation of the typically monitored parameters, as well as the additional parameters selected for these trials, showed that the co-firing trials closely followed the average of the baseline A trials. The steam output of the MHKW facility was maintained at about 29 t/hr during all trials.

The boiler was operated in the O₂ control mode throughout the trials. The system operated well as evidenced by the O₂ of the clean gas, which remained very close to 10.0 mg/m³ during all trials as shown in Table 5.

The grate speed during Trials B and C was set about 10% higher than normal to maintain a constant fuel bed depth. The speed was increased to about 30% higher than normal during Trial D.

The primary (underfire) and secondary (overfire) air systems operated at relatively constant levels throughout the trials. The primary air flow was increased slightly during the co-firing of coarse ASR (Trial D), but by less than 3%. The secondary combustion air system consistently operated at its maximum capacity throughout the two weeks of the baseline and co-combustion trials. The lack of adequate overfire air during the trials was evidenced by Martin's observation of the long flames, which reached the height of the auxiliary burners approximately 50% of the time during all trials. Moreover, the on line raw gas analyses showed spikes in the total organic carbon levels, especially during the first week, including Trial A0. The inadequacy was especially prevalent during Trials C and D as evidenced by higher total organic carbon levels in the raw gas from the manual sampling trains. However, the CO levels in the raw and clean boiler gases decreased during all of the ASR co-firing trials.

The emissions control system operated flawlessly during the trials and the consumption of operating media remained essentially unchanged, even during the ASR co-firing trials. The excess lime ratio, which is the ratio of the molar equivalent of the actual lime injected to the stoichiometric amount calculated from the HCl and SO₂ concentrations in the raw gas, remained within the normal operating range at the MHKW facility. The average quantities of lime actually added during Trials B and D did increase, but these increases also were within the normal operating experience at MHKW.

The activated carbon levels remained constant throughout the trials. Thus, based on the clean gas analyses, the typical quantities of activated carbon were sufficient for the co-combustion of ASR and MSW.

Ammonia containing water was injected into the gas stream upstream of the selective catalytic reduction system to maintain NO_x levels at approximately 60 mg/m³. Plant records indicate that the actual quantity injected was approximately 40 L/hr for all tests.

The potential problem of "catalyst poisoning" from the increased heavy metals concentration in the raw flue gases when co-firing ASR was a non-issue. The combination of an effective acid gas removal system, activated carbon injection and very efficient bag house sufficiently reduced the upstream metals levels to the point where no problems were experienced nor would any be anticipated in future operations.

CONCLUSIONS

The comprehensive demonstration trials conducted by APME, APC and the project team at the Würzburg MSWC in June and July 1997 have confirmed the viability of recovering the significant energy value from ASR by co-combusting it with MSW at modern, well operated waste-to-energy plants. This program involved co-firing approximately 200 metric tons of ASR with typical household MSW at substitution levels of 24-31% by weight. The following conclusions drawn from this program are expected to assist other MSWCs in permitting their facilities for the co-combustion of ASR:

- The co-combustion of ASR and MSW had no adverse impact on the clean gas emissions from the facility even though the heavy metals concentrations in the raw boiler gases increased significantly when co-firing ASR.
- The co-combustion of ASR and MSW had no adverse impacts on plant operations.
- Carbon monoxide levels in the gas stream decreased significantly when co-firing ASR.
- Grate combustion efficiency improved when co-firing ASR as evidenced by the excellent burnout (lower total organic carbon).
- Potential beneficial use of the grate ashes in Germany was not impacted when co-firing ASR (as measured by the German DEV S4 leaching protocol and LAGA beneficial use standards).

- Under the Swiss TVA leaching standards, the grate ashes from the ASR combustion trials met all the criteria for residue landfilling with the exception of the zinc concentrations and a slightly elevated level of copper in Trial B. None of the baseline nor co-combustion trials met the zinc limitation; the co-firing of ASR did increase the zinc concentrations by a factor of two to three.
- The grate ashes produced from the co-combustion of ASR with MSW at substitution levels of up to 31% (weight basis) met all US TCLP criteria.
- The co-combustion of ASR at the relatively high levels of this study significantly increased the concentrations of some heavy metals in the boiler and cyclone ashes, particularly zinc, lead, tin, antimony and cobalt. As a result, these ashes may need to be disposed of with the fabric filter residues, depending on the regulations of the specific country and the actual co-firing conditions. In many European countries, these residues are considered hazardous material.
- The consumption of activated carbon and ammonia containing water for the emissions control system did not change when co-firing ASR. The consumption of lime remained within the range of normal operations.

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Table 1. MSW Composition - Würzburg area.^a

<u>Component</u>	<u>Percent</u>
Organic Wastes	39.5
Disposables (Diapers, etc.)	9.3
Paper (Clean)	9.0
Plastics	5.4
Glass	3.4
Metals	2.4
Liquids Packaging (plastic coated paper)	1.9
Other	
Fines	7.2
Dirty Paper	6.5
Bonded Articles	4.9
Textiles	3.1
Minerals	2.6
Wood	2.1
Hazardous Wastes	1.3
Electric/Electronic Equipment	0.8
Bone, Leather, Rubber	<u>0.6</u>
Subtotal - Other	<u>29.1</u>
Total	100.0

^a Derived from APME's 1993/1994 Co-combustion demonstration program at Würzburg (MHKW).³

Table 2. Coarse ASR characteristics by category.

Category	Percent by Weight		Heat	Ash	Chlorine	Cadmium	Mercury	Lead
	March 97	April 97	Value (GJ/t)	Content (%)	(%)	mg/kg	mg/kg	mg/kg
Metals								
Copper		0.36	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sheet/Automobile		1.22	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sheet/Packaging		0.46	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Wires (non copper)		0.29	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Aluminum		0.07	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total Metals	2.0	2.40	n.a.	n.a.	n.a.	2.6	< 0.07	499
Foams								
Soft Foams		6.10	19.0	16.6	0.4	26.5	3.5	3,208
Hard Foams		0.26	26.5	7.7	0.6	19.0	1.4	1,095
Total Foams	3.5	6.36						
Rubber/Plastics								
Soft Rubber		0.82	29.4	14.7	2.0	20.7	< 0.2	358
Films		0.32	29.7	9.6	6.4	70.0	0.7	1,778
Soft Plastics		2.56	25.6	10.6	17.0	122	0.8	1,348
Hard Plastics	4.1	8.05	32.8	8.2	8.4	178	< 0.2	925
Total Plastics	4.1	11.75						
Paper/Wood		2.05	16.6	12.5	1.1	14.7	1.2	903
Textiles/Leather		1.10	18.5	18.4	1.3	86.7	2.2	1,845
Fines (in the Coarse ASR)								
5 – 10 mm		5.71	17.5	37.7	1.9	67.7	1.3	2,065
< 5 mm		37.02	5.3	79.7	0.4	67.3	4.3	4,811
Total Fines		42.73						
Fluff (Mixed Large)^a		27.58	17.3	29.3	1.4	55.6	3.9	2,948
Residuals (Mixed Sm.)^b	90.4	6.05	18.9	33.4	2.5	59.0	5.9	3,252
Totals	100.0	100.00	14.3^c	46.6^c	2.0^c	68.0^c	3.4^c	3,237^c

^a Large, entwined, difficult to separate components such as bundles of textiles, film plastics and foam tightly wrapped with wire and/or string.

^b Materials originally categorized as foam, rubber/plastics, metals or fines in the first sorting, but determined to be inappropriate in those categories in the second sorting.

^c Calculated value

Table 3. ASR characteristics.^a

<u>Parameter</u>	<u>Units</u>	<u>Coarse</u> <u>ASR</u>	<u>ASR</u> <u>Fines</u>	<u>ASR</u> <u>Mixture</u> ^b	<u>Typical</u> <u>Range</u>
Heating Value, H _u	GJ/t	14.1	6.0	10.9	9-20
Moisture	%	3.8	3.8	3.8	2-5
Ash Content ^c	%	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.
Main Metals					
Aluminum	%	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
Heavy Metals	mg/kg				
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

^a As received basis.

^b As calculated using 60/40 coarse/fines split

^c Includes hand-separated metals

Table 4. Raw gas sampling results.

<u>Parameter</u>	<u>Units</u>	<u>A(Ave)</u>	<u>B</u>	<u>C</u>	<u>D</u>
O ₂	%	8.9	9.4	9.2	9.0
CO ₂	%	9.8	10.1	10.2	9.0
CO	mg/m ³	21	13	14	9
NO _x	mg/m ³	441	489	456	339
SO ₂ (on line)	mg/m ³	130	140	126	95
SO ₂ (manual)	mg/m ³	98	109	87	104
HCl	mg/m ³	1,076	1,005	1,005	1,076
TOC	mg/m ³	3.0	< 2.0	6.0	19.0
Particulates	mg/m ³	3,524	4,206	3,991	3,161
PCDD/F	ng (ITE)/m ³	2.92	3.59	6.77	6.22
Temperature	°C	266	263	269	255
Volume	k m ³ /hr	50	51	53	58
Heavy Metals					
Cadmium (Cd)	mg/m ³	0.727	1.714	2.127	2.107
<u>Thallium (Tl)</u>	mg/m ³	<u>0.006</u>	<u>0.004</u>	<u>0.007</u>	<u>0.005</u>
Subtotal: Cd + Tl	mg/m³	0.733	1.718	2.134	2.112
Mercury (Hg)	mg/m³	0.210	0.454	0.211	0.194
Antimony (Sb)	mg/m ³	2.833	6.418	5.577	4.999
Arsenic (As)	mg/m ³	0.056	0.343	0.301	0.218
Lead (Pb)	mg/m ³	7.127	44.366	39.632	31.004
Chromium (Cr)	mg/m ³	0.709	0.781	0.784	0.638
Cobalt (Co)	mg/m ³	0.058	0.113	0.131	0.084
Copper (Cu)	mg/m ³	6.161	8.784	8.720	7.502
Manganese (Mn)	mg/m ³	5.469	5.840	5.456	3.775
Nickel (Ni)	mg/m ³	0.197	0.521	0.566	0.347
Vanadium (V)	mg/m ³	0.849	0.588	0.579	0.427
<u>Tin (Sn)</u>	<u>mg/m³</u>	<u>1.768</u>	<u>5.849</u>	<u>5.431</u>	<u>4.645</u>
Subtotal: Sb - Sn	mg/m³	25.228	73.603	67.177	53.638
Zinc (Zn)	mg/m³	55.970	344.001	341.482	263.688

Table 5. Clean gas sampling results.

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

^a German limits per 17.BImSchV.

^b For identification of metals included within these categories, see Table 4.

^c Metallic element not detectable