

**CONTRIBUTION OF POST-CONSUMER
PVC PRODUCTS TO LEAD INVENTORY
IN LANDFILLED WASTE**

Substance Flow Analysis Report

Commissioned by:

European Council of Vinyl Manufacturers (ECVM)

European Stabilisers Producers Association (ESPA)

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EXECUTIVE SUMMARY

The objective of this report was to calculate the relative contribution of post-consumer PVC products to the amounts of lead present in landfilled waste. To this aim, a material and substance flow analysis (MFA/SFA) was performed upon the basis of recent data regarding the available amounts of PVC waste and typical product formulations. The selected products comprise cables, pipes, windowframes, and other profiles, and thus represent practically the entire consumption of formulated lead stabilisers. Due to the waste lag of these products predominantly applied in the construction sector, the waste arising and the amounts expected in waste treatment facilities are not correlated with the contemporary consumption and are also of somewhat less relative importance as compared with the overall PVC waste (lead-stabilised PVC waste is approximately one fifth).

Realistic waste management scenarios were assumed. It was shown that out of the range of end-of-life PVC products collected with municipal solid waste (MSW) from households and offices/businesses, only cables and other electrical equipment as well as guttering or windows replaced by private owners contain lead. This share amounts to 25 % of the total amount of available lead-stabilised PVC waste. The greater part (62 %) of lead-stabilised PVC products is assigned to construction and demolition waste (C/D). A further 13 % are car cables in automotive shredder residues (ASR).

An overall portion of 86 % of these end-of-life PVC products is landfilled. MSW and ASR are allocated to sanitary landfills for non-hazardous waste, whereas C/D rubble is disposed of in inert waste landfills. The total mass flow is 401,000 tpa of lead-stabilised post-consumer PVC products, with 138,000 tpa (34 %) disposed of in sanitary landfills and 263,000 tpa (66 %) disposed of in inert waste landfills.

Based upon these mass flows and average formulations, the corresponding lead flows conveyed by PVC products are calculated to be 6,800 tpa of lead in total, with 2,900 tpa (43 %) being allocated to sanitary landfills, and 3,800 tpa (57 %) to inert waste landfills.

Depending on assumptions regarding the waste management practices, a certain amount of lead-stabilised PVC products in C/D waste may arise as sorting residues and could thus be re-directed to sanitary landfills to be mixed with MSW. Two scenarios with the respective »cross-waste stream disposal« percentages of 25 % and 50 % were examined and shifted the distribution to 3,900 tpa and 4,800 tpa of lead, respectively, entering sanitary landfills.

It is noteworthy that at 1,500 tpa of lead (23 % of the total), car cables in automotive shredder residues (ASR) constitute a substantial contribution bound for sanitary landfills. Therefore ASR management plays a crucial role. In the past, ASR was almost exclusively assigned to sanitary landfills (either mixed with MSW or deposited as a mono-fraction). This is about to change due to the current legislation and the on-going development of alternative concepts.

The earlier estimate of the lead flow amounting to 13,000 tpa [ARGUS 2000] is considerably too high. The reasons for this are primarily the overestimated mass flow of lead-stabilised end-of-life PVC products as well as the fact that a substantial share of post-consumer PVC products is assigned to construction/demolition waste and thus to inert waste landfills. Other studies by [MERSIOWSKY *et al.* 1999; MERSIOWSKY 2001] and [AEA 2000] confirm essential arguments of the present analysis.

Taking previous comprehensive experimental investigations about the leaching behaviour under landfill conditions into account [MERSIOWSKY *et al.* 1999], lead-stabilised PVC products in landfills of either kind are assessed to constitute no significant environmental impact. Due to the waste lag affecting PVC applications in the construction sector, the installation of efficient product-oriented recovery schemes and integrated waste management concepts for the future post-consumer PVC waste should now receive the foremost priority [MERSIOWSKY 2001].

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I. INTRODUCTION

I.1 Background

Stabilisers are additives used in the production of PVC compounds. They provide the necessary stability of the PVC polymer against heat during processing, as well as against weathering and ultraviolet (UV) light during use. Different types of stabilisers exist, primarily compounds based upon heavy metals and organotin, but also organic co-stabilisers. Depending on the specific application and desired product properties, various mixed formulations may be employed.

Among the heavy metals widely used for stabiliser compounds, lead takes a leading role. Commonly used compounds are, for instance, tribasic lead sulphate and dibasic or neutral lead stearate. Lead stabilisers are found mainly in cables, pipes, and profiles. Approximately 70 % of all stabilisers sold in Europe are formulated lead stabilisers. Another group of additives that may contain lead are pigments.

In the Green Paper on the environmental issues of PVC [EUROPEAN COMMISSION 2000], the European Commission noted that no exact data were available on the contribution of lead stabilisers in PVC to the overall lead load in municipal solid waste (MSW) being landfilled or incinerated. Estimates varied between negligible (1 %) and substantial (almost 30 %). In the ensuing discussions and the Public Hearing (held in Brussels/Belgium, 23 October 2000), the question was raised whether PVC products constitute a considerable contribution to the amounts of lead in landfilled waste.

I.2 Motivation

In a preliminary estimate of the amounts of lead introduced into landfilled waste by PVC products, [MERSIOWSKY *et al.* 1999] referred to a selection of four investigated product archetypes, including lead-stabilised cables and pipes. Because of a lack of more detailed knowledge, simple assumptions were made for the waste management practices applying to these products. An allocation by waste streams and by landfilling was conducted. As the experimental investigation of leaching and biodegradation effects referred to municipal solid waste and sanitary landfills, this was assumed as a worst-case scenario. Consequently, there was no differentiated discussion of amounts disposed of in inert waste landfills. The conservative assumption was rather that sorting residues from construction and demolition waste are entirely redirected to sanitary landfills. With the data available at that time for each application, an overall relative contribution by these exemplary products groups was calculated, amounting to less than 5 % of the lead inventory in landfills.

As the selected lead-stabilised product categories, cables and pipes, did not comprise all PVC products containing lead, this figure was discussed as possibly too low. Windowframes and other profiles needed to be considered as well, expanding the scope of the envisaged follow-up study.

Conversely, profiles, cables and pipes as well as other long-life construction products are in some cases not retrievable, or they remain in demolition waste. In the latter case, they are commonly separated from MSW streams and either recovered or disposed of in inert waste landfills. Therefore a considerable part of lead-stabilised products might not contribute to the lead levels in sanitary landfills at all. A more differentiated analysis of the fate of lead was required [MERSIOWSKY 2001].

[ARGUS 2000] assumed that post-consumer PVC products were either collected with MSW, or they are segregated from construction/demolition waste as non-recoverable materials to be disposed of in manner comparable to MSW. In fact, most lead-stabilised PVC applications are used in the construction sector and will not be assigned to MSW. Furthermore, [ARGUS 2000] calculated under the assumption of an overall landfilling ratio for the entirety of PVC waste and allocated this amount exclusively to sanitary (MSW) landfills. By applying an overall figure for the average contents of lead in PVC products, they thus arrived at a contribution of 28 % of the lead inventory in landfilled waste being introduced by PVC products. This result appeared overestimated and inconsistent with previous third-party estimates.

In a scientific workshop on the »Fate of PVC Products and their Additives in Landfills« held in Hamburg/Germany, 16–18 October 2000, the available information about the distribution of lead stabilisers throughout the variety of post-consumer PVC products was found to be insufficient for a more accurate estimate. Industry representatives of the European Council of Vinyl Manufacturers (ECVM)¹ and the European Stabiliser Producers Association (ESPA) were therefore asked to procure further information.

Industry have recently responded to this query by providing updated mass flow data as well as more detailed information about the composition of the respective products. A more consistent substance flow analysis thus became possible. The assumptions on waste management practices were likewise refined. The resulting model, calculations and estimates are presented in the following report.

I.3 Objective and Procedure

The objective of this report is to calculate the relative contribution of post-consumer PVC products to the amounts of lead present in landfilled waste. To this aim, assumptions are made about the applicable waste management practices, in particular the allocation of post-consumer products to municipal solid waste (MSW) and other waste streams, and the allocation to landfills for either non-hazardous or inert waste. The method used refers to material and substance flow analysis (MFA/SFA) [MERSIOWSKY 2001]. The following procedure was adopted in order to ensure a transparent calculation and facilitate the introduction of updated information.

¹ <http://www.ecvm.org>

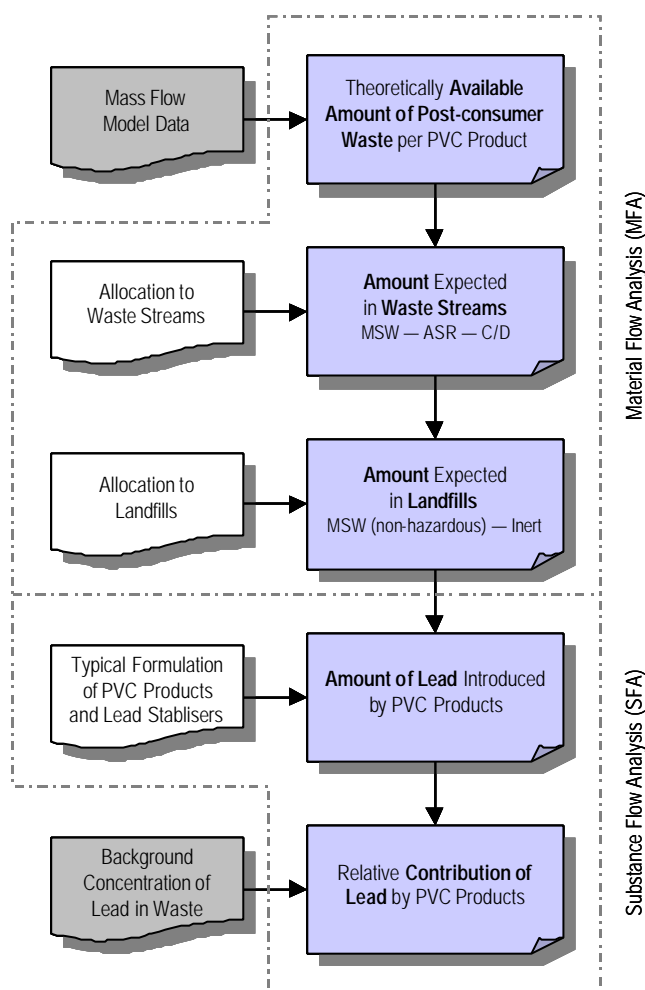


Figure 1: Procedure of substance flow analysis. The relative contribution of post-consumer PVC products to the amounts of lead in landfills is calculated from the mass flows of PVC products in landfilled waste streams and their respective formulations, relating the results to overall background concentrations of lead in these waste streams. Shaded boxes outside system boundary represent external data. Abbreviations: MSW, municipal solid waste; ASR, automotive shredder residues; C/D, construction and demolition waste.

II. FUNDAMENTALS

II. 1 Definitions

II. 1.1 *Municipal Solid Waste (MSW)*

Waste management involves three basic processes, waste generation (source and type of waste), waste collection and haulage, and treatment (sorting, recovery and disposal). For each stage, partly overlapping definitions and inconsistent statistical data may exist, as both private contractors and municipal authorities offer services. Additionally, waste streams may be segregated, diverted and reunited. For instance, a private contractor may separately collect demolition waste for sorting and recovery, then reject the non-recoverable materials to be disposed of by municipal facilities. However, the calculation of waste stream data and their allocation to disposal pathways hinges upon their consistency for statistical purposes.

As a consequence, nomenclature is an important consideration. Because of the widely divergent definitions of the term municipal solid waste (MSW) throughout the Member States of the European Union, the OECD definition as given by [EUROSTAT 2000] is adopted here: municipal waste is defined as waste collected by or on behalf of municipal authorities. It is further specified by waste sources, collection methods, and waste types.

In particular, municipal waste comprises household waste, similar waste from commerce and trade, office buildings, institutions (schools, hospitals, government buildings) and small businesses. It includes waste from these sources collected door-to-door or delivered to the same facilities used for municipally collected waste, as well as fractions collected separately for recovery operations (through door-to-door collection and/or through voluntary deposits) [...] The definition also includes bulky waste (for example, refrigerators, old furniture mattresses) [...] [EUROSTAT 2000]. In the following, the term municipal solid waste (MSW) will be used.

It is noteworthy that the OECD definition of municipal waste excludes waste from the municipal sewage network (e. g., sewage sludge) and municipal construction and demolition waste (cf. II. 1.3).

For the purposes of this report, it should be noted that scrapped household items and refuse from refurbishing (for instance, domestic and electrical appliances) would thus belong to municipal waste (as either household waste or bulky waste). In contrast to household waste and commercial waste, industrial waste (from production sites) is not a part of municipal waste.

II. 1.2 *Automotive Shredder Residues (ASR)*

The term automotive shredder residues (ASR) designates the light residual fraction after disassembly, recovery and milling of scrapped vehicles. It is used here only with reference to the disposal of cables from cars.

II. 1.3 Construction/Demolition Waste (C/D)

The term construction and demolition (C/D) waste refers to rubble and other waste materials arising from the construction, demolition, renovation or reconstruction of buildings [EUROSTAT 2000]. It consists mainly of construction materials (minerals, iron, wood), but may also comprise certain amounts of other materials (e. g., plastics and rubber). Again, definitions vary throughout EU Member States (for instance, regarding the inclusion of excavated soil that constitutes substantial amounts), thus impairing reliable statistics.

II. 1.4 Landfills

Landfills are in the framework of this report differentiated with reference to the European Landfill Directive [EUROPEAN COMMISSION 1999] into

- ◆ Landfills for non-hazardous waste: The term sanitary landfills is commonly used for these sites that accept predominantly municipal solid waste (MSW), but also other types of waste provided that it does not contain significant amounts of hazardous components. Because of the leaching and biological processes occurring in the deposited waste, barriers (base liner and top cover) as well as a collection and treatment of landfill leachate and gas are necessary.
- ◆ Landfills for inert waste: These sites are used to deposit construction and demolition waste which due to its prevalently mineral components allows for somewhat less strict standards concerning barrier systems and effluent treatment.

It should especially be noted that the widespread term »MSW landfill« is insofar misleading as it refers to a sanitary landfill operated by municipal authorities. However, this type of landfill will by all means accept waste other than municipal solid waste (MSW) according to the definition given in section II. 1.1. This is the reason why the terms »municipal solid waste (MSW)« and »waste assigned to a sanitary landfill« are carefully differentiated.

II. 2 Data Sources, Quality and Gaps

The external data sources are on the one hand, the model developed by the European Plastics Converters (EuPC)² for the prediction of PVC post-consumer waste arisings, and on the other hand, literature as given by references. Additionally, information about the typical formulation of PVC products and their additives was provided by producers, ECVI and ESPA. The model within the indicated system boundaries (Figure 1) relies upon expert knowledge and best guesses that may be refined as better data become available.

The knowledge about PVC products therefore appears rather satisfactory, whereas the most important uncertainties concern the overall waste statistics. Both mass flows (tonnage) of waste streams and the substance inventory depending on presence of specific materials are still subject to considerable knowledge deficits as for completeness, accuracy and reliability. More experimental and statistical research appears necessary in this respect.

III. SUBSTANCE FLOW ANALYSIS

III. 1 Assumptions

The substance flow analysis relied by necessity upon a number of hypotheses and best guesses which are subject to discussion and refinement. The key assumptions underpinning the analysis are summarised as follows:

- ◆ The reference period is the late 1990s. The material flow data from the EuPC model are calculated for 1999, and the formulations of the PVC products are likewise recent. Moreover, current waste management practices for central and western Europe were assumed.
- ◆ PVC applications in the construction sector (cables, pipes, windowframes and other profiles) are
 - assigned to municipal solid waste (MSW) only if they are accessible and removable, i. e. in all probability subject to refurbishment by private households (»do-it-yourself«);
 - assigned to construction/demolition (C/D) waste, if they are not readily recoverable (e. g., joined with the building structure, covered by plaster etc.) and thus subject to handling by contractors;
 - assumed to be not available for waste management at all if they are not retrievable (e. g., soil-buried); this case is already factored into the EuPC model of available waste arisings.
- ◆ PVC products for household applications and furniture etc. are allocated to bulky waste collected from households (and thus, MSW). While a certain part may be separately collected, non-recoverable materials are again assigned to municipal disposal facilities.
- ◆ Automotive shredder residues (ASR, i. e. car cables in this case) are assigned to sanitary landfills for non-hazardous waste, to be either mixed with municipal solid waste (MSW) or deposited as a mono-fraction. Obviously, this practice does not apply everywhere and is about to change because of new regulations and waste management concepts. A percentage of 80 % of the light-weight ASR fraction including car cables is assumed to be allocated to sanitary landfills, the rest being probably subject to different recovery or disposal options.
- ◆ If otherwise unspecified, MSW is allocated to sanitary landfills for non-hazardous waste at an overall European average ratio of approximately 70 %. If previous sorting appears probable, this deliberation was also performed for the non-recoverable residues, adjusting the ratio up or down.
- ◆ C/D waste is assigned to inert waste landfills. If C/D waste is subject to further treatment by contractors (e. g., careful demolition), it may undergo sorting for recovery purposes. In that case, non-mineral residues may be disposed of also in sanitary landfills to a certain extent. This

² <http://www.eupc.org>

factor was termed »cross-waste stream disposal« (»x-disposal«, Figure 2). Since average data about the disposal of C/D waste sorting residues in sanitary landfills were insufficient, scenarios were calculated for estimated x-disposal factors of 25 and 50 %, respectively.

- ◆ In cases where post-consumer PVC products did not emerge distinctly from a mixed waste stream to justify segregation, or if information about the handling of the waste stream was insufficient, the overall average landfilling ratio of approximately 70–80 % has been applied (sanitary landfills).

Figure 2 provides an overview of the most important material flows.

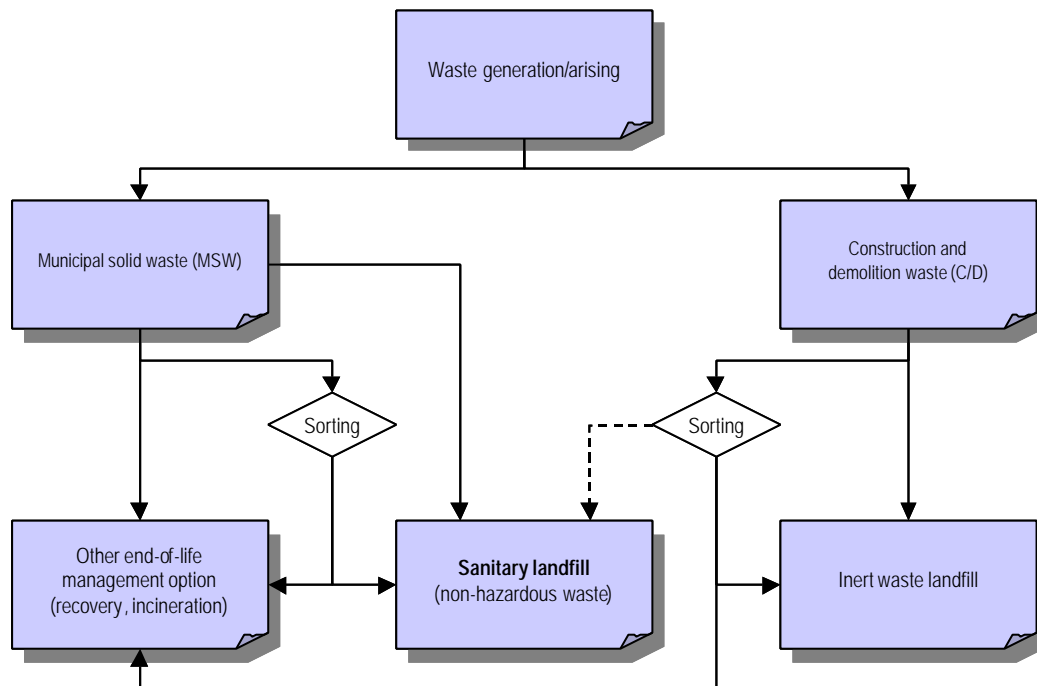


Figure 2: Waste streams and waste management options. Dashed arrow denotes »cross-waste stream disposal«: construction/demolition waste is sorted by contractor, non-recoverable residues being re-introduced into municipal waste management and disposed of in sanitary landfills as »commercial waste« from recovery facility.

III. 2 Calculations

The calculations are performed stepwise as indicated in Figure 1.

III. 2.1 Step 1: Theoretically Available Amount of Post-consumer Waste per PVC Product

The basis of the following calculations is the theoretically »available« amount of post-consumer PVC waste. The term »availability« is used in accordance with the definition by Prognos (in their report on »Mechanical Recycling of PVC Waste«) that was also adopted by [AEA 2000]. The term refers to the amount theoretically ending up in the MSW stream. Accordingly, assumptions had been made for e. g. pipes and cable in soil-buried applications that only a reduced portion was retrievable.

From the EuPC model for the prediction of available PVC waste arisings, the base data shown in Table 1 were extracted. In total, there are approximately 465,000 tpa of post-consumer waste from lead-stabilised PVC products, with cables (54 %) constituting the greatest single product group, followed by profiles for applications other than windows (31 %). This available amount compares to a total amount of PVC waste arisings of 560,000 tpa, i. e. 83 % overall availability. The remainder is assumed to be unavailable for waste management purposes.

Table 1: Theoretically available amount of post-consumer waste per PVC product. Tonnages given as tonnes per year (tpa). Source: J. Eckstein (EuPC) – personal communication.

PVC products	Available amount of waste per product [tpa]
Cables for domestic installations	21,176
Cables for automobiles	61,302
Cables for electrical appliances	70,581
Cables for telephones, conductors and appliances	45,290
Cables for information and power systems	37,600
Cables, miscellaneous	13,583
Product group subtotal: Cables	249,532
Pipes for potable water	1,750
Pipes for sewage	12,800
Pipes for cable protection	3,273
Pipes for drainage	2,615
Pipes for roof gutters	12,273
Pipes, miscellaneous	7,784
Product group subtotal: Pipes	40,495
Profiles for windows	30,850
Profiles for other building applications	116,056
Profiles for cable ducts	4,875
Profiles for furniture	9,750
Profiles, miscellaneous	13,900
Product group subtotal: Other profiles (w/o windows)	144,581
Overall total	465,458

III. 2.2 Step 2: Amount of Post-consumer PVC Products Expected in Waste Streams

From the range of end-of-life PVC products collected as MSW from households and commercial businesses, only cables and electrical equipment as well as any guttering or windows subject to replacement by private owners (»do-it-yourself«) contain lead. The majority of lead-stabilised PVC products, however, is subject to handling by contractors and is thus assigned to construction/demolition waste. Based upon the allocation of the post-consumer PVC products to waste streams, the expected amounts were calculated (Table 2).

Thus, of the 465,000 tpa of lead-stabilised PVC products in post-consumer waste, only approximately 116,000 tpa (25 %) are allocated to MSW, whereas the majority of approximately

288,000 tpa (62 %) are found in construction and demolition waste. A further 61,000 tpa (13 %) are car cables which are assigned to ASR.

Table 2: Amount of post-consumer PVC products expected in waste streams. Tonnages given as tonnes per year (tpa). Source: allocation by best estimates; calculation using available amounts of post-consumer waste per PVC product (Table 1).

PVC products	Allocation to waste streams [%]			Expected amounts in waste streams [tpa]		
	MSW	ASR	C/D	MSW	ASR	C/D
Cables for domestic installations	5 %	0 %	95 %	1,059	0	20,118
Cables for automobiles	0 %	100 %	0 %	0	61,302	0
Cables for electrical appliances	100 %	0 %	0 %	70,581	0	0
Cables for telephones, conductors and appliances	20 %	0 %	80 %	9,058	0	36,232
Cables for information and power systems	5 %	0 %	95 %	1,880	0	35,720
Cables, miscellaneous	20 %	0 %	80 %	2,717	0	10,867
Product group: Cables	34 %	25 %	41 %	85,294	61,302	102,937
Pipes for potable water	0 %	0 %	100 %	0	0	1,750
Pipes for sewage	0 %	0 %	100 %	0	0	12,800
Pipes for cable protection	0 %	0 %	100 %	0	0	3,273
Pipes for drainage	20 %	0 %	80 %	523	0	2,092
Pipes for roof gutters	10 %	0 %	90 %	1,227	0	11,045
Pipes, miscellaneous	10 %	0 %	90 %	778	0	7,005
Product group: Pipes	6 %	0 %	94 %	2,529	0	37,966
Profiles for windows	5 %	0 %	95 %	1,543	0	29,308
Profiles for other building applications	10 %	0 %	90 %	11,606	0	104,450
Profiles for cable ducts	0 %	0 %	100 %	0	0	4,875
Profiles for furniture	80 %	0 %	20 %	7,800	0	1,950
Profiles, miscellaneous	50 %	0 %	50 %	6,950	0	6,950
Product group: Other profiles (w/o windows)	18 %	0 %	82 %	26,356	0	118,225
Overall totals	—	—	—	115,721	61,302	288,435

In order to put these figures into perspective, the following background data on the magnitude of the waste streams are given for comparison:

- ◆ MSW: The amount of municipal waste arising in the European Union during the mid-90s, is in the range of 190,000 ktonnes/a by [EUROSTAT 2000].
- ◆ ASR: The amount of automotive shredder residues in Western Europe as of 2000 is estimated to be around 1,600–1,700 ktonnes/a by APME (F. Mark, personal communication). This figure includes materials other than plastics, e. g. certain mineral and metal residues as well.
- ◆ C/D waste: The amount of construction and demolition waste can be assumed to be about twice the amount of MSW [EUROSTAT 2000], or in the order of magnitude of 400,000 ktonnes/a. By a

very rough approximation, 90 % of this amount will be mineral residues (excavated soil, road building rubble, demolition rubble). The rest is rubble from construction sites with a combustible fraction of approximately 25 % according to an estimate for Germany by [BRANDRUP *et al.* 1995].

As a consequence, lead-stabilised PVC products constitute only negligible fractions (less than 1 %, respectively) of these post-consumer waste streams.

III. 2.3 *Step 3: Amount of Post-consumer PVC Products Expected in Landfilled Waste*

In this step, the waste streams were allocated to treatment options, taking the probable waste management practices for each product into consideration. Thus the expected amounts for disposal in landfills were obtained (Table 3).

The grand total is about 401,000 tpa of lead-stabilised post-consumer PVC products being landfilled. This constitutes 86 % of the total amount of the respective post-consumer waste arising, with the remainder being assigned to other treatment options (recovery or incineration). This rather high percentage results from the almost exclusive landfill disposal of construction and demolition waste. From the overall landfilled amounts, only the smaller share of 138,000 tpa (34 %) is disposed of in sanitary landfills for non-hazardous waste, while 263,000 tpa (66 %) are disposed of in inert waste landfills.

For the entire post-consumer PVC waste (irrespective of stabiliser system) being assigned to sanitary landfills, [ARGUS 2000] proposed an estimate amounting to 2,600,000 tpa. For the year 2000, [AEA 2000] calculated 750,000 tpa of landfilled post-consumer PVC products in household and commercial waste, and 980,000 tpa in construction and demolition waste. Estimates by [MERSIOWSKY *et al.* 1999] were also in the range of 2,000,000 tpa. These overall approximations, however, cannot be used as the basis for a calculation of the lead substance flow because of the necessary differentiation according to stabiliser system and disposal path. As the principal lead-stabilised products, profiles, pipes, and cables, are all subject to a substantial waste lag, their relative importance in landfilled waste decreases to about one fifth of the total PVC waste.

The difference should be noted once more between, on the one hand, landfilled lead-stabilised PVC products that are collected as MSW, and on the other hand, the input into sanitary landfills (»MSW landfills«) which is not restricted to municipal waste.

This concludes the material flow analysis (MFA). The quantities of lead-stabilised PVC products disposed of in landfills are the basis for the subsequent calculation of the lead substance flow in the next step.

Table 3: Amount of post-consumer PVC products expected in landfilled waste. Tonnages given as tonnes per year (tpa). Source: allocation by best estimates; calculation using expected amounts of end-of-life PVC products per waste stream (Table 2). Note that percentages refer to the respective waste stream tonnages, thus rendering only the landfilled portion; the remainder is assigned to non-landfill disposal and not considered further.

PVC products	Allocation to landfill disposal [%]		Expected amounts in landfills [tpa]	
	Sanitary landfill (non-hazardous)	Inert waste landfill	Sanitary landfill (non-hazardous)	Inert waste landfill
Cables for domestic installations	80 %	90 %	847	18,106
Cables for automobiles	80 %	0 %	49,041	0
Cables for electrical appliances	80 %	0 %	56,465	0
Cables for telephones, conductors and appliances	90 %	100 %	8,152	36,232
Cables for information and power systems	80 %	90 %	1,504	32,148
Cables, miscellaneous	80 %	90 %	2,173	9,780
Product group: Cables	89 %	94 %	118,182	96,266
Pipes for potable water	0 %	90 %	0	1,575
Pipes for sewage	0 %	90 %	0	11,520
Pipes for cable protection	0 %	90 %	0	2,945
Pipes for drainage	65 %	90 %	340	1,883
Pipes for roof gutters	65 %	90 %	798	9,941
Pipes, miscellaneous	65 %	90 %	506	6,305
Product group: Pipes	65 %	90 %	1,644	34,169
Profiles for windows	50 %	70 %	771	20,515
Profiles for other building applications	65 %	95 %	7,544	99,228
Profiles for cable ducts	0 %	95 %	0	4,631
Profiles for furniture	65 %	95 %	5,070	1,853
Profiles, miscellaneous	65 %	95 %	4,518	6,603
Product group: Other profiles (w/o windows)	65 %	95 %	17,131	112,314
Overall totals	—	—	137,728	263,264

III. 2.4 Step 4: Amount of Lead Introduced by PVC Products in Landfilled Waste

Formulated lead stabilisers are used almost exclusively in the three main applications, profiles, pipes, and cables. In 1998, the corresponding tonnage of lead metal was approximately 50,000 tonnes (J. Eckstein (EuPC), P. Donnelly (ESPA) – personal communication) [EUROPEAN COMMISSION 2000]. Due to the considerable waste lag of these long-life PVC applications, however, a delay of several decades must be taken into account before they enter the waste stream. Therefore the quantity of formulated lead stabilisers in 1998 is not correlated with the contemporary tonnage of lead in post-consumer PVC waste [MERSIOWSKY 2001].

The prediction of arisings on the basis of the EuPC model reflects this waste lag. Table 3 shows the quantities of end-of-life lead-stabilised PVC products disposed of in landfills. The next step is to calculate equivalent substance flows from these mass flows. To this aim, typical formulations of the

investigated PVC products and their lead stabilisers were used to compute the respective average lead contents in each of the products (Table 4).

Table 4: Average lead contents of PVC products, calculated from typical formulations of PVC compounds and lead stabilisers. Source: G. Zuschnig (Chemson), J. Eckstein (EuPC), P. Donnelly (ESPA) – personal communication.

PVC products	Lead contents [%]
Cables for domestic installations	0.9 %
Cables for automobiles	3.2 %
Cables for electrical appliances	1.6 %
Cables for telephones, conductors and appliances	1.6 %
Cables for information and power systems	1.0 %
Cables, miscellaneous	1.2 %
Pipes for potable water	0.8 %
Pipes for sewage	0.5 %
Pipes for cable protection	0.6 %
Pipes for drainage	0.7 %
Pipes for roof gutters	1.1 %
Pipes, miscellaneous	1.9 %
Profiles for windows	2.0 %
Profiles for other building applications	1.8 %
Profiles for cable ducts	1.6 %
Profiles for furniture	2.0 %
Profiles, miscellaneous	1.0 %

The quantities of lead introduced by lead-stabilised PVC products into the two types of landfills are thus calculated (Table 5). It should be noted that these figures represent only the lead flow incorporated in PVC products rather than any information about the background concentration in the conveying waste stream.

Table 5: Amount of lead introduced by PVC products in landfilled waste. Tonnages given as tonnes per year (tpa). Source: calculation using landfilled mass flows (Table 3) and lead contents (Table 4) of PVC products.

Products	Expected amounts of Pb in landfilled PVC [tpa]	
	Sanitary landfill (non-hazardous)	Inert waste landfill
Cables for domestic installations	7	154
Cables for automobiles	1,545	0
Cables for electrical appliances	875	0
Cables for telephones, conductors and appliances	126	562
Cables for information and power systems	15	321
Cables, miscellaneous	26	117
Product group: Cables	2,595	1,154
Pipes for potable water	0	13
Pipes for sewage	0	58
Pipes for cable protection	0	16
Pipes for drainage	2	12
Pipes for roof gutters	9	109
Pipes, miscellaneous	9	117
Product group: Pipes	20	325
Profiles for windows	15	410
Profiles for other building applications	136	1,786
Profiles for cable ducts	0	74
Profiles for furniture	101	37
Profiles, miscellaneous	45	66
Product group: Other profiles (w/o windows)	282	1,963
Overall totals	2,913	3,853

The grand total is approximately 6,800 tpa of lead introduced into landfills (irrespective of type) by lead-stabilised end-of-life PVC products. Of these, 2,900 tpa (43 %) are allocated to sanitary landfills, and 3,800 tpa (57 %) to inert waste landfills (Table 5). It is noteworthy that car cables in automotive shredder residues (ASR) were found to constitute 1,500 tpa (53 %) of the lead flow incorporated by PVC products that are disposed of in sanitary landfills – this fraction thus determines the results to a large extent (23 % of the grand total).

Cables constitute the main contribution to the lead flow (3,700 tpa, or 55 % of the grand total). Even excluding car cables in ASR, approximately 2,200 tpa of lead are from cables disposed of in landfills, with more than half of this being disposed of in inert waste landfills. [MERSIOWSKY *et al.* 1999] estimated approximately 1,400 tpa to be allocated to sanitary landfills. At 2,200 tpa of lead, the product group of profiles is another substantial contribution, but is almost exclusively allocated to inert waste landfills. In contrast to this, pipes and windowframes at 300 and 400 tpa, respectively, play minor roles. In contrast to the earlier estimate by [MERSIOWSKY *et al.* 1999] being restricted to cables and pipes, the present study shows the contribution by profiles as well and thus covers all principal uses of lead stabilisers.

[ARGUS 2000] proposed the approximation of, in total, 13,000 tpa of lead incorporated by end-of-life PVC products disposed of in sanitary landfills. When comparing the different estimates, the grand total of 6,800 tpa calculated above is found to be only 52 % of the figure by [ARGUS 2000]. The main reason is the waste lag of lead-stabilised PVC products. Additionally, the differentiation between sanitary landfills for non-hazardous waste (MSW) and inert waste landfills is now implemented, showing that only about 3,300 tpa of lead introduced by PVC products are actually subject to the sanitary landfill scenario.

It stands to reason that the amount of lead introduced by PVC products in landfilled waste is by no means a constant figure, but rather depends on the associated waste streams. With respect to the current production figures and the waste lag (discussed above), an increase is expected. Conversely, the probable development of the waste management practices suggests fairly constant amounts of PVC waste for landfill disposal during the next decades [MERSIOWSKY *et al.* 1999; AEA 2000; ARGUS 2000].

III. 2.5 **Step 5: Relative Contribution of PVC Products to Lead Inventory in Landfilled Waste**

The calculation of the relative contribution of PVC products to the lead inventory in the waste streams under consideration requires reliable estimates about the respective background concentrations of lead. Since these data are scarce and vague, the reference bases are subject to considerable uncertainty. It should be carefully noted that the following ballpark figures can only indicate the order of magnitude.

The reference base used for the comparison is the amount of municipal waste arising in the European Union during the mid-90s, amounting to 190,000 ktonnes/a according to [EUROSTAT 2000]. Furthermore, a contents of 70 % dry matter and an overall ratio of 70 % landfill disposal are assumed, rendering 93,100,000 tpa of dry waste being landfilled (Table 6). With an equally rough approximation of the lead levels found in MSW, 650 mg/kg of dry solids according to [TNO 1996; AEA 2000], we arrive at a lead substance flow of around 61,000 tpa in MSW.

Table 6: *Estimated magnitude of waste streams. Sources: original data as cited, percentages of total solids and landfilling ratio best estimates.*

Type of waste (source of data)	Amount, wet waste [tpa]	Amount, dry waste [tpa] (total solids contents, %)	Amount landfilled [tpa] (landfilling ratio, %)
Municipal waste in EU, mid-90s [EUROSTAT 2000]	190,000,000	133,000,000 (70 %)	93,100,000 (70 %)
Automotive shredder residues (ASR) [F. Mark (Dow), personal communication]	1,700,000	1,700,000 (100 %)	1,360,000 (80 %)
Construction/demolition waste in EU, mid-90s [EUROSTAT 2000] ¹⁾	400,000,000	400,000,000 (100 %)	360,000,000 (90 %)

¹⁾ Figure based upon semi-quantitative estimate (twice the amount of municipal waste).

For ASR, [FISHER/MARK 1999] calculated a lead contents in the order of magnitude of 3,000 mg/kg for the light-weight fraction and an overall range of 1,100–11,000 mg/kg for the entire ASR [MARK *et al.* 1998]. Later investigation seemed to indicate a lead contents rather 8,000–10,000 mg/kg in

ASR (F. Mark (Dow), personal communication), but the principal source of lead in that case are batteries and counterweights (used for balancing tyres) in the heavy-weight fraction. Assuming a lead contents of 1 % results in a lead flow of approximately 14,000 tpa with ASR (Table 6).

As shown in Table 2, the greatest amount of lead-stabilised post-consumer PVC products is assigned to C/D waste and thus to inert waste landfills. The calculation of a relative contribution, however, appears not reasonable due to even higher uncertainties about the waste stream and the respective lead inventory. Since the greatest part of C/D waste is mineral, the lead contents of concrete and other building materials might provide an indication. Conversely, the presence of metals and organic materials especially in segregated C/D waste streams may considerably affect the overall lead contents. As a ballpark figure, the order of magnitude might be in the range of several hundreds mg per kg, comparable with MSW.

With these broad approximations, the relative contribution by lead-stabilised end-of-life PVC products to the lead inventory in sanitary landfills is found to be less than 5 % (Table 7). It is noteworthy that more than half of this quantity arises from car cables assigned to ASR and thus as yet to sanitary landfills. Otherwise only cables from electrical equipment show any significant contribution at all (almost 2 %) whereas the other product groups are practically negligible. [MERSIOWSKY *et al.* 1999] estimated a contribution of lead by cables amounting to 3 %.

Table 7: *Relative contribution of PVC products to lead inventory in landfilled waste. Calculated from substance flow data in Table 5 and reference base for MSW in Table 6.*

PVC products	Contribution of lead to MSW [%]
Product group: Cables	4.3 %
– of which: car cables in ASR	2.6 %
Product group: Pipes	0.0 %
Profiles for windows	0.0 %
Product group: Other profiles (w/o windows)	0.5 %
Overall total	4.8 %

III. 3 Sensitivity and Scenario Analysis

Because the assumptions on the waste management practices determine the outcome of the analysis to a considerable extent and are subject to uncertainty, the application of sensitivity and scenario analyses are discussed.

III. 3.1 Sensitivity of Allocation

Since the allocation of end-of-life PVC products to waste streams and landfills has been performed on a rather conservative basis, the overall landfilling ratio is already 86 %. From the PVC products in MSW and ASR waste streams 78 % are landfilled, and 91 % of the PVC products in C/D waste (cf. Table 2 and Table 3). This corresponds very well with the estimates by [AEA 2000], 80 % for household and commercial waste, and 86 % for C/D waste, respectively.

As a consequence, a further sensitivity analysis of this allocation does not appear sensible when aiming at a conservative assessment. In other words, the share of landfilled PVC products is already reasonably high. The actual problem lies rather in the allocation between sanitary landfills and inert waste landfills. For this reason, this internal distribution was investigated in scenarios.

III. 3.2 *Scenarios »Cross-waste stream disposal«*

As indicated in the basic assumptions (section III. 1), a certain amount of end-of-life PVC products that had originally been collected as C/D waste may be sorted out and redirected into municipal waste treatment, i. e. sanitary landfilling. In the past, less distinction was made between MSW and rubble, disposing of both types of waste in mixed waste landfills. Conversely, if more recently C/D waste is not subject to further treatment, the entirety of non-mineral components like PVC products may also be disposed of in inert waste landfills.

Due to the insufficient knowledge about these practices, scenarios were calculated for estimated »x-disposal factors« of 25 and 50 %, respectively, i. e. 25 or 50 % of the PVC waste originally allocated to inert waste landfills are added to sanitary landfills. »Cross-waste stream disposal« is assumed to affect only those end-of-life PVC products probably handled by contractors, i. e. immobile cable and pipe installations and building profiles.

Table 8: *Effect of »cross-waste stream disposal« on the amounts of post-consumer PVC products and incorporated lead expected in sanitary landfilled waste. Products assumed to be affected by this re-direction are marked with an »x«. Tonnages given as tonnes per year (tpa). Source: calculation from allocation to landfills (Table 3) by re-directing the x-disposal percentage from inert waste landfills to sanitary landfills.*

PVC products	End-of-life PVC products in sanitary landfills [tpa]		Lead from PVC products in sanitary landfills [tpa]	
	x-disposal ¹⁾ factor 25 %	x-disposal factor 50 %	x-disposal factor 25 %	x-disposal factor 50 %
Cables for domestic installations (x)	5,374	9,900	46	84
Cables for automobiles	49,041	49,041	1,545	1,545
Cables for electrical appliances	56,465	56,465	875	875
Cables for telephones, conductors and appliances (x)	17,210	26,268	267	407
Cables for information and power systems (x)	9,541	17,578	95	176
Cables, miscellaneous (x)	4,618	7,063	55	85
Product group: Cables	142,249	166,316	2,883	3,172
Pipes for potable water (x)	394	788	3	6
Pipes for sewage (x)	2,280	5,760	14	29
Pipes for cable protection (x)	736	1,473	4	8
Pipes for drainage (x)	811	1,282	5	8
Pipes for roof gutters (x)	3,283	5,768	36	63
Pipes, miscellaneous (x)	2,082	3,658	39	68
Product group: Pipes	10,186	18,728	102	183
Profiles for windows	5,900	11,029	118	221
Profiles for other building applications (x)	32,350	57,157	582	1,029
Profiles for cable ducts (x)	1,158	2,316	19	37
Profiles for furniture	5,070	5,070	101	101
Profiles, miscellaneous (x)	6,168	7,819	62	78
Product group: Other profiles (w/o windows)	44,746	72,362	764	1,245
Overall totals	203,081	268,434	3,867	4,821

¹⁾ The »x-disposal factor« denotes the percentage of PVC waste rerouted from inert waste landfills to sanitary landfills due to previous sorting and disposal of non-recoverable residues.

The following conclusions are drawn (Table 8):

- ◆ For 25 % »cross-waste stream disposal«, the amounts disposed of in sanitary landfills increase from 138,000 tpa (Table 3) to 203,000 tpa (51 % of grand total). The quantities of lead introduced into sanitary landfills would thus increase from 2,900 tpa (Table 5) to 3,900 tpa (57 % of grand total), and the relative contribution from 4.8 % (Table 7) to 6.3 %.
- ◆ For 50 % »cross-waste stream disposal«, the amounts disposed of in sanitary landfills increase from 138,000 tpa (Table 3) to 268,000 tpa (67 % of grand total). The quantities of lead introduced into sanitary landfills would thus increase from 2,900 tpa (Table 5) to 4,800 tpa (71 % of grand total), and the relative contribution from 4.8 % (Table 7) to 8.0 %.
- ◆ Irrespective of this allocation, i. e. even in case all lead-stabilised PVC products were disposed of in sanitary landfills (x-disposal factor of 100 %), the relative contribution of PVC products to the levels of lead in sanitary landfills does not exceed 11 %. This extreme scenario corresponds

to the assumption by [ARGUS 2000] that all PVC products in C/D waste are segregated and returned to MSW as non-recoverable fraction.

III. 4 Discussion

Due to the waste lag for long-life applications in the construction sector, a gradual increase of post-consumer PVC waste, and thus also lead tonnages, is expected during the next decades. Since a declining importance of landfills is expected, the landfilled amounts will probably remain rather stable [MERSIOWSKY *et al.* 1999; AEA 2000; ARGUS 2000]. At the same time, the substantial waste lag of the main lead-stabilised construction applications means that these products are of less relative importance in currently landfilled waste as compared to the average life span and overall amounts of PVC waste. This line of reasoning emphasises the vital importance of installing waste management concepts and particularly recovery schemes that absorb the bulk incurred by the waste lag [MERSIOWSKY 2001].

In the present analysis, both the underlying product formulations as well as the waste management practices refer to a recent period. When considering the amounts of waste disposed during the last decades, the influence of variant and old formulations might be somewhat uncertain. For instance, other PVC products may have contained lead-stabilisers and – as in the case of PVC floorings – may have constituted considerable amounts. However, the formulations as of the reference year 1998 cover all principal lead-stabilised products. The use in profiles, pipes, and cables constitutes almost 99 % of the consumption of formulated lead stabilisers. The use of lead stabilisers in flooring products is restricted to solid calendered flooring tiles, rather than the predominant flooring formulations for spread coating (vinyl cushion flooring). These and other variant uses for lead stabilisers constitute less than 1.5 % of the total tonnage (P. Donnelly (ESPA) – personal communication). Furthermore, the overall tonnage of lead stabilisers is assumed to have been similar in previous years, as less PVC products tended to contain more lead stabilisers. Therefore, this aspect of varying formulations and different applications of lead-stabilisers is assessed to be of relatively minor significance for the overall outcome of this study.

Another uncertainty is the definition of the term »available« PVC waste as implemented in the EuPC model and various other predictions [MERSIOWSKY 2001]. Since this report relies on the data generated by the EuPC model in this respect, the pertinent assumptions are external expertise which might require further discussion. It was shown that the overall availability is 83 %, so the general outcome will probably not be significantly affected.

The most significant uncertainty is less the absolute lead flow incorporated by end-of-life PVC products, but rather the background level in the waste stream. The reported concentrations of heavy metals in waste and other materials vary widely. Concerning waste, the principal problem are the tremendous variation of its constituents and the difficulties of precise and reproducible sampling and analysis.

The investigation by [TNO 1996] estimated the contents of lead in the whole plastics fraction at 500 mg/kg. Since the plastics fraction constitutes only around 5 % wt. of the MSW, the actual contribution of PVC products to the lead inventory is probably in the range of a few percent. This approximation is corroborated by the SFA calculation presented herein.

In order to put the findings into prospective, the comparison with geological lead levels suggests itself. The US National Research Council in 1980 estimated that the natural concentrations in soil were 5–25 mg/kg. However, the levels will reflect the underlying geology (composition of bedrock). For instance, some marine black shales have levels up to 200 mg/kg. Studies in the UK show uncontaminated rural soils ranging from 15–106 mg/kg with a geometric mean value of 42 mg/kg (source: P. Donnelly (ESPA), personal communication). Table 9 shows a number of values from various soils and other materials for purposes of comparison.

Table 9: *Survey of lead background values in soil, materials applied to land, and contaminated areas. Source: [FÖRSTNER 1991]*

Material	Lead contents [mg/kg]
Typical soil (normal)	1–20; or: median 15 (range < 1–890)
Urban garden soil	300–700
Phosphate fertiliser	100
Fly ash (from incinerator flue gas cleaning)	330
Sewage sludge	700
Compost from households	1200
Wetland soil (wastewater irrigation)	2,470; 6,610; 7,200
Landfill	640; 5,100; 16,000; 34,000
Scrap yard	20,000; 30,700

IV. EMISSION SCENARIOS

If lead-stabilised PVC products are disposed of in landfills, they are subject to characteristic processes. Due to the infiltration of water, waste is subject to leaching. Additionally, sanitary landfills usually contain substantial amounts of biodegradable waste introduced by household and commercial waste. In this case, biological processes play a role. While biodegradation does not affect the PVC polymer [MERSIOWSKY 2001], it causes an pollution of the leachate by organic acids and suspended solids, thus increasing the leaching capacity for heavy metals. The following discussion briefly summarises the state of knowledge regarding the effects of leaching on PVC products and their stabilisers.

IV. 1 Experimental Findings

Stabilisers are fixed in the matrix of the PVC compound. Generally speaking, rigid PVC products are considered much less inclined to release their stabilisers than plasticised PVC. A release of stabilisers from the PVC products is probably attributable to leaching from the surface. This means that a very small quantity of the stabiliser is reasonably available to leaching at the exposed surface of the PVC product. However, the greater part of the lead contents is fixed in the matrix of the PVC compound and will under regular circumstances not migrate to the surface. Consequently, once the available lead is washed off from the surface and thus removed, a further leaching is not expected.

The release of stabilisers into waste and leachate was investigated in landfill simulation experiments by [MERSIOWSKY *et al.* 1999]. The assays confirmed that the influence of stabilisers on the leachate quality was generally minor. Since lead and other heavy metals will predominantly be precipitated or adsorbed in the solid waste matrix, they are subject to attenuation in the landfill body. When during a sampling the experimental lysimeters were slightly agitated, this resulted in a release of precipitated and/or adsorbed lead into the leachate causing a single outstanding peak in the measurements (Figure 3). Otherwise the lead concentrations attributable to the PVC cable (Figure 3) and the PVC pipe (Figure 4) were mostly indistinguishable from the ubiquitous background of these heavy metals in MSW. Moreover, the concentrations were very low despite the relatively high amounts of PVC products used in the experiments. Average concentrations measured in leachate from full-scale landfill sites are in the range of 100 µg/L, but vary from 10–1,000 µg/L. As would be expected, the early acidogenic stage of early landfill development was shown to possess the highest leaching efficiency due to low pH values and high organic leachate pollution [MERSIOWSKY 2001].

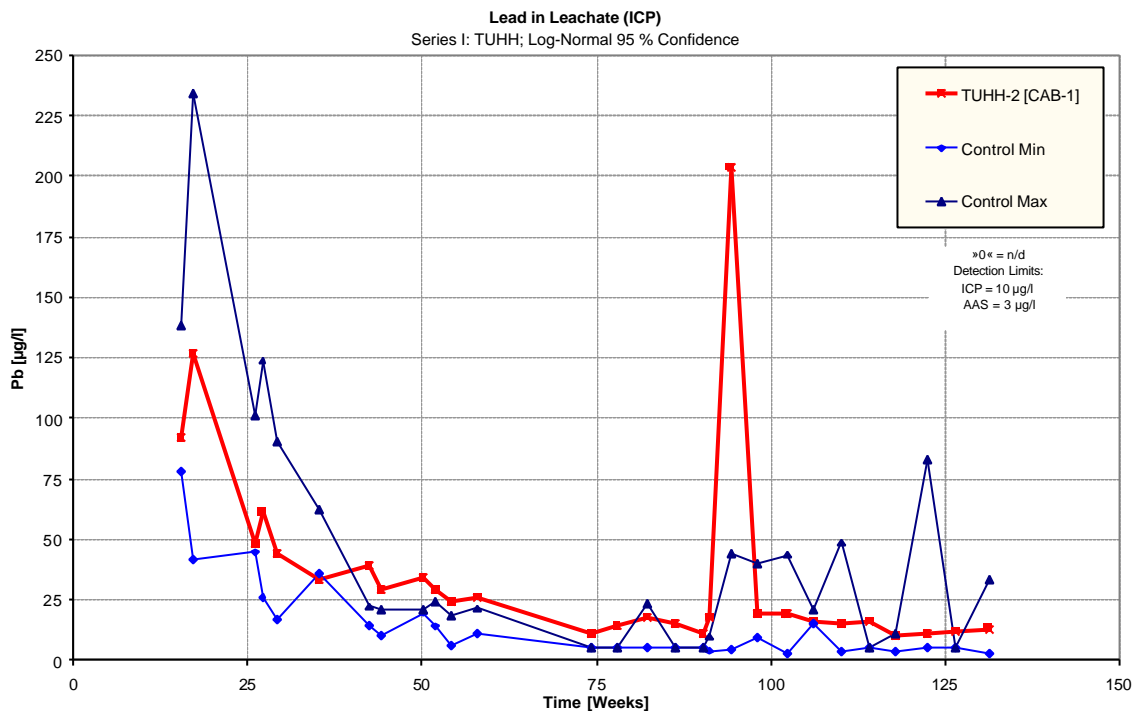


Figure 3: Concentrations of lead in leachate from lysimeters series I at TUHH; log-normal 95 % confidence interval with control minimum and maximum from TUHH-1, 3, 4; TUHH-2 with PVC cable [CAB-1]; determined by ICP [MERSIOWSKY et al. 1999]

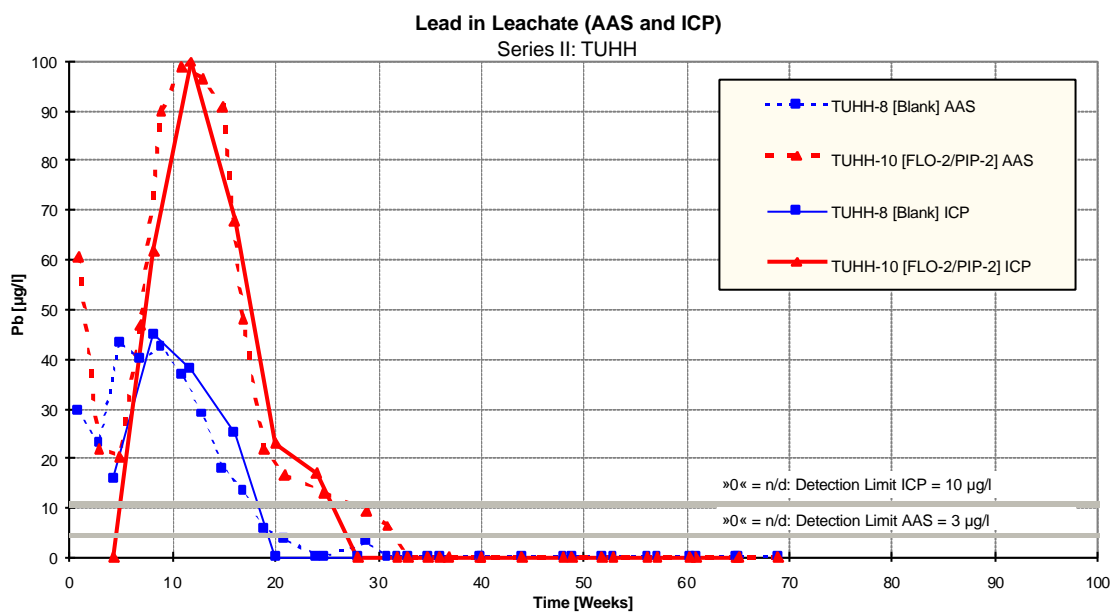


Figure 4: Concentrations of lead in leachate from lysimeters series II at TUHH; TUHH-8 blank control, TUHH-10 with PVC pipe [PIP-2]; determined by AAS (dotted) and ICP [MERSIOWSKY et al. 1999]

While lead-stabilised windowframes and other profiles have not been investigated by [MERSIOWSKY et al. 1999], they are comparable with pipes to a certain extent due to their similar formulations and are therefore expected to perform similarly. [ARGUS 2000] investigated cadmium-stabilised windowframes and found no losses of stabilisers. Furthermore, no release of heavy metals from the investigated PVC products into the leachate was detectable. These results corroborate the evalua-

tion presented above. The low leaching capacity of heavy metals from PVC products was also confirmed by [WASTE 1993] and by [MERSIOWSKY *et al.* 1999] by means of sequential elution assays.

IV. 2 Environmental Relevance

With respect to the behaviour of lead-stabilised PVC products in landfills and their possible environmental relevance, two scenarios need to be differentiated:

- ◆ On the one hand, the behaviour of lead-stabilised PVC products mixed with MSW in sanitary landfills was investigated in the comprehensive experimental studies cited above. Although this constitutes the worst-case with respect to the leaching efficiency, no significant influence on the leachate quality were found.
- ◆ On the other hand, the behaviour of lead-stabilised PVC products mixed with C/D rubble in inert waste landfills may be approximated by leaching tests and the comprehensive experience with the flushing of potable water pipes. As discussed above, any leaching of lead becomes non-detectable even to sensitive measurements once the minor quantities of stabilisers available at the surface have been removed.

As a consequence, lead-stabilised PVC products in landfills of either kind are assessed to constitute no significant environmental impact.

V. CONCLUSIONS

The objective of this report was to calculate the relative contribution of post-consumer PVC products to the amounts of lead present in landfilled waste. To this aim, a material and substance flow analysis (MFA/SFA) was performed upon the basis of recent data regarding the available amounts of PVC waste and typical product formulations. The selected products comprise cables, pipes, windowframes, and other profiles, and thus represent practically the entire consumption of formulated lead stabilisers. Due to the waste lag of these products predominantly applied in the construction sector, the waste arising and the amounts expected in waste treatment facilities are not correlated with the contemporary consumption and are also of somewhat less relative importance as compared with the overall PVC waste (lead-stabilised PVC waste is approximately one fifth).

Realistic waste management scenarios were assumed. It was shown that out of the range of end-of-life PVC products collected with municipal solid waste (MSW) from households and offices/businesses, only cables and other electrical equipment as well as guttering or windows replaced by private owners contain lead. This share amounts to 25 % of the total amount of available lead-stabilised PVC waste. The greater part (62 %) of lead-stabilised PVC products is assigned to construction and demolition waste (C/D). A further 13 % are car cables in automotive shredder residues (ASR).

An overall portion of 86 % of these end-of-life PVC products is landfilled. MSW and ASR are allocated to sanitary landfills for non-hazardous waste, whereas C/D rubble is disposed of in inert waste landfills. The total mass flow is 401,000 tpa of lead-stabilised post-consumer PVC products, with 138,000 tpa (34 %) disposed of in sanitary landfills and 263,000 tpa (66 %) disposed of in inert waste landfills.

Based upon these mass flows and average formulations, the corresponding lead flows conveyed by PVC products are calculated to be 6,800 tpa of lead in total, with 2,900 tpa (43 %) being allocated to sanitary landfills, and 3,800 tpa (57 %) to inert waste landfills.

Depending on assumptions regarding the waste management practices, a certain amount of lead-stabilised PVC products in C/D waste may arise as sorting residues and could thus be re-directed to sanitary landfills to be mixed with MSW. Two scenarios with the respective »cross-waste stream disposal« percentages of 25 % and 50 % were examined and shifted the distribution to 3,900 tpa and 4,800 tpa of lead, respectively, entering sanitary landfills.

It is noteworthy that at 1,500 tpa of lead (23 % of the total), car cables in automotive shredder residues (ASR) constitute a substantial contribution bound for sanitary landfills. Therefore ASR management plays a crucial role. In the past, ASR was almost exclusively assigned to sanitary landfills (either mixed with MSW or deposited as a mono-fraction). This is about to change due to the current legislation and the on-going development of alternative concepts.

The earlier estimate of the lead flow amounting to 13,000 tpa [ARGUS 2000] is considerably too high. The reasons for this are primarily the overestimated mass flow of lead-stabilised end-of-life PVC products as well as the fact that a substantial share of post-consumer PVC products is assigned to construction/demolition waste and thus to inert waste landfills. Other studies by [MERSIOWSKY *et al.* 1999; MERSIOWSKY 2001] and [AEA 2000] confirm essential arguments of the present analysis.

Taking previous comprehensive experimental investigations about the leaching behaviour under landfill conditions into account [MERSIOWSKY *et al.* 1999], lead-stabilised PVC products in landfills of either kind are assessed to constitute no significant environmental impact. Due to the waste lag affecting PVC applications in the construction sector, the installation of efficient product-oriented recovery schemes and integrated waste management concepts for the future post-consumer PVC waste should now receive the foremost priority [MERSIOWSKY 2001].

VI. APPENDICES

VI. 1 References

- AEA Technology Environment. 2000. Brown KA, Holland MR, Boyd RA, Thresh S, Jones H, Ogilvie SM. *Economic Evaluation of PVC Waste Management*. Report for European Commission General Directorate Environment (DG XI). Abingdon/UK.
- ARGUS ARBEITSGRUPPE UMWELTSTATISTIK AN DER TU BERLIN in association with University of Rostock and Carl Bro a/s (Denmark). 2000. *The Behaviour of PVC in Landfill*. Report for European Commission General Directorate Environment (DG XI). Brussels/Belgium
- BRANDRUP J, BITTNER M, MCHAEI W, MENGES G (editors). 1995. *Die Wiederverwertung von Kunststoffen*. Chapter 6.1.6, pp. 591–595. Munich/Germany: Carl Hanser.
- EJLERTSSON J, HÖRSING M, MERSIOWSKY I. 2000. *Behaviour of PVC Products in Landfilled Municipal Solid Waste at Different Temperatures – Modular Environmental Test System (METS) Study in Support of the Research Project »Long-term behaviour of PVC products under soil-buried and landfill conditions«*. Final Report for ECVm, Norsk Hydro ASA, ECPI, ESPA and ORTEP, Linköping/Hamburg
- EUROPEAN COMMISSION. 1999. Council Directive 99/31/EC. The Landfill of Waste. Brussels/Belgium
- EUROPEAN COMMISSION. 2000. *Green Paper – Environmental Issues of PVC*. COM(2000)469 as of 26/7/2000. Brussels/Belgium
- EUROSTAT. 2000. *Waste Generated in Europe – Data 1985–1997*. Luxembourg: Office des publications officielles des Communautés européennes.
- FISHER M M, MARK F. 1999. *The Role of Plastics in Automotive Shredder Residues (ASR): Characterization and Environmental Assessment*. Report 1999-01-0664 to Society of Automotive Engineers.
- FÖRSTNER U. 1991. *Umweltschutztechnik*. 2nd edition. Berlin/Germany: Springer; ISBN 3-540-53952-2
- HJERTBERG T, GEVERT T. 1995. *Evaluation of Possible Degradation of Pipes and Cable Insulation of PVC: Results Obtained with Samples Collected After about 25 Years Use*. Report for Hydro Plast (Stenungsund). Gothenburg/Sweden
- MARK F, FISHER M M, SMITH K A. 1998. *Energy Recovery from Automotive Shredder Residue through Co-combustion with Municipal Solid Waste*. Report to APME. Brussels/Belgium.
- MERSIOWSKY I, EJLERTSSON J, STEGMANN R, SVENSSON B H. 1999. *Long-term behaviour of PVC products under soil-buried and landfill conditions*. Report for Norsk Hydro ASA, ECVm, ECPI, ESPA and ORTEP. Hamburg/Germany
- MERSIOWSKY I, STEGMANN R, EJLERTSSON J. 1999. Long Term Behaviour of Poly(Vinyl Chloride) Products under Soil-buried and Landfill Conditions. PRC – Plastics, Rubber and Composites, 28:321–326
- MERSIOWSKY I. 2001. *Integrated Assessment and End-of-Life Management of PVC Products and their Additives*. Dissertation manuscript submitted to Technical University of Hamburg-Harburg/Germany.
- MERSIOWSKY I, WELLER M, EJLERTSSON J. 2000. *Fate of Plasticised PVC Products under Landfill Conditions: A Laboratory-Scale Landfill Simulation Reactor Study*. (accepted by Water Research, in press)
- TNO, RIJPKEMA L P M, ZEELVALKINK J A. 1996. *Specific Processing Costs of Waste Materials in a Municipal Solid Waste Combustion Facility*. TNO Report R 96/248 to APME and Ministerie VROM. The Netherlands.
- WASTE PROGRAM. 1993. *Waste Analysis, Sampling, Testing and Evaluation (WASTE) Program: Effect of Waste Stream Characteristics on MSW Incineration: The Behaviour of Metals*. Final report of the Mass Burn MSW Incineration Study (Burnaby, B. C.). Vol. I. April 1993. Burnaby/Canada.

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VI. 3 Abbreviations

AEA — AEA Technology Environment, Abingdon/UK

APME — Association of Plastics Manufacturers of Europe

ARGUS — Arbeitsgruppe Umweltstatistik an der TU Berlin/Germany

ASR — automotive shredder residues, light residual fraction after disassembly, recovery and milling of scrapped vehicles

C/D (waste) — construction and demolition waste (predominantly inert rubble, but also other building materials)

ECVM — European Council of Vinyl Manufacturers

ESPA — European Stabiliser Producers Association

EuPC — European Plastics Converters

ktonnes/a — kilotonnes per year (10^6 kg/a)

MFA — material flow analysis, calculation of input, output and flow data of a product or material in a defined system

MSW — municipal solid waste

Pb — lead

PVC — poly(vinyl chloride)

SFA — substance flow analysis, calculation of input, output and flow data of a (chemical) substance in a defined system

tpa — tonnes per year (10^3 kg/a)

w/o — without