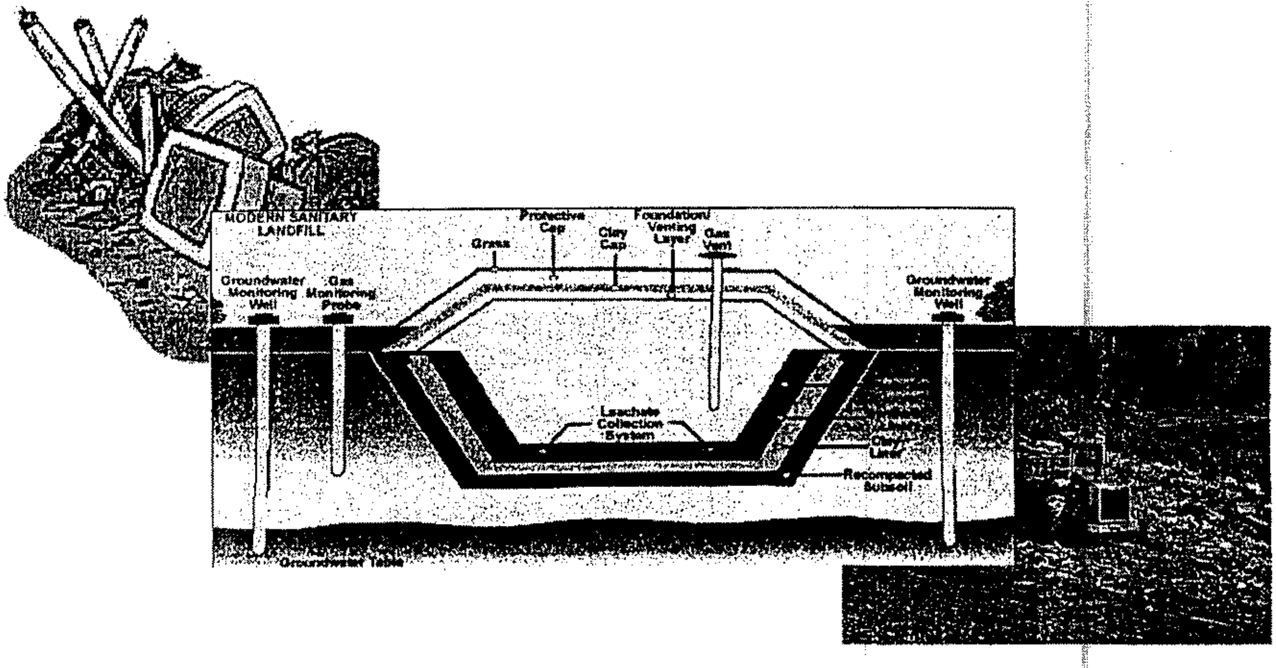
ANEXO 5B

The Effectiveness of Municipal Solid Waste Landfills in Controlling Releases of Heavy Metals to the Environment



Prepared for:

The SWANA Applied Research Foundation
Disposal Group Subscribers

March 2004

SWANA®
SOLID WASTE ASSOCIATION
of North America

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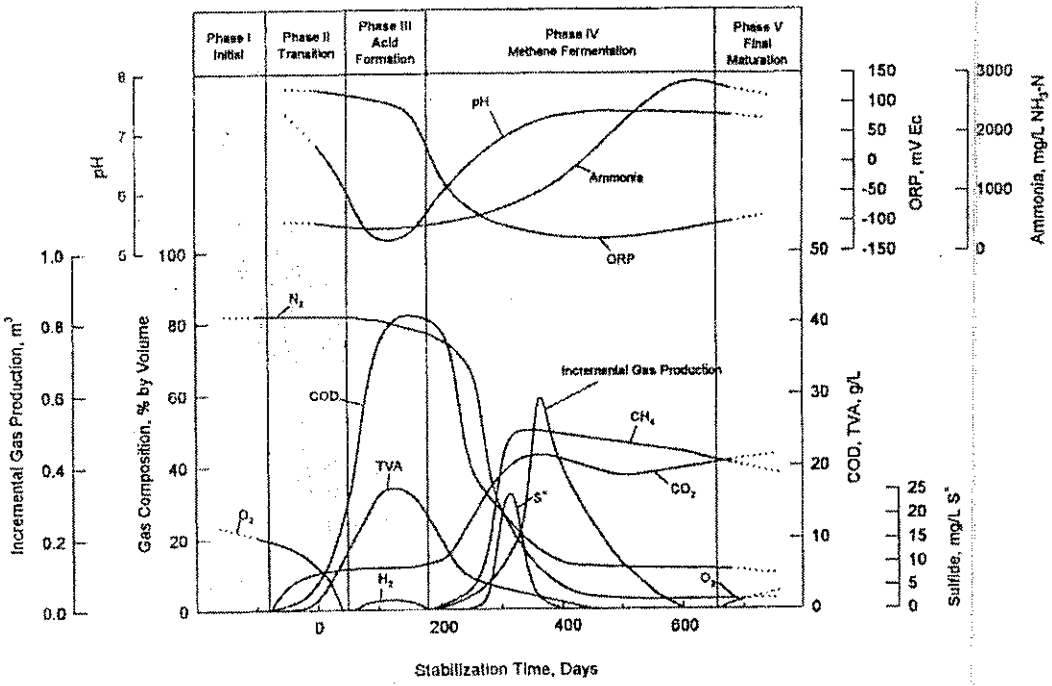
This report is dedicated to the memory of Dr. Frederick G. Pohland, who passed away on January 9, 2004.

Dr. Pohland served as the principal advisor to SWANA in the development of this report. Dr. Pohland's life-long research into the chemical and biological processes that take place in landfills formed the scientific foundation that supports the important conclusions of this report.

Dr. Pohland was the Weidlein Chair of Environmental Engineering in the Department of Civil and Environmental Engineering at the University of Pittsburgh. He served as Editor of the IWA Water Research Journal and was a past President of the American Academy of Environmental Engineers and recipient of its Kappe and Fair Awards. Dr. Pohland was a member of the National Academy of Engineering, and was the recipient of an Honorary Degree of Doctor of Science from Valparaiso University.

Dr. Pohland taught for many years at Georgia Tech, where he pioneered the concept of the "wet landfill" in the 1970s. Dr. Pohland was perhaps the world's expert with respect to understanding the processes that occur within the landfill environment. His figure depicting the changes in key process parameters as waste decomposes in a landfill environment is world renowned and is presented below as a testimony to his many invaluable contributions to the field of solid waste management. A number of the leading academicians and practitioners in the solid waste field, including Dr. Debra Reinhart of the University of Central Florida, conducted their graduate work under Dr. Pohland's guidance.

Dr. Pohland set a high standard for professionalism and academic excellence in the field of environmental science and technology. He will be sorely missed by all who knew him.



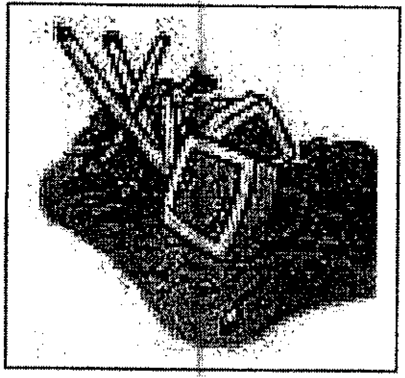
INTRODUCTION

This report presents the findings of a year-long research project that investigated the effectiveness of municipal solid waste (MSW) landfills in controlling releases of heavy metals to the environment.

In recent years, there has been a growing movement to ban certain products from disposal in MSW landfills due to the concern over the potential release of heavy metals contained in these products to the environment. In response, the SWANA Applied Research Foundation's Disposal Group felt that there was a need to summarize and document what is known concerning the actual environmental releases of heavy metals associated with the landfill disposal of these products.

The purpose of this report is to provide up-to-date scientific and technical information regarding the effectiveness of MSW landfills in controlling releases of heavy metals to the environment due to the disposing of products containing heavy metals in MSW landfills. This report presents data, findings, and conclusions based on a comprehensive review of the published literature and ongoing research related to this topic.

HEAVY METALS IN MUNICIPAL SOLID WASTE



Heavy metals are metallic elements with relatively high atomic weights that are used in a variety of consumer products and industrial processes. At trace levels, many of these elements are necessary to support life. However, at elevated levels they become toxic and become a significant health hazard.

"RCRA heavy metals" are those metals and metalloids for which specific groundwater limits are established in the "Resource Recovery and Conservation Act" (RCRA), which was enacted in 1976 to address the management and disposal of municipal and industrial solid wastes. RCRA heavy metals, which include arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, are the focus of this report.

As indicated in Table ES-1, it appears that about 130,200 tons per year of RCRA heavy metals were disposed in MSW landfills in the U.S. in the year 2000. This tonnage represents 0.08% of the 162 million tons of MSW that were disposed in that year. Lead represents the major fraction (97.6%) of the RCRA heavy metals being disposed of in MSW landfills on an annual basis, followed by cadmium (2.1%) and mercury (0.3%).

Table ES-1

Tonnage Estimates for Three Heavy Metals Disposed in MSW Landfills in 2000

Heavy Metal	Tons/Year	Percent
Lead	127,108	97.6
Cadmium	2,680	2.1
Mercury	383	0.3
Total	**130,171**	**100.0**

The available data indicates that the relative fractions of products containing heavy metals in the waste stream are changing. For example, the contribution of lead-acid batteries used in automobiles to the levels of lead in MSW appears to be declining, while lead contributions from discarded consumer electronics appear to be increasing. The available data also indicate that, despite the dramatic increase in the disposal of discarded consumer electronics in recent years, the tonnages of heavy metals being disposed in MSW landfills have decreased over the last 15 years due primarily to the recycling of lead-acid batteries.

HEAVY METALS IN MSW LANDFILL LEACHATE

The concentrations of heavy metals in leachate vary over a wide range, depending on a number of factors, including waste composition, landfill age, and moisture availability.

On average, heavy metal concentrations in leachate have been reported in numerous recent studies to be relatively low.

For example, a draft database has been developed for the U.S. Environmental Protection Agency (EPA) entitled "LEACH 2000" that includes leachate data from over 200 MSW landfills. As shown in Table ES-2, the mean concentrations of the RCRA heavy metals are relatively low, averaging less than 1 milligram per liter (or part per million) in all cases.

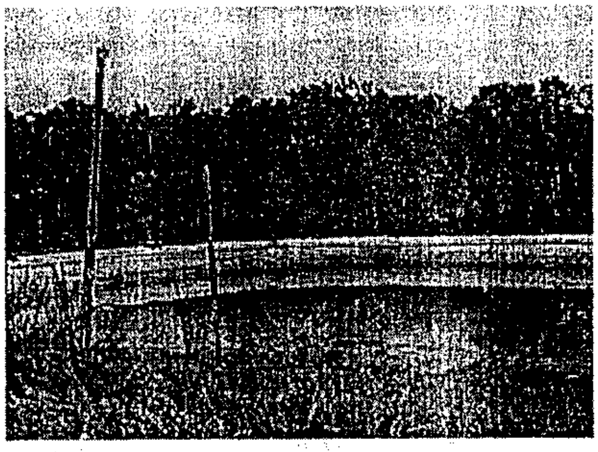


Table ES-2
LEACH 2000 Database – Data for MSW Leachate

Metal	N[a]	% Detected	Median (mg/l)	Mean (mg/l)	90th %ile (mg/l)	TCLP Regulatory Level (mg/l)
Arsenic	2,444	71.1	0.020	**0.441**	0.100	5
Barium	1,779	93.4	0.405	**0.866**	1.700	100
Cadmium	2,351	31.5	0.010	**0.0283**	0.079	1
Chromium	2,776	63.0	0.051	**0.235**	0.341	5
Lead	2,539	50.2	0.021	**0.133**	0.250	5
Mercury	2,078	18.0	0.00059	**0.00715**	0.0046	0.2
Selenium	1,754	18.2	0.010	**0.0585**	0.180	1
Silver	1,830	17.8	0.0113	**0.0537**	0.056	5

Source: Science Applications International Corporation. Characterization and Evaluation of Landfill Leachate. (Draft). Arlington, VA: EPA, September 2000 (with additions).

(a) Data are from over 200 MSW landfills. "N" refers to the number of samples from over 200 MSW landfills. The 10th percentile indicates the value at which 10% of the measurements are equal to or below the indicated value. Similarly, for the 90th percentile, 90% of the measurements fall at or below the indicated value.

The "Toxicity Characteristic Leaching Procedure" (TCLP) is a federally-prescribed test used to determine whether or not a solid waste should be classified as hazardous. As indicated in Table ES-2, the mean concentrations of RCRA heavy metals reported in the LEACH 2000 database for non-hazardous waste landfills are at least 10 times less than the TCLP regulatory levels. In addition, the "90th Percentile" leachate values for RCRA heavy metals (values for which 90% of the data points are equal to or below) are all lower than the TCLP regulatory levels.

Table ES-3
Analysis of Florida Landfill Leachate

Metal	Detects	Mean (mg/l)
Barium	230	0.216
Cadmium	205	0.00752
Chromium	409	0.0416
Lead	288	0.0292
Mercury	175	0.000696
Selenium	175	0.0197
Silver	137	0.0291

A 1997 study conducted at the University of Central Florida to characterize MSW landfill leachate in Florida found the average concentrations of the RCRA heavy metals to be low, "generally on the order of micrograms per liter" (see Table ES-3).

In all, five studies representing all recent published investigations regarding leachate characteristics were reviewed in this research effort and are summarized in this report. All of these studies concluded that heavy metal concentrations in leachate are, on average, relatively low.

The EPA confirmed the findings of recent studies regarding the low levels of heavy metals in leachate in December 1999 when it published final effluent limitation guidelines, pretreatment standards, and new source performance standards for the landfill's point source category. (Effluent limitation guidelines are national regulations that establish restrictions on the discharge of pollutants to surface waters or to publicly owned treatment works (POTWs) by specific categories of industries.)

In establishing final effluent guidelines, the EPA concluded that national pretreatment standards were not necessary for landfills. The EPA found that POTWs adequately treated pollutants in landfill wastewater and only a very small quantity of pollutant loads discharged by landfills to POTWs are further discharged to rivers, streams, or estuaries. Finally, the EPA concluded that wastewater discharges from landfills do not cause operational problems at POTWs. Based on these findings, no national pretreatment standards were established for RCRA heavy metals or any other pollutants in MSW landfill leachate. In addition, the EPA did not establish direct discharge limits for any of the RCRA heavy metals for MSW landfill leachate that is directly discharged to receiving waters following on-site treatment at the landfill.

The reasons provided by the EPA for not establishing direct discharge limits for any of the RCRA heavy metals in MSW leachate are presented in Table ES-4.

Table ES-4
Subtitle D Non-Hazardous Subcategory – Median Raw Wastewater Concentrations

Pollutant	Subtitle D Municipal Median Concentration (mg/l)	Regulatory Limit Set by EPA for Direct Dischargers?	
		Yes/No	Reason
Arsenic	Not detected at treatable levels	No	
Barium	0.483	No	Present in concentrations that are not likely to cause toxic effects
Cadmium	Not detected at treatable levels	No	
Chromium	0.028	No	Present in concentrations that are not likely to cause toxic effects
Chromium (Hexavalent)	0.030	No	Present in concentrations that are not likely to cause toxic effects
Lead	Not detected at treatable levels	No	
Mercury	Not detected at treatable levels	No	
Selenium	Not detected at treatable levels	No	
Silver	Not detected at treatable levels	No	

Source: EPA. Development Document for Final Effluent Limitations, Guidelines, and Standards for the Landfills Point Source Category. (EPA-821-R-99-019). Washington, DC: Office of Water, January 2000.

The mean concentrations reported for MSW landfills in the LEACH 2000 database are also compared with two national standards in Table ES-5, as described below.

- **EPA Groundwater MCLs** – The EPA has established "Maximum Contaminant Levels" (MCLs) for allowable concentrations of RCRA heavy metals in groundwater for MSW landfills that are designed with alternative liner systems. In comparison to these MCLs, the LEACH 2000 mean concentrations for RCRA heavy metals are all less than 10 times higher than their respective MCL limits. In the case of barium, the mean concentration is shown to be less than the MCL established for barium. The MCL is measured at the "relevant point of compliance" (i.e., a location that is required to be no more than 150 meters (164 yards) from the waste management unit boundary). The EPA established the MCL limits by assuming that the TCLP maximum concentrations would be "diluted and attenuated" (and therefore lowered) by a factor of 100 before reaching the relevant point of compliance.[1] Applying the same dilution and attenuation factor (DAF) to the LEACH 2000 mean concentrations, it is apparent that the RCRA heavy metals in leachate would most likely be diluted and/or attenuated to comply with their respective MCLs before any uncontained and/or uncollected landfill leachate reached the relevant point of compliance.

Table ES-5

Comparison of RCRA Heavy Metal Leachate Concentrations With Other Relevant Standards

Metal	Leach 2000 Database (mg/l)	EPA National Primary Drinking Water Standards[1] Maximum Cont. Level (mg/l)	RCRA Regulations Groundwater Maximum Cont. Level[2] (mg/l)
Arsenic	0.441	0.05	0.05
Barium	0.866	2	1
Cadmium	0.0283	0.005	0.01
Chromium[3]	0.235	0.1	0.05
Lead	0.133	0.015	0.05
Mercury	0.00715	0.002	0.002
Selenium	0.0585	0.05	0.01
Silver	0.0537	N/A	0.05

1. U.S. EPA. List of Drinking Water Contaminants and MCLs. (www.eap.gov/safewater/mcl.html)
2. U.S. EPA. Solid Waste Disposal Facility Criteria – Technical Manual. (EPA530-R-93-017). Washington: EPA, Nov 1993.
3. The Groundwater MCL standard is for hexavalent chromium.

- **U.S. Drinking Water Standards** – The U.S. primary drinking water standards are among the highest standards for water purity in the world. Table ES-5 compares the mean RCRA heavy metal concentrations in leachate (collected at the bottom of MSW landfills) to the primary drinking water standards which are required to be met "at the tap" by public water supply systems in the U.S. It is noteworthy that all of the LEACH 2000 average concentrations for RCRA heavy metals are less than 10 times higher than the drinking water standards established for these metals. In addition, the mean concentration for barium (0.866 mg/l) is less than the drinking water standard for barium (2 mg/l), while the mean concentration for selenium (0.0585 mg/l) is only slightly higher than the drinking water standard for selenium (0.05 mg/l).

Under the current regulatory framework for water pollution control, a local government can establish pretreatment standards, based on local conditions, for industrial wastewaters such as landfill leachate that are discharged for treatment to a local POTW. The objectives of local pretreatment standards are to prevent pass-through of pollutants to receiving water bodies, interference with treatment plant operations, and to improve opportunities to recycle and reclaim wastewater and sludges.

The pretreatment standards for RCRA heavy metals established by four counties located in different parts of the U.S. are presented in Table ES-6. As indicated, the average RCRA heavy metal concentrations reported in the LEACH 2000 database are lower than the pretreatment standards established by two of the four counties. However, in one county (Broward County, FL) leachate pretreatment would be required to meet local pretreatment standards for arsenic, while in another county (Henrico County, VA) leachate pretreatment would be required to meet local standards for mercury. It is clear that, in these two cases, leachate pretreatment would be required to meet the relatively stringent local pretreatment standards set by these counties.

Table ES-6

Comparison of RCRA Heavy Metal Leachate Concentrations With Local Government Pretreatment Standards

Metal	LEACH 2000 Database (mg/l)	Local Government Pretreatment Standards			
		Broward County, FL[1] Maximum Concentration (mg/l)	Camden County, NJ[2] Max. Daily Concentration (mg/l)	Henrico County, VA[3] Max. Daily Concentration (mg/l)	King County, WA[4] Daily Avg. Maximum (mg/l)
Arsenic	0.441	0.1	1	N/A	1
Barium	0.866	N/A	N/A	N/A	N/A
Cadmium	0.0283	0.7	0.04	0.23	0.5
Chromium	0.235	1	2	2.75	2.75
Lead	0.133	0.4	0.3	0.44	2
Mercury	0.00715	0.1	0.01	0.0031	0.1
Selenium	0.0585	N/A	N/A	N/A	N/A
Silver	0.0537	0.35	N/A	1.58	1

Notes:
1 Broward County, FL, Office of Environmental Services. Discharge Limits. (http://www.broward.org/oes/oei01000.htm. 12/8/03
2 Camden County, NJ, Municipal Utilities Authority. Sewer Use Ordinance Industrial Pretreatment Rules and Regulations). http://www.ccmua.org/ipptablei.html. 12/8/2003
4 Henrico County, VA, Excerpt from Henrico County Code Recodified as Title 23 (Amended August 13, 1997).
5 King County, WA, Wastewater Treatment Division. King County Local Limits. (http://dnfr.metrokc/gov/wlr/indwaste/local.htm

In summary, based on database and research data representing thousands of samples from hundreds of MSW landfills, the average concentrations of RCRA heavy metals in MSW landfill leachate were found to be significantly lower than the TCLP regulatory levels. The average RCRA heavy metal concentrations in MSW leachate were in compliance with the final effluent limitation guidelines and the national pretreatment standards set by the EPA in 1999 for the landfill's point source category. When compared with drinking water standards (i.e., water purity standards at the tap), average concentrations for RCRA heavy metals in leachate (from the bottom of an MSW landfill) were found to be less than 10 times higher than the drinking water standards and, for one metal, were found to meet drinking water standards. Finally, average RCRA heavy metal leachate concentrations were found to meet local pretreatment standards without leachate treatment except in cases where stringent pretreatment standards had been established for specific metals.

Attenuating mechanisms in MSW landfills that limit the leaching of RCRA heavy metals include the formation of relatively insoluble heavy metal precipitates due to the presence of sulfide, carbonate, and hydroxide ions and the adsorption and/or absorption of the heavy metals within the waste mass.

Theoretically, RCRA heavy metal concentrations in leachate could increase over very long periods of time following the closure of a landfill if the landfill liner systems are breached and air re-enters the landfill, enabling aerobic decomposition processes to be reinitiated. This scenario would require the restoration and sustainment of a viable aerobic microbial consortium, with continuing availability of oxygen and nutrients. Computer modeling, and limited laboratory investigations, regarding this long-term risk have indicated that mobilization of heavy metals from closed landfills, if it does occur, is not likely to occur within a very long timeframe.

HEAVY METALS IN MSW LANDFILL GAS

Data from recent and historical studies of landfill gas indicate that the quantities of heavy metals in landfill gas are also relatively low. For example, as indicated in Table ES-7, in a study conducted at the Central Solid Waste Management Center Landfill of the Delaware Solid Waste Authority, mercury concentrations were found in the nanograms per cubic meter range (i.e., billionths of grams per cubic meter).

The same attenuating mechanisms that limit the leaching of heavy metals in landfills—including reducing conditions, neutral pH, and presence of sulfides—also limit the release of significant gas phase metals (including metallic or methylated mercury). In addition, the low vapor pressures for all metals except mercury are also limiting factors.

Table ES-7
Sampling Results for the Initial Mercury Sampling Campaign Conducted at the CSWMC Landfill

Type of Gaseous Mercury	Measured Concentrations: Nanograms Per Cubic Meter (ng/m³) Mean	Range	No. of Samples
Total Gaseous Mercury (TGM)	408	376-440	2
Dimethyl Mercury (DMM)	38.1	37.4-38.9	3
Monomethyl Mercury (MMM)	1.296	1.241-1.333	3

Source: Frontier Geosciences, Inc. Determination of Total, Dimethyl and Monomethyl Mercury in Raw LFG at the Central Solid Waste Management Center for the Delaware Solid Waste Authority. (Draft Report). February 2003.

The low quantities of heavy metals contained in landfill gas are evidenced by the fact that, in its issuance of "National Emission Standards for Toxic Air Pollutants" for MSW landfills in January 2003, the EPA did not establish standards for any of the RCRA heavy metals.

There is evidence of the existence of gaseous mercury in LFG in the range of micrograms per cubic meter. In addition, recent studies have identified both monomethyl mercury and dimethyl mercury as being constituents of the total gaseous mercury in LFG.

The relative amount of mercury emitted into the air by MSW landfills is also very low when compared to the amounts of mercury emitted from other sources. In 1997, as required by the Clean Air Act Amendments of 1990, the EPA issued a report to Congress referred to as the "Mercury Study." This eight-volume study provides an inventory of mercury emissions to the air from a number of sources related to human activity.

As indicated in Table ES-8, the EPA estimated that, in 1994-95, landfills emitted a total of 70 kilograms of mercury to the atmosphere. This quantity represented less than 0.1% of the total amount emitted from all source categories.

Table ES-8

Best Point Estimates of 1994-1995 Mercury Emission Rates in the U.S.

Source of Mercury	1994-95 (Kilograms/Year)		Percent of Total Inventory	
	Subtotal	Total	Subtotal	Total
Area Sources		3,100		2.2%
Landfills	*70*		*<0.1%*	
Point Sources		141,000		97.8%
Combustion	125,300		87.0%	
Manufacturing	14,400		10.0%	
Miscellaneous	1,300		0.8%	
Total		144,100		100%

Source: EPA. Mercury Study – Report to Congress. Volume 1 – Executive Summary. EPA-452/R-97-003). Research Triangle Park, NC: EPA, December 1997.

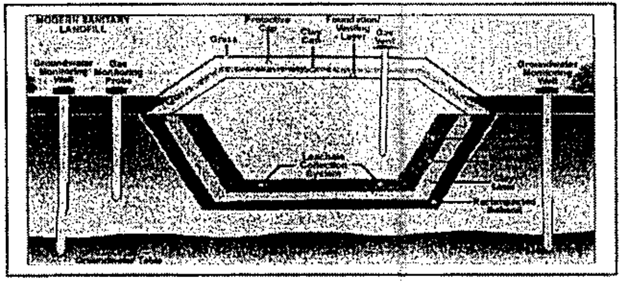
The New Jersey Department of Environmental Protection also convened a Mercury Task Force in 1998 that addressed mercury sources.

Based on source-specific data collected for the late 1990s to 2001, the Task Force estimated that 2,043 kilograms of mercury are emitted to the air on an annual basis in New Jersey. Of this amount, the Task Force estimated that 14 kilograms per year are emitted from New Jersey landfills. This represents 0.7% of total mercury air emissions for the state.

The Task Force also addressed the issue of dimethyl mercury in its consideration of mercury emissions from landfills. Assuming a rate of 50 nanograms of dimethyl mercury per cubic meter of LFG that was measured in a recent study, the Task Force also estimated that approximately 85 grams of dimethyl mercury could be emitted each year from New Jersey landfills.[2] The Task Force called this amount "relatively insignificant."

EFFECTIVENESS OF LANDFILL POLLUTION CONTROL SYSTEMS

Landfill liner systems substantially prevent the leaking of leachate from the landfill to the land upon which the landfill is constructed. Based on recent investigations, these liners appear to have a "half life" (i.e., a timeframe during which a 50% change in the material properties of the liner occurs) of 970 years.[3] Therefore, the integrity of the liner system can be expected to last through the timeframe when significant quantities of leachate are being generated.



Due to the effectiveness of the landfill liner systems that have been constructed with good quality assurance programs, it appears that 99% or more of the leachate generated in MSW landfills is collected and treated.

For landfills equipped with LFG collection and control systems, the combustion of gas in landfill flares or energy recovery technologies enables the conversion of methylated mercury (and other methylated metal compounds) to elemental metal forms, which, at least in the case of mercury, are much less hazardous.

OVERALL CONCLUSIONS

Based on a review of recent studies and published literature, it is concluded that MSW landfills can provide for the safe, efficient, and long-term management of disposed products containing RCRA heavy metals without exceeding limits that have been established to protect public health and the environment. MSW landfills should contain the releases of RCRA heavy metal pollutants at levels that protect public health and the environment for extremely long periods of time if not forever.

As is evident from its organizational goals and policies, SWANA endorses and actively promotes the implementation of economically and environmentally sound waste reduction and recycling programs for products containing heavy metals. However, as evidenced in this report, modern MSW landfills can provide an effective "safety net," as well as an environmentally sound means of disposal, for those products containing heavy metals that are not diverted through waste reduction and recycling programs.

1.1 OVERVIEW

This report presents the findings of a year-long research project that investigated the effectiveness of municipal solid waste (MSW) landfills in controlling releases of heavy metals to the environment due to the disposal of heavy metal products in MSW landfills.

In recent years, there has been a growing movement to ban certain products from disposal in MSW landfills due to the concern over the potential release of heavy metals contained in these products to the environment. In response, the SWANA Applied Research Foundation's Disposal Group felt that there was a need to summarize and document what is known concerning actual environmental releases associated with the landfill disposal of these products. Statements published in recent publications frame the issue being faced by local government solid waste managers regarding the disposal of products containing heavy metals as follows:

> "Because of the high lead content, ***CRT glass should not be disposed of in the trash or municipal landfills***." [4] (emphasis added).
>
> "There are hazardous materials, such as lead, mercury, and hexavalent chromium, in circuit boards, batteries, and color cathode ray tubes... If improperly handled, ***these toxics can be released into the environment*** through incinerator ash ***or landfill leachate***." [5] (emphasis added).

The SWANA Applied Research staff addressed this issue through the development of four technical memoranda, as presented in Table 1. These technical memoranda are summarized in this report.

Table 1

Technical Memoranda Developed to Address the Issue of the Effectiveness of MSW Landfills in Controlling Releases of Heavy Metals to the Environment

TM No. 1	Heavy Metals in Municipal Solid Waste
TM No. 2	Heavy Metals in Landfill Leachate
TM No. 3	Heavy Metals in Landfill Gas
TM No. 4	Effectiveness of Landfill Environmental Protection Systems in Preventing Releases of Heavy Metals to the Environment

1.2 THE SWANA APPLIED RESEARCH FOUNDATION

The Solid Waste Association of North America (SWANA) was founded in 1961 to exchange ideas and foster professionalism and education in the field of MSW management. With over 7,000 members and 46 chapters in the United States and Canada, SWANA continues its mission to educate solid waste professionals.

In 2001, the SWANA Applied Research Foundation was formed through the vision and commitment of a group of founding subscriber organizations. The primary goal of the SWANA Applied Research Foundation is to advance the state-of-the-art of MSW management through the conduct of applied research on collectively defined topics that directly benefit Foundation subscribers.

The SWANA Applied Research Foundation is being conducted as a pilot program of SWANA. Mr. N.C. Vasuki, PE, DEE, Executive Director of the Delaware Solid Waste Authority, chairs the Foundation's Development Committee. The members of the Committee are presented in Table 2.

Table 2

The SWANA Applied Research Foundation Development Committee

Name	Title
Mr. N.C Vasuki, Chairperson	Executive Director, Delaware Solid Waste Authority
Mr. John Hadfield	Executive Director, Southeastern Public Service Authority
Mr. Michael Long	Executive Director, Solid Waste Authority of Central Ohio
Mr. Colin Covington	General Manager, Three Rivers Solid Waste Authority

The SWANA Applied Research Foundation (ARF) is managed by Jeremy K. O'Brien, P.E., SWANA's Director of Applied Research.

1.3 THE SWANA ARF DISPOSAL GROUP

In the second year of the SWANA ARF, a total of 19 local governments and other organizations participated in the SWANA ARF Disposal Group as Foundation Subscribers.

Each of these local governments and organizations contributed a "penny a ton" of waste managed by their organizations toward the funding of collective applied research in the area of MSW disposal. A listing of the 19 Disposal Group Subscribers is provided in Table 3.

In Year 2 of the ARF research program (September 2002 - August 2003), representatives from each of these subscribers voted to select, as their top research priority, the need to document the state-of-the-knowledge regarding the environmental releases associated with disposing of products containing heavy metals in MSW landfills.

1.4 ABOUT THIS REPORT

The purpose of this report is to provide current information regarding the effectiveness of MSW landfills in controlling releases of heavy metals to the environment due to the disposing of products containing heavy metals. This report presents data, findings, and conclusions based on a comprehensive review of the literature and ongoing research related to this topic.

The need to document the state-of-the-knowledge regarding the environmental releases associated with the disposal of products containing heavy metals grew in response to a number of relatively recent developments, including:

- A significant increase in the tonnage of discarded consumer electronics (DCE) being disposed in MSW landfills.
- The growing awareness that DCE wastes contained significant quantities of heavy metals.
- The concern that the disposal of increased quantities of DCE wastes in municipal solid waste landfills would result in significant negative environmental impacts.

The presentation of this information does not imply that SWANA favors the landfill disposal of these and other products containing heavy metals over other solid waste management options such as waste reduction and recycling. SWANA's mission is to advance the practice of environmentally and economically sound municipal solid waste management in North America. SWANA's technical policies include the endorsement and active support of solid waste reduction and recycling programs as key elements of integrated solid waste management systems. Rather, this information is presented to provide insights regarding the environmental releases of heavy metals associated with the landfill disposal of those products containing heavy metals that, for historical, economic, or other reasons, have not been diverted through waste reduction or recycling programs.

This report was prepared by Jeremy O'Brien, P.E., SWANA's Director of Applied Research. Mr. O'Brien holds a Master's Degree in Urban and Environmental Engineering from Duke University and has over 25 years of experience in the field of solid waste management.

To provide an independent review of the research findings and conclusions presented in this report, SWANA engaged the services of Dr. Frederick Pohland. Dr. Pohland was the Weidlein Chair of Environmental Engineering in the Department of Civil and Environmental Engineering at the University of Pittsburgh. He served as Editor of the IWA Water Research Journal and was a past President of the American Academy of Environmental Engineers and recipient of its Kappe and Fair Awards. Dr. Pohland was a member of the National Academy of Engineering, and was the recipient of an Honorary Degree of Doctor of Science from Valparaiso University. Dr. Pohland received his Ph.D. in Environmental Engineering from Purdue University in 1961. To the great loss of family, friends, colleagues and the environmental protection community, Dr. Pohland passed away on January 9, 2004.

Additional comments and guidance were provided by the representatives of the Applied Research Foundation's Disposal Group listed in Table 3. Draft copies of each of the technical memoranda prepared during the project were submitted to the Group for review and comments. In addition, two Subscriber review meetings were held in conjunction with SWANA conferences to provide an opportunity for interpersonal feedback and group discussions.

Finally, this report has been subjected to an outside peer review by an independent panel comprised of the leading academicians and researchers in this field:

- Dr. Debra R. Reinhart, Chair, Civil and Environmental Engineering Department and Professor and Associate Dean, College of Engineering and Computer Science, University of Central Florida
- Dr. Morton A. Barlaz, Professor and Associate Head, Department of Civil, Construction and Environmental Engineering, North Carolina State University
- Dr. Timothy G. Townsend, Associate Professor, Department of Environmental Engineering Sciences, University of Florida.

The report was subsequently revised to respond to the questions and comments raised through the peer review process.

Table 3

SWANA Applied Research Foundation – Year 2 Disposal Group Subscribers

Jurisdiction/Organization	Name	Title
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SCS Engineers, Inc.	Robert Gardner	Senior Vice President
Three Rivers Solid Waste Authority (Aiken, SC)	Colin Covington	General Manager
Waste Management, Inc.	John Baker	Director, New Technology

2.1 INTRODUCTION

The disposal of products containing heavy metals in MSW landfills is currently permitted under federal regulations if these products are generated by households or by businesses in small quantities. Alternatively, if products containing heavy metals are generated by businesses or industries in large quantities, they may be prohibited from disposal in MSW landfills if they "fail" a test called the "Toxicity Characteristic Leaching Procedure" (TCLP).

The policies and practices that both allow and restrict the disposal of products containing heavy metals in MSW landfills have been established through federal regulations that have been supplemented, in some cases, by state and local laws and regulations. The purpose of this section is to present background information on the federal and state laws and regulations that address the disposal of municipal solid waste in order to establish the context for the issue addressed in this report.

2.2 MSW DISPOSAL REGULATIONS

Municipal solid waste is non-hazardous solid waste that is generated by the residents, businesses, institutions, and industries in a community. MSW that is not incinerated or diverted through recycling or composting programs is disposed of in MSW landfills.

In the United States, the disposal of MSW is regulated under the federal Resource Conservation and Recovery Act (RCRA), which was enacted in 1976 to address the huge volumes of municipal and industrial solid waste generated nationwide. Two of RCRA's goals are to protect human health and the environment from the hazards posed by waste disposal and to ensure that wastes are managed in an environmentally safe manner. Since its enactment in 1976, RCRA has been amended several times, most significantly by the Hazardous and Solid Waste Amendments of 1984.

The "Subtitle D" section of RCRA addresses municipal solid waste, which is generated by businesses and households and which is typically collected and disposed in MSW landfills. The Subtitle D program includes technical criteria for MSW landfills to ensure that such landfills will be fully protective of human health and the environment.[6]

Federal RCRA MSW landfill regulations are codified in Part 258 of Title 40 of the Code of Federal Regulations (CFR). These regulations, which are often referred to as "Subtitle D" regulations and which were promulgated by the U.S. Environmental Protection Agency (EPA) in 1991, are implemented by states and territories that have landfill regulatory programs that have been approved by the EPA. (Forty-nine of the 50 states have approved programs).

The federal MSW disposal regulations establish a cost-effective and practical system for managing the nation's waste by "specifying safe design and management practices that will prevent releases of contaminants into the groundwater."[7]

Leachate is defined as liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from the waste. Leachate is formed as precipitation or other water percolates through the landfill and collects contaminants, such as heavy metals, that are leached from the waste and/or are produced during the waste decomposition process. The federal MSW regulations require that leachate be collected and treated both during the active life of the landfill, as well as during the landfill's post-closure period, which is expected to last for a minimum of 30 years following the closure of the landfill.

The Federal Subtitle D regulations require that MSW landfills meet minimum design or performance standards. The regulations allow for landfill owners and operators to implement either a "standard" landfill liner system or a liner system that incorporates a performance-based design.

2.2.1 STANDARD LANDFILL LINER SYSTEMS

The design requirements for a "standard composite liner system" include the following components (from top to bottom):

- A leachate collection and removal system that limits the depth of the leachate that is allowed to remain on the top of the composite liner to 12 inches.
- A "geomembrane" that serves as the upper component of the composite liner. (Geomembranes are thin factory-manufactured plastic sheets that are widely used as hydraulic barriers due to their non-porous structure, flexibility, and ease of installation.) If the geomembrane is made of high-density polyethylene (HDPE), it must be at least 0.06 inches thick.
- A 24-inch thick compacted clay liner (CCL) that serves as the lower component of the composite liner.

The composite liner system has been found to provide an effective hydraulic barrier because it combines the complementary properties of two different materials into one system: 1) compacted soil with a low hydraulic conductivity, and 2) a geomembrane. The EPA acknowledges that geomembranes may contain defects that are caused during the manufacturing or construction processes. These defects may include tears, improperly bonded seams, and pinholes.

The basic premise behind requiring the use of composite liners in MSW landfills is that leakage that may occur through a hole or defect in the geomembrane is impeded from escaping from the liner system by the presence of the compacted clay liner constructed underneath the geomembrane. Due to their superior performance, composite liners have been incorporated into minimum federal requirements for both MSW and hazardous waste landfills, and they are being increasingly used in a wide variety of waste containments systems.[8]

In effect, the standard composite liner system required by EPA forms a relatively impermeable barrier that substantially prevents the leachate that is produced from escaping from the landfill and seeping into the groundwater below the landfill.

2.2.2 LINER SYSTEMS INCORPORATING PERFORMANCE-BASED DESIGNS

Owners and operators of MSW landfills have the option of proposing a performance-based design for the landfill's liner system, provided that certain criteria can be met. Specifically, the landfill owner or operator must demonstrate that the liner system design will not allow certain pollutants to exceed their "Maximum Contaminant Levels (MCLs)" at the "relevant point of compliance."

The demonstration involves an assessment of the potential for leachate production and leakage from the landfill to the groundwater and the anticipated fate and transport of leachate pollutants to relevant point of compliance. The relevant point of compliance is required to be no more than 150 meters (164 yards) from the waste management unit boundary and must be located on the land owned by the landfill owner.

Among the pollutants for which MCL compliance must be demonstrated are eight heavy metals, which are listed in Table 4 along with their respective MCL limits. These eight heavy metals (which are actually six heavy metals and two metalloids) are referred to throughout this report as the "RCRA heavy metals."

Table 4
RCRA Heavy Metal Regulatory Limits

Chemical	Groundwater Maximum Contaminant Levels (MCLs) Milligrams per Liter (mg/l)	TCLP Regulatory Levels (mg/l)
Arsenic	0.05	5
Barium	1.0	100
Cadmium	0.01	1
Chromium (hexavalent)	0.05	5
Lead	0.05	5
Mercury	0.002	0.2
Selenium	0.01	1
Silver	0.05	5

It should be noted that the federal standards established by the EPA for both the standard composite liner and performance-based liner systems are minimum standards that must be met for all MSW landfills. Under RCRA, states are required to incorporate these minimum standards into the design requirements they establish for MSW landfills permitted in their jurisdictions. However, states are free to adopt standards that are more stringent than the federal Subtitle D standards. For example, New York State requires that MSW landfills have double composite liner systems rather than the single composite liner system required under federal Subtitle D regulations.

2.3 DISPOSAL OF HOUSEHOLD HAZARDOUS WASTES AND CONDITIONALLY-EXEMPT SMALL QUANTITY GENERATOR WASTES IN MSW LANDFILLS

Federal RCRA regulations prohibit MSW landfills from disposing of hazardous wastes. As used by EPA, the term "hazardous waste" has a very specific legal definition. As defined in Part 261 of Title 40 of the Code of Federal Regulations, a waste is hazardous if:

- It is listed as a hazardous waste (listed hazardous wastes are specifically identified in 40 CFR 261, Part D).
- It is mixed with or derived from a hazardous waste as defined by EPA.
- It is not excluded from the hazardous waste definition.
- It possesses any one of four characteristics described in 40 CFR 261, Subpart C: i) ignitability; ii) corrosivity; iii) reactivity; or (iv) toxicity as determined by the Toxicity Characteristic Leaching Procedure (TCLP).

Some categories of wastes, such as household waste, are specifically excluded by RCRA from the definition of hazardous waste even though these wastes may contain small amounts of hazardous waste. For example, it is commonly known that household waste contains small amounts of hazardous waste" (HHW), which includes products such as paints, cleaners, oils, batteries, and pesticides that are discarded by residents and that contain potentially hazardous ingredients.

Discarded products and/or materials containing heavy metals that are generated by households are not classified as hazardous wastes under federal regulations even if they fail the TCLP. It should be noted, however, that at least one state (California) has not adopted the RCRA household waste exclusion.

Similarly, RCRA allows for the disposal of small amounts of hazardous wastes generated by businesses or industries. These waste generators, referred to in RCRA as "Conditionally Exempt Small Quantity Generators (CESQGs), can dispose of the hazardous waste they generate in an MSW landfill if they produce less than 100 kg (220 pounds) per month of hazardous waste.

The regulatory language contained in the Code of Federal Regulations that addresses these exemptions is presented in Table 5.

Table 5

Regulatory Language Regarding HHW and CESQG Exemptions from Hazardous Waste Classification

261.3	Regulated hazardous waste means a solid waste that is a hazardous waste, as defined in 40CFR 261.3, that is not excluded from regulation as a hazardous waste under 40 CFR 261.4(b) or was not generated by a CESQG as defined in 261.5 of this title
261.4(b)	Solid wastes which are not hazardous wastes. The following solid wastes are not hazardous wastes: (1) Household waste, including household waste that has been collected, transported, stored, treated, disposed, recovered, or reused
261.5	Special requirements for hazardous waste generated by CESQGs. (a) A generator is a CESQG in a calendar month if it generates no more than 100 kilograms of hazardous waste in that month.

The EPA estimates that in 2000, about 1.6 million tons of HHW were generated, representing about 0.7% of the 232 million tons of MSW generated that year.[9] There is no question that many HHW products would "fail" the TCLP and therefore be classified as hazardous wastes due to their toxicity. However, when promulgating the RCRA Subtitle D regulations, the EPA allowed for the disposal of HHW in MSW landfills due to the relatively small percentage of HHW in the MSW stream. Therefore, in effect, products containing heavy metals, such as lead acid batteries and discarded consumer electronics, have been permitted to be disposed of in MSW landfills since the promulgation of the Subtitle D regulations in 1991, if these products are discarded by the residents and CESQG businesses in a community. (As noted above, at least one state has not adopted the HHW exclusion.)

The following example illustrates this point. In 1989, the EPA published a report entitled Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste in the United States, 1970 to 2000. Sources of lead in MSW over the period 1970 to 2000 are presented in Table 6.

As indicated, the EPA anticipated the presence of products containing heavy metals, such as lead-acid batteries and discarded consumer electronics, in the MSW disposal stream both before and after the promulgation of the federal Subtitle D regulations in 1991.

Table 6

Lead in Products Discarded in MSW, 1970 to 2000 (In Short Tons)

Products	1970	1986	2000	Tonnage	Percentage (By Weight)
Lead-acid batteries	83,825	138,043	181,546	Increasing	Variable
Consumer electronics	12,233	58,536	85,032	Increasing	Increasing
Glass and ceramics	3,465	7,956	8,910	Increasing	Increasing; stable after 1986
Plastics	1,613	3,577	3,228	Increasing; decreasing after 1986	Fairly stable
Soldered cans	24,117	2,052	787	Decreasing	Decreasing
Pigments	27,020	1,131	682	Decreasing	Decreasing
All others	12,567	2,537	1,701	Decreasing	Decreasing
Totals	164,840	213,652	281,887		

Source: EPA Office of Solid Waste. Characterization of Products Containing Lead and Cadmium in Municipal Solid Waste in the United States, 1970 to 2000. (EPA/530-SW-89-015C). Washington: EPA, January 1989.

2.4 THE TOXICITY CHARACTERISTIC LEACHING PROCEDURE

The "toxicity characteristic" of a waste is determined, under federal RCRA regulations, by the conduct of the TCLP.

The TCLP is a batch leaching test in which 100 grams (0.22 pounds) of waste are placed into two liters (2.1 quarts) of leaching fluid and are leached for a period of 18±2 hours. The leaching fluid that is used is designed to match the worst-case acid conditions that can possibly develop as waste decomposes in a MSW landfill. Unless the waste being tested is very alkaline, the TCLP leaching fluid consists of acetic acid that is buffered (with sodium hydroxide) to sustain a pH of 4.93±0.05.

To test a solid waste material or product, a small (100 gram) representative sample must be obtained. The particle size of the sample must be small enough to pass through a 9.5-mm (0.375-inch) sieve. For most products or materials in the MSW stream, this means that the product or material must be crushed, shredded, or otherwise reduced in size to meet the TCLP particle size requirements for the sample.

Once the sample and TCLP leaching solution are prepared, they are placed in a container that is rotated for the prescribed leaching period at a speed of 30+2 revolutions per minute.

Following the leaching period, the leachate is analyzed for any or all of the 40 chemicals that can cause the waste to be characterized as hazardous if they are present in the leachate above regulatory levels. The TCLP list of regulated chemicals includes the same eight heavy metals for which MCL groundwater limits are prescribed under Subtitle D regulations for MSW landfills designed with performance-based liners. These heavy metals are listed in Table 4, along with the TC regulatory level established for each metal.

The TCLP is a required analysis that must be conducted to determine if a solid waste product or material should be classified as "hazardous" under federal regulations. However, the leachate pollutant concentrations measured by the TCLP are not necessarily indicative of the leachate pollutant concentrations that can be expected under actual landfill conditions. In this regard, the TCLP was never intended to be used to predict actual leachate pollutant concentration, since it, by definition, represents "worst-case" (as opposed to average) leaching conditions in a landfill. For example, the pH of the TCLP leaching solution is 4.9, while the pH of typical landfill leachates is much closer to neutral (i.e., 7.0).

Because of these differences, the application and use of the TCLP as a meaningful indicator of the leachability of a waste in a landfill environment has come under scrutiny in recent years. On February 26, 1999, the EPA's Science Advisory Board (SAB) Environmental Engineering Committee issued a letter report asking that the EPA "review and improve EPA's current waste leachability testing procedure, i.e., the Toxicity Characteristic Leaching Procedure (TCLP)."[10] In June 2003, the SAB's Environmental Engineering Committee provided a consultation to the EPA's Office of Solid Waste on improving leach testing. In a communication summarizing this meeting, the EPA stated that:

> "While EPA believes that TCLP remains an appropriate and valid test in its regulatory functions, the Agency also believes that leach testing more tailored to known disposal conditions can be the basis for better environmental decision-making when regulatory programs allow such flexibility."[11]

2.5 CURRENT RESEARCH ACTIVITIES RELATING TO THE TCLP AND DISPOSAL OF PRODUCTS CONTAINING HEAVY METALS

2.5.1 INTRODUCTION

There have been a number of research projects conducted recently that have addressed the issue of the characterization of disposed heavy metal products using the TCLP and the significance of TCLP results regarding the implementation of appropriate management strategies for products containing heavy metals.

All of the three research projects described below either have been or are being conducted at the University of Florida in Gainesville. Two of these projects received funding from the Florida Center for Solid and Hazardous Waste Management (FCSHWM)—a state-funded research organization devoted to addressing solid waste management issues in the state. The third project received funding from EPA Regions 4 and 5.

2.5.2 FLORIDA CENTER FOR SOLID AND HAZARDOUS WASTE MANAGEMENT

2.5.2.1 Characterization of Lead Leachability from Cathode Ray Tubes Using the Toxicity Characteristic Leaching Procedure

This project, which was completed in December 1999, was sponsored by the FCSHWM and was conducted at the University of Florida's Department of Environmental Engineering Sciences.[12]

Cathode ray tubes (CRTs) are the display devices used in most televisions and desktop computers. Using the EPA Toxicity Characteristic Leaching Procedure (TCLP) test, lead leachability from CRTs was studied. Samples from a total of 36 CRTs were processed and analyzed. The average lead concentration in the resulting sample solution was 18.5 mg/l. This concentration is significantly higher than the regulatory limit of 5.0 mg/l above which a waste would be characterized as hazardous. The major source of lead was found to be the CRT funnel section, specifically the "frit seal" for color CRTs. The sample solution from monochrome CRTs did not exceed the regulatory limit of 5.0 mg/l, indicating that monochrome CRTs would not be classified as hazardous wastes under federal regulations. A peer-reviewed paper was published presenting the results of this research.[13]

The study investigators made no inferences, based on the study results, as to whether or not lead from CRTs would be expected to leach in a landfill environment. As discussed further in this report, the differences between the TCLP conditions and the landfill environment include the following:

- **Leachate pH** – The TCLP is conducted with a solution having a pH of 4.9. This pH represents acidic leachate and aggressive leaching conditions in a landfill. Leachate characteristics are different for leachate that is generated under conditions where the pH is at or near neutral (i.e., 7).
- **Particle Size** – The TCLP requires that the CRT sample be ground to a particle size of 3/8 inches. In a landfill, it is unlikely that CRTs, even when crushed, would have this average particle size.
- **Landfill Attenuation Mechanisms** – There are a number of attenuation mechanisms in landfills that would cause lead that leached from a CRT to precipitate out of the leachate. These mechanisms are discussed in Section 4.4.2.

2.5.2.2 *Assessment of True Impacts of E-Waste Disposal in Florida*

This project is being funded by the FCSHWM as a follow-up to the 1999 project, with a project timeframe of September 2002 through December 2003. The purpose of this project is to provide data pertaining to the impact of electronic waste disposal in MSW landfills and incinerators in Florida.[14]

Specific tasks and objectives defined for the project include the following:

1. Measure the concentration of heavy metals and brominated flame retardants (BFRs) in leachate from simulated landfills that contain known amounts of electronic wastes.
2. Measure the leachability of heavy metals in several common electronic products with actual Florida landfill leachates as compared to the leachability via the TCLP extraction fluid.
3. Measure concentrations of brominated flame retardants and heavy metals in Florida landfill leachates.
4. Use the results from the above tasks to assess the true impacts of electronic waste disposal in MSW landfills in Florida.

As of November 2003, all of the research – with the exception of the installation of the simulated landfill columns – has been completed. Installation of the simulated landfill columns was completed in February 2004, with monitoring scheduled to occur through the end of 2004 when a final report will be prepared and published.

A paper presenting the results of the second task – comparing the leaching of metals from DCE when landfill leachate rather than the TCLP extraction fluid is used as the leaching medium – has been recently published in a peer-reviewed journal.[15] In this task, two common components of DCE – printed wire boards and cathode ray tubes – were leached using the TCLP extraction fluid as well as leachates from 11 Florida landfills. The results, which are summarized in Table 7, indicated that the lead concentrations in the leaching solution were significantly lower when MSW leachate was used as the leaching solution than when the TCLP extraction fluid was used.

The study investigators concluded that the pH of the leaching solution and the ability of the organic acids (present in the TCLP extraction fluid) to form complexes with the lead are factors that determine the amount of lead that is leached.

The study investigators also concluded that the results of this investigation indicate that the leaching of lead from printed wire boards (PWBs) and CRTs will be less than might be estimated based on TCLP results.

Table 7

Summary of Leaching Test Procedures and Test Results - CRTs

Parameter	TCLP Extraction Fluid	MSW Landfill Leachate
pH	4.93 ±0.05	7.6[a]
Acid/Base Used Establish and Control pH	Acetic Acid and Sodium Hydroxide	N/A
No. of CRTs Used	30	30
Solid to Liquid Ratio	100 g/2 L	100g /2 L
Extraction Period	18+2 hours	18+2 hours
Avg. Lead (Pb) Conc. (mg/L)	413	4.06

a. Average of 11 landfill leachates.
b. Source: Jang, Y. and Townsend, T., "Leaching of Lead from Printed Wire Boards and Cathode Ray Tubes by Municipal Solid Waste Landfill Leachates," Environmental Science and Technology (accepted for publication).

2.5.3 EPA REGIONS 4 AND 5

2.5.3.1 *Toxicity Characteristic Testing of Discarded Electronic Devices*

Work is currently underway at the University of Florida to determine whether discarded electronic devices exhibit toxicity characteristics when subjected to the TCLP. This research is being funded by EPA Regions 4 and 5 as well as the Florida Center for Solid and Hazardous Waste Management. The work involves applying the standard TCLP as well as two modifications of the TCLP:

- **Modified Small Scale TCLP** – This method follows all of the requirements of the EPA TCLP protocol (EPA Method 1311) except that the devices being tested are not size-reduced. It is envisioned that this modified test will be used for smaller electronic devices such as cellular phones and remote controls.
- **Modified Large Scale TCLP** – This method has been developed for larger electronic products such as CRTs. The objective is to be able to test the product without having to size-reduce it and test a small sample. A rotating, 55-gallon drum is used as the test container. The same TCLP extraction fluid is used; however, the drum is rotated at a lower speed (14 rpm) versus the 30 rpm specified

in the TCLP procedure. The device is dismantled (versus being size-reduced) before being placed in the drum.

A paper presenting some preliminary results of this research was presented at SWANA's 2nd Annual Special Waste Symposium (Phoenix, AZ – Dec. 4-6, 2002).[16] Preliminary results indicate that color CRTs will continue to fail the TCLP even when they are tested in a dismantled form (as opposed to size-reduced to a 3/8-inch particle size).

2.6 ADOPTION OF MORE STRINGENT REGULATIONS BY CERTAIN STATES

As discussed above, current federal regulations allow for the disposal of products containing heavy metals and other hazardous waste in MSW landfills if these products come from residences or are generated by businesses or industries in relatively small quantities. The federal regulations give states the flexibility to impose tighter restrictions than are contained in the federal code.

Many states have taken advantage of this option and have, for example, instituted bans prohibiting the disposal of lead acid batteries in MSW landfills. Two states—Massachusetts and California—have instituted bans prohibiting the disposal of lead-containing cathode ray tubes (CRTs) (i.e., television and computer monitor screens) in MSW landfills.

The reasons for the institution of these bans differ. In Massachusetts, the rationale given for the ban was stated as follows:

> "Discarded consumer electronics contain significant quantities of lead, cadmium, mercury and plastics, all of which eventually wind up in landfills or incinerators if not recycled. Recognizing the need to stem the tide of computers and televisions destined for disposal, Massachusetts, on April 1, 2000, became the first state in the nation to ban the disposal of cathode ray tubes (CRT) containing devices.[17]

In California, the State Department of Toxics and Substance Control (DTSC) issued a regulatory "clarification" in 2001 indicating that all lead-containing CRTs were hazardous wastes and therefore could not be disposed in Subtitle D landfills.

2.7 CONCLUSIONS

Based on this review of background regulatory information regarding the disposal of products containing heavy metals, the following conclusions are made:

- Due to the promulgation of federal landfill regulations in 1991, MSW landfills (also referred to as Subtitle D landfills) are now equipped with liners and leachate collection systems that are designed to collect and treat landfill leachate as well as to prevent the release of landfill leachate and its contaminants to the environment (i.e., specifically to the groundwater beneath the landfill).
- MSW landfills are permitted to dispose of hazardous waste products if they come from residences and businesses or industries that generate them in relatively small quantities. A number of these products – such as lead acid batteries – are known to fail the TCLP. However, their disposal in MSW landfills is permitted under federal regulations due to their relatively small quantities.
- Recent research has confirmed that certain heavy metals (most notably lead) that are present in cathode ray tubes (CRTs) will leach into solution, when subjected to the TCLP, at levels that

would cause CRTs to be classified as a hazardous waste if the CRTs are generated in quantities greater than 220 pounds per month by a business or industry.

- The TCLP has come under scrutiny, in recent years, with respect to its usefulness as a meaningful indicator of the leachability of a waste in a landfill environment. In this regard, recent research has concluded that the leaching of lead from PWBs and CRTs in an MSW landfill will be less than might be expected based on TCLP results.
- To respond to the growing quantities of DCE waste and the concern regarding the fate of the heavy metals in this waste at MSW landfills, a small but growing number of states have instituted, or are considering the institution of, bans on the disposal of CRTs and other DCE waste products.

3.1 INTRODUCTION

Metals are those elements that are characterized by a tendency to give up electrons and by having good thermal and electrical conductivity.[18] Of the 115 or so stable elements listed in the periodic table, 87 are classified as metals.

There is disagreement in the literature regarding a precise definition of "heavy metals." Webster's defines heavy metal as "any metal or alloy having a specific gravity of greater than 5.0" (i.e., an atomic weight greater than 90). Another source defines heavy metals as "those metals having atomic weights between 63.546 and 200.590 and a specific gravity greater than 4.0."[19] A recent paper in Chemistry International concluded that "the term 'heavy metal' has never been defined by any authoritative body" and "it has been given such a wide range of meaning by different authors that it is effectively meaningless."[20]

The Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor recently revised its terminology to refer to "toxic metals" rather than heavy metals. According to OSHA:

> "Toxic metals, which include 'heavy metals' are individual metals and metal compounds that negatively affect the health of people... At trace levels, many of these elements are necessary to support life. However, at elevated levels they become toxic, may build up in biological systems, and become a significant health hazard."[21]

3.2 HEAVY METALS OF CONCERN IN MSW

As discussed in Section 2.0, there are eight heavy metals that are identified by RCRA as indicative of toxicity if they are present in the waste and can leach from the waste above the threshold concentrations when subjected to the TCLP.[22] These are the same eight heavy metals for which groundwater MCLs were established by EPA for compliance by MSW landfills constructed with performance-based liner systems.

Because of the fact that they are singled out by RCRA as metals of concern in solid wastes, these eight metals – referred to throughout this report as "RCRA heavy metals" constitute the focus for this report. For ease of reference, the RCRA heavy metals are again listed in Table 8, along with their respective TCLP regulatory limits and groundwater MCLs.

Table 8

RCRA Heavy Metals Targeted in This Report

Heavy Metal[1]	Groundwater Maximum Contaminant Level (MCL) (mg/l)	RCRA TCLP Threshold Concentrations (mg/l)[23]
Arsenic (As)	0.050	5
Barium (Ba)	1.0	100
Cadmium (Cd)	0.01	1
Chromium (Cr)	0.05	5
Lead (Pb)	0.05	5
Mercury (Hg)	0.002	0.2
Selenium (Se)	0.01	1
Silver (Ag)	0.05	5
Notes: 1) Though technically not metals, arsenic and selenium are metalloids which are often classified as heavy metals.		

Of the eight RCRA heavy metals, four—lead, mercury, cadmium, and chromium—were targeted in a recent report on heavy metals in solid waste prepared for the European Commission. A list of the common applications of these four heavy metals is provided in Table 9.[24]

Table 9

Common Applications of Heavy Metals

Lead	Mercury	Cadmium	Chromium
Batteries	Chlorine-alkaline production	Plating	Leather tanning
Cable Sheathing	Dental amalgam	Silver-cadmium alloys	Wood preservatives (CCA = copper, chromium, arsenic)
Flashing	Mercury-oxide batteries	Copper-cadmium alloys	Stainless steel and other alloys
Roofing Plates	Other batteries	Nickel-cadmium batteries	Dyes, colors, and pigments
Corrosion Protection Sheets	Medical thermometers	PVC stabilizers	
Leaded Window Frames	Other thermometers	Pigments	
Solder for Electronics	Measuring and control equipment	Photovoltaic cells	
Solders for Food Cans	Electric and electronic switches		
Solders for Electrical Bulbs	Fluorescent tubes and lamps		
Solder for Pipes	Laboratory chemicals		
Ammunition	Gold extraction		
Bearings	Pesticides and biocides		
Hot Dip Galvanizing			
Balance Weights for Vehicles			
Plating of Gasoline Tanks			
Radiation Shielding			
PVC Stabilizer			
Pigments			
Rust-Inhibitive Primers			
Siccatives in Paint			
Lubricants (industrial)			
Cathode Ray Tubes			
Lead Crystal Glass			
Glazes and Enamels			

Source: Compiled from tables in Heavy Metals in Waste. (COWI Consulting Engineers and Planners. European Commission DG ENV.E3). February 2002.

3.3 HEAVY METAL CONCENTRATIONS IN MSW

Concern regarding the environmental impacts of disposing of heavy metal products and materials has existed for many years. Recently, this concern has increased due to the significant increases in the disposal of discarded consumer electronics and other products, such as wood treated with the chromated-copper-arsenate (CCA) preservative, which are known to contain heavy metals.

Despite this concern, there have been relatively few studies that have been conducted in recent years to determine the quantities and characteristics of heavy metals in MSW. In a 2002 report entitled Heavy Metals in Waste prepared for the European Commission, it is stated that:

> "Only very few and incomplete analyses exist of the content of heavy metal containing products in household waste and other complex waste fractions."[25]

This section summarizes a few, mostly-dated, studies reported in the literature on this subject.

- *Characterization of Products Containing Lead and Cadmium in MSW in the United States, 1970 to 2000*

  In the late 1980s, the EPA sponsored a series of projects that characterized the products containing lead, cadmium, and mercury in MSW over the 30-year period of 1970 to 2000.[26] [27]

  These studies projected that the amount of heavy metals disposed of in the MSW stream would continue to rise over the period from 1970 to 2000, even with the implementation of recycling programs for a number of heavy metal products, such as lead acid batteries. For example, the EPA predicted that the amount of lead disposed in MSW landfills would rise from 213,652 tons in 1986 to 281,886 tons in 2000.

  The EPA's projections for the sources of lead in MSW are presented in Table 10. As indicated, lead-acid batteries were projected to represent 64% of the lead disposed in MSW in 2000. Although these projections were made in the late 1980s, they were based on the assumption that a recycling rate of over 80% would be achieved for lead acid batteries.[28]

Table 10

Lead in Products Discarded in MSW for the Year 2000
(Projected by the EPA in 1989)

	Tons of Lead Per Year	Percent
Lead-Acid Storage Batteries	181,546	64
Consumer Electronics	85,032	30
Glass and Ceramic Products	8,910	3
Plastics	3,228	1
Soldered Cans	787	1
Pigments	682	
Other Products	1,701	1
Total	**281,886**	**100**

Source: US Environmental Protection Agency. Characterization of Products Containing Lead and Cadmium in MSW in the United States, 1970-2000. (EPA/530-SW-89-015B). Washington: EPA, January 1989.

The sources of cadmium in MSW, as projected by the EPA in 1989 for the year 2000, are presented in Table 11. As shown, nickel-cadmium (ni-cad) batteries and plastics were projected to generate 90% of the cadmium disposed in MSW in 2000.

Table 11
Cadmium in Products Discarded in MSW for the Year 2000
(Projected by the EPA in 1989)

	Tons of Cadmium Per Year	Percent
Household Batteries	2,035	76
Plastics	380	14
Consumer Electronics	67	3
Appliances	57	2
Pigments	93	3
Glass and Ceramics	37	1
Other Products	11	-
Total	2,680	100

- ***Municipal Solid Waste in the United States: 2000 Facts and Figures***

A report, prepared by Franklin Associates Ltd. for the EPA and published in 2000, describes the national MSW stream based on data collected over a 40-year study period (1960 to 2000).[29] The study relies on a materials flow methodology, as opposed to actual waste stream sampling, to estimate the tons of materials and products generated, recycled, or disposed on an annual basis. For most of the 40-year study timeframe, consumer electronic products were included in the category of "Miscellaneous Durables." In 1999, the EPA began to track consumer electronic products as a separate subcategory under Miscellaneous Durables.

The projections for two products containing heavy metals—namely, lead-acid batteries and selected consumer electronics—are presented in Table 12. The EPA estimates presented in Table 12 indicate that the tonnages of lead acid batteries disposed have decreased dramatically since 1995 to an estimated disposal tonnage of 70,000 in 2000. Of the 70,000 tons of lead acid batteries disposed, the EPA estimated that the weight of the lead metal disposed in lead acid batteries was 30,000 tons.[30] This estimate is significantly lower than the former EPA projection for the year 2000, made in 1989, of 181,546 tons of lead disposed. The discrepancy is likely due to the much higher recycling rate assumed in the EPA Franklin report (96%, as compared with the recycling rate of 83% assumed for the year 2000 by the EPA in 1989) as well as other factors.

The EPA began estimating the quantities of discarded selected consumer electronics in 1999. As also indicated in Table 12, the EPA estimated that 1.93 million tons of consumer electronics were disposed in 2000. This tonnage represents a 21% increase over the tonnages estimated in 1999 for disposal.

Table 12
Products Discarded in the MSW Stream, 1995-2000 (in Thousands of Tons)

Product	1995	1998	1999	2000
Lead Acid Batteries	190	60	70	70
Selected Consumer Electronics	N/A	N/A	1,600	1,930

Source: U.S. Environmental Protection Agency. Municipal Solid Waste in the United States: 2000 Facts and Figures. (EPA530-R-02-001). www.epa.gov. June 2002. See Table 14 (p. 68).

- *The Materials Flow of Mercury in the Economies of the U.S. and the World*

A circular was published by the U.S. Geological Survey in 2000[31] that presents mercury disposal estimates for the U.S. for the year 1996. Disposal estimates reported in the study are presented in Table 13 to indicate the relative contributions of the various discarded products containing mercury to the tonnages of mercury disposed in that time period. As shown, significant sources of mercury in that time period included electrical wiring and switches and measurement and control devices. Also, the major portion of mercury in MSW (62%) was reported to be from unspecified or undefined sources.

Table 13
Sources of Mercury in MSW in the U.S. in 1996

Source	Tons/Year of Mercury Disposed	Percent
Chlorine-Alkali Production	19.8	5
Dental Amalgams	5.5	1
Laboratory Analyses	3.3	1
Measurement and Control Devices	59.5	16
Wiring Devices and Switches	17.6	5
Electric Wiring	22.0	6
Batteries	17.6	5
Other	237.0	62
Total	382.5	100

Source: Calculated from Table 3.8 in Heavy Metals in Waste. (COWI Consulting Engineers and Planners. European Commission DG ENV.E3). February 2002. p 31. (Note: disposal includes incineration, land and landfill disposal.)

3.4 RECENT PROLIFERATION OF DISCARDED CONSUMER ELECTRONICS

Consumer electronics, such as televisions, stereos, and radios, have been discarded in the MSW stream since the 1950s. As indicated in Table 6, this MSW subcategory represented over 12,000 tons of MSW on an annual basis as far back as 1970.

Recently, the issue of disposing of products containing heavy metals has resurfaced due to the explosive growth in the disposal of discarded consumer electronics (DCE). This substream of MSW consists of televisions, computer monitors, central processing units (CPUs), VCRs, and the like (see Table 14).

Table 14
Products that are Considered Consumer Electronics Waste When Discarded

- Televisions and Monitors
- Computers
- Computer Peripherals
- Audio/Stereo Equipment
- VCRs
- Video Game Consoles
- DVD Players
- Telephones
- Fax and Copying Machines
- Cellular Phones
- Wireless Devices

Source: EPA. Electronics: A New Opportunity for Waste Prevention, Reuse and Recycling. EPA 530-F-01-006. Washington: EPA, June 2001. (http://www.epa.gov/epr).

The EPA estimates that over 1.9 million tons of consumer electronics were disposed of in the U.S. in 2000. This represents 1.2% of the 162 million tons of MSW that were disposed of in that year.[32]

Concern has been growing regarding the management of DCE waste for two reasons:

- This waste substream has been growing dramatically in recent years. Research completed in Europe concluded that electronics waste is growing at three times the rate of other MSW.[33]
- Cathode ray tubes (CRTs), circuit boards, batteries, and other electronic components often contain hazardous constituents such as lead, mercury, and cadmium.[34] Color televisions and CRT monitors contain, on the average, 4 pounds of lead per device. Electronics have been cited as a leading source of mercury in MSW.[35] A list of heavy metals typically found in discarded electronic devices is presented in Table 15.

Table 15

Heavy Metals Typically Found in Electronic Devices[36]

Metal	Application/Location
Arsenic	Transistors, Printed Wire Boards (PWB)
Barium	Cathode Ray Tube (CRT)
Cadmium	Battery, Housing, PWB, CRT
Chromium	Housing
Lead	CRT, PWB
Mercury	Batteries, Switches, Housing, PWB, Flat Panel Screens
Selenium	Rectifiers, PWB
Silver	Conductivity/PWB, Connectors
Beryllium	Pigment, Housing
Copper	Conductivity/CRT, PWB, Connectors
Zinc	Battery, Phosphor Emitter, PWB, CRT
Rare Earth Metals	Semiconductors, PWB, Conductors, Housing, CRT Diodes/Housing, PWB, CRT, Connectors
Note: Metals in bold are RCRA Heavy Metals	

3.5 HEAVY METALS IN DISCARDED CONSUMER ELECTRONICS

EPA tonnage estimates for the generation, recovery, and disposal of consumer electronics in the MSW stream are presented in Table 16.[37] As indicated, the EPA estimates that over 90% of consumer electronics were disposed in 2000, with only 9% recovered for recycling.

The EPA also estimated the material composition of consumer electronics in the EPA/Franklin report published in 2000 (see Table 17).[38]

Based on this data, metallic lead represented 4.2% of the 1.93 million tons of consumer electronics disposed in 2000. This translates to approximately 81,800 tons of lead disposed of in the form of discarded consumer electronics.

Table 16
Generation, Recovery, and Discards of Consumer Electronics in the MSW Stream 2000 (Annual Tons)

Type of Consumer Electronics		Total Generation (Tons)	Total Recovery (Tons)	Amount Recovered	Total Discards (Tons)
Video Products	Televisions (TVs), Projection TVs, High Definition (HD) TVs, Liquid Crystal Display (LCD) TVs, Videocassette Recorders (VCRs), TV/VCR) Combinations, VCR Decks, Camcorders, Laserdisc Players, Digital Versatile Disc Players, TV/Personal Computer (PC) Combinations	859,300	1,200	0.1%	858,100
Audio Products	Rack Audio Systems, Compact Audio Systems, Portable Compact Discs (CDs), Portable Headset Audio, Total CD Players, Home Radios	348,200	0	Neg.	348,200
Information Products	Cordless/Corded Telephones, Wireless Telephones, Telephone Answering Machines, Fax Machines, Personal Word Processors, Personal Computers, Computer Printers, Computer Monitors, Modems/Fax Modems	916,900	192,500	21%	724,400
Total		**2,124,400**	**193,700**	**9%**	**1,930,700**

Table 17
Material Composition of Discarded Consumer Electronics

Type of Consumer Electronics	Steel	Copper and Brass	Aluminum	Lead	Other Metals[39]	Glass	Wood	Plastic	Other
Video Products	22%	3%	0%	7%	10%	27%	20%	11%	0%
Audio Products	21%	0%	0%	0%	30%	0%	3%	47%	0%
Information Products	27%	5%	4%	3%	4%	8%	0%	46%	2%
Total	**24%**	**3%**	**2%**	**4%**	**11%**	**15%**	**9%**	**32%**	**1%**

In its 1989 report, the EPA projected that discarded consumer electronics would account for about 85,000 tons of metallic lead disposed of in MSW landfills in the year 2000. Adjusting the EPA projections for a 9% recycling rate projected for 2000 yields a disposal rate of 77,350 tons of lead in discarded consumer electronic products—a number in reasonably close agreement with the 81,800 tons of lead disposed in consumer electronic products estimated in 2000 in the EPA/Franklin report.

3.6 ESTIMATED QUANTITIES OF HEAVY METALS DISPOSED IN MSW LANDFILLS

Based on the above information, ballpark estimates of the tonnages of three of the most prevalent RCRA heavy metals that are currently disposed in MSW landfills are provided in Table 18. As indicated, lead is estimated to account for over 97% of the tonnages disposed for these three metals. Tonnage data for other RCRA heavy metals disposed in MSW landfills are not available. However, it is likely that the combined tonnages of the other RCRA heavy metals disposed in MSW landfills would account for a very small percentage of the total tonnage of RCRA heavy metals disposed in MSW landfills on an annual basis.

Table 18

Ballpark Estimates of Tonnages of Three Heavy Metals Disposed in MSW Landfills in 2000

Heavy Metal	Tons/Year	Percent
Lead (1)	127,108	97.6
Cadmium (2)	2,680	2.1
Mercury (3)	383	0.3
Total	**130,171**	**100.0**

Notes (1) Lead tonnage calculated as follows: 281,886 tons (total projected by EPA in 1989) – 181,546 (quantity of lead projected in 1989 as being disposed from lead acid batteries in the year 2000) + 30,000 (lead content of disposed lead acid batteries estimated by Franklin Associates for the year 2000) – 85,032 (projected quantity of lead in 1989 as being disposed in consumer electronics in 2000) +81,800 (quantity of lead disposed in discarded consumer electronics in the year 2000 as estimated using data from the EPA/Franklin report).
(2) See Table 11.
(3) See Table 13.

The heavy metals identified in Table 18 are estimated to account for approximately 130,200 tons of MSW disposed in the year 2000. This tonnage represents 0.08% of the 162 million tons of MSW disposed in the U.S. for that year.[40] This tonnage is significantly less than the 284,600 tons of lead and cadmium that were projected by the EPA in 1986 to be disposed in MSW landfills in the year 2000. Therefore, it can be concluded that, despite the dramatic increase in the disposal of certain heavy metal products such as discarded consumer electronics in recent years, the tonnages of heavy metals being disposed in MSW landfills have decreased over the last 15 years due primarily to the recycling of lead acid batteries.

3.7 CONCLUSIONS

Based on a review of the literature, as well as an assessment of current research projects, the following conclusions are offered with respect to the characterization of products containing RCRA heavy metals that are currently being disposed in MSW landfills.

- The few studies identified in the literature that present information on the quantities and characteristics of heavy metals in MSW rely, for the most part, on data that are at least 15 years old. The one exception is the EPA/Franklin study (2000) that relies on material flow estimates rather than data obtained from actual field sampling.
- Based on available data, it appears that about 130,200 tons per year of RCRA heavy metals were disposed in MSW landfills in the U.S. in the year 2000. This tonnage represents 0.08% of the 162 million tons of MSW that were disposed in that year. This tonnage is significantly less than the 284,600 tons of lead and cadmium that were estimated by the EPA to be disposed in MSW landfills in 1986. Lead represents the major fraction (97.6%) of the major RCRA heavy metals being disposed of in MSW landfills on an annual basis, followed by cadmium (2.1%) and mercury (0.3%).
- The available data indicate that the relative fractions of products containing heavy metals in the waste stream are changing. For example, the contribution of lead-acid batteries to the levels of lead in MSW appears to be declining, while lead contributions from discarded consumer

electronics appear to be increasing. The available data indicate that, despite the dramatic increase in the disposal of discarded consumer electronics in recent years, the tonnages of RCRA heavy metals being disposed in MSW landfills have decreased over the last 15 years due primarily to the recycling of lead-acid batteries.

- The scarcity of current field data, along with these changing conditions, underscores the need for current field research in this area. For example, there is a need to update the work sponsored by the EPA in the late 1980s regarding the sources, quantities, and characteristics of heavy metals in MSW.

4.1 INTRODUCTION

This section presents the findings of current and recent research, as well as summarizes the relevant published literature, with regard to heavy metals in MSW landfill leachate.

4.2 BACKGROUND INFORMATION ON LANDFILL LEACHATE

4.2.1 WHAT IS LEACHATE?

Leachate can be defined as "a liquid that is produced when water or another liquid comes in contact with waste."[41] Leachate is formed as water percolates through the landfill and collects contaminants that are leached from the waste and/or are produced during the waste decomposition process.

As a result of Federal Subtitle D MSW landfill regulations promulgated by the EPA in 1991, landfill managers are required to collect and treat leachate both during the active life of the landfill, as well as during the landfill's post-closure period, which lasts for a minimum of 30 years following the closure of the landfill.

4.2.2 LANDFILL PROCESSES THAT IMPACT LEACHATE QUALITY

When MSW is disposed in an MSW landfill, it is generally accepted that the waste undergoes a decomposition, or stabilization, process that occurs in five sequential phases, as presented in Figure 1 and described below.[42]

- **Phase I: Initial Adjustment** – This phase is associated with the initial placement of the solid waste and the availability of sufficient moisture to support the biological decomposition process. An initial lag time occurs until an active community of microorganisms develops. Preliminary changes in environmental factors occur that result in favorable conditions for biochemical decomposition.

- **Phase II: Transition Phase** – In the transition phase, a transformation from an aerobic (i.e., with air or oxygen) to an anaerobic (i.e., without air or oxygen) environment occurs, as evidenced by the depletion of oxygen trapped within the landfilled waste. A trend toward reducing conditions (i.e., conditions where elements or molecules gain electrons) is established with the shifting of electron "acceptors" from oxygen to nitrates and sulfates. By the end of this phase, measurable concentrations of chemical oxygen demand (COD) and volatile organic acids (VOAs) can be detected in the leachate.

- **Phase III: Acid Formation Phase** – During this phase, a portion of the solid waste is hydrolyzed, reacting with water and producing chemical byproducts that are soluble in water. The anaerobic, acid-forming bacteria, which are the dominant type of bacteria during this phase, metabolize biodegradable organic matter in the waste and generate volatile organic acids (VOAs) as a metabolic byproduct. Due to the high concentrations of VOAs in this phase, a lower pH is often observed, indicating a more acidic leachate solution. The more acidic leachate, in turn, may tend to dissolve the metals present in the waste, to a certain extent, as the solubility of metals generally increases at lower pHs. The predominant features of this phase are the development of a viable biomass of acid-forming bacteria and the rapid fermentation of organic matter.

- **Phase IV: Methane Fermentation Phase** – In this phase, also referred to as the methanogenic phase, another group of anaerobic bacteria (the methanogens) predominate.

These bacteria convert the organic acids produced in Phase III to methane and carbon dioxide. A highly-reducing chemical environment develops, resulting in the reduction of sulfur compounds (e.g., sulfate (SO_4^{-2}) to sulfide (S^{-2})). The pH of the leachate is elevated due to the depletion of the volatile organic acids and the presence of ammonium (NH_4^+) ions. The elevated pH, in turn, is controlled by a bicarbonate (HCO_3^-) buffering system, which supports the growth of the methane-forming bacteria. Due to the higher pH and presence of sulfides and hydroxides (OH^-), conditions are favorable for metals precipitation.

- **Phase V: Maturation Phase** – In this phase, the biological activity of microorganisms shifts to relative dormancy, due to the limited availability of nutrients and readily-degradable organic matter. As a result of decreased microbial activity, gas production also decreases and the concentration of leachate pollutants, while steady, is much lower than in earlier phases.

Each of these decomposition processes, which occur at different rates depending on local conditions, involves a complex series of biological and chemical reactions that both respond to, as well as change, the chemical characteristics of the leachate being generated. Additionally, there are specific chemical and physical conditions that are associated with each phase that directly impact the leachability of metals in disposed products.

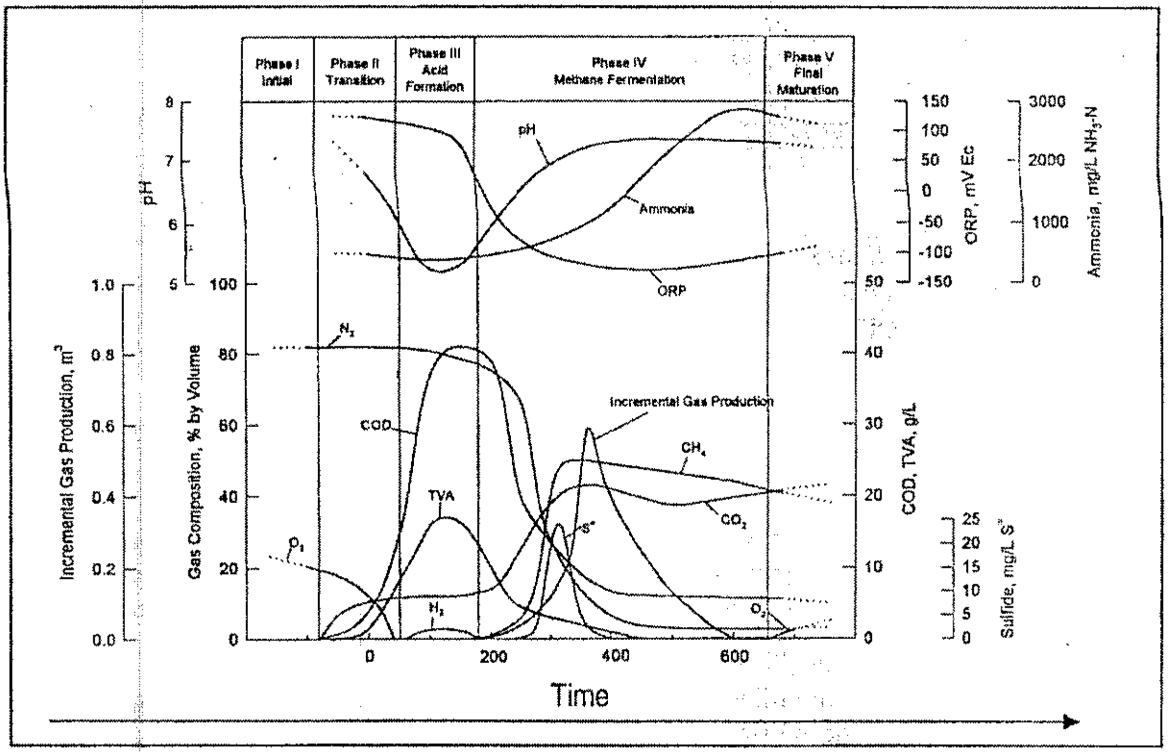

Figure 1 – Changes in Selected Indicator Parameters During The Phases of Landfill Stabilization

Source: Pohland, F.G., A.B. Al-Yousfi , and D.R. Reinhart, "Anaerobic Digestion of Organic Solid Waste in Bioreactor Landfills" in Biomethanization of the Organic Fraction of Municipal Solid Wastes. (Mata-Alvarez J. (Ed.) London, England: IWA Publishing, 2003. Chapter 11 (13 pp)

4.2.3 OTHER FACTORS THAT IMPACT LEACHATE COMPOSITION

In addition to the decomposition stages occurring in a landfill, leachate composition is also impacted by a number of other factors which are summarized below.

- **Waste Composition** – While regulations vary from state to state, MSW landfills can generally accept any or all of the following types of MSW substreams for disposal:
  - Residential waste;
  - Commercial waste;
  - Industrial, non process waste;
  - Non-Infectious medical waste;
  - Dewatered sludges (water and wastewater; industrial);
  - Construction and demolition waste;
  - Special wastes (asbestos, etc.).

  It is evident that the composition of leachate will vary depending on the relative quantities of each of the MSW substreams that are disposed in a given landfill. Additionally, there is significant variation in the material and chemical composition of each waste substream.

- **Landfill Age** – Leachate composition is significantly influenced by the length of time that has elapsed since waste placement, due, in large part, to the different phases of waste decomposition that occur. Since landfills are progressively filled with wastes, the average "age" of the waste in the landfill will increase over time. Therefore, the relative percentages of landfilled waste undergoing each of the five stages of decomposition will also change. For example, for a young landfill less than two years old, significant amounts of the landfilled wastes may be in the early phases of decomposition (i.e., Phases I, II, and III). Alternatively, in a landfill nearing the end of its 20-year life, most of the landfilled waste will be in Phases IV and V. No landfill has a single "age" but rather a family of ages associated with the various sections or cells within the landfill complex and their respective progress toward stabilization. Moreover, the rate of progress through these phases may vary depending on the physical, chemical, and microbiological conditions developed within each section with time.[43]

- **Moisture Availability** – Water is the most significant factor influencing the rate and perhaps the degree of waste stabilization as well as the quantity and strength of leachate. Moisture within the landfill serves as a reactant (in hydrolysis reactions), and dissolves metabolites and an array of soluble organic and inorganic waste constituents. In addition, it serves as a transport mechanism for nutrients and reaction products associated with waste biodegradation. Water also provides an opportunity for compounds that inhibit biodegradation to be diluted and/or attenuated, and it exposes the waste surface area to microbial attack. Recommended moisture contents, as reported in the literature, range from a minimum of 25 percent of the weight of the waste (as reported on a "wet" basis) to an optimum range of 40 to 70 percent.[44]

- **Landfill Design and Operation** – To achieve the optimum range of 40 to 70 percent moisture content of the waste, some landfills are designed and operated for leachate recirculation and/or bioreactor landfill operations. As the name implies, leachate recirculation involves the injection of collected leachate back into the landfill. The bioreactor landfill has evolved from the leachate recirculation concept and may include other liquids besides leachate that may be needed to achieve optimum moisture content of the entire landfill waste mass. These practices have been found to promote more rapid stabilization of the waste, the more rapid generation of landfill gas (thereby increasing the opportunity for better gas control and utilization) and the "in situ" (i.e., in-place) treatment of the leachate in the landfill.

Other landfill factors that also impact leachate composition include depth of waste, types and quantities of daily and intermediate cover materials, landfill temperature, and degree of waste processing (i.e., shredding or baling).[45]

4.3 HEAVY METAL CONCENTRATIONS IN LANDFILL LEACHATE

4.3.1 INTRODUCTION

Leachate from MSW landfills has been studied for over 40 years. Within the last six years, however, there have been five major studies that have attempted to characterize the types, quantities, and characteristics of organic and inorganic constituents that are contained in landfill leachate and to present the scientific basis and understanding regarding the factors that influence these parameters.

These recent studies on landfill leachate are summarized below.

4.3.2 RECENT RESEARCH EFFORTS TO CHARACTERIZE LANDFILL LEACHATE

4.3.2.1 Characterization and Evaluation of Landfill Leachate [46]

In September 2000, a draft report entitled Characterization and Evaluation of Landfill Leachate was submitted to the EPA by Science Applications International Corporation (SAIC).

This report presents the results of a broad-based effort to collect and review landfill leachate data. This effort included a review of existing scientific literature on landfill leaching processes and the factors that influence leachate generation and characteristics.

An integral part of the project was the development of a comprehensive database of landfill leachate characteristics. The database (which is entitled "LEACH 2000" and is still in draft form) includes data for conventional pollutants, metals, and organics in leachate from a variety of landfill types, including over 200 MSW landfills. The database was compiled using data from the following sources:

- Data representing 60 MSW landfills owned by Browning Ferris Incorporated (BFI).
- A 1992 Chemical Waste Management study of leachate quality that included data from 47 landfills, including a number of MSW landfills.
- Data collected by the EPA during the development of effluent guidelines for landfills, that included 21 MSW landfills.
- Data from the State of Florida on leachate characteristics for 65 MSW landfills.
- Data (adjusted by SAIC during the study) from the State of Wisconsin on leachate characteristics for 39 MSW landfills.

Although a large number of MSW landfills are represented in this database, they do not constitute a statistically representative sample of MSW landfills by geographic region or any other criterion. Nevertheless, these landfills do represent a variety of locations, ages, and other factors that are expected to result in variation between landfills.

The data on RCRA heavy metals concentrations in the LEACH 2000 database are presented in Table 19. As indicated, the mean concentrations of the RCRA heavy metals are relatively low, averaging less than 1 milligram per liter (or part per million) in all cases.

Table 19

Composition of MSW Leachate (mg/l)

Metal	N[a]	% Detected	10th %ile[b]	Median	Mean	90th %ile
Arsenic	2,444	71.1	0.006	0.020	**0.441**	0.100
Barium	1,779	93.4	0.084	0.405	**0.866**	1.700
Cadmium	2,351	31.5	0.001	0.010	**0.0283**	0.079
Chromium	2,776	63.0	0.010	0.051	**0.235**	0.341
Lead	2,539	50.2	0.004	0.021	**0.133**	0.250
Mercury	2,078	18.0	0.00014	0.00059	**0.00715**	0.0046
Selenium	1,754	18.2	0.0017	0.010	**0.0585**	0.180
Silver	1,830	17.8	0.002	0.0113	**0.0537**	0.056

Source: Science Applications International Corporation. Characterization and Evaluation of Landfill Leachate. (Draft). Arlington, VA: EPA, September 2000 (with additions).

(a) Data are from over 200 MSW landfills. "N" refers to the number of samples taken from over 200 MSW landfills. The 10th percentile indicates the value at which 10% of the measurements are equal to or below the indicated value. Similarly, for the 90th percentile, 90% of the measurements fall at or below the indicated value.

4.3.2.2 *Present and Long-Term Composition of MSW Landfill Leachate – A Review*[47]

This paper presents summary information on what is known about leachate from MSW landfills, based on a comprehensive scientific review of the literature. The paper includes a table (see Table 20) that presents heavy metal concentrations in leachate for over 125 European and Canadian landfills. As indicated, while the data are from non-U.S. landfills and is provided for only three of the eight RCRA heavy metals of concern in the U.S., the heavy metal concentrations are extremely low and, in most cases, are at or below U.S. Drinking Water Standards for the metals indicated.

The authors of this report concluded that:

> " The content of heavy metals in the leachates is generally very low as a result of attenuating processes (sorption and precipitation) that take place within the disposed waste."[48]

Table 20

Heavy Metal Concentration in Leachate from European and Canadian Landfills (a)

Metal	1	2	3	4	5	6	7	8	9	10	U.S. Stand. (b)
Cadmium	0.006	0.005	0.006	0.0002	0.0004	0.0003	0.0036	0.002-0.008	0.0002-0.018	<0.01-<0.04	0.005
Nickel	0.130	0.17	0.05	0.028	0.084	0.054	0.062	0.01-0.08	0.0036-0.348	<0.01-0.1	---
Zinc	0.67	0.6	2.2	0.2	0.36	0.085	5.31	0.003-0.011	0.05-9	<0.01-0.47	5.0
Copper	0.07	0.065	0.04	0.002	0.007	0.034	0.002	---	0.004-0.27	<0.02-0.17	1.3
Lead	0.07	0.09	0.02	<0.005	<0.005	0.056	0.188	0.016-0.067	0.005-0.019	<0.04-0.13	0.0
Chromium	0.08	0.28	0.01	0.003	0.016	0	0.002	0.033-0.085	0.005-1.62	<0.01-0.05	0.1

Source: Kjeldsen, P., M.A. Barlaz, A.P. Rooker, A. Baun, A. Ledin, and T.H. Christensen, 2003, "Present and Long-Term Composition of MSW Landfill Leachate – A Review," CRC Critical Reviews in Environmental Science and Technology, 32,4, pp. 297-336.

1. Average (undiluted) leachate concentration from 106 old, Danish landfills.[49]
2. Average leachate concentration in 20 German landfills in the methanogenic phase.[50]
3. Average leachate concentration in a full-scale test cell operated with leachate recirculation.[51]
4-7. Average leachate concentrations at four Danish landfills. Only site 4 has been closed.[52]
8. Ranges of leachate concentrations in the most contaminated groundwater wells at North Bay Landfill, Canada. [53]
9. Ranges of typical leachate concentrations in a study of 21- to 30-year old, German landfills.[54]
10. Ranges of typical leachate concentrations at six old landfills in the UK.[55]
-- Data not available.
a. Data listed are either the average or range for a given study in mg/l.
b. National primary drinking water regulations (www.epa.gov/OGWDW/wot/appa.html).

4.3.2.3 *Analysis of Florida MSW Landfill Leachate Quality*

In 1996-97, a study was conducted at the University of Central Florida to characterize leachate characteristics from MSW landfills in Florida.[56]

The analyses performed in the study were designed to identify trends in leachate characteristics and to determine the impacts of climate, location, landfill age, and waste characteristics.

To conduct the study, leachate data were obtained from the Florida Department of Environmental Protection, which provided leachate composition data from 55 "Class I" (i.e., MSW only) landfills. Data from unlined landfills were excluded from the study due to the potential for groundwater dilution and other sampling errors. In addition, facilities having less than one year of data were also excluded. These selection criteria resulted in the inclusion of 39 landfills in the study.

It is almost certain that data from these 39 facilities were also included in the LEACH 2000 database; however, the exclusion criteria described above were not applied to the database. Therefore, the analytical results presented in this study represent lined landfills for which no dilution of landfill leachate has occurred.

Another important aspect of this study was its attempt to characterize the leachate samples as representative of either the acidogenic phase (i.e., Phase III: Acid Formation Phase) or methanogenic phase (i.e., Phase IV – Methane Fermentation Phase) of waste decomposition. As indicated above, the chemical and physical leachate-forming conditions (such as pH) associated with each of these phases are different. Therefore, the leachate concentrations of pollutants such as heavy metals are expected to be different for each phase.

The results of the study of Florida landfill leachate are presented in Table 21 for heavy metal pollutants. As indicated, the average (mean) concentrations for the RCRA heavy metals (excluding arsenic) were found to be very low, with the mean concentrations of all metals (except barium) reported to be less than 0.1 mg/l.

Table 21

Analysis of Florida Landfill Leachate (mg/l)

Metal	Detects	Mean (mg/l)	Standard Deviation (mg/l)
Barium	230	0.216	0.487
Cadmium	205	0.00752	0.0239
Chromium	409	0.0416	0.0674
Lead	288	0.0292	0.114
Mercury	175	0.000696	0.00326
Selenium	175	0.0197	0.102
Silver	137	0.0291	0.249

Source: Reinhart, Debra R. and Caroline J. Grosh. Analysis of Florida MSW Landfill Leachate Quality. (Report #97-3) Gainesville, FL: Florida Center for Solid and Hazardous Waste Management, July 1998.

Note: It is not clear how non-detects were accounted for in this study.

According to the authors, the study results indicate that the Florida climate appears to produce dilute leachate that results in relatively low concentrations of organic and inorganic constituents compared to values that are reported in the literature. The authors concluded that, although heavy metals were found in Florida landfill leachate, "the concentration of these constituents is generally on the order of micrograms per liter."

4.3.2.4 *Life Cycle Inventory of a Modern MSW Landfill*

In 1997, the Environmental Research and Education Foundation (EREF) funded a study to analyze the life cycle environmental impacts of MSW landfills.[57] Conducted by Ecobalance, Inc., the results of the study were subsequently utilized by the EPA Office of Research and Development (EPA ORD) in the Landfill Module of its "Municipal Solid Waste Decision Support Tool (MSW-DST)."

The MSW-DST was developed by EPA ORD to help solid waste planners in the evaluation of costs and environmental issues and make informed decisions about MSW management. Extensive and detailed databases have been assembled and incorporated into a sophisticated software program that provides a comprehensive and standard method to screen MSW management strategies and ultimately bridge the gap between public policy and environmental science. Included in the MSW-DST are multiple design options for waste collection, transfer stations, materials recovery facilities, mixed MSW and yardwaste composting, combustion, refuse-derived fuel combustion, and disposal.[58]

Based on the study, high and low median concentrations for RCRA heavy metals in leachate were established as "default" input data for the MSW-DST. These default concentrations, which are presented in Table 22, are recommended for use if a community does not have access to actual local data for landfill leachate concentrations.

As indicated, even the high median concentrations provided by ORD as default values in its Municipal Decision Support Tool are very low, with the concentrations of all RCRA heavy metals (except barium) being less than 0.1 mg/l.

4.3.2.5 *Development Document for Final Effluent Limitations, Guidelines, and Standards for the Landfills Point Source Category*

In December 1999, the EPA published the "Final Effluent Limitation Guidelines and Pretreatment Standards for the Landfills Point Source Category Rule." This regulation established technology-based effluent limitations for wastewaters discharged directly to receiving waters from the operations of new and existing landfill facilities.[59] The regulation does not apply to landfills that discharge wastewater into a publicly-owned wastewater treatment facility (referred to as a "publicly-owned treatment works, or POTW).

In the development of this rule, the Agency, with support from Science Applications International Corporation (SAIC), prepared a Development Document for Final Effluent Limitations Guidelines and Standards for the Landfills Point Source Category.[60]

Table 22

Metal Concentrations in Leachate for Traditional and Bioreactor Landfills

Metal	Median Concentrations (mg/l)	
	Low Median	High Median
Arsenic	0.029	0.030
Barium	0.679	0.860
Cadmium	0.0025	0.007
Chromium	0.052	0.085
Lead	0.0057	0.013
Mercury	0.00010	0.00042
Selenium	0.0025	0.0097
Silver	0.0125	0.066

Source: Life-Cycle Inventory of a Modern Municipal Solid Waste Landfill, Environmental Research and Education Foundation, Alexandria, VA, 1999.

Note: High and low median concentrations are median concentrations developed from industry data divided into high and low data sets.

Low Median = average of leachate concentrations using detected values and half of the minimum reporting limit for non-detected values

High Median = average of leachate concentrations using only detected values, non-detected values were not included in this average

The wastewater covered by the rule, and investigated during the project, includes leachate, landfill gas condensate, drained free liquids, laboratory-derived wastewater, contaminated stormwater, and contact washwater from truck washings and surface areas having direct contact with solid waste. The document noted that leachate typically represents over 97% of the total wastewater volume from Subtitle D landfills.

In developing the regulation, the EPA assumed that the wastewater would be treated at the landfill in an on-site treatment facility that would include the treatment processes of equalization, activated sludge biological treatment, and multimedia filtration.

To support the development of the landfill effluent guidelines, the EPA collected data from a variety of different sources, including:

- Existing data from previous EPA and other governmental data collection efforts.
- Industry-provided information.
- New data collected from questionnaire surveys (220 respondents).
- Field sampling data (including characterization sampling at ten Subtitle D non-hazardous landfills in addition to influent data collection during six, week-long sampling episodes).

The median raw wastewater concentrations of RCRA heavy metals from Subtitle D Non-Hazardous landfills, as measured by the EPA, are presented in Table 23.

As Table 23 indicates, the EPA found that six of the eight RCRA heavy metals were not detected at "treatable" levels (i.e., levels that would be reduced by selected treatment processes). The metals that were detected—barium and chromium (including hexavalent chromium)—were excluded from regulation, because "at the concentrations found at non-hazardous landfills, these pollutants are not likely to cause toxic effects."[61]

Table 23

Subtitle D Non-Hazardous Subcategory – Median Raw Wastewater Concentration

Pollutant	Subtitle D Municipal Median Concentration (mg/l)	Regulatory Limit Set by EPA for Direct Dischargers?	
		Yes/No	Reason
Arsenic	Not detected at treatable levels	No	
Barium	0.483	No	Present in concentrations that are not likely to cause toxic effects
Cadmium	Not detected at treatable levels	No	
Chromium	0.028	No	Present in concentrations that are not likely to cause toxic effects
Chromium (Hexavalent)	0.030	No	Present in concentrations that are not likely to cause toxic effects
Lead	Not detected at treatable levels	No	
Mercury	Not detected at treatable levels	No	
Selenium	Not detected at treatable levels	No	
Silver	Not detected at treatable levels	No	

Source: EPA. Development Document for Final Effluent Limitations, Guidelines, and Standards for the Landfills Point Source Category. (EPA-821-R-99-019). Washington, DC: Office of Water, January 2000.

With respect to raw wastewater at municipal landfills, the EPA concluded that:

> "Generally, toxic heavy metals were found at relatively low concentrations. EPA did not find toxic metals such as arsenic, cadmium, mercury, and lead at treatable levels in any of EPA's sampling episodes.[62]

The only heavy metal selected for regulation for this group of landfills was zinc, which the EPA stated was "selected for regulation in spite of its relatively low untreated wastewater concentration." The EPA selected zinc for regulation because it observed incidental removals of zinc at the treatment systems selected for "Best Practicable Control Technology (BPT)[63]

In establishing final effluent guidelines, the EPA concluded that national pretreatment standards were not necessary for landfills. The EPA found that POTWs adequately treated pollutants in landfill wastewater and only a very small quantity of pollutant loads discharged by landfills to POTWs are further discharged to rivers, streams, or estuaries. Finally, the EPA concluded that wastewater discharges from landfills do not cause operational problems at POTWs. Based on these findings, the EPA did not establish direct discharge limits for any of the RCRA heavy metals for MSW landfill leachate that is directly discharged to receiving waters following on-site treatment. In addition, no national pretreatment standards were established for RCRA heavy metals or any other pollutants in MSW landfill leachate.

It should be noted that the EPA's decision not to establish effluent standards for any of the RCRA heavy metals does not mean that the Agency concluded that treatment for removal of these metals from landfill leachate would not be required in some cases. Rather, it indicates that treatment requirements for RCRA heavy metals should be determined by local conditions and therefore should be developed through local wastewater pretreatment programs.

4.3.3 PERSPECTIVES REGARDING AVERAGE HEAVY METAL CONCENTRATIONS IN LANDFILL LEACHATE

Based on a review of recent studies, it can be concluded that RCRA heavy metal concentrations in leachate are relatively low.

To provide a perspective on how low these concentrations are, the mean concentrations reported for MSW landfills in the Leach 2000 database are compared with various standards in Table 24, as described below.

- **TCLP Regulatory Levels** – The regulatory levels that are used in the TCLP to determine whether or not a solid waste should be classified as hazardous are also provided in Table 24. The mean concentrations of RCRA heavy metals reported in the LEACH 2000 database for non-hazardous waste landfills are less than 10% of the TCLP regulatory levels. In addition, the "90th Percentile" leachate values for RCRA heavy metals presented in Table 19 (values for which 90% of the data points are equal to or below) are all lower than the TCLP regulatory levels.
- **U.S. Drinking Water Standards** – The U.S. primary drinking water standards are among the highest standards for water purity in the world. Table 24 compares the mean RCRA heavy metal concentrations in leachate (collected at the bottom of MSW landfills) to the primary drinking water standards which are required to be met "at the tap" by public water supply systems in the U.S. It is noteworthy that all of the LEACH 2000 average concentrations for RCRA heavy metals are less than 10 times higher than the drinking water standards established for these metals. In addition, the mean concentration for barium (0.866 mg/l) is less than the drinking water standard for barium (2 mg/l), while the mean concentration for selenium (0.0585 mg/l) is only slightly higher than the drinking water standard for selenium (0.05 mg/l).
- **EPA Groundwater MCLs** – The EPA has established "Maximum Contaminant Levels" (MCLs) for allowable concentrations of RCRA heavy metals in groundwater for MSW landfills that are designed with alternative liner systems. In comparison to these MCLs, as presented in Table 24, the LEACH 2000 mean concentrations for RCRA heavy metals are all less than 10 times higher than their respective MCL limits. In the case of barium, the mean concentration is shown to be less than the MCL established for barium. The MCL is measured at the "relevant point of compliance" (i.e., a location that is required to be no more than 150 meters (164 yards) from the waste management unit boundary). The EPA established the MCL limits by assuming that the TCLP maximum concentrations would be "diluted and attenuated" (and therefore lowered) by a factor of 100 before reaching the relevant point of compliance.[64] Applying the same dilution and attenuation factor (DAF) to the LEACH 2000 mean concentrations, it is apparent that the RCRA

heavy metals in leachate would most likely be diluted and/or attenuated to comply with their respective MCLs before any uncontained and/or uncollected landfill leachate reached the relevant point of compliance.

- **Local Government Pretreatment Standards** – The pretreatment standards for RCRA heavy metals established by four counties located in different parts of the U.S. are also presented in Table 24. As indicated, the average RCRA heavy metal concentrations reported in the Leach 2000 database are lower than the pretreatment standards established by two of the four counties. However, in one county (Broward County, FL) leachate pretreatment would be required to meet local pretreatment standards for arsenic, while in two other counties (Henrico County, VA and Camden County, NJ) leachate pretreatment would be required to meet local standards for mercury. It is clear that, in these two cases, leachate pretreatment would be required to meet the relatively stringent local pretreatment standards set by these counties.

In summary, based on database and research data representing thousands of data points from hundreds of MSW landfills, the average concentrations of RCRA heavy metals in MSW landfill leachate were found to be significantly lower than the TCLP regulatory levels. The average RCRA heavy metal concentrations in MSW leachate were in compliance with the final effluent limitation guidelines and the national pretreatment standards set by the EPA in 1999 for the landfills point source category. When compared with drinking water standards (i.e., water purity standards at the tap), average concentrations for RCRA heavy metals in leachate (from the bottom of an MSW landfill) were found to be less than 10 times higher than the drinking water standards and, for one metal, were found to meet drinking water standards. Finally, average RCRA heavy metal leachate concentrations were found to meet local pretreatment standards without leachate treatment except in cases where stringent pretreatment standards had been established for specific metals.

4.4 LANDFILL CONDITIONS AND PROCESSES THAT IMPACT THE LEACHING OF HEAVY METALS FROM DISPOSED PRODUCTS

4.4.1 INTRODUCTION

The low average concentrations of heavy metals in leachate documented by recent studies are not caused by the lack of heavy metals in MSW. As presented in Section 3, it is estimated that 130,200 tons of RCRA heavy metals are disposed in MSW landfills each year in the U.S. It has been concluded in one study that less than 0.02% of heavy metals in landfills are leached after 30 years of disposal.[65]

As described above, there are certain physical and chemical conditions that are associated with each phase of waste stabilization of landfilled waste. For example, during Phase III (Acid Formation), the pH of the leachate decreases due to the production of organic acids during this phase.

The physical and chemical conditions associated with each phase of decomposition, in turn, affect the occurrence of certain chemical and physical processes that control the leaching of heavy metals. These conditions and processes are described below.

Table 24

Comparison of RCRA Heavy Metal Leachate Concentrations To Published Standards

Metal	Leach 2000 Database – Mean Values (mg/l)	Local Government Pretreatment Standards				U.S. Drinking Water [5]Maximum Cont. Level (mg/l)	RCRA Regulations	
		Broward County, FL [1] Maximum Concentration (mg/l)	Camden County, NJ [2] Max. Daily Concentration (mg/l)	Henrico County, VA [3] Max. Daily Concentration (mg/l)	King County, WA [4] Daily Avg. Maximum (mg/l)		Groundwater Maximum Cont. Level (mg/l)	TCLP Regulatory Level (mg/l)
Arsenic	0.441	0.1	1	N/A	1	0.05	0.05	5
Barium	0.866	N/A	N/A	N/A	N/A	2	1	100
Cadmium	0.0283	0.7	0.04	0.23	0.5	0.005	0.01	1
Chromium	0.235	1	2	2.75	2.75	0.1	0.05	5
Lead	0.133	0.4	0.3	0.44	2	0.015	0.05	5
Mercury	0.0715	0.1	0.01	0.0031	0.1	0.002	0.002	0.2
Selenium	0.0585	N/A	N/A	N/A	N/A	0.05	0.01	1
Silver	0.0537	0.35	N/A	1.58	1	N/A	0.05	5

Notes:
1 Broward County, FL, Office of Environmental Services. Discharge Limits. (http://www.broward.org/oes/oei01000.htm. 12/8/03
2 Camden County, NJ, Municipal Utilities Authority. Sewer Use Ordinance Industrial Pretreatment Rules and Regulations). http://www.ccmua.org/ipptablei.html. 12/8/2003
3 Henrico County, VA, Excerpt from Henrico County Code Recodified as Title 23 (Amended August 13, 1997).
4 King County, WA, Wastewater Treatment Division. King County Local Limits. (http://dnfr.metrokc/gov/wlr/indwaste/local.htm
5 U.S. EPA. List of Drinking Water Contaminants and MCLs. (www.eap.gov/safewater/mcl.html)

4.4.2 LANDFILL PROCESSES THAT IMPACT THE LEACHING OF HEAVY METALS

Three processes are primarily responsible for the control of heavy metal concentrations in landfill leachate:

- **Sorption** – Sorption (which includes adsorption and absorption) refers to a process whereby ions, such as heavy metal ions, adhere to oppositely charged sites of colloidal particles, calcite, clay minerals, organics, and oxides of iron, manganese, aluminum, and silicon.[66] Landfilled waste contains soils and organic matter that, especially at the neutral to high pH values, have a significant sorptive capacity.[67] Alternatively, heavy metal ions can adhere to small, suspended particles (colloids) in the leachate, causing leachate metal concentrations to increase.[68] Finally, metal cations can be chelated by compounds such as carboxylic acids and iron hydroxides that are formed during the refuse oxidation process.[69]

- **Complexation** – Complexation refers to the chemical bonding of metal ions with non-metallic molecules referred to as "ligands." This process can increase the solubilities, and therefore the concentrations, of metals in leachate.

- **Precipitation** – Precipitation refers to the formation of insoluble compounds from soluble reactants in a solution. The solubilities of many metals are low in the presence of sulfide, carbonate, and hydroxide anions. The presence of sulfides is particularly important in attenuating heavy metals by in situ precipitation of low-solubility metal sulfides under the reducing conditions that exist during Phase IV of the stabilization process.[70]

Other processes that also control leachate heavy metal concentrations, especially at landfills that employ leachate recirculation, include in situ filtration of the leachate and the capture of leachate in stagnant pools of interstitial water within the landfilled waste. All of these processes point to the inherent capacity of the landfill to provide for attenuation of inorganic waste constituents such as heavy metals.[71]

4.4.3 LANDFILL CONDITIONS AND LEACHATE CHARACTERISTICS DURING THE METHANOGENIC PHASE

The five phases of waste stabilization described above are sequential for waste placed in the landfill. The sequencing of each phase is indicated in Figure 1. At operating landfills, it is likely that all of these phases are occurring simultaneously. On a given day at a "middle-aged" landfill, water percolating through the landfill will most likely flow through wastes that are in each of the five stages of decomposition.

It is evident, from Figure 1, the anaerobic decomposition process that occurs in Phase IV (the methanogenic phase) is the dominant stabilization process. The most important chemical condition regarding Phase IV is that there is no oxygen available to react with any soluble heavy metals and other pollutants or to allow aerobic metabolic processes to occur. The result is that a "reducing environment" exists in Phase IV waste, causing the RCRA heavy metal ions to react with sulfides and other anions and precipitate out of the leachate.

The characteristics of leachate generated during Phase IV (the methanogenic phase) strongly favor the removal of any soluble metals from the leachate through precipitation processes. These characteristics include the following:

- **Neutral to High pH** – In Phase IV of the stabilization process, anaerobic bacteria metabolize the organic acids produced in Phase III, producing methane, carbon dioxide and ammonium (NH_4^+) ions as byproducts. As a result, the prevailing pH is neutral or above.

- **Availability of Sulfide, Carbonate, and Hydroxide Ions** – In oxidation-reduction chemical reactions, elements either lose electrons (and are oxidized) or gain electrons (i.e., are reduced). In Phase IV of the stabilization process, reducing conditions exist, meaning that elements and compounds tend to gain electrons using organic matter as the electron donor. For example, in this phase sulfate ions (SO_4^{-3}) are reduced to sulfide ions (S^{-2}). These sulfide ions, as well as carbonate and hydroxide ions, are then available during subsequent phases to react with many heavy metal species to form insoluble compounds that effectively remove these heavy metals from the leachate.[72]

- **In Situ Filtration** – The landfilled waste effectively acts as a filter, especially for landfills with leachate recirculation. The cleansing effect of this "in situ" filtration mechanism results in the removal of suspended solids and other leachate constituents.

- **Forms of Heavy Metals in Disposed Products** – The forms in which heavy metals occur in the products which are disposed are also likely to impact their leaching behaviors.[73] One study found that a major portion of the total metal content in MSW existed in forms that were not likely to undergo chemical reactions in landfills.[74] Examples include the disposal of cadmium in plastics. and zinc in scrap metal.

It should be noted that, while Phase IV is the dominant stabilization process, it may be preceded by a relatively long-term Phase III. This acid phase is the most vulnerable phase with respect to heavy metal mobility due to the greater solubility of metals under low pH conditions and the abundance of mobilizing species.

Since landfills are constructed in horizontal layers, leachate generated in the uppermost layers undergoing the initial phases of stabilization percolates through the bottommost layers of the landfill, which, except for the first few years of the landfill's life, will have reached Phases IV or V of the stabilization process. Therefore, heavy metals that may be mobilized in the uppermost layers due to Phase III conditions, are likely to be precipitated out as the leachate passes through lower landfill lifts due to the conditions described above which occur in Phases IV or V of the stabilization process. This percolation process would not take effect, however, if the leachate flow is "short circuited" through the waste mass due to the development of vertical leachate channels.

4.4.4 IMPACTS OF CONDITIONS THAT EXIST DURING THE METHANE FERMENTATION PHASE ON HEAVY METAL CONCENTRATIONS

The impacts of conditions that exist during the methane fermentation phase (Phase IV) of waste stabilization on any soluble heavy metals in landfill leachate are summarized in Table 25.

Sulfide precipitation is often cited as an explanation for low concentrations of heavy metals in leachate.[75] In general, concerning the presence of heavy metals in leachate, the impact of sulfide precipitation is expected to dominate the impact of complexation.[76] Of the RCRA heavy metals, arsenic, cadmium, lead, mercury, selenium and silver all react with sulfide ions to form insoluble precipitates.

Other anions—namely carbonate (CO_3-) and hydroxide (OH-) anions—are also present in leachate formed during Phase IV. Carbonate anions are abundant in landfill leachate. However, the solubilities of metal carbonates are generally higher than metal sulfides. Insoluble hydroxide precipitates, such as chromium hydroxide, form at all landfill pH ranges even in the presence of sulfides.[77]

During Phase IV, there is a potential for many of the metals, including mercury, to be "methylated" by reaction as a result of the anaerobic decomposition process that occurs during this phase. (The impact of this process on heavy metals concentrations in landfill gas is discussed in the next section.)

Table 25

Impact of Phase IV Conditions on Heavy Metal Concentrations in Landfill Leachate

RCRA Heavy Metals	Impact of Conditions that Exist During The Methane Fermentation Phase
Arsenic	Precipitates out as arsenic sulfide due to presence of sulfides, higher pH, and reducing conditions that exist during methane fermentation phase of landfill decomposition.
Cadmium	Precipitates out as cadmium sulfide due to presence of sulfides, higher pH, and reducing conditions that exist during methane fermentation phase of landfill decomposition.
Chromium (III)	Is insoluble in the neutral and alkaline pH ranges. In addition, chromium forms insoluble precipitates with hydroxides.
Chromium (Hexavalent)	Under intermediate and reducing conditions, hexavalent chromium reduces to trivalent chromium, which is insoluble in the neutral and alkaline pH ranges. Chromium hydroxide, which is insoluble, forms at all pH ranges, even in the presence of sulfides.
Lead	Precipitates out as lead sulfide due to presence of sulfides, higher pH, and reducing conditions that exist in methanogenic phase of landfill decomposition.
Mercury	The insoluble mercuric sulfide is formed under mildly reducing conditions.

In summary, many of the RCRA heavy metals that may be present in landfill leachate will form insoluble metal sulfides and therefore precipitate out of the leachate. While chromium does not form an insoluble sulfide precipitate, it tends to form insoluble precipitates with hydroxide. Additionally, heavy metal ions are adsorbed or absorbed by daily and intermediate cover soils or constituents of the landfilled solid wastes. These processes are favored by the leachate conditions, such as high pH levels and high concentrations of sulfide ions, which exist during the methanogenic phase of waste stabilization. Finally, the in situ filtration of leachate, as well as the interstitial storage of leachate in the waste mass, are additional processes that occur during this phase to further reduce heavy metal leachate quantities and concentrations.

4.5 THE POTENTIAL FOR METALS TO LEACH OUT OF LANDFILLS OVER THE LONG-TERM

As discussed above, the landfill conditions and leachate characteristics associated with Phase IV of the waste stabilization process create an environment in which solubilized heavy metals are readily redeposited out of leachate by precipitation, absorption or adsorption into the landfilled waste mass. As shown in Figure 1, Phase IV conditions carry over to Phase V – the Maturation Phase.

There have been some studies that have investigated whether Phase V conditions could change over long periods of time (on the order of thousands of years). Specifically, if oxygen re-enters the landfill, aerobic decomposition of the remaining degradable waste could be initiated. This scenario, however, would require the restoration and sustaining of a viable aerobic microbial consortium, with continuing availability of oxygen and nutrients, which is very unlikely.

Other changes in Phase V conditions that would impact the long-term concentrations of metals in leachate include a mild lowering of the pH and an increase in the oxidation-reduction potential of the waste mass. The pH would be lowered due to the production of carbon dioxide during the aerobic decomposition process. The oxidation-reduction potential would also increase due to the renewed availability of oxygen.

In summary, there are a number of processes that theoretically can affect the leaching of any redeposited metals from landfills over long periods of time.

The authors of a recent study on landfill leachate addressed the issue of the potential for landfilled metals to mobilize and leach out over the long term.[78] They report that a model has recently been developed to predict the long-term emissions of metals from landfills.[79] The model considers the eventual oxidation of all refuse organic matter, reactions with humic substances, and metal sulfide precipitates that bind metals as well as the pH buffering resulting from calcite dissolution. The rate and impact of oxygen diffusion into landfills were evaluated over a range of landfill geometries and degrees of saturation. Based on the model outputs, the model developers concluded that mobilization of heavy metals in closed landfills would not occur for thousands of years.

The leachate study authors also referenced another recent study which found that landfills contain sufficient buffering capacity to maintain alkaline conditions for more than 2,000 years and predicted that remobilization of heavy metals due to lower pH levels would not occur for many centuries.[80]

Both the modeling and studies that have been conducted to date indicate that any remobilization of heavy metals within the landfill, if it does occur, may proceed very slowly and is not likely to occur for thousands of years.

Finally, soil environments generally exist within and around MSW landfills in which metals mobility is very low. Thus, it is very likely that any releases of metals that may occur - due to changes in landfill conditions that occur over very long timeframes - will be contained either within the landfill itself or within the immediate vicinity of the landfill.

4.6 CONCLUSIONS

Based on a review of recent studies and relevant literature, the following conclusions are drawn with respect to the presence of heavy metals in leachate from MSW landfills.

- Database and research data representing thousands of data points from hundreds of MSW landfills indicate that the average concentrations of RCRA heavy metals in MSW landfill leachate are significantly lower than the TC regulatory levels.

- When compared with drinking water standards (i.e., water purity standards at the tap), average concentrations for RCRA heavy metals in leachate (from the bottom of an MSW landfill) were found to be less than 10 times higher than the drinking water standards and, for one metal, were found to meet drinking water standards.

- Attenuating mechanisms within the landfill that limit the leaching of heavy metals include the precipitation of the heavy metals due to the presence of sulfide, carbonate and hydroxide ions and the adsorption and/or absorption of the heavy metals within the waste mass.

- The EPA confirmed the findings of recent studies regarding the low levels of heavy metals in leachate in 1999 when it promulgated final effluent limitation guidelines for landfills. In its action, the EPA did not establish national regulatory discharge limits for any of the RCRA heavy metals for leachate that is directly discharged to a surface water body following on-site treatment at the landfill.

- The EPA's decision not to promulgate national discharge limits for any of the RCRA heavy metals anticipated the possible implementation of local pretreatment standards based on local conditions. When comparing the average concentrations of RCRA heavy metals reported in the LEACH 2000 database to industrial pretreatment standards established in four U.S. counties, it was found that the average concentration for two metals - arsenic and mercury – were higher than local pretreatment standards. Based on this finding, it is apparent that, although the concentrations of RCRA heavy metals in leachate are generally low, they may be high enough to require pretreatment in certain areas.

- Theoretically, heavy metal concentrations in leachate could increase over very long periods of time following the closure of a landfill if the landfill liner systems are breached and air re-enters the landfill, enabling aerobic decomposition processes to be reinitiated. This scenario would require the restoration and sustainment of a viable aerobic microbial consortium, with continuing availability of oxygen and nutrients. Even if a site does turn aerobic, precipitation of metal hydroxides and carbonates will still limit the release of metals. Computer modeling and limited laboratory investigations addressing this long-term risk have indicated that mobilization of heavy metals from closed landfills, if it does occur, is not likely to occur within a very long timeframe (i.e., thousands of years).

5.1 INTRODUCTION

This section addresses the subject of RCRA heavy metals in landfill gas. The findings of current and recent research, as well as summaries of the relevant published literature, are presented.

5.2 BACKGROUND INFORMATION ON LANDFILL GAS

5.2.1 WHAT IS LANDFILL GAS?

Landfill gas (LFG) is a natural byproduct of the biological decomposition of the organic fraction of landfilled solid waste.[81] The primary constituents of LFG are methane and carbon dioxide. However, LFG also contains a number of trace constituents including hydrogen sulfide, water vapor, ammonia, and a variety of volatile organic compounds (VOCs). Typical concentration ranges for the primary constituents of LFG are presented in Table 26. As is the case with heavy metals in leachate, the constituent concentrations of landfill gas are temporally dependent on the stabilization phase or phases that are occurring in the landfilled waste.[82]

Table 26
Typical Range of Gases in LFG

Constituent	Typical Concentration Range (% by Dry Volume)
Methane	45.0 – 60.0
Carbon Dioxide	35.0-45.0
Nitrogen	1.0-2.0
Oxygen	0.2-1.0
Trace Constituents	0.1-0.3
Characteristics	
Temperature (Degrees F)	
As Generated	100-120
At the Wellhead	60-120
Moisture Content	Saturated
Specific Gravity	0.98-1.02
Heating Value (Btus/SCF)	400-550

Source: Hickman, H. Lanier, Principles of Integrated Solid Waste Management. Annapolis, MD: American Academy of Environmental Engineers, 1999.

The federal Subtitle D landfill regulations promulgated by the EPA in 1991 addressed the explosion hazards associated with LFG. (Methane exhibits explosive characteristics at 5% to 15% by volume). To comply with these regulations, landfill managers are required to manage LFG so that it does not present an explosion hazard in either on- or off-site structures or enclosures.

Additional LFG regulations were promulgated by the EPA under the Clean Air Act in 1996.[83] The purpose of these regulations was to address two additional concerns associated with LFG; namely, the global warming impact of the methane in LFG and the potential health impacts associated with a group of trace LFG constituents referred to as "non-methane organic compounds" (NMOCs).

With respect to global warming, landfills have been found to be the largest contributor to anthropogenic methane emissions in the U.S., generating about one-third of U.S. methane emissions.[84] On a molar basis, methane has 20 to 25 times the impact of carbon dioxide on global warming.

LFG contains a number of contaminants that are of concern with respect to human health and the environment. Landfills have been found to emit more than 100 types of NMOCs. The majority of these NMOCs are volatile organic compounds (VOCs), which contribute to urban smog. In addition, over 30 of the NMOCs are hazardous air pollutants.

As a result of the 1996 regulations, large landfills (i.e., landfills with over 2.76 million tons of waste in place and with estimated NMOC emissions of over 55 tons per year) are now required to collect and control LFG emissions. It should be noted that the collection and control of LFG generally involves the combustion of the gas, which results in the destruction and/or transformation of many of the NMOCs and other pollutants contained in the gas.

In January 2003, the EPA promulgated additional Clean Air Act regulations that established national emission standards for hazardous air pollutants from MSW landfills. The regulations also require bioreactor landfills that are subject to existing Clean Air Act regulations (i.e., large bioreactor landfills) to collect and control LFG emissions within 180 days after the landfill has reached a moisture content of 40% (i.e., the landfill has met EPA's definition of a bioreactor landfill).[85]

5.2.2 LANDFILL PROCESSES THAT IMPACT LFG CHARACTERISTICS

The five stages of decomposition that landfilled wastes undergo were described in Section 4. The impact of these decomposition stages on the characteristics of LFG are described below.

- **Phase I: Initial Adjustment** – As indicated in Section 4, this phase is associated with the initial placement of the solid waste and the accumulation of moisture within the landfill. In this initial phase, aerobic bacteria use oxygen to metabolize the readily-decomposable portions of the waste. Carbon dioxide and water vapor are the main gaseous byproducts of this phase.

- **Phase II: Transition Phase** – In the transition phase, a transformation from an aerobic (i.e., with air or oxygen) to an anaerobic (i.e., without air or oxygen) environment occurs, as evidenced by the depletion of oxygen trapped within the landfilled waste.

- **Phase III: Acid Formation Phase** – During this phase, the solid waste is hydrolyzed, reacting with water and producing chemical byproducts that are soluble in water. The anaerobic, acid-forming bacteria, which are the dominant type of bacteria during this phase, metabolize the biodegradable organic content of the waste and generate volatile organic acids as a metabolic byproduct. The principal gas generated in this phase is carbon dioxide. However, hydrogen gas is also produced and is sometimes detected in Phase III as the development of a more reducing chemical environment continues. Hydrogen gas is important in the reduction of carbon dioxide to methane that occurs during Phase IV.

- **Phase IV: Methane Fermentation Phase** – In this phase, also referred to as the methanogenic phase, another group of anaerobic bacteria (the methanogens) predominate. These bacteria convert the organic acids produced in Phase III to methane. In addition, ammonia and hydrogen sulfide gases are produced by other types of bacteria (e.g., heterotrophic bacteria). However, these compounds exist as weak bases or acids in solution and their release in any magnitude in gaseous form is dependent on pH. Water vapor derived principally from the moisture contained within the waste mass is also carried off with the gas generated. The presence of sulfides causes heavy metals to be attenuated through precipitation and this attenuation mechanism affects whether or not significant quantities of heavy metals, including metallic and methylated mercury, can be released in gaseous form. Also, the production of methane by the methanogenic bacteria can promote the methylation of mercury and other metals, which could subsequently lead to the volatilization and potential release of these metals in the gas transport phase.

- **Phase V: Maturation Phase** – In this phase, the biological activity of microorganisms shifts to relative dormancy, due to the limited availability of either moisture or nutrients and organic matter. As a result of decreased microbial activity, gas production also decreases. In the very long-term, oxygen may re-enter the landfill, increasing the potential for the aerobic decomposition process to be restarted. If this occurs, the gas phase oxidation products—namely carbon dioxide and water vapor—would again be produced.

Each of these decomposition processes occur at different rates, depending on local conditions, and involves a complex series of biological and chemical reactions that both respond to, as well as change, the chemical characteristics of the LFG being generated.

5.2.3 OTHER FACTORS THAT IMPACT LFG COMPOSITION

In addition to the decomposition stages occurring in a landfill, LFG composition is impacted by a number of other factors, which are summarized below.

- **Waste Composition** – While regulations vary from state to state, MSW landfills can generally accept any or all of the following types of MSW substreams for disposal:
  - Residential waste;
  - Commercial waste;
  - Industrial, non-process waste;
  - Non-Infectious medical waste;
  - Dewatered sludges (water and wastewater; industrial)
  - Construction and demolition waste;
  - Special wastes (asbestos, etc.).

  It is evident that the composition of landfill gas will vary depending on the relative quantities of each of the MSW substreams that are disposed in a given landfill. For example, disposal of significant quantities of construction and demolition wastes containing wallboard (gypsum) leads to sulfide production under anaerobic sulfate reducing conditions, with excess sulfide potentially released as hydrogen sulfide. Additionally, there is significant variation in the material and chemical composition of each waste substream.

- **Landfill Age** – LFG composition is significantly influenced by the length of time that has elapsed since waste placement, due in large part to the different phases of waste decomposition that occur.

- **Moisture Availability** – Water is the most significant factor influencing the degree and rate of waste stabilization as well as the quantity and characteristics of LFG. Recommended moisture contents, as reported in the literature, range from a minimum of 25% (wet basis) to an optimum range of 40 to 70% to support full stabilization of the organic portion of the waste.[86]

- **Vapor Pressure** – The low vapor pressures exhibited by all metals except mercury over the range of temperatures that occur in MSW landfills are also limiting factors with respect to gaseous metal emissions.

5.3 HEAVY METAL CONCENTRATIONS IN LFG

5.3.1 INTRODUCTION

Of all the RCRA heavy metals found in MSW, mercury is the only metal that has historically caused concern with respect to its concentration in LFG. This is because, at ambient temperatures, mercury is the only metal that exists in liquid form. Mercury has a relatively high vapor pressure compared to the other RCRA heavy metals and has the highest volatility of any metal. When it vaporizes, mercury becomes a colorless, odorless gas.

In addition to its elemental form (Hg), mercury can be metabolized by anaerobic bacteria to produce methyl mercury. Methyl mercury can be produced either as mono-methyl mercury (CH_3-Hg) or dimethyl mercury (CH_3-Hg-CH_3). (In addition to mercury, other RCRA heavy metals, including arsenic, selenium, and lead, can also be metabolized to form gaseous methylated metal compounds.)

Mercury and its compounds are toxic to humans.[87] The toxicity varies among different types of mercury. Generally, organic forms of mercury (i.e., methyl mercury) are much more toxic than the inorganic forms.

In a recent report to Congress by the EPA, the following points were made with respect to mercury in the environment. .[88]

- Mercury moves through the environment as a result of both natural and human activities.
- The human activities that are most responsible for causing mercury to enter the environment are the combustion of mercury-containing fuels and materials and industrial processes.
- Concentrations of mercury in air and water are usually low and of little direct concern. However, once mercury enters water bodies, either through direct discharge of water or deposition from the air, it can bioaccumulate in fish and animal tissue in its most toxic form (methyl mercury).
- Predatory fish and fish-eating birds and mammals can bioaccumulate concentrations of mercury that are thousands to millions of times greater than the concentrations found in their water environment.
- Human exposure to mercury occurs primarily through eating contaminated fish.

Mercury compounds, as well as a number of other metallic compounds, are included in a list of 33 pollutants identified as a part of the EPA's "National Air Toxics Assessment Program" (see Table 27). Through this program, the EPA is working with state, local, and tribal governments to reduce air toxic releases to the environment.

Table 27

Metallic Compounds Included in the National-Scale Air Toxics Assessment

Arsenic
Beryllium
Cadmium
Chromium
Lead
Manganese
Mercury
Nickel
Source: http://www.epa.gov/ttn/atw/nata/34poll.html

There are no ambient air quality standards for mercury or any of the other metallic compounds listed in Table 27. However, exposure limits have been established for workers by the Occupational Health and Safety Administration (OSHA) for these metals. These exposure limits are presented in Table 28.[89]

Table 28

OHSA Permissible Exposure Limits

Metal	Limit (mg/m^3)
Antimony	0.5
Arsenic (inorganic)	0.01
Beryllium	0.002
Cadmium (fume)	0.005
Chromium	1
Lead	0.050
Manganese	5
Mercury (organo) alkyl compounds (as Hg)	0.01
Mercury compounds (except organo alkyls) (as Hg)	0.1
Nickel	1
Note: Limits are based on Time Weighted Averages (TWA) for an 8-hour workday	

5.3.2 RECENT RESEARCH EFFORTS TO CHARACTERIZE MERCURY AND OTHER HEAVY METAL EMISSIONS FROM LANDFILLS

Unlike the case with landfill leachate, there have been relatively few studies done over the past ten years to characterize the concentrations and speciation of heavy metals in LFG.

The recent studies and reports on heavy metals in LFG that were identified by the ARF research staff are summarized below.

5.3.2.1 *Mercury Study Report to Congress*[90]

In 1997, as required by the Clean Air Act Amendments of 1990, the EPA issued a report to Congress referred to as the "Mercury Study." This eight-volume study:

- Provides an inventory of mercury emissions to the air from a number of sources related to human activity.
- Estimates the health and environmental impacts associated with these emissions.
- Describes the technologies (and associated costs) available to control mercury emissions.

The study includes the estimated mercury emission rates by source category for the U.S. in 1994-1995. Selected source categories, including landfills, are presented in Table 29.

As indicated, the EPA estimated that, in 1994-95, landfills emitted a total of 70 kilograms of mercury to the atmosphere. This quantity represented less than 0.1% of the total amount emitted from all source categories.

Table 29

Best Point Estimates of 1994-1995 Mercury Emission Rates in the U.S.

Source of Mercury	1994-95 (Kilograms/Year)		Percent of Total Inventory	
	Subtotal	Total	Subtotal	Total
Area Sources		3,100		2.2%
Landfills	***70***		*<0.1%*	
Point Sources		141,000		97.8%
Combustion	125,300		87.0%	
Manufacturing	14,400		10.0%	
Miscellaneous	1,300		0.8%	
Total		144,100		100%

Source: EPA. Mercury Study – Report to Congress. Volume 1 – Executive Summary. EPA-452/R-97-003). Research Triangle Park, NC: EPA, December 1997.

5.3.2.2 *New Jersey Mercury Task Force Report*

The New Jersey Department of Environmental Protection convened the first Mercury Task Force in 1993. In 1998, a second Mercury Task Force was convened, which addressed a much wider variety of mercury sources.

Based on source-specific data collected for the late 1990s to 2001, the Task Force estimated that 2,043 kilograms of mercury are emitted to the air on an annual basis in New Jersey. Of this amount, the Task Force estimated that 14 kilograms per year are emitted from New Jersey landfills. This represents 0.7% of total mercury air emissions for the state.

The Task Force also addressed the issue of dimethyl mercury in its consideration of mercury emissions from landfills. Assuming a rate of 50 nanograms of dimethyl mercury per cubic meter of LFG that was measured in a recent study, the Task Force also estimated that approximately 85 grams of dimethyl mercury could be emitted each year from New Jersey landfills.[91] The Task Force called this amount "relatively insignificant."

5.3.2.3 *Methylated Mercury Species in MSW LFG Sampled in Florida*[92]

This study was performed in 1998 by scientists from the Oak Ridge National Laboratory (ORNL) for the Florida Department of Environmental Protection (DEP). The goals of the study were to confirm the existence of total gaseous mercury (TGM) at relatively high concentrations in LFG and to establish that methylated mercury compounds, such as monomethyl mercury (MMM) and dimethyl mercury (DMM), were LFG constituents.[93]

In a previous study, also performed by ORNL for the Florida DEP, the study authors had measured TGM levels in LFG in the range of micrograms per cubic meter.[94] In addition, monomethyl mercury (MMM) was identified in LFG condensate.

The 1998 study involved the collection and analysis of LFG samples during one day of sampling (11/17/98) at the Brevard County Central Disposal Facility near Orlando, Florida. The samples were taken from two in-line vent ports upstream of the LFG flare used to process all LFG from the site.

The results of the day of sampling at the Brevard County Landfill are presented in Table 30. As indicated, the concentrations are presented in "nanograms per cubic meter" (i.e., billionths of a gram per cubic meter). The data presented in Table 30 indicate the following:

- Total gaseous mercury was measured in the "micrograms per cubic meter range" (i.e., millionths of a gram per cubic meter).
- Dimethyl mercury was identified as being a LFG constituent and measured in the nanograms per cubic meter range.
- Monomethyl mercury was not actually found in the LFG but, just as in the previous study, was identified in the LFG condensate. The gaseous concentration of 6 nanograms per cubic meter was estimated based on the concentrations of monomethyl mercury measured in the condensate.

The project investigators report that this study represents the first positive identification of dimethyl mercury in LFG in the U.S. They reference studies that indicate that sulfate-reducing bacteria, such as are present during the anaerobic decomposition of the landfilled waste decomposition process, have been found to convert elemental mercury to monomethyl and dimethyl mercury through metabolic processes.[95]

The study authors compared the levels of the various types of mercury identified in the LFG to other sources and concentrations (see Table 30).

A follow-up study that involved more extensive sampling over a one-week period of MMM, DMM, and TGM was conducted at two landfills in central Florida (including Brevard County) as well as landfills in Minnesota and California. The results of this study have not yet been published.[96]

Table 30
Summary of the Types and Concentrations of Mercury Measured in LFG at the Brevard County Landfill on November 17, 1998

Mercury Species and Sample Type	Mercury Concentrations	Reference Concentrations for Comparison	
	Mean (ng/m³)	Conc. (ng/m³)	Comparison
Total Gaseous Mercury (TGM) (Charcoal)	7,190	1,000 – 10,000	Immediate Downward Plume of Coal-Fired Power Plants
Total Gaseous Mercury (TGM) (backup trap)	4		
Dimethyl Mercury (DMM)	30	0.003+/- 0.004	Ambient Air in Seattle, WA[97]
DMM/TGM	0.4%		
Monomethyl Mercury (MMM)	6	0.007+/- 0.004	Ambient Air in Seattle, WA

5.3.2.4 *Determination of Total, Dimethyl, and Monomethyl Mercury in Raw LFG at the Central Solid Waste Management Center*

The Delaware Solid Waste Authority (DSWA) has taken a leadership role in the effort to more accurately determine the levels and types of mercury in LFG. In January 2003, the DSWA contracted with Frontier Geosciences, Inc. to conduct an initial sampling campaign at DSWA's Central Solid Waste Management Center (CSWMC) landfill.[98]

A draft report on the findings of the initial campaign was distributed in February 2003. A summary of the sampling results included in the draft report is presented in Table 31.

Table 31
Sampling Results for the Initial Mercury Sampling Campaign Conducted at the CSWMC Landfill

Type of Gaseous Mercury	Measured Concentrations		
	Nanograms Per Cubic Meter (ng/m³)		No. of Samples
	Mean	Range	
Total Gaseous Mercury (TGM)	408	376-440	2
Dimethyl Mercury (DMM)	38.1	37.4-38.9	3
Monomethyl Mercury (MMM)	1.3	1.241-1.333	3

Based on the sampling results, it was concluded that the CSWMC LFG concentrations for total and monomethyl mercury—408 and 1.3 nanograms per cubic meter, respectively—were similar to concentrations recently measured at other U.S. landfills but were lower than those reported by Lindberg, et al, in the Florida study published in 2001.

The mean concentration of 38.1 nanograms per cubic meter measured for dimethyl mercury represented 9.3% of the total gaseous mercury measured in the LFG. The draft report emphasized that, if the CSWMC LFG is combusted, the dimethyl mercury in the gas will most likely be converted to elemental mercury.

5.3.2.5 *EPA Field Test Programs to Update LFG Emissions Data*

In a recent paper, the EPA's National Risk Management Research Laboratory (NRMRL) reported that it is currently conducting two field tests programs to provide updated data for characterizing LFG emissions.[99]

The updated data will be used by the EPA in its evaluation of residual risk from U.S. MSW landfills to determine the need for any additional requirements for LFG collection and control under the Clean Air Act.

The two field test programs being conducted by the EPA are as follows:

- **EPA – EREF Partnership** – In June 2001, a partnership was formed between EPA's NRMRL and the Environmental Research and Education Foundation (EREF) through a Cooperative Research and Development Agreement (CRADA). The purpose of the CRADA is to obtain up-to-date, credible data for LFG emissions by conducting field tests at sites that are typical of U.S. landfills.

  Measurements were conducted of the raw LFG and the post-combustion gases. The first phase of the study was completed in January 2003. Two sites were included in Phase 1. One site involved an enclosed flare while another site utilized internal combustion engines to combust the LFG.

  Phase 2 was conducted in the summer of 2003, and the final report is scheduled for completion by January 2004. Target analytes for the outlet exhaust include lead, arsenic, cadmium, chromium, manganese, nickel, and mercury.

  Results from Phases 1 and 2 were available for oral presentation at the Sardinia Landfill Conference in the Fall 2003.

- **EPA – WM Partnership** – Through a second CRADA, EPA has developed a partnership with Waste Management, Inc. (WM) to evaluate bioreactor landfills. Through this partnership, sampling is being conducted for mercury in the raw LFG for total, elemental, methyl, and dimethyl mercury. A final report is scheduled for spring 2004.

5.3.2.6 *Mercury and Other Metals Testing at the GSF Energy, Inc. LFG Recovery Plant at the Fresh Kills Landfill*[100]

The Fresh Kills Landfill, which until recently, disposed of MSW from the city of New York, covers approximately 3,000 acres and was the largest landfill in the U.S. The gas generated within the landfill is collected, purified, and sold to a local utility (Brooklyn Union Gas).

In 1996, Eastern Research Group, Inc. conducted testing on the two LFG collection headers, the purified LFG (Sales Gas) and the Thermal Oxidizer for mercury, arsenic, beryllium, cadmium, chromium, lead, and antimony. Testing was performed during the week of July 15, 1996. The test results are presented in Table 32.

As Table 32 indicates, mercury, arsenic, and antimony were all detected in significant quantities during the sampling program. The following comments were offered with respect to the detection of heavy metals in LFG during the test program:

- **Antimony** – Was detected at significantly high levels in both the North and South Header runs.
- **Arsenic** – Was detected in significant quantities in both the North and South Headers.
- **Beryllium** – Was not detected in any of the samples or field blanks at levels above the "Method Detection Limit" (MDL).
- **Cadmium** – Was not detected in any of the North Header samples and was found in two of the South Header samples at insignificant levels.
- **Chromium** – Was detected due to its presence in the test reagents and was not actually present at detectable levels in the sampled landfilled gas.
- **Lead** – Was detected at levels less than 5 times the MDL.
- **Mercury** – Was detected in the North and South Headers at levels significantly above the MDL.

Table 32

Average Metals Concentrations in the North and South Headers (Blank-Corrected)

Metal	Micrograms/Dry Standard Cubic Meter (ug/dscm) (a)		Method Detection Limits (MDLs) (ug/m^3)	
	North Header	South Header	North Header	South Header
Mercury (Hg)	7.32-7.57	17.5-17.8	0.31-0.34	0.30-0.36
Arsenic (As)	66.6 (c)	131-132	1.25-1.38	1.22-1.42
Beryllium (Be)	0.13	0.13	0.30-0.34	0.30-0.36
Cadmium (Cd)	0.13	0.13 (b) -0.20	0.30-0.34	0.30-0.36
Chromium (Cr) (d)	1.11-1.16	1.62	0.94-1.03	0.91-1.07
Lead (Pb) (e)	0.22	0.22	0.63-0.69	0.61-0.71
Antimony (Sb)	117 (c)	240 (c)	1.25-1.38	1.22-1.42

Notes:

a The first value in each range represents "greater than or equal to" while the second value in each range represents "but less than." Note: "dscm" refers to dry standard cubic meter.
b Less than five times the MDL in one or two runs; the other values were non-detect.
c These values are "equal to" not "greater than."
d Reagent contamination likely.
e Because of the high levels of lead in the header blank, data are also reported as less than without blank correction.

The detection of significant quantities of antimony and arsenic during the Fresh Kills sampling program was the first and only reference to the identification of these metals in LFG in any of the studies reviewed for this project. On the other hand, the detection of mercury at significant levels correlates with the findings of both the Florida and Delaware studies described above. Unfortunately, little diagnostic assessment was conducted to link the results of this study to operational circumstances and disposal conditions at the landfill. As the chemistry and thermodynamics of gas-phase metal behavior is known, it could have been applied in this case as an aid to interpreting the study results.[101]

5.3.3 ESTABLISHMENT OF NATIONAL EMISSION STANDARDS FOR HAZARDOUS AIR POLLUTANTS FROM MSW LANDFILLS

Section 112 (d) of the Clean Air Act required the EPA to regulate emissions from major sources of 188 types of hazardous air pollutants (HAPs).

On July 16, 1992, the EPA published a list of industrial source categories that emitted one or more of these HAPs. MSW landfills were identified as a source category on this list. As a result, the EPA was required to promulgate standards for the control of HAP emissions from both new and existing MSW landfills that were determined to be major sources of HAPs. These emission standards are referred to as "Emission Guidelines" (EG) for existing landfills and "New Source Performance Standards" (NSPS) for new landfills.

Under section 112 (k) of the Clean Air Act, the EPA is required to develop a strategy for the control of HAPs from area sources in urban areas. The EPA identified 33 HAPs generated by area sources that presented the greatest threat to public health in the largest number of urban areas. MSW landfills were again listed as an area source category to be regulated pursuant to section 112 (k) because 13 of the listed HAPs were found to be emitted from MSW landfills.

On January 16, 2003, the EPA promulgated national emission standards for hazardous air pollutants (NESHAP) for MSW landfills. In this action, emission limits were not established for mercury or any other heavy metal.

With respect to mercury, the EPA indicated that there were "insufficient data to characterize the concentrations of mercury in LFG or determine its significance."[102] The EPA indicated that section 112 (f) of the CAA requires that EPA evaluate residual risks and promulgate standards to address residual risk within eight years of the promulgation of the NESHAP. If additional information on mercury emissions and control techniques that would alter the decision not to require mercury reductions becomes available, the EPA can amend the NESHAP rule at that time.

In the background document published in conjunction with the new regulation, the EPA stated that "it should be considered that, once mercury has been created, the next best method of control may be disposal in a modern, lined landfill that combusts the generated gas in accordance with the EG/NSPS. In this case, the mercury is converted to a less hazardous, inorganic form through the combustion process."[103]

5.4 SUMMARY FINDINGS AND CONCLUSIONS

Based on this review of recent studies and relevant literature, the following summary findings and conclusions are made with respect to the presence of RCRA heavy metals in LFG from MSW landfills.

5.4.1 SUMMARY FINDINGS

- There is evidence of the existence of gaseous mercury in LFG in the range of micrograms per cubic meter.
- The amount of mercury contributed to the environment from MSW landfills is relatively insignificant compared to other sources.
- In its issuance of "National Emission Standards for Toxic Air Pollutants" for MSW landfills in January 2003, the EPA did not promulgate standards for any RCRA heavy metals. However, the EPA has the right under the Clean Air Act to promulgate standards for heavy

metals in LFG in the next eight years if residual risks associated with the non-regulated pollutants are identified.

- Under current partnerships with private organizations, the EPA is conducting detailed studies to update its database regarding LFG constituents, including heavy metals.
- Recent studies have identified both monomethyl mercury and dimethyl mercury as being constituents of the total gaseous mercury in LFG. In addition to mercury, other RCRA heavy metals, including arsenic, selenium, and lead, can also be metabolized to form gaseous methylated metal compounds.
- Methyl mercury compounds, as well as other gaseous methylated metal compounds are converted back to inorganic metal forms through combustion processes such as flaring or LFG energy recovery systems.
- Inorganic mercury emissions, however, are not controlled through LFG flaring or LFG energy recovery systems.
- Two other metals, arsenic and antimony, were identified at significant levels in one of the recent studies on LFG.

5.4.2 CONCLUSIONS

- Mercury appears to be a trace constituent of LFG.
- The same attenuating mechanisms that limit the leaching of heavy metals in landfills—including reducing conditions, neutral pH, and presence of sulfides —also limit the release of significant gas phase metals (including metallic or methylated mercury).
- Since inorganic mercury is not controlled through the flaring or combustion of LFG for energy recovery, the best methods of controlling mercury LFG emissions are programs that eliminate mercury from the waste stream through recycling and source reduction.
- If the evidence from recent studies regarding the presence of methyl mercury compounds in LFG is corroborated through future studies, there may be a move to require more landfills to collect and combust LFG.
- While arsenic and antimony were identified at significant levels in a single study, the lack of measurements of the quantities of these metals from other studies makes it premature to draw conclusions whether or not these metals are typically found in LFG.
- The research projects reviewed during this investigation underscore the need for additional research regarding the presence of RCRA heavy metals in LFG. Such future research initiatives would provide a more scientifically and technically sound process on which to base future regulations. The research being conducted by the EPA through partnerships with private organizations represents a good first step in this regard.

6.1 INTRODUCTION

The relatively low concentrations of RCRA heavy metals in leachate and landfill gas have been documented in Sections 4 and 5. The purpose of this section is to document the performance of landfill pollution control systems—namely the leachate collection and treatment system and the landfill gas management system—in minimizing the release of RCRA heavy metals in leachate and landfill gas to the environment.

6.2 BACKGROUND INFORMATION ON POLLUTION CONTROL SYSTEMS AT SUBTITLE D LANDFILLS

6.2.1 INTRODUCTION

The environmentally safe and secure containment of wastes in landfills took a major step forward with the promulgation of "Subtitle D" landfill regulations in 1991 by the EPA.[104]

These regulations established national standards and minimum requirements for a number of pollution control systems that are required to be constructed in conjunction with MSW landfills. These systems include:

- Landfill Liner System
- Leachate Collection and Removal System
- LFG Collection and Control System
- Landfill Final Cover System.

A brief overview of each of these systems, which are illustrated in Figure 2, is provided below.

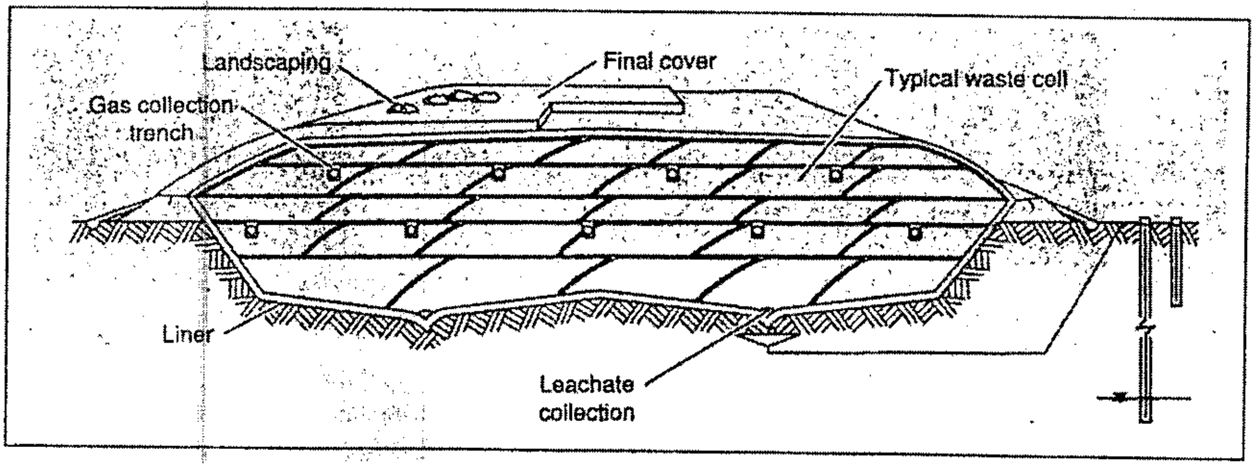

Figure 2 – MSW Landfill Pollution Control Systems

6.2.2 LANDFILL LINER SYSTEM

MSW landfills can be defined as land-based waste management cells that contain MSW.[105] To protect the environment, MSW landfills are now constructed with waste containment systems, which consist of 1) a liner system that underlies the waste, and 2) a final cover system constructed over the waste.

Leachate is wastewater that is formed as water percolates through the landfilled waste and collects contaminants that are present in the waste and/or are produced during the waste decomposition process. Leachate generated in landfills flows downward by gravity and, if not for the liner system, would eventually flow through the soil underneath the landfill and could potentially pollute the groundwater below.

The landfill liner system provides a relatively impermeable barrier between the landfilled waste and the land on which the landfill has been constructed. The primary purpose of the liner system is to minimize the migration of waste constituents out of the landfill. Another purpose of the liner system is to enable the landfill leachate and LFG to be collected and treated.

Federal Subtitle D regulations require that the liner system be constructed as a "composite" liner. A composite liner is an effective hydraulic barrier because it combines the complementary properties of two different materials (namely compacted soil and a synthetic geomembrane) into one system.

Geomembranes are thin, factory-manufactured plastic materials that are widely used as hydraulic barriers due to their non-porous structure, flexibility, and ease of installation. However, geomembranes may contain defects, including tears, improperly bonded seams, and pinholes. In the absence of an underlying, low permeability soil liner, the flow of leachate through a defect in the geomembrane is essentially unrestrained. Therefore, federal Subtitle D regulations require that the geomembrane be underlain with a low-permeability soil liner to limit the flow rate of leachate through any defects that may exist or develop in the geomembrane liner.

Subtitle D regulations stipulate that the two components of the composite liner meet the following requirements:

- **Soil Component** – The lower component of the composite liner, as illustrated in Figure 2, must consist of at least a 2-foot layer of compacted soil. This layer must have a hydraulic conductivity of no more than 1×10^{-7} cm/sec.
- **Flexible Membrane Component** – The upper component must consist of a synthetic flexible membrane liner (FML) of at least 30-mil (0.03 inch) thickness. If the FML is high-density polyethylene (HDPE), then it must be at least 60-mil (0.06 inch) thick.[106]

6.2.3 LEACHATE COLLECTION AND REMOVAL SYSTEM

Subtitle D regulations also require that MSW landfills be equipped with a leachate collection and removal system (LCRS) that limits the depth of leachate retained over the liner systems to 12 inches (30 centimeters).

As shown in Figure 2, the LCRS will generally include a pipe network that allows leachate to drain by gravity to a sump at the low elevation of the landfill cell. From the sump, the leachate is removed from the landfill either through a gravity drainage pipe or through a sump pump. Once removed, the leachate is treated in either on-site or off-site treatment systems.

A typical leachate collection and treatment system consists of the following components:

- **Leachate Collection Pipes** – These pipes, which generally consist of perforated HDPE plastic piping, are located over the bottom liner system in a grid or spoked pattern.

- **Drainage Layer** – The drainage layer, which generally consists of sand or geosynthetic material, is designed to allow leachate, as well as LFG, to enter into the leachate collection pipes.
- **Filter Layer** – In some cases, a protective filter layer consisting of soil or geosynthetic materials is installed over the drainage layer to prevent physical clogging of the drainage layer material.
- **Leachate Header Pipes** – The leachate collection pipes are connected to one or more leachate headers, which convey the leachate to a leachate pump or storage area.
- **Leachate Pump/Storage Area** – Leachate is generally required to be pumped to either an on-site treatment system or to a sewer for off-site treatment.
- **Leachate Treatment System** – Off-site treatment generally involves transport of the leachate to a "publicly-owned treatment works" (POTW). In some cases, on-site leachate treatment is provided. This treatment generally consists of aerated lagoons, stabilization basins, and/or separate biological or physical/chemical treatment systems. In the case of bioreactor landfills, leachate may be pretreated by collection and recirculation through the landfilled waste.

6.2.4 LFG COLLECTION AND CONTROL SYSTEM

Federal Subtitle D regulations do not require every Subtitle D landfill to install a LFG collection and control system. Rather, the regulations require that the concentration of methane gas generated by the facility does not exceed 25% of the lower explosive limit for methane in facility structures nor exceed 100% of the LEL at the facility property boundary.

LFG emissions are, however, regulated by the EPA under the Clean Air Act (CAA). In March 1996, the EPA promulgated CAA regulations for MSW landfills. These regulations require that large MSW landfills (i.e., those with a design capacity of 2.76 million tons or more of waste) must collect and control LFG if their estimated emissions of "non-methane organic compounds" (NMOCs) are 50 megagrams (55 tons) per year or more.[107]

In January 2003, the EPA promulgated additional Clean Air Act regulations that promulgated national emission standards for hazardous air pollutants from MSW landfills. The regulations also required bioreactor landfills that are subject to existing Clean Air Act regulations (i.e., large bioreactor landfills) to collect and control LFG emissions within 180 days after the landfill has reached a moisture content of 40% by weight.

6.2.5 FINAL COVER SYSTEM

Final cover systems represent another important pollution control element of MSW landfills. The final cover system effectively prevents the infiltration of water or air into the landfill once the landfill (or landfill cell) is closed.

Subtitle D regulations require that the final cover must be placed over the landfill within one year after the landfill reaches its final permitted height. The following minimum design criteria are required for final cover systems for MSW landfills:

- A 6-inch layer of earthen material above the geomembrane liner
- A 60 mil (0.06 inch) thick HDPE geomembrane

- An 18-inch thick compacted soil liner having a maximum hydraulic conductivity of $1x10^{-7}$cm/s.

The final cover system must provide the same maximum level of hydraulic conductivity as the bottom liner system. With respect to the long-term control of pollution from the landfill, final cover systems are as important as, and in some ways more important than, the liner system.[108]

6.3 EFFECTIVENESS OF SUBTITLE D LANDFILL ENVIRONMENTAL PROTECTION SYSTEMS IN PREVENTING HEAVY METAL RELEASES TO THE ENVIRONMENT

6.3.1 INTRODUCTION

The purpose of this section is to present the findings of recent research regarding the effectiveness of the pollutant control systems required for MSW landfills in minimizing releases of RCRA heavy metals disposed in MSW landfills to the environment.

6.3.2 EFFECTIVENESS OF LINER SYSTEMS

6.3.2.1 Introduction

In December 2002, the EPA published the results of a four-year study that assessed the performance of waste containment systems, including the liner systems required for MSW landfills.[109]

This broad-based study, which is documented in a report of over 1,000 pages in length, addressed three categories of issues related to the design, construction, and performance of waste containment systems used at landfills, namely:

- Technical issues associated with geosynthetic liners
- Technical issues associated with natural material liners
- Field performance of waste containment systems.

Of particular relevance to the effectiveness of bottom liner systems in preventing heavy metal releases to the environment were research tasks that addressed two key issues:

1) The expected service life of composite Subtitle D landfill liners.
2) The leachate leakage rates associated with the primary liner.

The findings reported in the study on these two issues are summarized below.

6.3.2.2 Prediction of Geomembrane Service Life

One of the most often-asked questions regarding the use of geomembranes in an MSW landfill bottom liner system is "How long will the geomembrane last?" The recently published EPA study addressed this question.

For most MSW landfill bottom liner systems, high-density polyethylene (HDPE) liners have been the geomembrane of choice. HDPE geomembranes (GMs) are comprised of the following materials:

- Polyethylene resin (97%)
- Carbon black (2%)

- Antioxidants (1%).

HDPE geomembranes "age" when the polyethylene molecules that comprise the liner react with oxygen (i.e., are oxidized). This reaction causes breaks in the polymer chains and results in an embrittling of the liner.

Antioxidants are sacrificial chemicals that are mixed in with the polyethylene resin. Antioxidants inhibit the liner oxidation process by reacting with oxygen that comes in contact with the liner and thereby preventing the polyethylene oxidation reaction from occurring.

The long-term aging process for HDPE geomembranes proceeds in three sequential stages:

- **Depletion of Antioxidants** – As oxygen or oxygen containing chemicals come in contact with the liner, the antioxidants contained in the liner are eventually depleted.
- **Induction** – During the induction period, oxidation reactions cause a scission (or cutting) of the polymer structure.
- **Oxidation of the Polyethylene Resin** – During this stage, the polyethylene continues to be oxidized until the engineering properties of the material are reduced by 50%. A 50% change in materials properties (i.e., density, melt index, and tensile strength), which is generally interpreted by polymer engineers to be significant, is called the "half life" of the material. In the EPA report, the half-life was arbitrarily chosen to signal the end of the service life of the geomembrane.

Through the utilization of field data in conjunction with material behavior models, a service life on the order of 1,000 years was estimated for a 1.5-millimeter (0.06-inch) thick HDPE liner under simulated landfill conditions[110] (see Table 33). In addition, even if a leak eventually develops in the geomembrane liner, the soil liner and landfill cover will continue to function to minimize water infiltration into the landfill or leachate migration out of the landfill.

Table 33

Estimated Life of 1.5 mm (0.06 inch) HDPE Geomembrane Evaluated in the EPA Study

Stage of Degradation	Description	Duration (Years)
A	Antioxidant Depletion	200
B	Induction Time	20
C	Half-life of Engineering Property	750
Total	**Life Estimate**	**970**

Degradation of liner resulting in liner retaining 50% of original engineering properties of density, melt index, and tensile strength.

Source: EPA. Assessment and Recommendations for Improving the Performance of Waste Containment Systems. (EPA/600/R-02/099). Cincinnati, OH: EPA National Risk Management Research Laboratory, December 2002.

6.3.2.3 *Field Performance of Composite Liner Systems*

Double-lined landfills are landfills that have two liners as a part of their bottom liner systems. In a double-lined landfill, a leak detection system (LDS) is constructed between the primary and secondary liners. Double-lined landfills are particularly useful in the determination of leakage rates through primary geomembrane liners because of their leak detection systems (LDS). Any leachate that leaks through the primary liner is contained by the secondary liner and is subsequently collected, with its quantities recorded.

As described above, Subtitle D regulations require MSW landfills to be constructed with a composite liner. The minimum composite liner requirement includes a geomembrane liner underlain with a compacted soil (or clay) liners. These composite liners are referred to in the literature as "Geomembrane/Compacted Clay" or GM/CC liners.

Previous field studies of GM/CC liners were not able to quantify the leakage rates through these liners due to the masking effects of "consolidation" water (i.e., water from liner construction activities), the very low anticipated flow rates through the composite liner, and the relatively long breakthrough times for the CC component of the liner.[111]

As a part of the recently published EPA study of waste containment systems, liquids management data were evaluated for 13 double-lined cells with GM/CC primary liners to better understand the field performance of landfill primary liners.

With respect to the performance of GM/CC liners, the study investigators concluded that "The current database is not sufficient to draw definite conclusions on the performance of GM/CC ... primary liners." However, the following observations were offered:

- Available data suggest that the average monthly active-period LDS flow rates attributable to leakage through GM/CCL constructed with quality assurance (CQA) programs, are probably similar to those for "Geomembrane/Geocomposite Clay" (GM/GC) primary liners constructed with CQA. The average monthly active-period LDS flow rates attributable to leakage through geomembrane/geosynthetic clay liners (GM/GC) will often be less than 18.7 gallons per acre per day but occasionally in excess of 93.5 gallons per acre per day.
- Subtitle D (i.e., GM/CC) composite liners constructed with good construction quality assurance programs can achieve true hydraulic efficiencies of 99% to more than 99.9%.
- GM/CC composite liners are capable of substantially preventing leachate migration over the entire period of significant leachate generation for typical landfill operation scenarios (i.e., scenarios that do not include leachate recirculation or disposal of liquid wastes or sludges).

6.3.3 EFFECTIVENESS OF LEACHATE COLLECTION AND REMOVAL SYSTEMS

As indicated above, Subtitle D composite liner systems are capable of keeping 99% or more of the leachate contained within the landfill where it can be collected and removed or recirculated by the leachate collection and removal system.

As previously discussed, heavy metal concentrations in leachate have been found to be very low. The leachate that is collected is either treated on-site or is pumped or trucked to off-site wastewater treatment systems.

6.3.4 EFFECTIVENESS OF LANDFILL GAS COLLECTION AND TREATMENT SYSTEMS

In a recent paper, the EPA's National Risk Management Research Laboratory (NRMRL) estimated that 50% of the 162 million tons of MSW landfilled each year goes to MSW landfills which have landfill gas (LFG) controls in place. Of the landfills with LFG controls in place, 50% combust the collected gas in landfill flares, while the remaining 50% combust the gas using energy recovery technologies such as boilers, internal combustion engines and gas turbines.[112]

During the combustion process that occurs in landfill flares and energy recovery technologies, methylated forms of mercury and other heavy metals are converted to elemental metal forms which, at least in the case of mercury, are much less hazardous.

With respect to mercury, the EPA has stated that "it should be considered that, once mercury has been created, the next best method of control may be disposal in a modern, lined landfill that combusts the generated gas in accordance with Clean Air Act regulations.[113]

As discussed in Section 5, the EPA NRMRL is currently conducting field tests programs to provide updated data for characterizing LFG emissions, including emissions from LFG flares and LFG energy recovery systems.

6.4 CONCLUSIONS

Based on this review of recent studies and relevant literature, the following conclusions are offered with respect to the effectiveness of landfill pollution control systems in minimizing the discharges of RCRA heavy metals to the environment.

- Landfill liner systems substantially prevent the leaking of leachate from the landfill to the land upon which the landfill is constructed. Based on recent investigations, these liners appear to have a service life on the order of 1,000 years.
- Due to the effectiveness of the landfill liner systems that have been constructed with good quality assurance programs, it appears that 99% or more of the leachate generated in MSW landfills is collected and treated by recirculation or other on-site or off-site wastewater treatment systems.
- For landfills equipped with LFG collection and control systems, the combustion of gas in landfill flares or energy recovery technologies enables the conversion of methylated mercury (and other methylated metal compounds) to elemental metal forms, which, at least in the case of mercury, are much less hazardous.

The purpose of this report is to present the findings of recent literature and current research efforts regarding the effectiveness of municipal solid waste (MSW) landfills in controlling releases of heavy metals to the environment. The following overall conclusions are offered with respect to this issue:

1. Based on historical data, it appears that about 130,200 tons per year of RCRA heavy metals are disposed in MSW landfills. (As noted in Section 3, RCRA heavy metals are eight heavy metals or metalloids for which groundwater maximum contaminant levels and TC regulatory limits have been established by the EPA.) This equates to 0.08% of the 162 million tons of MSW disposed in landfills on an annual basis.

2. Historical data indicated that the total tonnage of RCRA heavy metals disposed in MSW landfills has decreased over the last 15 years due to increased recycling and/or substitution of heavy metals with other materials.

3. Lead appears to represent over 97% (by weight) of the RCRA heavy metals disposed in MSW landfills.

4. The types of products containing heavy metals that are disposed in MSW landfills are changing. For example, the disposal of lead in the form of lead acid batteries has decreased in recent years due to recycling, while the disposal of lead in the form of discarded consumer electronics has increased dramatically.

5. Recent studies have confirmed that certain products that contain heavy metals, such as cathode ray tubes (CRTs) from color televisions and computer monitors, will fail the TCLP and can be categorized as hazardous wastes if they are not generated by households or are generated by businesses at a rate greater than 100 kilograms (220 pounds) per month. Other recent studies have indicated, however, that the metal concentrations leached from CRTs under actual landfill conditions will be less than might be estimated using the TCLP results.

6. Based on database and research data representing thousands of data points from hundreds of MSW landfills, the average concentrations of RCRA heavy metals in MSW landfill leachate were found to be significantly lower than the TCLP regulatory levels. The average RCRA heavy metal concentrations in MSW leachate were found to be in compliance with the final effluent limitation guidelines and the national pretreatment standards set by the EPA in 1999 for the landfills point source category. When compared with drinking water standards (i.e., water purity standards at the tap), average concentrations for RCRA heavy metals in leachate (from the bottom of an MSW landfill) were found to be less than 10 times higher than the drinking water standards and, for one metal, were found to meet drinking water standards. Finally, average RCRA heavy metal leachate concentrations were found to meet local pretreatment standards without leachate treatment except in cases where stringent pretreatment standards had been established for specific metals.

7. The reasons for the low levels of RCRA heavy metals in leachate include both the form of the metals in the disposed products and the conditions in the landfill. These conditions discourage the leaching of the heavy metals from the disposed products and, for those metals that do leach, promote the removal of heavy metals from leachate by precipitation and/or absorption of the metals within the waste mass.

8. Although there have been fewer studies of landfill gas, indications are that RCRA heavy metal concentrations in landfill gas from MSW landfills are also low. In this regard, no regulatory limits were established by the EPA for heavy metal emissions from LFG in its promulgation of national emission standards for hazardous air pollutants from MSW landfills in January 2003.

9. The major factors responsible for the low levels of RCRA heavy metals in landfill leachate—namely the conditions created as a consequence of the mechanisms of waste stabilization and the in situ attenuation of the metals within the landfill—are also responsible for the low levels of RCRA heavy metals in landfill gas.

10. Recent studies indicate that the geomembrane component of a landfill containment system can last on the order of 1,000 years. Also, modeling of the eventual failure of these containment systems indicates that remobilization of the heavy metals in landfills could take thousands of years, if it ever occurs.

11. In summary, MSW landfills can provide for the safe, efficient, and long-term management of disposed products containing RCRA heavy metals without exceeding limits that have been established to protect public health and the environment. MSW landfills should contain the releases of RCRA heavy metal pollutants at levels that protect public health and the environment for extremely long periods of time.

12. As indicated in the introduction to this report, SWANA endorses and actively promotes the implementation of economically and environmentally sound waste reduction and recycling programs for products containing heavy metals. Modern MSW landfills can provide an effective "safety net," as well as an environmentally sound means of disposal, for those products containing heavy metals that are not diverted through waste reduction and recycling programs.

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[1] See Federal Register, Vol.55, No. 61, Thursday, March 29, 1990, p. 11827. SWANA is aware that the EPA has updated its pollutant dispersion modeling approach since 1990 and may have developed constituent-specific dilution attenuation factors for certain metals. (See 60CFR 66344 (Dec. 21, 1995).

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[11] The EPA also stated that the "EPA has initiated both internal and external research to begin work toward a more comprehensive assessment framework and set of testing protocols for evaluation of leaching potential of waste materials under relevant environmental conditions. The Office of Solid Waste requested input from the SAB on the direction of work performed to date and the Agency's consideration of recent and ongoing academic research. In response, the Environmental Engineering Committee provided a consultation on improving leach testing of waste for the Office of Solid Waste. For additional information, see http://www.epa.gov/sab/eecconsultationonleaching.html.

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[29] U.S. Environmental Protection Agency. Municipal Solid Waste in the United States: 2000 Facts and Figures. (EPA530-R-02-001). www.epa.gov. June 2002.

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[31] Sznopek, J.L. and T.G. Goonan. The Materials Flow of Mercury in the Economies of the United States and the World. USGS Circular 1197. Denver, CO: U.S. Geological Survey, 2000.

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[38] Ibid., See Table C-4, p. 157.

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[42] Pohland, F.G., A.B. Al-Yousfi , and D.R. Reinhart, "Anaerobic Digestion of Organic Solid Waste in Bioreactor Landfills" in Biomethanization of the Organic Fraction of Municipal Solid Wastes. (Mata-Alvarez J. (Ed.) London, England: IWA Publishing, 2003. Chapter 11 (13 pp). It should be noted that this figure was developed for a discrete amount of readily decomposable refuse undergoing rapid stabilization with leachate recirculation.

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[61] Ibid. p. 7-12.

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[64] See Federal Register, Vol.55, No. 61, Thursday, March 29, 1990, p. 11827. SWANA is aware that the EPA has updated its pollutant dispersion modeling approach since 1990 and may have developed constituent-specific dilution attenuation factors for certain metals. (See 60CFR 66344 (Dec. 21, 1995).

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