การปนเปื้อนโลหะหนักในน้ำชะมูลฝอยที่เกิดจากถ่านไฟฉายที่ใช้แล้วในขยะชุมชน

นางสาวปวีณา ลิมปิทีปราการ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาการจัดการสิ่งแวดล้อม (สหสาขาวิชา)
บัณฑิตวิทยาลัย จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2548

ISBN 974-14-1962-7

HEAVY METAL CONTAMINATION IN LEACHATE FROM SPENT BATTERIES IN MUNICIPAL SOLID WASTES

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A Thesis Submitted in Partial Fulfillment of Requirements
for the Degree of Master of Science Program in Environmental Management
(Inter-Department)
Graduate School
Chulalongkorn University
Academic Year 2005

ISBN 974-14-1962-7

Thesis Title HEAVY METAL CONTAMINATION IN LEACHATE FROM SPENT BATTERIES IN MUNICIPAL SOLID WASTE.
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Field of Study Environmental Management
Thesis Advisor Associate Professor Somjai Karnchanawong

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

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ปวีณา ลิมปิทีปราการ : การปนเปื้อนโลหะหนักในน้ำชะมูลฝอยที่เกิดจากถ่านไฟฉายที่ใช้แล้วในขยะชุมชน. (HEAVY METAL CONTAMINATION IN LEACHATE FROM SPENT BATTERIES IN MUNICIPAL SOLID WASTE) อ. ที่ปรึกษา : รศ. สมใจ กาญจนวงศ์ 124 หน้า ISBN 974-14-1962-7

การศึกษานี้มีวัตถุประสงค์เพื่อประเมินความเสี่ยงของปริมาณโลหะหนักจากถ่านไฟฉายที่ทิ้งปนเปื้อนไปกับขยะชุมชน โดยแบ่งการทดลองออกเป็น 2 ส่วน คือการทดสอบการชะละลายของโลหะหนักจากถ่านไฟฉายโดยวิธีการทดสอบแบบแบทช์ และการจำลองสภาวะการฝังกลบโดยใช้ถังจำลอง ทั้งนี้เพื่อเป็นการศึกษาความเสี่ยงของสารเคมีที่ปนเปื้อนจากถ่านไฟฉายออกสู่น้ำชะมูลฝอย การทดสอบการชะละลายของถ่านไฟฉายทำตามวิธีการของ Toxicity Characteristic Leaching Procedure โดยใช้ถ่านไฟฉาย 4 ชนิด จำนวน 36 ตัวอย่าง ขนาดแตกต่างกัน การจำลองการฝังกลบได้ใช้ถังจำลองจำนวน 5 ถัง ความสูง 2 เมตร และขนาดเส้นผ่าศูนย์กลาง 20.32 เซนติเมตร สองถังสำหรับบรรจุถ่านไฟฉายที่ผ่านการทุบ และไม่ผ่านการทุบ ส่วนอีก 3 ถังสำหรับบรรจุขยะชุมชนที่ผสมถ่านไฟฉายร้อยละ 0, 1 และ 5 โดยน้ำหนักตามลำดับ

จากผลการทดลองพบว่า ในการทดสอบการชะละลาย มีเพียงการชะละลายของแคดเมียมในถ่านไฟฉายชนิดนิเกิล-แคดเมียม เกินกว่ามาตรฐานลักษณะของสารเป็นพิษที่กำหนดโดยสหรัฐอเมริกา สังกะสีถูกพบเป็นส่วนประกอบหลักในน้ำชะละลาย เนื่องมาจากมีการใช้สังกะสีเป็นองค์ประกอบหลักในขั้วบวกของถ่านไฟฉาย ในขณะที่คุณสมบัติของน้ำชะมูลฝอยที่เกิดจากถังจำลองที่บรรจุถ่านไฟฉายที่ผ่านการบดอัด และไม่ผ่านการบดอัดไม่สามารถเปรียบเทียบกันได้ เนื่องจากเกิดปัญหาการอุดตันของถังจำลอง ผลจากถังจำลองการฝังกลบมูลฝอยอีก 3 ถัง พบว่าเหล็กเป็นโลหะที่ถูกพบส่วนใหญ่ในน้ำชะมูลฝอย และพบว่าถังจำลองมูลฝอยที่บรรจุถ่านไฟฉายร้อยละ 5 มีความเข้มข้นของ แคดเมียม แมงกานีส สังกะสี นิเกิล ตะกั่ว และเหล็ก สูงกว่าถังจำลองที่บรรจุเฉพาะขยะชุมชนและถังจำลองที่ผสมถ่านไฟฉายกับขยะชุมชนร้อยละ 1 อย่างมีนัยสำคัญ สำหรับถังจำลองที่ผสมถ่านไฟฉายกับขยะชุมชนร้อยละ 1 มีค่าความเข้มข้นของเหล็ก นิเกิล และสังกะสีในน้ำชะมูลฝอยแตกต่างจากถังจำลองที่บรรจุเฉพาะขยะชุมชนอย่างมีนัยสำคัญ อย่างไรก็ตามเมื่อเปรียบเทียบลักษณะของน้ำชะมูลฝอยของทั้งสามถังจำลองกับมาตรฐานคุณภาพน้ำใต้ดินเพื่อการบริโภคที่ออกภายใต้ พ.ร.บ. น้ำใต้ดิน ปี 2520 พบว่ามีความเข้มข้นของ แคดเมียม เหล็ก แมงกานีส และสังกะสี สูงกว่าค่าสูงสุดที่ยอมรับได้อย่างมาก จึงสามารถสรุปได้ว่าการทิ้งถ่านไฟฉายในขยะชุมชนมีผลทำให้เกิดการปนเปื้อนของโลหะหนักในน้ำชะมูลฝอยอย่างเห็นได้ชัด

สหสาขาวิชาการจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต..

ปีการศึกษา 2548 ลายมือชื่ออาจารย์ที่ปรึกษา..

4789477220 : MAJOR ENVIRONMENTAL MANAGEMENT

KEY WORD: HEAVY METAL/ LEACHATE/ SPENT BATTERIES/MUNICIPAL SOLID WASTE/LYSIMETER

PAWENA LIMPITEEPRAKAN : HEAVY METAL CONTAMINATION IN LEACHATE FROM SPENT BATTERIES IN MUNICIPAL SOLID WASTE. THESIS ADVISOR: ASSOC. PROF. SOMJAI KARNCHANAWONG 124 pp. ISBN 974-14-1962-7

This study was aimed to determining the risk of heavy metals from spent batteries disposed of directly into the municipal solid waste. Two types of experimental tests were performed on the spent batteries, i.e. batch leaching tests and simulated landfill lysimeter tests. These two types of tests were conducted in order to address the concerns associated with the leaching of chemicals from batteries into the landfill leachate. A series of batch leaching tests, TCLP tests, utilizing four types of batteries with thirty-six samples of spent batteries of various types and sizes, were performed. Five lysimeters, made from PVC pipes, each with a height and diameter of 2 m and 20.32 cm, respectively were prepared for the leaching column tests. Two lysimeters were filled solely with batteries, one with broken batteries and the other without. The other three lysimeter were filled with municipal waste mixed with batteries at zero, 1 and 5 percent by weight of the waste, respectively.

It was found that in the batch leaching tests, only the Cd concentration, which leached from Ni-Cd batteries, exceeded the US TCLP Toxicity Characteristic Regulatory limit. Mainly, Zn was found as a major element in the leaching solution due to the composition of the zinc plate in the anode. The leachate characteristics generated from the lysimeter filled with and without broken batteries could not be compared due to a clogging problem. Among the three landfill lysimeters, Fe was found to be the major metal that leached out. The landfill lysimeter with five percent batteries generated significantly higher concentrations of Cd, Mn, Zn, Ni, Pb and Fe than the lysimeter filled solely with municipal wastes and the lysimeter containing municipal waste mixed with one percent of batteries. The results also indicated that Fe, Ni and Zn concentrations in the leachate generated from the lysimeter containing municipal waste mixed with one percent of batteries were significantly higher than the lysimeter filled solely with municipal wastes. Moreover, when the leachate characteristics were compared against the Groundwater Standards for drinking purposes, the concentrations of Cd, Fe, Mn and Zn were found to be much higher than the allowance standards as ruled under the Groundwater Act B.E.2520 (1977). It could be concluded that the disposal of spent batteries into the municipal waste stream creates a high potential risk of heavy metal contamination in landfill leachate.

Field of Study Environment Management Student's signature......Pawena L.......

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ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to Associate Professor Somjai Karnchanawong for her valuable suggestions and openhanded guidance. Whenever I needed to consult with her, she always had a warm welcome and time for me. I appreciate her for accepting and guiding my opinions during the thesis work. Special respect and thanks are also extended to Dr. Manaskorn Rachakornkij, Assistant Professor Dr. Suraphong Wattanachira, Dr. Pichaya Ratchadawong and Mister Rangsan Pinthong for their many valuable comments.

I am indebted to the Chiang Mai Meteorological Station for providing the Chiang Mai meteorological data. Special thanks are extended to all faculty, friends and staffs members from both of the National Research Center for Environmental and Hazardous Waste Management’s International Postgraduate Programs in Environmental and Hazardous Waste Management of Chulalongkorn University and the Department of Environmental Engineering, under the Faculty of Engineering of Chaing Mai University for their warm support and continual help over the entire period of this research.

I also would like to express my appreciation for Mr. Thongchai Baitrakul, at the Bangkok Metropolitan Administration, whose suggestions have been beneficial to this study. Recognition must also be given to Miss Ramnaree Natvichien at Chulalongkorn University and my friends from the Public Health Faculty of Khon Kaen University for their support.

Moreover, I am thankful to Miss Akiko Uyeda for her valuaed guidance and help with fixing my thesis report.

Finally, unlimited gratitude is extended to my family for their love and inspiration and to Mr. Tawesak Sritanyarat for his heartening support and words of encouragement throughout my study.

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ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
As	Arsenic
BOD	Biochemical Oxygen Demand
Cd	Cadmium
CH_4	Methane
Cr	Chromium
COD	Chemical Oxygen Demand
DOC	Dissolved Organic Carbon
EPA	Environmental Protection Agency
EPPO	Energy Policy and Planning Office
Fe	Iron
Hg	Mercury
HgCl	Mercuric Chloride
HgO_2	Mercury Oxide
ICP	Inductively Couple Plasma
KOH	Potassium Hydroxide
l	liter
mm	millimeter
Mn	Manganese
MnO_2	Manganese Dioxide
MnOOH	Manganese Oxophydroxide
MSW	Municipal Solid Waste
NaOH	Sodium Hydroxide
NEB	National Environment Board
NEMA	The National Electrical Manufactures Association
NH_4Cl	Ammonium Chloride
Ni	Nickel
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
Pb	Lead
PCD	Pollution Control Department

ABBREVIATIONS (CONTINUED)

ppb	Part per billion
ppm	Part per million
PVC	Poly Vinyl Chloride
TA	Total Alkalinity
TCLP	Toxicity Characteristic Leaching Procedure
TEI	Thailand Environment Institute
TISI	Thai Industrial Standards Institute
TOC	Total Organic Carbon
VFA	Volatile Fatty Acid
VOC	Volatile Organic Carbon
USEPA	United State Environmental Protection Agency
V	Volt
Zn	Zinc
$ZnCl_2$	Zinc Chloride
ZnO	Zinc Oxide

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

Nowadays, the demand for batteries has increased with the expanding amount of household portable devices; for example, cameras, recorders, portable CD players and MP3 players. As a result, an amount of spent batteries have been increasingly generated as waste materials, which are scattering into the municipal solid waste stream. The Pollution Control Department (PCD) had forecast that the total waste generation by dry cell batteries for 2002, 2007, 2012, 2017 and 2022 would be 3,218, 5,535, 6,270, 7,060 and 7895 tons/year, respectively (PCD, 1998). Based on a questionnaire of 200 samples in size conducted in the Phitsanulok Municipality area by Jirattigalachote (2003), it was found that 35 % of the consumers bought dry cell batteries once a month or more, 34% bought them once every two or three months, and 16% bought them every six months or longer. In spent batteries, there are some hazardous elements such as mercury, cadmium, nickel, lithium and lead. At present, most of the spent dry cell batteries are still discarded into the municipal solid waste stream and then transported to the disposal site. Therefore, the heavy metals contained in the batteries have the potential to leach out into the leachate and cause a subsequent impact to the nearby water resources, especially during the acidogenic phase where the low pH conditions of this phase enhance the dissolution of heavy metals into the landfill leachate.

The National Electrical Manufactures Association (NEMA) reported that a small amount of mercury was formerly used as an additive in alkaline and zinc carbon batteries to suppress the formation of internal gasses, which otherwise would probably lead to leakage, ruptures, or a short shelf life (NEMA, 2002). According to the Notification of Ministry of Industry No.2 (2000) (PCD,1998), dry cell batteries that contain heavy metals as components can be classified as hazardous waste group toxic substances. At present, the disposal of municipal solid waste in landfills has been used, and is connected with the risk of pollution. Unlike the waste streams originating from industrial sources, household hazardous waste in Thailand is not strictly controlled under household hazardous waste regulations. Therefore, a study of leachate characteristics generated from landfills containing spent household batteries is necessary in order to determine its environmental impacts.

1.2 Objectives

In general, the objective of this study is to obtain information on the leachate characteristics generated from a simulated landfill lysimeter containing different portions of spent household batteries. This study focuses on what occurs during the acidogenic phase.

Main Objectives

- To determine the leaching of various spent household battery types using the Toxicity Characteristic Leaching Procedure (TCLP) test.
- To compare among the heavy metal contents in the leachates that are generated from municipal landfill lysimeters containing different portions of household batteries.

Sub-objectives

- To identity the potential impact of heavy metal contamination in the leachate generated from a municipal waste landfill disposal site.

1.3 Hypotheses

- Under the acidogenic phase of municipal waste landfill, there is a high dissolution of heavy metals from the waste into the leachate occurs.

- Landfill compaction would increase the risk of heavy metals being leached from battery into the leachate.

1.4 Scopes of this work

The experiments in this study consist of: the leaching tests of several types of dry cell batteries in order to determine their leaching behavior, and the lysimeter tests in order to determine the leachate characteristics generated from the different conditions of the simulated landfill disposal. The scopes of this study are as follows.

1. Leaching behavior using the TCLP test
    - Leaching tests following the USEPA Method 1311.
    - Measurements of heavy metals were As, Cd, Fe, Hg, Mn, Ni, Pb and Zn in the leaching solution.
    - The use of two types of batteries in the leaching test: primary batteries (non-rechargeable batteries) and secondary batteries (rechargeable batteries).
    - The sizes of the batteries used are as follows:
        1) Five sizes of Leclanché type batteries or Zinc carbon (Size AAA, AA, C, D and 9V)
        2) Four sizes of alkaline batteries (Size AAA, AA, D, and 9V)
        3) One size of Ni-Cd batteries (size AA)
        4) One size of Ni-MH batteries (size AA)
2. Lysimeter test
    - Investigations were conducted on leachates generated using 5 simulated landfill lysimeters (pilot scale) with different portions and conditions of batteries were conducted.
    - The research focused on the leachate generation from the lysimeters during the rainy season using simulated rainfall for 6 months.
    - The types and sizes of batteries that were used in the lysimeter were the same as those in the leaching test.

1.5 Benefits of this work

- To better understand the leaching behaviors of heavy metals from spent household batteries in a landfill.
- The results investigated from the study may be used in the planning of spent household battery management.

CHAPTER II

LITERATURE REVIEW

2.1 Household Batteries

Household batteries are the small portable batteries used daily in devices such as radios, toys, flashlights and lanterns, games, watches, calculators, hearing aids, cameras, telephones and other communications devices, but do not include the larger batteries used in motor vehicles, and commercial industrial, military and other applications. Typically, household batteries are small, 1.5 volt cells that can be readily purchased off the shelf. These batteries come in standard shapes and sizes as shown in Table 2.2 (New Technology Batteries guide, 2005). They are called “dry cell batteries” because they contain no freestanding bodies or pools of liquid electrolytes. Household batteries are divided into two large categories, primary and secondary batteries (NEMA, 2002)

1) A primary battery is a battery that is designed to be cycled (fully discharged) only once and then discarded. It is most commonly used in smaller, portable devices with either low current drain, only used intermittently, or used well away from an alternative power source. Although primary batteries are often made from the same base materials as secondary (rechargeable) batteries, the design and manufacturing processes are not the same. Battery manufacturers recommend that primary batteries not be recharged. The following are some example of primary batteries used in this study:

1.1) Zinc-carbon batteries, also known as “Leclanche cells” are widely used because of their relatively low cost. They were the first widely available household batteries. Zinc-carbon cells are composed of a manganese-dioxide-and-carbon cathode, a zinc anode, and zinc chloride (or ammonium chloride) as the electrolyte. The chemical reaction in a Leclanche cell is shown in the following equation:

$$Zn + 2MnO_2 + 2NH_4Cl \longrightarrow Zn(NH_3)_2Cl_2 + 2MnOOH \qquad (2.1)$$

One notable drawback to these kinds of batteries is that the outer, protective casing of the battery is made of zinc. The casing serves as the anode for the cell and in some cases if the anode does not oxidize evenly, the casing can develop holes that allow for the leakage of the mildly acidic electrolyte, which can damage the device being powered.

1.2) Alkaline batteries, when an alkaline electrolyte—instead of the mildly acidic electrolyte—is used in a regular zinc-carbon battery, it is called an "alkaline" battery. An alkaline battery can have a useful life of 5 to 6 times that of a zinc-carbon battery.

2) A secondary battery is commonly known as a rechargeable battery. It is usually designed to have a lifetime of between 100 and 1000 recharge cycles, depending on the composite materials. Secondary batteries are generally, more cost effective over time than primary batteries, because the battery can be recharged and reused. A single discharge cycle of a primary battery, however, will provide more current for a longer period of time than a single discharge cycle of an equivalent secondary battery (National Institute of Justice, 1997). Table 2.2 shows the types of dry cell batteries found in the municipal solid waste stream (Environmental, Health and Safety Online, 2006). The following are some examples of secondary batteries that were used in this study:

2.1) Nickel-cadmium cells are the most commonly used rechargeable household batteries. They are useful for powering small appliances, such as garden tools and cellular phones. The basic galvanic cell in a Ni-Cd battery contains a cadmium anode, a nickel-hydroxide cathode, and an alkaline electrolyte. Batteries made from Ni-Cd cells offer high currents at a relatively constant voltage and they are tolerant of physical abuse. Nickel-cadmium batteries are also tolerant of inefficient usage cycling. The chemical reaction in a nickel-cadmium battery is shown in equation 2.2.

$$Cd + 2H_2O + 2NiOOH \longrightarrow 2Ni(OH)_2 + Cd(OH)_2 \qquad (2.2)$$

However, nickel-cadmium technology is relatively expensive because cadmium is an expensive metal and also toxic.

2.2) Nickel-Metal Hydride (Ni-MH): Battery designers have investigated several other types of metals that could be used instead of cadmium to create high-energy secondary batteries that are compact and inexpensive. The nickel-metal-hydride cell is a widely used alternative. The anode of a Ni-MH cell is made of a hydrogen storage metal alloy, the cathode is made of nickel oxide, and the electrolyte is a potassium hydroxide solution. According to one manufacturer, Ni-MH cells can last 40% longer than Ni-Cd cells of the same size and will have a life-span of up to 600 cycles (*The Story of Packaged Power*, Duracell International, Inc., July, 1995). This makes them useful for high-energy devices such as laptop computers, cellular phones, and camcorders. Ni-MH batteries have a high self-discharge rate and are relatively expensive to purchase.

Table 2.1 Various Popular Household-Battery Sizes

Size	Shape and Dimensions	Voltage
D	Cylindrical, 61.5 mm tall, 34.2 mm diameter.	1.5 V
C	Cylindrical, 50.0 mm tall, 26.2 mm diameter.	1.5 V
AA	Cylindrical, 50.5 mm tall, 14.5 mm diameter.	1.5 V
AAA	Cylindrical, 44.5 mm tall, 10.5 mm diameter.	1.5 V
9-Volt	Rectangular, 48.5 mm tall, 26.5 mm wide, 17.5 mm deep.	9 V

Note: Three other standard sizes of household batteries are available, AAAA, N, and 6-Volt (lantern) batteries. It is estimated that 90% of portable, battery-operated devices require AA, C, or D battery sizes.

2.1.1 Component of batteries

The main component parts of any dry cell battery are the anode, the cathode and the electrolyte. The cathode is a metal that is combined, naturally or in the laboratory, with oxygen—the combination is called an *oxide*. The anode is a metal that would oxidize if it were allowed to and, other things being equal, is more likely to oxidize than the metal that forms part of the cathode. The electrolyte is a chemical combination that has the property of being alkaline. Thus, an alkaline battery is one that makes use of an alkaline electrolyte.

Table 2.2 Types of dry cell batteries found in the municipal solid waste stream

Battery Type	**Common Name**	**Sizes Available**	**Examples of Use**
Alkaline Manganese	Coppertop, Alkaline	AAA, AA, C, D, 6V, 9V	Flashlights, calculators, toys, clocks, smoke alarms, remote controls
Button	Mercuric Oxide, Silver Oxide, Lithium, Alkaline, Zinc-Air	Sizes vary	Watches, hearing aids, toys, greeting cards, remote controls
Carbon Zinc	"Classic", Heavy Duty, General Purpose, All Purpose, Power Cell	AAA, AA, C, D, 6V, 9V	Flashlights, calculators, toys, clocks, smoke alarms, remote controls, transistor radios, garage door openers
Lithium	Usually has "lithium" label on the battery	3V, 6V, 3V button	Cameras, calculators, computer memory back-up, tennis shoes
Nickel-Cadmium (Rechargeable)	Either unlabeled or labeled " Ni-Cd"	AAA, AA, C, D, 6V, 9V	Flashlights, toys, cellular phones, power tools, computer packs
Nickel-Metal Hydride *(Rechargeable)*	labeled "Ni-MH"	AAA, AA	Flashlights, calculators, toys, clocks, radios, remote controls

Changes in the compositions of the anode and the cathode will provide more or less electricity. The precise adjustment of all of the materials used in a cell can affect the amount of electricity that can be produced, the rate of production, the voltage at which electricity is delivered through the lifetime of the cell, and the cell's ability to function at different temperatures. All of these possibilities do, in fact, exist, and their various applications have produced the many different types of batteries available today (lithium, mercury, and so on). For years, however, the most common cell has been the 1.5 volt alkaline battery. Different batteries function better in different circumstances. Table 2.3 shows the main components of each dry cell batteries type and Table 2.4 shows the different chemical substances in batteries.

A cell will not produce electricity by itself unless it is placed in a circuit that has been rendered complete by a simple switch, or by some other switching connection in the appliance using the battery. While their other ends are connected, the anode draws oxygen atoms toward it, thereby creating an electric flow. If there is a switch in the circuit (similar to any wall or lamp switch), the circuit is not complete and electricity cannot flow unless the switch is in the closed position. If, in addition to the switch, there is something else in the circuit, such as a light bulb, the bulb will light from the friction of the electrons moving through it.

The Regulation Guide for Green Label Dry Cell Batteries provided information on the main six components of a battery which are a carbon rod, chemical substances (for example: MnO_2, NH_4Cl, $ZnCl_2$, ZnO and $HgCl_2$), a separator or seal, metal bottom, outside jacket and metal top cap (Thailand Environment Institute:TEI, 1996). Table 2.5 also shows the estimation of chemical substances in leclanche batteries.

Table 2.3 Main Components of dry cell batteries (Environment Canada, 1991)

Type	**Cathode**	**Anode**	**Electrolyte**
Carbon-zinc	MnO_2	Zinc	NH_4Cl
Alkaline-manganese	MnO_2	Zinc powder	KOH
Mercury-oxide	HgO_2	Zinc powder	KOH or NaOH
Silver Oxide	Silver-oxide	Zinc powder	KOH or NaOH
Nickel-cadmium	Nickel-oxide	Cadmium	KOH or NaOH

Table 2.4 Percent by weight of battery components (Environment Canada, 1991)

Type	Zn	MnO_2	Hg	Ag	C	Paper/ plastic	Metal	Cd
Carbon-zinc	17	29	0.01	-	7	10	16	0.08
Alkaline-manganese	14	22	0.5-1	-	2	5	37	-
Mercury-oxide	11	-	33	-	-	7	22	-
Silver Oxide	10	-	1	27	-	7	22	-

Table 2.5 Examples of chemical components in leclanche batteries (TEI, 1996)

Chemical Substance	Lechanche batteries
MnO_2	Around 51.00 %
Carbon black	Around 10.00 %
NH_4Cl	Around 1.00 %
$ZnCl_2$	Around 10.00 %
ZnO	Around 0.20 %
$HgCl_2$	Around 0-0.02 %

2.1.2 Battery lifetime

Primary batteries are designed to be used only once. Even if never taken out of the original package, they can lose two to twenty-five percent of their original charge every year, depending heavily on temperature. This is known as the "self discharge" rate and is due to chemical reactions that occur within the cell even if no load is applied to it.

Secondary batteries self-discharge more rapidly than primary batteries. In fact, they can self-discharge up to three percent a day (again, depending on temperature). Due to their poor shelf life, they shouldn't be left in a drawer and then relied upon to power a flashlight or a small radio in an emergency. For this reason, it is a good idea to keep a few alkaline batteries on hand. In fact, Ni-Cd batteries are almost always "dead" when you get them, and need to be charged before first use. Most Ni-MH batteries can be recharged 500-1000 times while Ni-Cd batteries can only be recharged about 400 times.

Many people believe that storing batteries at cool temperatures, such as in the refrigerator, reduces the rate of these side reactions and extends the storage life of the battery -- this may have been true in the past with older technology batteries. Modern batteries should be stored in a dry place and at normal room temperatures. Also, some brands of batteries (like Duracell or Energizer) will provide dependable long life even after 5 years of storage in these conditions. Extreme temperatures also reduce battery performance.

2.1.3 Environmental impact

With any battery disposal method, the potential exists to release heavy metals into the environment. Because batteries are made from various chemicals such as cadmium, mercury, copper, zinc, lead, manganese, nickel, and lithium, there are potential environment problems or hazards that can be produced if batteries are not properly disposed. Lakes and streams can be polluted as the metals vaporize into the air when batteries are burned. Disposing batteries into landfills can contribute to heavy metals that may potentially leach from solid waste landfills.

Of the spent household batteries around 70% are discharged to the environment. Considering in terms of the quantity of heavy metals, i.e. Mn, Zn, Hg, Cd and Pb, generated from the household batteries, their amounts are higher than the total amount of the heavy metals generated by the industrial section (TEI, 1996). In a recent EPA study, nickel-cadmium (Ni-Cd) rechargeable batteries were found to contribute over 50% of the cadmium in the waste stream (Rawrence waste reduction and recycling, 2003).

Several types of batteries still use heavy metals as electrodes or to increase their life span. Cadmium, lead, and mercury are the heavy-metal components most likely to be the target of environmental concerns (National Institute of Justice, 1997). Even at low levels, mercury can impair the central nervous system, kidneys, lungs and liver. Mercury bioaccumulates in the food chain expose species at the top to the highest concentrations. Elevated levels of cadmium can damage the kidneys, liver, respiratory tract and lungs. (Universal Waste Coordinator, 2006).

Some of the battery components, such as paperboard and carbon powder, are relatively organic and can quickly merge into the ecosystem without noticeable impact. Other components, such as steel, nickel, and plastics, while not actively toxic to the ecosystem, will add to the volume of a landfill, since they decompose slowly. Of most concern however are the heavy-metal battery components which when discarded, can be toxic to plants, animals, and humans.

2.1.4 Battery Manufacturing Situation

At present, the number of factories that produce dry cell batteries in Thailand have decreased in particular, small factories have been going out of business. According to the data from the Thai Industrial Standards Institute, under the Ministry of Industry, only seven companies in Thailand are registered as shown in Table 2.6. However, the need for comsumption still increases every year, so the amount of imported batteries from other country such as Japan, China, Korea and Malaysia is increasing. It has been estimated that around 400 million pieces of dry cell batteries are produced per year in Thailand and around 95 percent are used in the country (Energy Policy and Planning Office, 2006).

Table 2.6 List of the factories producing batteries (Thai Industrial Standards Institute, 2006)

Factory name	Battery type	Location
Panasonic Battery (Thailand) Co.,Ltd.	Alkanline (AA) Lechanche (AA,C,D)	Samutprakan Province
Rocket Thai Co.,Ltd.	Alkaline (AA, AAA)	Chachoengsao Province
Alkaline (Thailand) Co.Ltd.	Alkaline	Samutprakan Province
Mutsushita Battery (Thailand) Co.,Ltd.	Mercurry Free Manganese Dry cell	Samutprakan Province
Karnkamon Co.,Ltd.	15 V (BA-386)	Bangkok
Paisarnsang Co.Ltd.	15 V (BA-386)	Bangkok
Raylam Battery Co.Ltd.	6 V (BA-386)	Bangkok

2.2 Leaching Test Basics

2.2.1 Leaching test objectives

Many batch leaching test protocols have been developed to simulate the leaching processes of waste materials in landfill or other disposal scenarios to evaluate potential risks to human and groundwater. The results of batch leaching tests should be carefully evaluated before being used for regulatory or design purposes. The basic objectives of leaching tests are as follow:

- Classify either as hazardous or non-hazardous waste for regulatory application
- Evaluate leaching potential of pollutants resulting from a waste under specified environmental conditions
- Simulate waste or site-specific leaching conditions to evaluate leaching potential
- Provide an extract that is representative of the actual leachate produced from a waste in the field
- Measure treatment effectiveness of a waste
- Identify appropriate waste management scenario or waste disposal environment
- Determine partition and kinetic parameters for the purpose of contaminant transport modeling

2.2.2 Types of leaching tests

Common batch leaching tests include Extraction Procedure Toxicity (EP-Tox; US EPA Method 1310, 2001), Toxicity Characteristic Leaching Procedure (TCLP; US EPA Method 1311, 2001), Synthetic Precipitation Leaching Procedure (SPLP; US EPA Method 1312, 2001), Waste Extraction Test (WET; California Code of Regulations, 1985), American Society for Testing and Materials extraction test (ASTM D 3987-85, 2001), and Multiple Extraction Procedure (MEP; US EPA Method 1320). The major differences among these tests are leaching solution, liquid to solid (L/S) ratio, and number and duration of extraction.

A column or lysimeter test has also been used for simulation of leaching from waste. This test involves the placement of waste material in a column or lysimeter and then the addition of leaching solution to the material to produce leachate. Unlike the batch leaching tests, the leaching solution is under continuous flux. Therefore, this test is often called a dynamic test and may be more representative of field conditions. However, it is not easy to control experimental conditions for this test. Some operational problems, such as channeling and clogging of the column, may result in a non-reproducible case. No standardized column test is currently available in the United States. Table 2.7 summarizes the main differences between batch leaching and column leaching tests.

Table 2.7 Comparisons of batch test with column test (Townsend et al.,2003)

Parameters	Batch test	Column test
Testing period	Short-term (hours to days)	Long-term (days to months)
Operation	Easy to operate	Difficult to operated (channeling due to non-uniform packing of waste or clogging of column)
Cost	Relatively low	Relatively high
Application of results	Depending on type of batch test	More specific scenario
L/S ratio	Relatively high (To estimate Maximum amounts of Pollutants to be leached)	Relatively low (close to field conditions)
pH control	Easy to control pH with appropriate chemical	Material dictates its own chemical environment

2.2.3 Interpretation of leaching test results

To be classified as a hazardous waste, the battery must be tested to determine if it meets the definition of one of the four characteristics of a hazardous waste established by the US Environmental Protection Agency. These characteristics are ignitability, corrosivity, reactivity and toxicity. The dry cell batteries do not exhibit the characteristics necessary to be classified as reactive or ignitable wastes.

To determine if a waste exhibits the characteristic of toxicity, the EPA requires the waste to be evaluated using the Toxicity Characteristic Leaching Procedure (TCLP). The procedure involves obtaining a TCLP extract and analyzing that extract for the constituents that are regulated. The criteria for determining toxicity are a comparison of the contaminant concentration in the extract with a stipulated chemical-specific regulatory limit. If the extract concentration exceeds the TCLP limit, the waste source of the extract is characterized as toxicity and is classified as hazardous waste (Envir ene,1995). Table 2.8 and Table2.9 shows the TCLP Toxicity Characteristic Regulatory Levels and the other Regulatory used in this test.

Table 2.8 TCLP Toxicity Characteristic Regulatory Levels

Chemical	Regulatory Level (mg/l)	Source
Arsenic	5	(1)
Cadmium	1	(1)
Mercury	0.2	(1)
Lead	5	(1)
Nickel	70	(2)

(1) U.S. Code of Federal Regulations (CFR), Title 40, Chapter 1, Part 261.24 “Toxicity Characteristic”

(2) U.S. Code of Federal Regulations (CFR), Title 40, Appendix VII, Part 266 “Health-Based Limits for Exclusion of Waste-Derived Residues”

Table 2.9 Soluble Threshold Limit Concentration and Secondary Drinking Water Regulation

Chemical	Regulatory Level (mg/l)	Source
Zinc	250	(1)
Ferrous	30	(2)
Manganese	5	(2)

(1) Soluble Threshold Limit Concentration from California Code of Regulations (CCR), Title 22, Division 4.5, Chapter 11, Section 66261.24 “Characteristic of Toxicity”

(2) 100 times of the Secondary Drinking Water Regulations in Drinking Water Standards and Health Advisories; EPA 822-B-00-001

The 100 times of the Secondary Drinking Water Regulations in Table 2.9 were used for safety factor which takes into account the attenuating processed underground.

2.3 Landfill Leachate

2.3.1 Leachate generation

For many decades, landfills have served as the ultimate disposal sites for all types of wastes: residential, commercial, and industrial, both innocuous and hazardous. Landfill technology has evolved from the open, burning dump to highly engineered sites designed to minimize the tile impact of contaminants in the waste on the adjacent environment (Farquhar, 1989). Even though a landfill is the most economical waste management option, there are still some disadvantages, especially the possibility of groundwater contamination through the leaching of deposited materials by percolating waters. When precipitation falls on a landfill, it either becomes surface runoff, returns to the atmosphere via evaporation and transpiration, or infiltrates the refuse (Freeze, 1979). The infiltrating water ultimately will form leachate and this leachate can contaminate either groundwaters or surface waters. The first thing to occur when rainfall reaches the ground will be runoff. After runoff occurs, a certain amount of water will be lost due to evaporation and transpiration (Cheremisinoff and Gigliello, 1983). So, a simple water budget for a sanitary landfill can be constructed using the following equation (Noble, 1976):

$$L = P - (E + T + R)$$

where:
L = Leachate
P = Precipitation
E = Evaporation
T = Transpiration
R = Runoff

Leachate is a potential indicator of the disposal of hazardous substances in a municipal solid waste (MSW) site. A number of leachate studies have revealed that there are potentially harmful chemicals in the leachate of MSW landfills, and of VOCs in landfill gas at trace concentrations (Slack et al., 2004). Contaminants carried in leachate are dependent on solid waste composition and on the simultaneously occurring physical, chemical, and biological activities within the fill. The quantity of contaminants in leachate from a completed landfill where no more waste in being dispose of can be expected to decrease with time (Weiss, 1974).

The differences in the leachate composition between the acid phase and methanogenic phase are summarized in Table 2.10.

Table 2.10 Leachate compositions in terms of average values and range under acidogenic phase and methanogenic phase. (Kjeldsen et al.,2002)

Parameter	Acid phase		Methanogenic phase		Average
	Average	Range	Average	Range	
pH	6.1	4.5 – 7.5	8	7.5 – 9	
Biochemical Oxygen Demand (BOD_5)	13,000	4,000-40,000	180	20-550	
Chemical Oxygen Demand (COD)	22,000	6,000-60,000	3,000	500-4,500	
BOD_5/COD (ratio)	0.58		0.06	10-420	
Sulfate	500	70-1,750	80	20-600	
Calcium	1,200	10-2,500	60	40-350	
Magnesium	470	50-1,150	180	3-280	
Iron	780	20-2,100	15	0.03-45	
Manganese	25	0.3-65	0.7		
Ammonia – N					740
Chloride					2,120
Potassium					1,085
Sodium					1,340
Total Phosphorus					6
Cadmium					0.005
Chromium					0.28
Cobalt					0.05
Copper					0.065
Lead					0.009
Nickel				0.03-4	0.17
Zinc	5	0.1-120	0.6		

* All values in mg/L except pH and BOD_5 /COD

** Rang based on Ehring 1983 and 1988

2.3.2 Phase of degradation

The following five stages play an important role in the proportions of the leachate constituents that the landfill produces (Whittleton, 2004).

Stage 1: Hydrolysis & aerobic degradation

The initial stage of organic decomposition occurs during the emplacement of the waste in the landfill and for the period of time after, when oxygen is available within the waste. There chemical processes are initiated and facilitated by the presence of aerobic micro-biota which metabolize a fraction of the organic waste to produce simpler hydrocarbons, water, carbon dioxide and, as this is an exothermic reaction, heat. The heat generated can raise the temperature of the waste to up to 70ºC - 90ºC, however compacted waste achieves lower temperatures due to the reduced availability of oxygen. In these reactions, water and carbon dioxide are produced in the greatest concentrations. The carbon dioxide can dissolve in the water, forming a leachate that is rich in carbonic acid which in turn, lowers the pH of the surroundings. This stage generally lasts for a matter of days or weeks, depending on the amount of oxygen that is available within the waste.

Stage 2: Hydrolysis and fermentation

The removal of oxygen in Stage 1 facilitates a change in conditions from aerobic (oxygen present) to anaerobic (oxygen absent). Thus the majority of micro-biota found within the waste change to anaerobic species. Carbohydrates are hydrolysed (a chemical process in which a molecule is split into two parts by the addition of a water molecule) to sugars, which are then further decomposed to form carbon dioxide, hydrogen, ammonia and organic acids. Proteins decompose via deaminisation (the removal of an amino - NH_2 group) to form ammonia, carboxylic acids and carbon dioxide. The leachate that is produced at this stage contains a high concentration of ammoniacal nitrogen. Acetic acid is the main organic acid formed but propionic, butyric, lactic and formic acids and acid derivative products are also produced, and their formation is affected by the composition of the initial waste material. The temperatures in the landfill drop to between 30ºC and 50ºC. Gas composition may rise to levels of up to 80% carbon dioxide and 20% hydrogen.

Stage 3: Acetogenesis

In this stage, anaerobic conditions are still present and the organic acids that were formed in the hydrolysis and fermentation stage are now converted, via specific microorganisms to acetic acid, acetic acid derivatives, carbon dioxide and hydrogen. Other microorganisms convert carbohydrates directly to acetic acid in the presence of carbon dioxide and nitrogen. Hydrogen and carbon dioxide levels begin to diminish towards the end of this stage, with the lower hydrogen concentrations promoting the methane-generating microorganisms (methanogens), which subsequently generate methane and carbon dioxide from the organic acids and their derivatives generated in the earlier stages.

Stage 4: Methanogenesis

This stage encompasses the main processes that lead to the production of landfill gas. At this point, the chemical processes involved are comparatively slow and can take many years to complete. Oxygen-depleted, anaerobic conditions still remain as in the previous two stages. Low levels of hydrogen are required to promote the methanogenic organisms, which generate carbon dioxide and methane from the organic acids and their derivatives such as acetates and formates formed in the earlier stages. Methane generation may also occur from the direct conversion of hydrogen and carbon dioxide (via microorganisms) into methane and water: Hydrogen concentrations, produced during Stages 2 and 3, therefore fall to low levels during this fourth stage.

Stage 5: Oxidation

Oxidation processes mark the final stage of the reactions involved in the biodegradation of waste. As the acids are used up in the production of landfill gas (as seen in Stage 4), new aerobic microorganisms slowly replace the anaerobic forms and re-introduce oxygen to the region. Microorganisms that convert methane to carbon dioxide and water may also become established.

The diagram below shows the anaerobic digestion pathway (Habil, 2006) and Figure 2.2 shows theleachate composition in each phase (Stegmann, 2005).

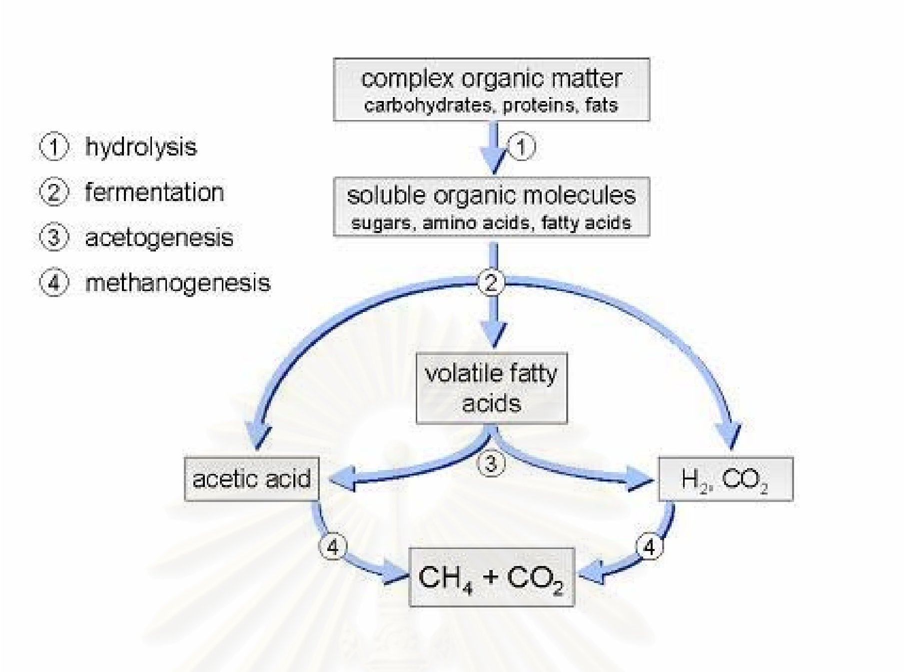


Figure 2.1 Anaerobic digestion pathway

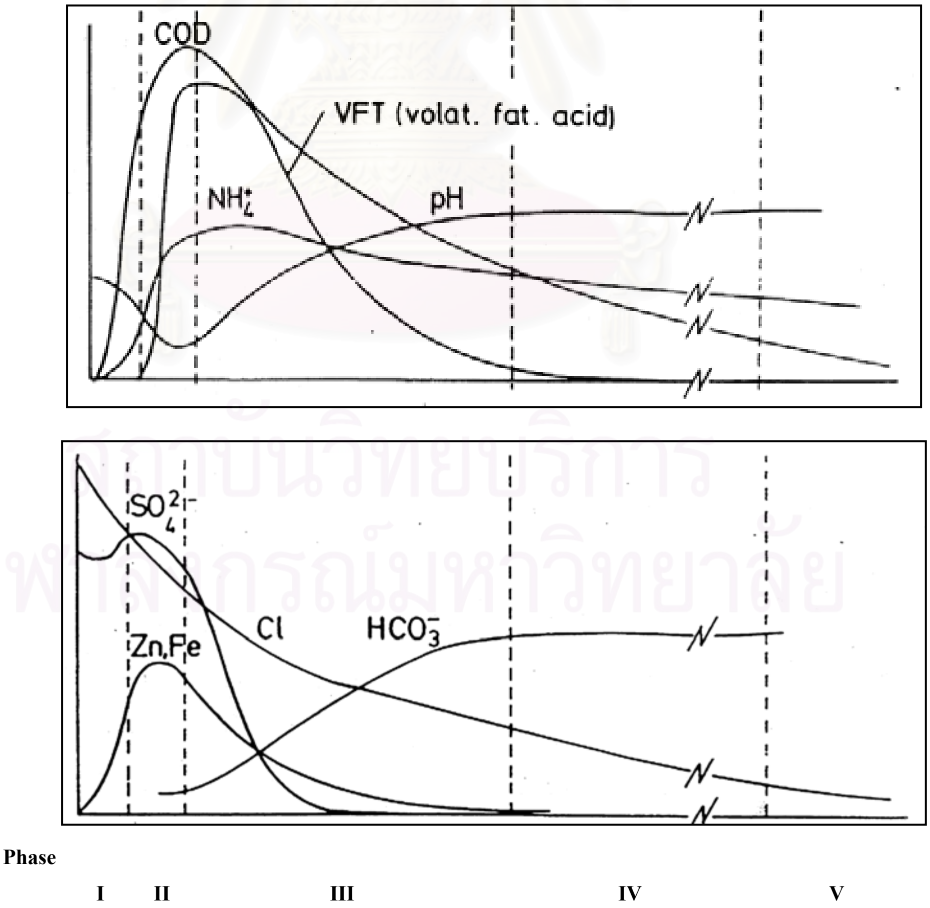


Figure 2.2 Leachate composition

2.4 Groundwater Standards

Since there is no leachate standard in Thailand, therefore the Groundwater Standards for drinking purpose from a Notification of the Ministry of Industry will be referred to in order to compare the results of the heavy metal contents from the lysimeter test.

Table 2.11 shows the heavy metal standards from Notification of the Ministry of Industry, No. 4, B.E. 2521 (1978).

Table 2.11 Heavy metal standards from the Groundwater Standards for drinking purpose

Parameters	Units	Standards	
		Suitable allowance	Maximum allowable
1. Ferrous (Fe)	mg/l	Not more than 0.5	1.0
2. Manganese (Mn)	mg/l	Not more than 0.3	0.5
3. Zinc (Zn)	mg/l	Not more than 5.0	15.0
4. Chloride (Cl)	mg/l	Not more than 250	600
5. Arsenic (As)	mg/l	None	0.05
6. Lead (Pb)	mg/l	None	0.05
7. Mercury (Hg)	mg/l	None	0.001
8. Cadmium (Cd)	mg/l	None	0.01

Source: Notification of the Ministry of Industry, No. 4, B.E. 2521 (1978), issued under the Ground Water Act B.E. 2520 (1977), published in the Royal Gazette, Vol. 95, Part 66, dated June 27, B.E. 2521 (1978).

2.5 Related research

The Thailand Health Research Institute (1992) found that 0.033% of the waste by weight of the waste discharged from households and shops in Bangkok was composed of batteries.

Boonyanupong (1999) studied the direction of hazardous waste management in Chiang Mai Province. It was found that the average battery weight generated from a household per year was 0.52 kg from 17.21 kg total weight of 12 types of hazardous waste. It was concluded that batteries were found to take up around 3 % of the total amount of hazardous waste.

Watananugulkit et al. (2003) assessed the impact on water quality from leachate at the On-Nuch Disposal Center in Bangkok. It was found that the level of BOD, COD and DO of surface water were in the ranges of 650-1,525 mg/l, 1,098-2,508 mg/l and 0.39-2.30 mg/l, respectively. The manganese and cadmium contents were in the ranges of 0.430-2.680 ppm and 0.002-0.20 ppm, respectively. The leachate had not only a high organic load, but also high alkalinity, hardness, nitrate nitrogen, and manganese contents, which are related to high conductivity.

Sohn et al. (2002) studied the leaching characteristics of various spent batteries containing heavy metals by using various types of batteries. It was determined that the Hg concentrations in the leaching solution of a silver oxide battery, mercury oxide battery, conventional carbon-zinc battery and alkaline manganese battery were 1.24, 25.0, 0.008 and 0.13 mg/l, respectively. The concentrations of Zn and Mn in the leaching solution exceed the fixed limits of 5 mg/l and 10 mg/l, respectively in all alkaline and zinc carbon batteries. These results mean that these spent batteries should be treated as hazardous waste.

Puetpaiboon et al. (2001) investigated the leachate characteristics from the disposal of dry cell batteries in a sanitary landfill by using two PVC lysimeters with a diameter of 30 cm and a height of 4 m, respectively. One model was solely filled with the municipal waste while the other model was filled with the municipal waste with addition of 2 pieces of dry cell batteries. The results of the leachate characteristic showed that the maximum concentrations of Mn, Cr and Ni generated in dry batteries added model were 8.39 mg/l, 2.86 mg/l and 0.28 mg/l, respectively. In the other model filled with solely municipal waste, the maximum concentrations of Mn, Cr and Ni were 6.86 mg/l, 2.57 mg/l and 0.24 mg/l, respectively. The maximum concentrations of heavy metals in the leachate were found during the aerobic and hydrolysis phases of degradation.

Beccaloni et al. (2000) conducted investigations on arsenic and some other heavy metal (Cd, Cr, Hg and Pb) in three leachate topologies produced from a municipal waste landfill plant, lab-scale aerobic landfill and lab-scale anaerobic landfills. Leachate was collected and analyzed monthly. All heavy metal were determined after mineralization except for Hg that was determined before mineralization. It was found that low concentrations of all heavy metal were found in all leachates especially in the leachate from the lab-scale anaerobic reactors, where low pH values had been found.

Photong (1998) investigated the detoxification of heavy metals in spent battery powder by solidification. The batteries used in this study were large size carbon-zinc batteries collected from the On-Nuch transfer station. The leaching test of the battery powder followed the Notification of MOI No.6 B.E.2540 (1997), and showed that most battery powders were classified as hazardous waste. In particular, the BO6 battery (National green color) which is highly consumed had Cd and Hg in its the leaching solution at concentrations of 3.75 mg/l and 1.24 mg/l, respectively. These values exceeded the standards of leachable substances set by the Ministry of Industry in Promulgation vol.25, 1988, for cadmium and mercury (not more than 1 mg/l and 0.2 mg/l, respectively).

Thapanandana (1992) studied the contamination of mercury, cadmium and manganese in the leachate generated from the solid waste disposal sites of the Bangkok Metropolitan Administration. Mercury contamination in the leachate storage pools was found to be ranged from 2.47-39.13 ppb at the On-nuch disposal site, which was higher than the permissible level of the industrial effluent standard, as ruled by the Office of the National Environment Board (NEB) (5 μg/l). The manganese content detected from the leachate storage pools and the surrounding waterways was found to be in the same range of 0.01-2.88 ppm. The Cd contents in water samples were detected to be lower than 0.03 ppm.

Karnchanawong et al. (2002) investigated the effects of multiple batch-fed waste filling and season on quantity and characteristics of the leachate generated from a sanitary landfill for a period of four years. A Lysimeter with a 1.9 m diameter was used and filled with solid wastes collected from the Chiang Mai municipal area. Three lifts of wastes were prepared. Each lift was 2 m and was filled after the filling of the former one for 6 months. Leachate quantity and leachate characteristics were measured and analyzed. It was found that the 1st lift of the waste produced very high organic contents in the leachate. The filling of the wastes in the rainy season generally provide high concentrations of pollutants. Table 2.12 shows the P50% of leachate characteristics investigated in each season.

Table 2.12 P50% of leachate characteristics investigated in each season.

Parameter	Season						
	1st rainy	2nd dry	2nd rainy	3rd dry	3rd rainy	4th dry	4th rainy
pH	7.69	7.96	7.71	8.38	7.92	8.38	7.55
Conductivity (mS/cm)	13.48	22.93	17.1	18.6	13.9	18.6	14.0
Alkalinity (mg/l $CaCO_3$)	8,020	8,405	12,300	12,200	13,900	12,200	6,770
Acidity (mg/l $CaCO_3$)	114	237	505	309	265	309	597
VA (mg/l)	2,330	336	455	745	504	745	164
COD (mg/l)	6,450	2,090	3,430	1,340	1,830	1,340	957
BOD (mg/l)	4,610	442	633	179	251	179	121
TOC (mg/l)	3,520	573	626	481	548	481	208
TS (mg/l)	16,600	12,200	12,800	7,920	9,700	7,920	5,790
TDS (mg/l)	15,900	12,000	12,600	7,830	9,400	7,830	5,750
TKN (mg/l N)	1,500	1,610	2,450	1,730	2,100	1,730	1,380
NH_3-N (mg/l N)	1,300	1,435	2,190	1,560	2,020	1,560	1,230
TP (mg/l P)	21	19.4	24.3	29.9	32	29.9	25.5
Cl^- (mg/l)	3,220	2,750	3,120	2,260	2,880	2,260	963
BOD/COD	0.71	0.22	0.19	0.13	0.14	0.13	0.12

Farquhar (1989) reviewed current methods and data available for estimating leachate production and variability. It was found that most contaminants, especially biodegradable organics, tended to reach peak concentrations in the leachate in the earlier months of leaching and then reduced subsequently. This study also reviewed the trace metals in landfill leachate as shown in Table 2.13.

Table 2.13 Trace metals in landfill leachate

Metal	**Concentration range (mg/l)**
Arsenic	1.0-10.0
Lead	1.0-10.0
Nickel	1.0-10.0
Cadmium	0.1-1.0
Mercury	< 0.1
Zinc	100-200

Kylefors (2002) conducted studies on how to predict the leaching from MSW and measured to improve leachate management in landfills. It was found that there were several different phases of decomposition of the MSW in a landfill. An aerobic phase is a short duration (months) that is sometimes divided into an oxygen-consuming and a nitrate-consuming phase. An anaerobic acidogenic phase (years) and an anaerobic methanogenic phase (decades) can be divided into initial and a stable methanogenic phases. Table 2.14 shows the metal concentrations in landfill leachates.

Table 2.14 Metal concentrations in landfill leachates. Unit: μg/l

	Average, (Ehrig 1989	Acidogenic, (Robinson and Gronow 1993)	Methanogenic, (Robinson and Gronow 1993)	Interval Acidogenic, (Rastas 2002)[a]	Interval Methanogenic (Ratas 2002)[a]	Interval (Ehrig 1989)
As	160	24	34	-	-	5-1600
Cd	6	20	15	<0.2-100	<0.01-900	0.5-140
Ni	200	420	170	<10-1800	36-600	20-2050
Pb	90	280	200	<1-900	<0.1-1900	8-1020
Cr	300	130	90	< 10-1500	<0.01-700	30-1600
Hg	10	0.4	0.2	-	-	0.2-50

[a] Base on data from (Ehrig 1989), (Kettunen 1997), (Kruempelbeck and Ehrig 1999), (Kruempelbeck and Ehrig 1999), (Kruse 1994), (Marttinen et al. 2000), (Robinson 1995) and (Tchobanoglous et al. 1993)

CHAPTER III

METHODOLOGY

Leaching and lysimeter tests were conducted in this study. The details of the experiments are described below:

3.1 Leaching Test

3.1.1 Leaching and analytical procedures

Leaching test or batch test have been developed to simulate the leachate process of waste materials in landfill or other disposal scenarios to evaluate potential risk to human and groundwater. The batch test typically involves mixing size-reduced waste with extraction and then agitating the mixture. These tests are typically for a short period of time (for hours or days).

The regulatory leaching test, the TCLP developed by the USEPA, was used in this study. This method utilizes a buffered organic acid solution as an extraction fluid. The acid used was acetic acid, one of the organic acids formed during the anaerobic decomposition of organic matter in MSW.

The TCLP requires that the batteries first be size-reduced to less than 0.95 cm. One hundred grams of the size-reduced batteries were placed in a 2.2 l polyethylene extracting vessel, and a 2-liter of the extracting solution was added. The slurry was mixed in a rotary extractor for 18 ± 2 hours and then filtered through a 0.7 μm glass fiber filter. The filtrate was collected in 1-l plastic bottles and preserved to a pH of less than two using a nitric acid. The pictures of battery size used in this study and the picture of a rotary agitator are shown in Figures 3.1.

There are two types of extraction fluids, i.e. extraction fluid No. 1 and No.2. The preparations for of both types of fluids are as follows:

Extraction fluid No. 1 was prepared by adding 11.4 ml of glacial acetic acid (CH_3CH_2OOH) to 1 liter of deionized water. Then 128.6 ml of 1N NaOH was added, and solution was brought to volume of 2 liters. The resulting solution pH was 4.93 ± 0.05.

Extraction fluid No. 2 was prepared by the dilution of 5.7 ml of glacial acetic acid (CH_3CH_2OOH) in1 liter of deionized water. The resulting solution pH was 2.88 ± 0.05.

An appropriate TCLP extraction fluid was examined by weighing five grams of crushed batteries in a 500 ml beaker. Then, 96.5 ml of deionized water was added to the beaker and covered with a watch glass. After that, a magnetic stirrer was used to stir the mixture vigorously for 5 minutes. Then, the pH was measured and recorded. Extraction fluid No.1 was used when the pH was less than 5.0. In addition, 3.5 ml of 1N HCL was added when the pH was more than 5.0. After covering the beaker and heating it up to 50°C for 10 minutes, the solution was cooled to the room temperature and pH was recorded. If the pH was more than 5.0, extraction fluid No. 2 was used. The filtrate was collected and examined for the heavy metals by using ICP spectroscopy except for arsenic and mercury that were analyzed using the hydride generation and cold vapor technique, respectively. For more details on battery brands name, see Table 3.1.

3.2 Lysimeter test

Lysimeter test or column test has also been used for simulation of leaching form waste. This test involves the placement of waste material in a column or lysimeter and then the addition of leaching solution to the material to produce leachate. Unlike the batch leaching tests, the leaching solution is under continuous flux.

The lysimeter tests were divided into two different types of experiments. The first type was the lysimeter tests solely for batteries, and the second type was the lysimeter test for municipal solid waste containing different portion of batteries. Five lysimeter made from PVC were prepared indoors at the Department of Environmental Engineering, Faculty of Engineering, Chiang Mai University. The cross section of each lysimeter is shown in Figure 3.2. The height and diameter of each lysimeter were 2 m and 20.32 cm (8 in), respectively. The lysimeter was closed in order to simulate the anaerobic condition. In the upper part of each lysimeter, there was a pipe for rainfall addition and a pipe for gas ventilation. Gravel was filled into the bottom part as a waste layer base to allow the leachate to be stored and to flow through the effluent pipe. The waste layer's height in each lysimeter was 1.25 m. Figure 3.3 shows an overview of the five lysimeters.

(a) Battery size AAA (b) Battery size AA

(c) Battery size C (d) Battery size 9V

(e) Battery size D (f) Rotary Agitator

Figure 3.1 Battery size and rotary agitator used in the leaching test

Table 3.1 Battery brands name

Label	Battery type	Battery size	Battery brands name	Made in
B1	Zinc-carbon	AA	Panasonic (black),National (black)	Japan
B2	Zinc-carbon	AA	Panasonic (green),National (green)	Thailand
B3	Zinc-carbon	AA	Panasonic (red) National (red)	Thailand
B4	Zinc-carbon	AA	Eveready (black)	Malaysia
B5	Zinc-carbon	AA	Eveready (red)	Singapore
B6	Zinc-carbon	AA	Super power (black-silver)	China
B7	Zinc-carbon	AA	Leader price	China
B8	Zinc-carbon	AA	Power (black-goldbrown)	China
B9	Zinc-carbon	AAA	Panasonic (black),National (black)	Japan
B10	Zinc-carbon	AAA	Power (black-goldbrown)	China
B11	Zinc-carbon	AAA	White horse	Thailand
B12	Zinc-carbon	D	Panasonic (black),National (black)	Thailand
B13	Zinc-carbon	D	Panasonic (green),National (green)	Thailand
B14	Zinc-carbon	D	Panasonic (red), National (red)	Thailand
B15	Zinc-carbon	D	Eveready (black)	Indonesia
B16	Zinc-carbon	D	Eveready (blue)	Indonesia
B17	Zinc-carbon	D	Superay	China
B18	Zinc-carbon	C	Panasonic (black),National (black)	Malaysia
B19	Zinc-carbon	C	Panasonic (green),National (green)	Thailand
B20	Zinc-carbon	C	Panasonic (red), National (red)	Thailand
B21	Zinc-carbon	C	Eveready (black)	Indonesia
B22	Zinc-carbon	C	Eveready (red)	Indonesia
B23	Zinc-carbon	9V	Panasonic (black),National (black)	Japan
B24	Zinc-carbon	9V	Panasonic (red), National (red)	China
B25	alkaline	AA	Panasonic alkaline (black-yellow)	Thailand
B26	alkaline	AA	Energizer alkaline	Singapore
B27	alkaline	AA	Duracell	China
B28	alkaline	AAA	Panasonic alkaline (black-yellow)	USA
B29	alkaline	AAA	Energizer alkaline	Singapore
B30	alkaline	AAA	Duracell	China
B31	alkaline	D	Energizer alkaline	USA
B32	alkaline	9V	Duracell	China
B33	Ni-Cd	AA	National recharge (Ni-Cd)	China
B34	Ni-Cd	AA	Panasonic recharge (Ni-Cd)	Japan
B35	Ni-MH	AA	Sanyo twicell 1700 (Ni-MH)	Japan
B36	Ni-MH	AA	SPA recharge (Ni-MH)	Thailand

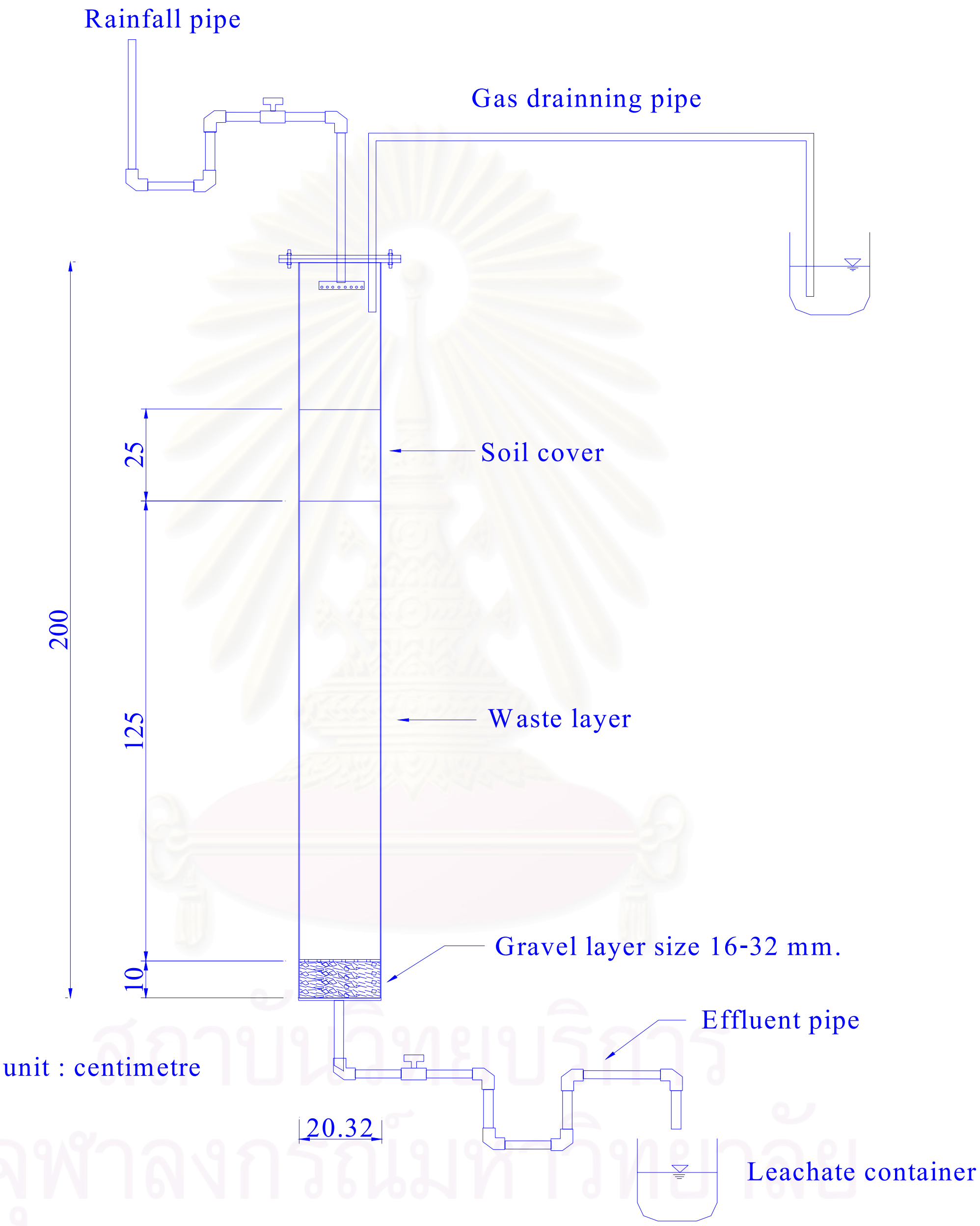


Figure 3.2 Lysimeter cross section

(a) Overview of lysimeter

(b) Rainfall pipe and Gas draining pipe

(c) Effluent pipe and Leachate container

Figure 3.3 Overview of the lysimeter

3.2.1 Lysimeter test for batteries

One hundred fifty kilograms of spent household batteries were collected from different places, i.e. the battery disposal box at Chulalongkorn University and the battery disposal box at Chiang Mai University as shown in Figure 3.4. Then the batteries were classified by type and size as shown in Table 3.2. The top ten brands and sizes of batteries were then ranked. Finally, the batteries were selected and filled into the lysimeters according to the ranked data.

(a) Battery disposal box at Chulalongkorn University

(b) Battery disposal box at Chiang Mai University

Figure 3.4 Batteries sampling point

Table 3.2 Amount of each battery after classified by type and size

Battery size	**Battery type**				**Total**
	Zinc- carbon	**Alkaline**	**Ni-Cd**	**Ni-MH**	**(pcs.)**
AAA	245	447	5	5	702
AA	1618	1050	67	33	2768
C	225	7	-	-	232
9V	87	20	4	-	111
D	721	23	1	-	745
Total	2896	1547	77	38	**4558**

Lysimeter No. 1 was filled with the uncompacted batteries which resulted in a density of 1200 kg/m^3 and weight of 48.6 kg. While, batteries filled in Lysimeter No.2 were manually hammered, in order to simulate the compaction process in the actual landfill. Table 3.3 gives the details of the batteries filling conditions.

Table 3.3 Details of battery filling conditions in Lysimeter No.1 and No. 2

Lysimeter	Type of waste	Total Amount of Weight (kg)	Density (kg/m^3)
No.1	Solely spent batteries	48.6	1200
No.2	Solely broken spent batteries	48.6	1200

3.2.2 Lysimeter test for municipal solid waste mixed with batteries

In this experiment, another three lysimeters (Lysimeter No.3, No.4 and No.5) were filled with municipal wastes mixed with different portion of batteries.

Wastes filled in the lysimeters simulated compositions in accordance with the waste compositions of the Chiang Mai Municipality, during the year 2004, as collected by the Pollution Control Department (http://www.pcd.go.th/info_serv/waste municipk.html).

Table 3.4 Waste Characteristics of Chiang Mai Municipality, year 2004

Physical component	**% wet weight**
Food Waste	54.0 %
Paper	11.0 %
Plastic	15.1 %
Glass	9.6 %
Metal	2.1 %
Rubber and leather	0.9 %
Cloth	2.6 %
Garden Waste	1.2 %
Stone and ceramics	2.1 %
Miscellaneous	1.4 %
Total	100
% moisture content	53.5 %

Firstly, each component of waste was chopped into small pieces, then mixed together according to the wet weight percentage in Table 3.4 and filled into Lysimeters No.

3 to 5. The moisture content of each component was predetermined and the results are shown in Table 3.5. After mixing the wastes, the moisture contents were recalculated using the data in Tables 3.4 and 3.5. The moisture content of the mixed waste was later adjusted to 53.5 % according to the actual moisture content in Table 3.4.

Table 3.5 Moisture content of each component

Physical component	**% Moisture**
Food Waste	71.60
Paper	6.18
Plastic	0.51
Glass	0.08
Metal	2.55
Rubber and leather	0.97
Cloth	8.65
Garden Waste	12.72
Stone and ceramics	0.47
Miscellaneous	1.46

Generally, the solid wastes in landfills have a density of around 600-800 kg/m^3 (Tchobanoglous et al, 1993). In this study, a density at 600 kg/m^3 was selected. Equal weights of wastes were filled in the lysimeter for every 25 cm height in order to get the same density throughout the lysimeter. Batteries were added in the lysimeter according to the details shown in Table 3.6.

Figure 3.5 shows the pictures of waste components filled in the lysimeter while Figure 3.6 shows the mixing and filling processes of the waste.

Table 3.6 Detail of waste filling condition in Lysimeters No.3 to 5

Lysimeter	Type of waste	Batteries, (%)	Total Amount of Weight (kg)	Density (kg/m^3)
No.3	Solely municipal waste	0	24.3	600
No.4	Municipal waste + broken spent batteries with 1% by weight	1 (0.243 kg)	24.3	600
No.5	Municipal waste + broken spent batteries with 5% by weight	5 (1.215 kg)	24.3	600

(a) Food Waste

(b) Paper

(c) Plastic

(d) Glass

(e) Metal

(f) Rubber and leather

(g) Cloth

(h) Garden Waste

Figure 3.5 Waste components filled in the lysimeter

(a) Stone and ceramics (b) Miscellaneous

Figure 3.5 Waste components filled in the lysimeter (continued)

(a) Mixing wastes

(b) Waste filling

Figure 3.6 The mixing and filling process of the waste

3.3 Precipitation Data

The daily precipitation data, shown in Table 3.7, that obtained in Chiang Mai province during May 2004 to October 2004 from the Meteorological Department, under the Ministry of Information and Communication Technology of Thailand was used to simulate rainfall in this study because its pattern was likely to be the same as in the past ten year. For more details see Appendix B. A high amount of rainfall was investigated in May and September. The total rainfall was 1208.9 mm.

To simulate the actual rainfall of a location with a slope of 3% and compacted top soil, a runoff-coefficient of 0.22 was used. The result of the evaporation from the landfill in Chiang Mai province was estimated to be 28% of the total rainfall (JICA and CMU, 1992). As a consequence, the infiltration to landfill was estimated to be 50% of the rainfall. Therefore, in this study, 50% of the simulated rainfall was fed into the lysimeter according to the days that had rainfall. The detail information of daily added rainfall is shown in Appendix B.

Table 3.7 Daily Rainfalls (mm) between May – October 2004 of Chiang Mai Province

Date	May	June	July	August	September	October
1	9.5	2.5	0.1	16.5	T	3.0
2	9.2	0.0	0.0	5.0	17.2	0.7
3	18.4	0.0	0.4	0.3	14.7	0.0
4	0.0	0.0	0.0	13.2	4.0	0.0
5	113.8	0.0	1.7	0.7	0.0	0.0
6	1.4	1.9	8.9	13.8	0.0	0.0
7	10.2	0.3	T	0.0	0.0	0.0
8	0.0	0.4	1.4	12.0	22.7	0.0
9	0.0	11.9	2.3	4.2	144.4	0.0
10	0.0	34.1	1.0	11.0	21.0	1.9
11	0.0	14.6	31.6	4.9	0.1	T
12	0.0	12.1	5.3	0.8	4.1	T
13	2.8	0.4	19.2	0.0	21.5	0.0
14	0.0	46.6	1.6	2.0	55.7	0.0
15	6.7	23.8	0.0	2.4	8.2	0.0
16	1.7	1.7	T	0.0	19.6	0.0
17	4.4	6.2	T	0.0	7.8	0.2
18	T	4.1	0.0	T	0.0	22.0
19	9.1	0.4	0.0	1.8	4.1	0.0
20	22.2	0.0	6.0	21.7	20.8	0.0
21	10.1	T	4.7	0.0	5.5	7.0
22	T	0.0	12.7	0.0	0.0	4.0
23	0.1	T	4.4	0.0	0.0	0.0
24	0.0	0.0	17.7	0.0	0.0	0.0
25	0.8	0.0	34.6	0.0	0.0	0.0
26	0.2	0.0	2.1	0.0	0.0	0.0
27	3.5	5.8	40.6	0.0	0.0	0.0
28	1.3	4.0	1.6	0.0	T	0.0
29	2.5	7.3	5.8	T	0.0	0.0
30	2.4	0.7	2.5	5.4	0.0	0.0
31	18.8	-	11.8	0.0	-	0.0
Total	249.1	178.8	218.0	115.7	371.4	38.8

T = Rainfall amount less than 0.1 mm

3.4 Sampling and Analyses

The quantity of leachate generated from each lysimeter was measured everyday. For the 1st month, leachate was sampled and analyzed twice a week and after that once a week until the end of experiment, except for mercury was analyzed twice a month. The parameters and analytical methods used are shown in Table 3.8.

It should be remarked that the heavy metal parameter selected to be analyzed in this study as shown in Table 3.8 were based on the toxicity level, battery components and the results from the past researches. (Sohn, 2002, Photong, 1998 and Puetpaiboon, 2001)

The quality control, such as field blank, method blank and spikes were done in order to satisfy recommended minimum criteria for acceptable data quality.

3.5 Statistical Analyses

In order to analyze the data, a one-way ANOVA at a 95 % confidence intervals was used to compare the results in this study.

Table 3.8 Monitoring parameters and analytical methods

Measurement/Analysis	Method	Reference
1. Leaching test	TCLP	USEPA Method 1311
- Heavy metal*:		
Hg	AA:Cold vapor technique (GBC Avanta Model HG 3000)	USEPA Method 7470A
As	AA:Hidride Generation (GBC Avanta Model HG 3000)	Standard Method APHA, AWWA (1995)
Cd, Mn, Ni, Pb, Fe and Zn	Induced Couple Plasma (Varian Vista-MPX CCD simultaneous)	„
2. Lysimeter study		
- Leachate Quantity	Weight measurement	
- pH	pH meter (HORIBA F-21)	
- Conductivity	Conductivity Meter (Cond 330i/set)	
- Heavy metal	Same as in the leaching test Extraction method : Acid digestion	USEPA Mehod 3010A
- Chloride	Mercuric Nitrate Titration	Standard Method APHA, AWWA (1995)
- Chemical Oxygen Demand	Dicromate Reflux	
- Total Organic Carbon	TOC Analyzer :Wet Oxidation (Shimadzu TOC-VcpH)	„
- Dissolve Organic Carbon	TOC Analyzer :Wet Oxidation (Shimadzu TOC-VcpH)	„
- Volatile Fatty Acid	Direct Titration	„
- Total Alkalinity	Acid Titration	„

CHAPTER IV

RESULTS AND DISCUSSIONS

The results from the leaching test of batteries, lysimeter tests of batteries and municipal solid waste mixed with batteries are as follows.

4.1 Leaching test

The TCLP test was developed to provide a relatively quick test on a solid waste. The objective of the TCLP test was to find out whether the solid waste should be characterized as a hazardous material or not so that an appropriate management approach can be assigned. The acetic acid used in the test simulates the organic acids produced from decomposing waste in anaerobic environments such as a landfill (Townsend et al., 2004).

Based on current regulations, the concentrations of specific compounds in the TCLP extraction fluid must be compared with the listed Toxicity Characteristic (TC) levels specified in Title 40 of the US Code of Federal Regulations (CFR) part 261.24 (1992). The waste is considered to be a hazardous material if the extract from the TCLP test contains any one of the toxic constituents in an amount equal to or greater than the concentrations specified in the TC list.

The heavy metals of interest in the leaching solution were As, Cd, Fe, Hg, Mn, Ni, Pb and Zn. However, only As, Cd, Hg and Pb were regulated under the TC list so the other regulations were used to compare the Ni, Zn, Fe and Mn concentrations. The Ni concentration was compared with the Health-Based Limits for Exclusion of Waste-Derived Residuals from Title 40 of the US CFR part 266 Appendix VII (1993).

The Zn concentration was compared with the Soluble Threshold Limit Concentration (STLC) specified in Title 22 of California Code of Regulations (CCR) section 66261.24 (1985). It should be remarked that the STLC was identical to the TCLP in application, and differs only by the nature of the extraction fluid utilized. It is used within the state of California for hazardous waste characterization, to determine which type of landfill will be able to accept the material. The leaching fluid is a buffered solution that is prepared using sodium hydroxide and citric acid.

The Fe and Mn concentrations were compared with the 100 times of the US Nation Secondary Drinking Water Regulations based on the study of Peralta, et al., 1992. This factor takes into account the attenuating processes such as dilution and absorption occurring underground that will reduce the leachate concentration from the point of leachate generation to the point of human or environmental exposure.

In this study, the TCLP test was performed on four different types of batteries. The batteries used consisted of twenty-four zinc-carbon batteries, eight alkaline batteries, two Ni-Cd batteries and two Ni-MH batteries. The results of the leaching tests of dismantled household batteries are shown in Figures 4.1a to 4.1h (more details are located in Table A-2, Appendix A).

According to the US TC list, the results of the TCLP test performed indicated that non- rechargeable zinc carbon (B1-B24) and alkaline (B25-B32) batteries were not considered hazardous wastes since the As, Cd and Pb concentrations were below the TCLP limits on the TC list of 5mg/l, 1 mg/l, and 5 mg/l for As, Cd and Pb, respectively, except for the Hg concentrations that were detected below the detection limit of 0.005 mg/l. As for the rechargeable battery, Ni-Cd (B33-B34), it generated a leaching solution containing Cd concentrations above the TCLP limit. Therefore, it can be concluded that the Ni-Cd battery can be categorized as a hazardous waste.

In the case of the Ni-MH batteries, it was found that the Ni concentration were below the Health-Based Limits for Exclusion of Waste-Derived Residues, which is stated at 70 mg/l. However, the Ni-MH batteries still pose a risk to the environment, so an appropriate management approach should be assigned to this kind of battery.

From Figure 4.1f, it can be seen that Zn was a major element in all batteries, and most of the Zn concentrations were above the Soluble Threshold Limit Concentration stated at 250 mg/l. This might be due to the composition of the zinc plate in the anode. It was observed that the Ni-Cd battery at the AA size, which had its zinc concentration below 250 mg/l. It has been observed that in terms of battery size, the size D battery had the maximum concentration of Zn leach out.

There were all zinc-carbon batteries in which the concentrations of Mn in the leaching solution were above the 100 times of the Secondary Drinking Water Standard stated at 5 mg/l, as shown in Figure 4.1(g). There were three alkaline batteries that the concentrations of Mn were below the Standard. The maximum concentration of Mn (55.7 mg/l) was found in the zinc-carbon battery, size D.

None of the samples had Fe exceed 100 times of the Secondary Drinking Water Standard recommended by the Office of Water USEPA, stated at 30 mg/l.

In conclusion, it can be implied that the type of batteries influenced the concentration of heavy metals in the leaching solution. Even if zinc-carbon batteries and alkaline batteries are not classified as hazardous waste, those batteries must not be disposed directly into the municipal waste stream due to the high amounts of Zn and Mn that can leach out.

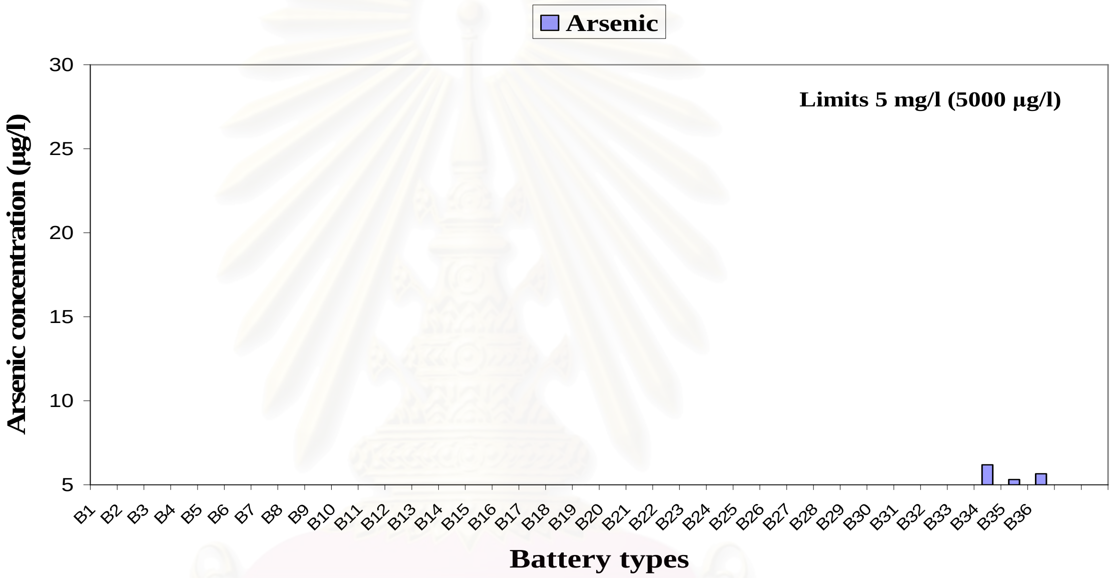


Figure 4.1 (a) Arsenic concentration in the leaching solution of various battery types

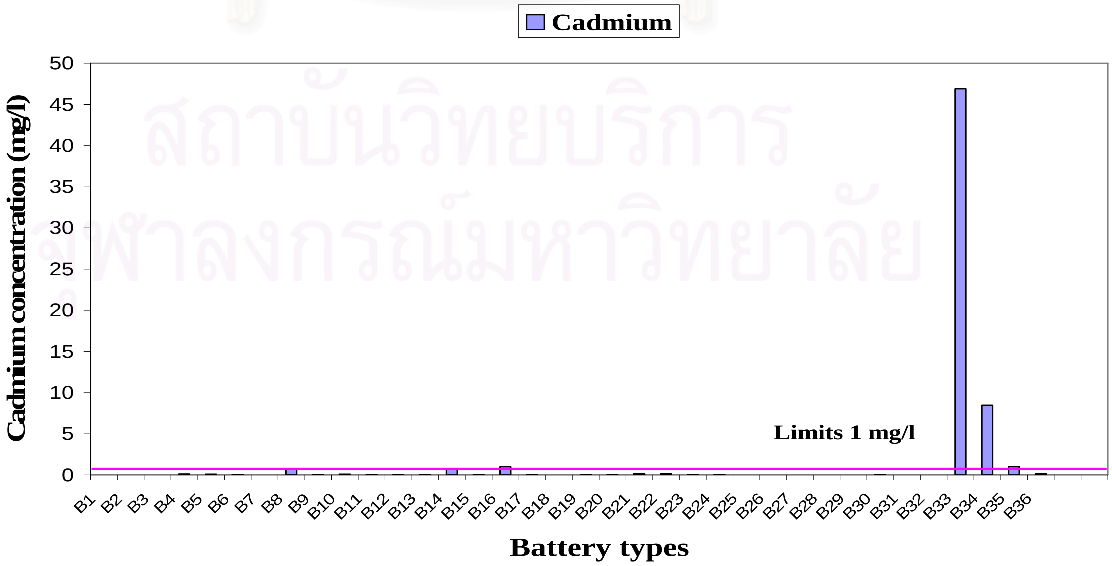


Figure 4.1(b) Cadmium concentration in the leaching solution of various battery types

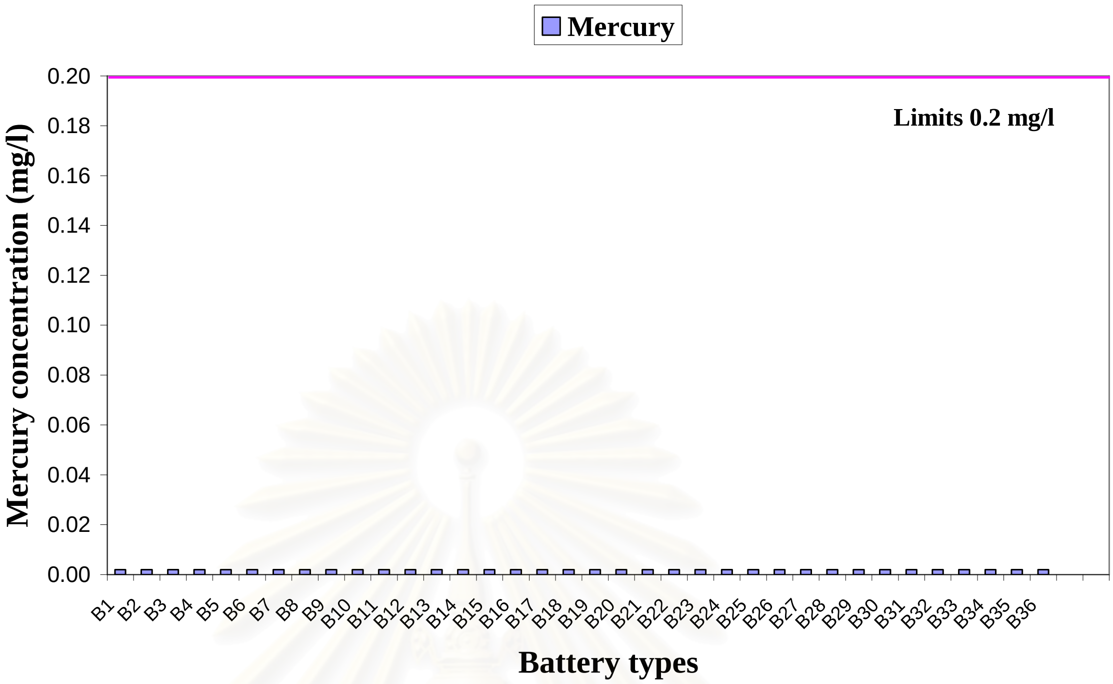


Figure 4.1(c) Mercury concentration in the leaching solution of various battery types

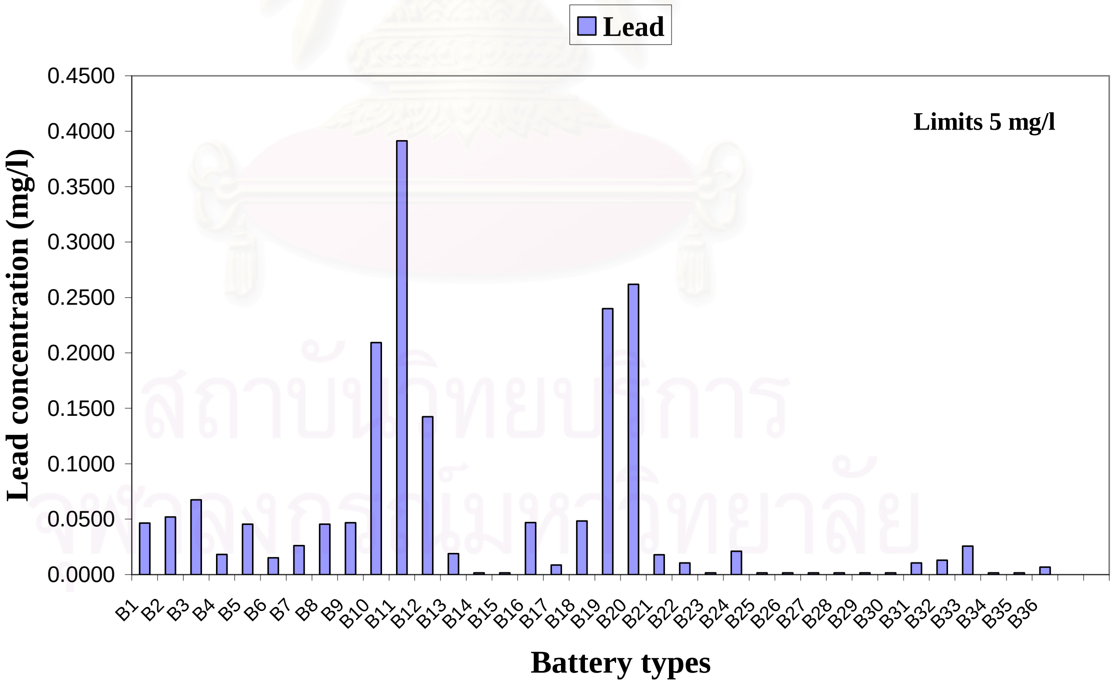


Figure 4.1(d) Lead concentration in the leaching solution of various battery types

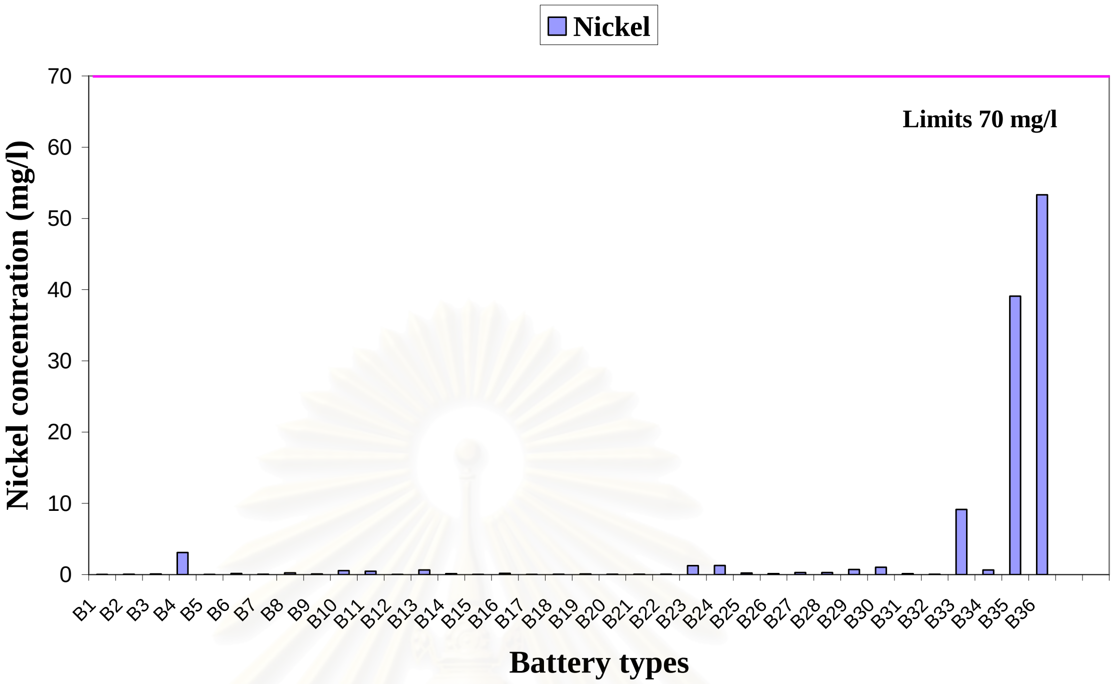


Figure 4.1(e) Nickel concentration in the leaching solution of various battery types

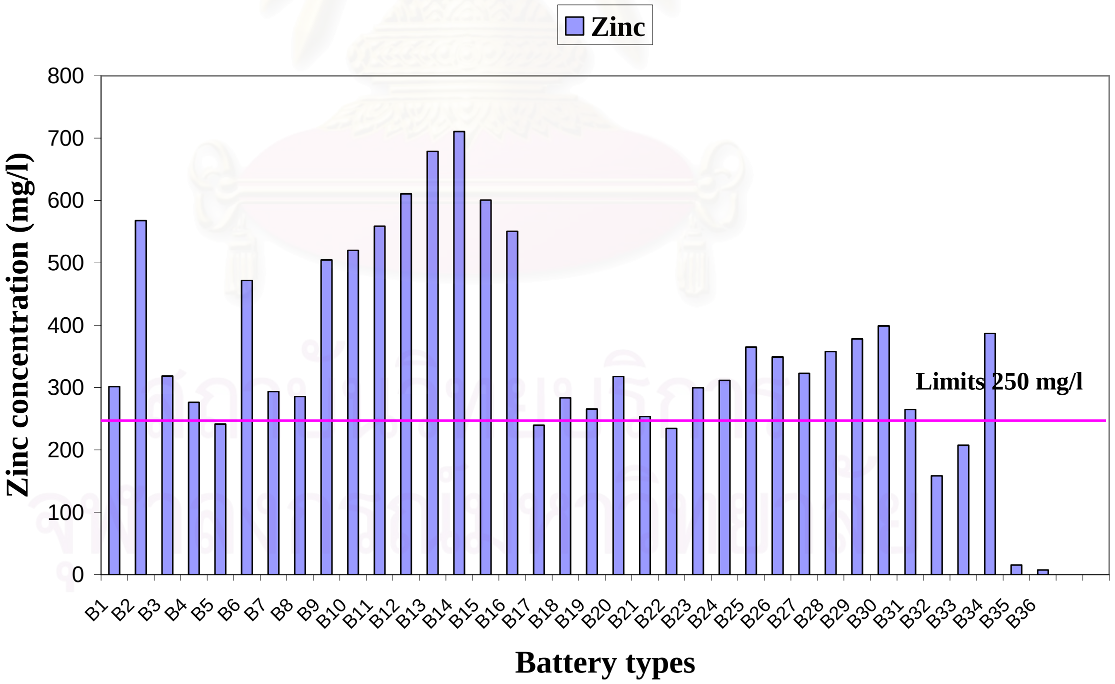


Figure 4.1(f) Zinc concentration in the leaching solution of various battery types

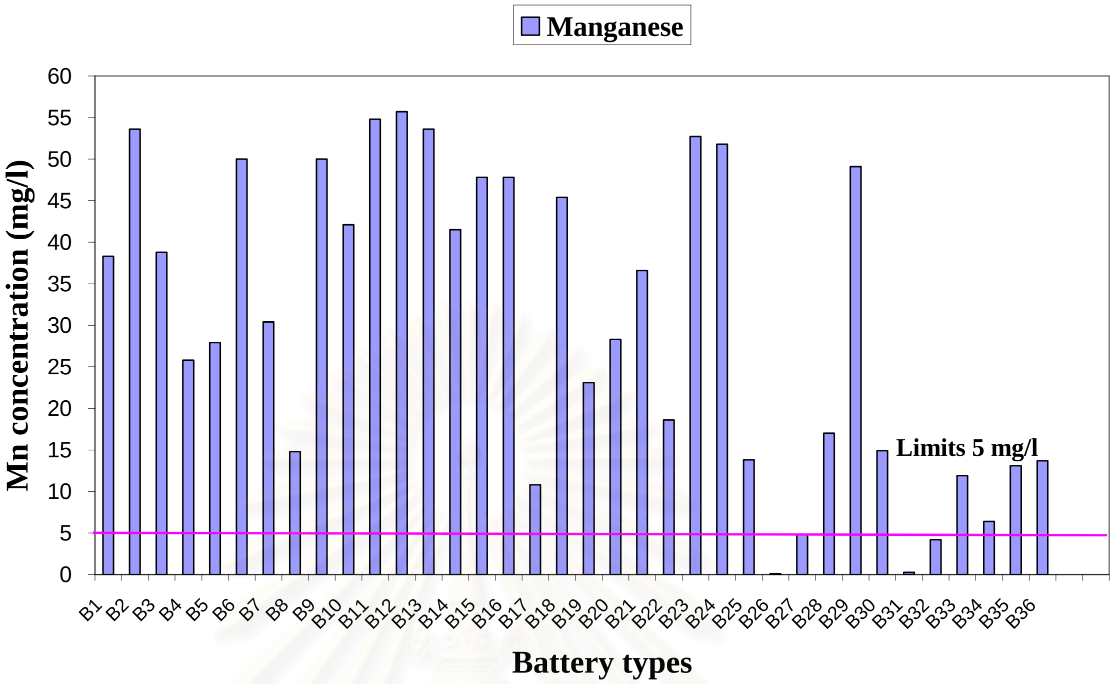


Figure 4.1(g) Manganese concentration in the leaching solution of various batteries type

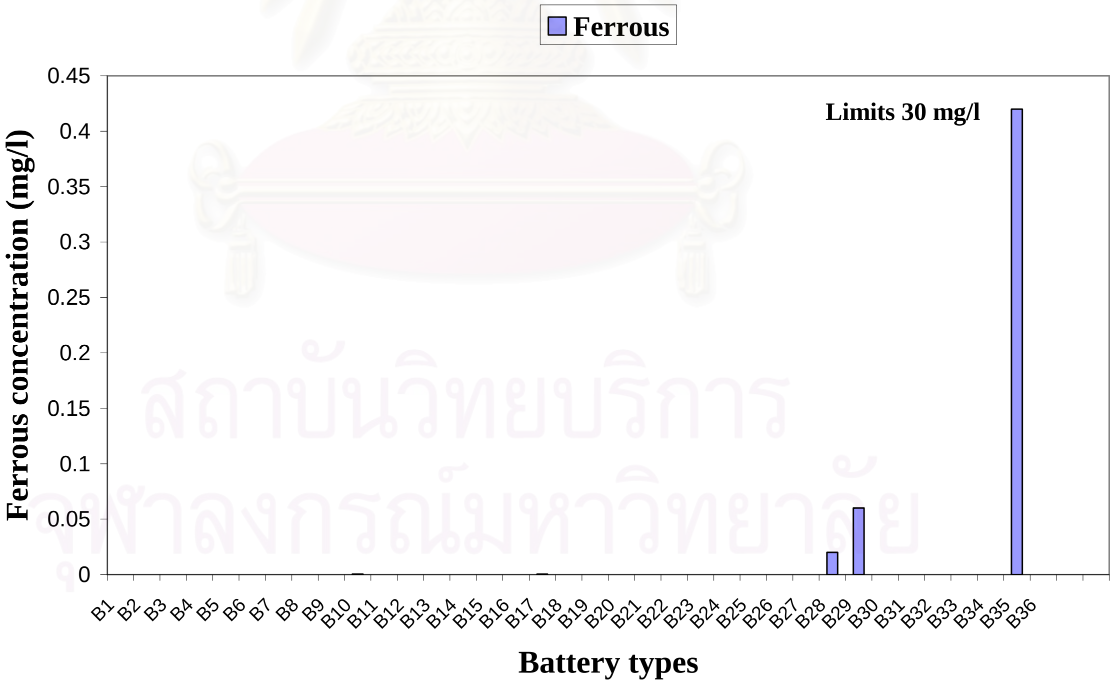


Figure 4.1(h) Ferrous concentration in the leaching solution of various batteries type

4.2 Lysimeter test

4.2.1 Simulated Rainfall Added

During the experimental period, the quantity of water introduced in each lysimeter was 50% of the daily rainfall. This 50 % value was calculated from the precipitation data collected at the Chiang Mai Metrological Station from May 1st, 2004 to October 31st, 2004 (more details can be found in Table B-2, Appendix B)

The simulated rainfall water values were added from the first day of loading until the 174th day of the experiment. The 1st and 3rd months had the highest number of days in which simulated rainfall was added, which were 21 and 23 days, respectively. The lowest number of days (7 days) was added in the 6th month. In the 5th month, the highest amount of added water was recorded at 6,018 ml. The quantity of water added in each lysimeter ranged from 1.62-2,340 ml, and the total amount of water added in the lysimeter was 19 L. Figure 4.2 shows the daily amounts of the water added to the lysimeter.

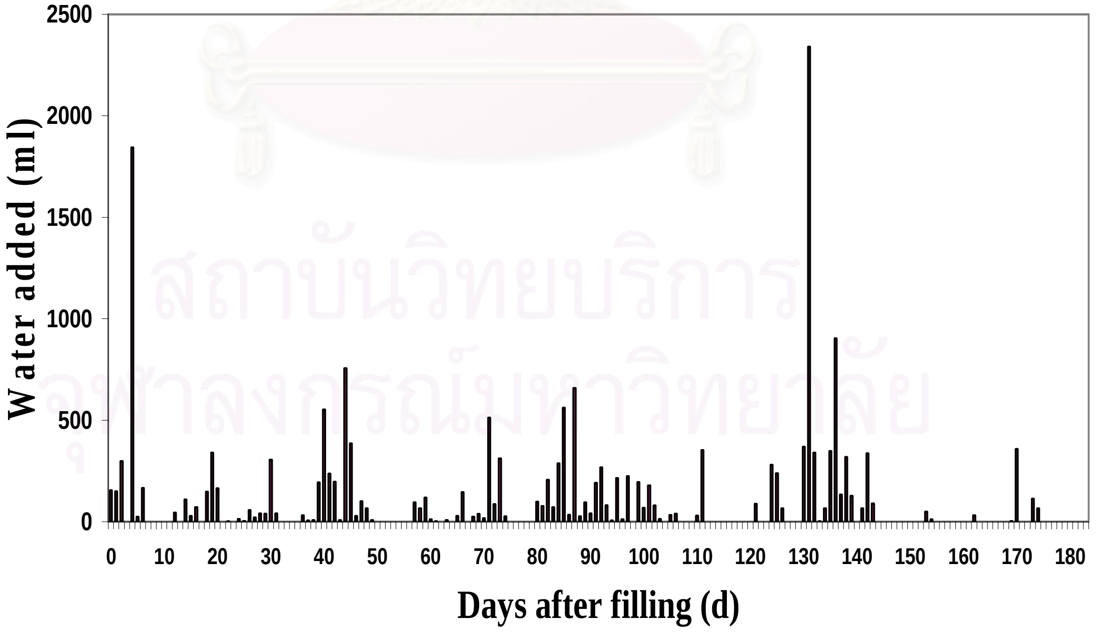


Figure 4.2 Daily amount of water added to the lysimeter

4.2.2 Leachate generation

In this study, leachate volumes were measured daily. The leachate generation data from the five lysimeters are shown in Appendix C, and Figure 4.3 illustrates the color of the leachates generated from each lysimeter in the 5th month.

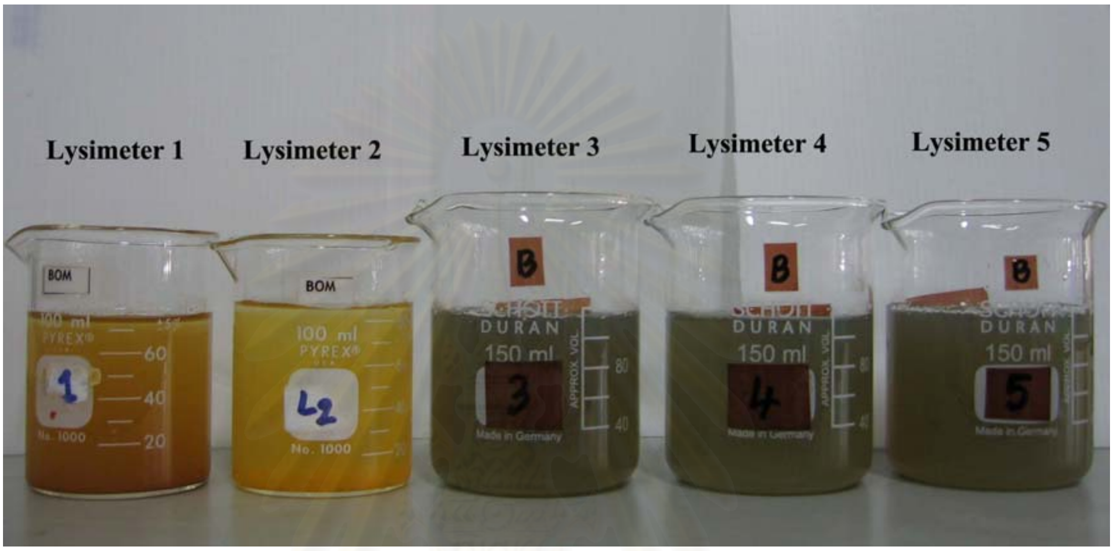


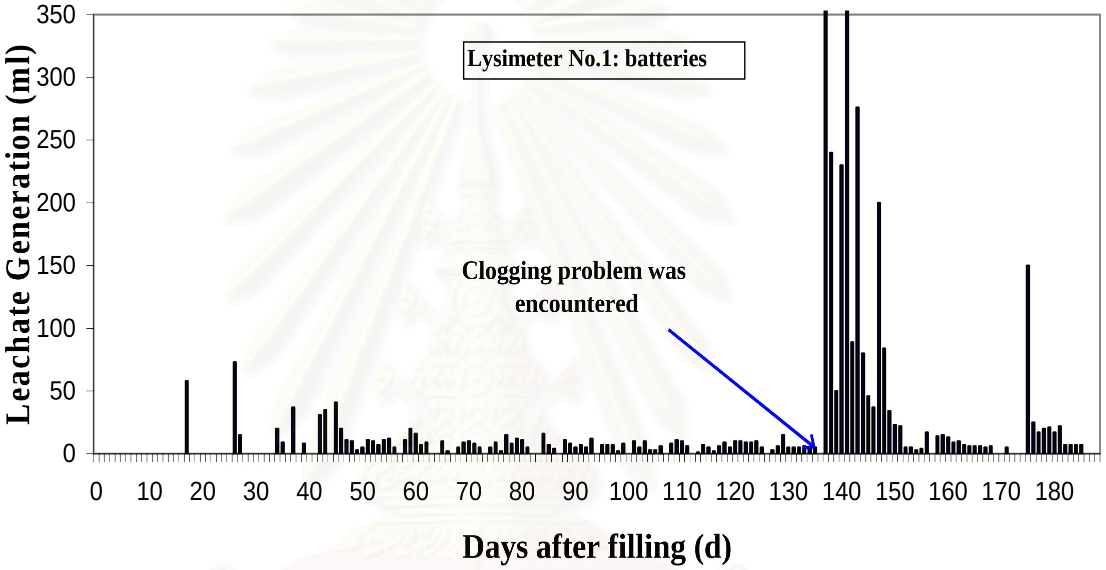
Figure 4.3 Color of leachate generated from five lysimeter in the 5th month

4.2.2.1 Battery lysimeter test

The same amount of 48.6 kg of batteries was filled into both Lysimeters No. 1 and No.2. In Lysimeter No.2, batteries were hammered in order to simulate the compaction which occurs in a landfill. In the 1st month, the quantity of leachate generated was very low due to the low moisture contents in the batteries. As a result, there were not enough leachate amounts to be analyzed. In the 2nd month, the leachate generated from both lysimeters increased slightly. Figure 4.4 illustrates the leachate generated from Lysimeters No.1 and No.2.

It was observed that the leachate quantities generated from Lysimeter No. 1 during the 2nd to the 4th months of the experiment was quite low compared with that of Lysimeter No.2. On the 132nd day of the experiment, a clogging problem was found and none of the leachate leached out from Lysimeter No. 1. Therefore, Lysimeter No. 1 was uncovered in order to solve the clogging problem. After that, the experiment proceeded again. According to the low amount of leachate generated from

Lysimeter No.1 as presented in Figure 4.4, it could be clearly noticed that the clogging might have occurred since the 2nd month of the experiment. Therefore, only the results from both lysimeters from the 132nd day until the end of the experiment were compared. It was found that the means of leachate generation from Lysimeters No. 1 and No.2 were not significantly different at a 95% confidence limit. For more details, see Appendix D.



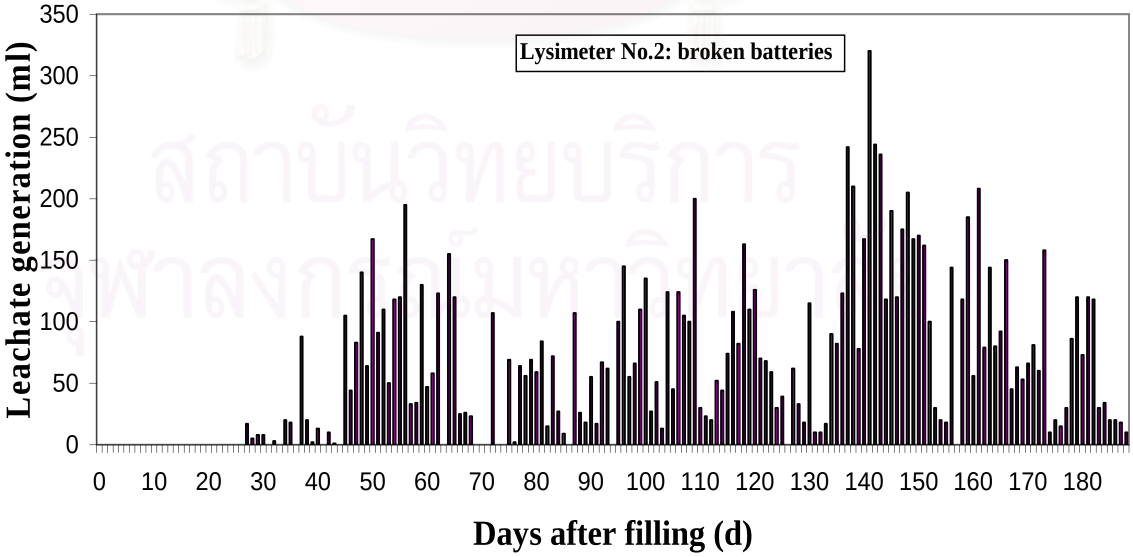


Figure 4.4 The leachate generation from Lysimeter No. 1 and No. 2

4.2.2.2 Landfill lysimeter test

The water applied to a waste layer is considered to be absorbed partly by the waste until a moisture content of the waste layer reaches a field capacity when the initial moisture of a filled waste is below the field capacity. Even though the moisture content of the waste layer is below field capacity, some of the water applied is normally observed to be leached out by channeling. The volume of this channeled water, however, seems small and could be followed by the times at which no leachate was produced despite the addition of water. Generally, the release of a significant volume of leachate marks the point at which the field capacity is attained. The leachate would be a mixture of applied water and stored water whose origin may be the inherent moisture in the waste or some parts of the applied water (Ikeguchi, 1991).

Figure 4.5 illustrates the leachate generated from Lysimeters No.3 to No.5. It can be seen from the graphs that the leachate generation patterns were quite the same in all lysimeters. Water was added on the first day of waste loading. A high amount of water was added in the 4th day of a waste filling, which resulted in a significant volume of leachate generation in Lysimeters No.3, No.4 and No.5 immediately after being filled. It can be presumed that the waste layer attained or exceeded the field capacity in the beginning period. During days 130-140, the leachate amount was very high in every lysimeter due to the very high amount of the added water.

Figure 4.6 reflects the cumulative leachate volume of each lysimeter during the study period. It appears that the quantity of leachate produced depended on the quantity of the added water. A statistical analysis shows that the amount of leachate generated from Lysimeters No.3, 4 and 5 were not significantly different, at a 95% confidence limit. For more details, see Appendix D.

4.2.3 Leachate characteristics

4.2.3.1 Battery lysimeter test

pH, conductivity, Cl^-, Cd, As, Fe, Hg, Mn, Ni, Pb and Zn were the parameters measured for their concentrations in the leachates generated from Lysimeters No.1 and No.2. Table 4.1 shows the ranges of the characteristics of the leachates generated from these two lysimeters.

Figure 4.7a shows the pH for Lysimeters No. 1 and No. 2, and it was found that they were slightly base. This indicates that the batteries induced the base condition.

The clogging problem, which occurred in Lysimeter No.1 as mentioned in topic 4.2.2.1, caused the low amount of leachate produced during the 30th to the 132nd days. The leachate characteristics as shown in Figure 4.7 illustrates that higher concentrations of the metals in the leachate from Lysimeter No.1 were found during the clogging period. Therefore, only the results of the leachate characteristics after solving the clogging problem were compared for Lysimeters No.1 and No.2 in order to determine the effects of landfill process compaction on the leaching out of the heavy metals from batteries.

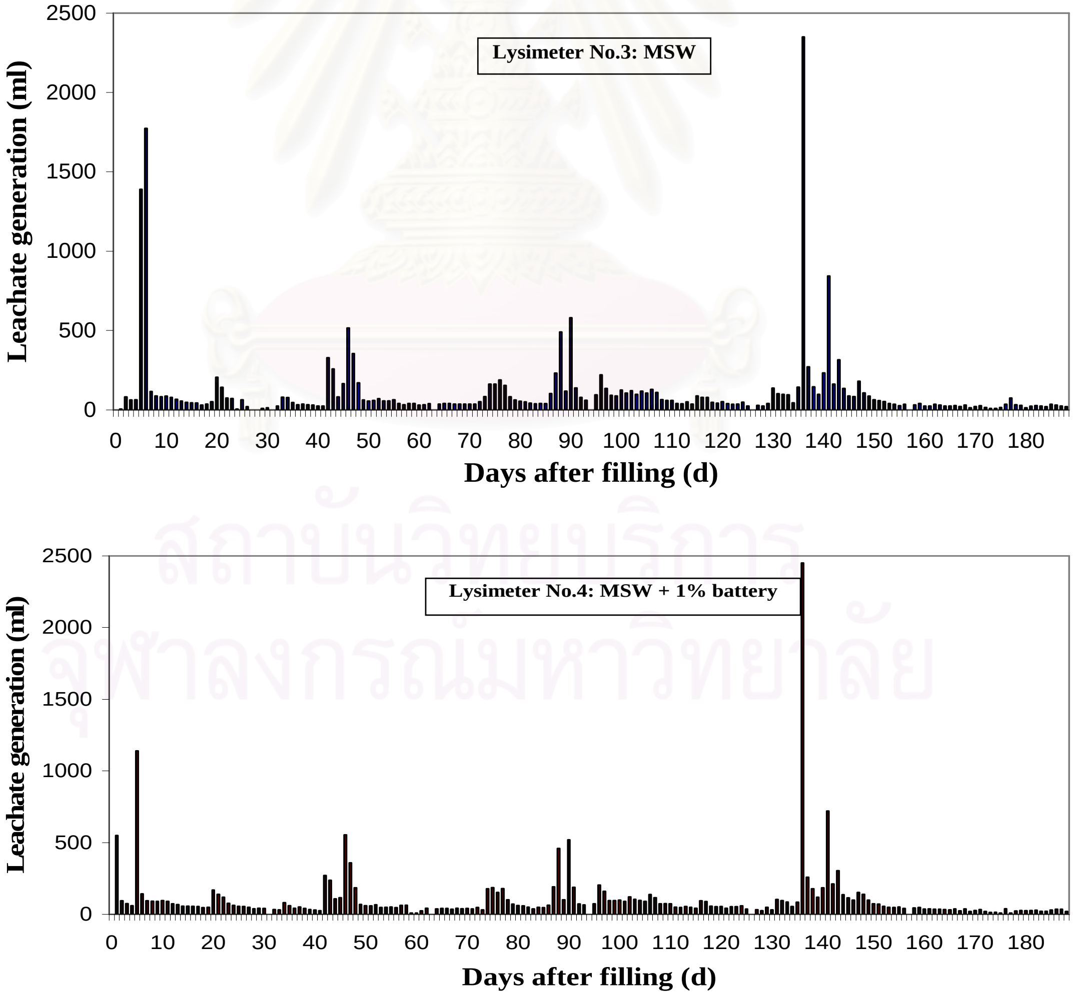


Figure 4.5 Leachate generation from Lysimeters No.3 to No.5

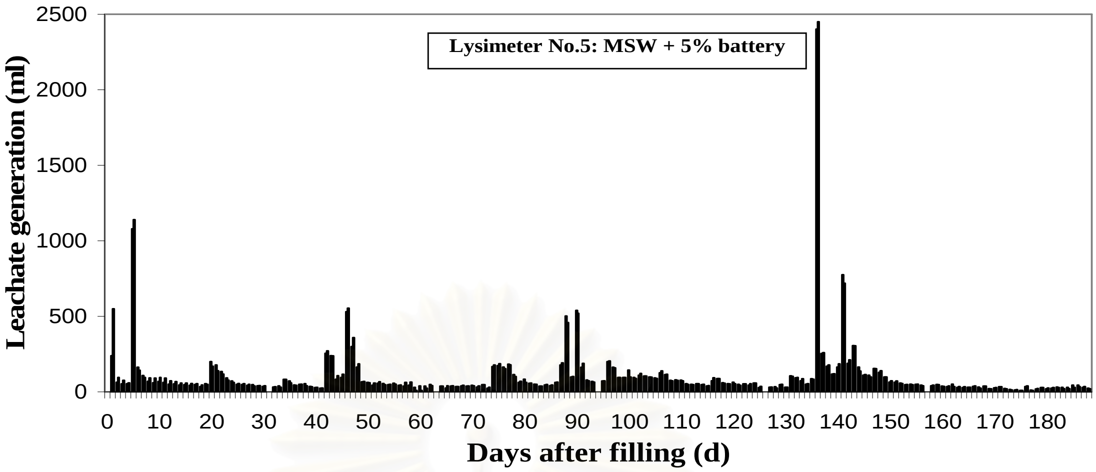


Figure 4.5 Leachate generation from Lysimeters No.3 to No.5 (continued)

Table 4.1 Range and total mass of leachate characteristics from Lysimeters No. 1 and No. 2

Parameter	Unit	Lysimeter No. 1	Lysimeter No. 2
pH		3.45-9.18	5.01-9.05
Conductivity	ms/cm	12.5-75.4	5.6-18.3
Chloride	mg/l	2250-40000	2250-8100
As	µg/l	< 5-16.80	9.48-11.60
Cd	mg/l	0.0009-1.6700	0.0014-0.1920
Fe	mg/l	20-510	11-188
Hg	mg/l	< 0.0002- 0.0333	0.0056-0.0084
Mn	mg/l	0.65-98.20	0.50-43.60
Ni	mg/l	0.1330-2.1400	0.0132-0.3950
Pb	mg/l	0.0078-0.4820	0.0019-0.1390
Zn	mg/l	0.41-185.00	0.28-55.20

From the statistical data analysis, it was found that the mean concentration of Ni and Zn in the leachate from Lysimeter No. 1 were significantly higher than that of Lysimeter No. 2 at a 95% confidence level. The longer contact time the between water and batteries during the clogging period might have resulted in the higher corrosion in the batteries. Therefore, Ni and Zn might have been in forms that leached easily, when compared with those of Lysimeter No.2. In addition, the mass leach-out per unit of kg dry waste as showed in Table 4.2 also showed that Ni and Zn concentration (mg/kg dry waste) from Lysimeters No.1 were higher than Lysimeter No.2.

Table 4.2 Generated leachate volume and extracted total mass of pollutants from Lysimeters No.1 and No.2

Parameter	Lysimeter No.*	
	1	2
Leachate volume (l/kg dry waste)	0.24	0.24
Material extracted (g/kg dry waste)		
Chloride	1.65	1.10
Heavy metal (mg/kg dry waste)		
Hg	-	0.0002
As**	-	0.10
Cd	0.02	0.02
Mn	4.83	5.79
Ni	0.16	0.03
Pb	0.01	0.01
Fe	25.59	27.08
Zn	29.00	3.01

Remarks: * Lysimeter No.1: Spent batteries
Lysimeter No.2: Broken spent batteries
** *u*g/kg dry waste

For pH, chloride, Cd, As, Fe, Hg, Mn and Pb, there were no significant differences among their means between the two lysimeters. However, due to the clogging problem which occurred in Lysimeter No.1, no definitive conclusion on the comparison of Lysimeters No.1 and 2 could be drawn from this test (see more details in Appendix E).

When the leachate characteristics from Lysimeter No.2 were considered, the following results were investigated.

Fe was found to be the major element in the leachate generated from Lysimeter No.2, followed by Zn, Mn, Ni, Cd, Pb, Hg and As, at the concentrations of 188 mg/l, 55.2 mg/l, 43.6 mg/l, 0.395 mg/l, 0.192 mg/l, 0.139 mg/l, 0.0084 mg/l, 11.6 μg/l, respectively. It could be inferred that the top three heavy metals that leached from the batteries were Fe, Zn and Mn, respectively. Their high ranking may be due to the fact that they are major components in dry cell batteries.

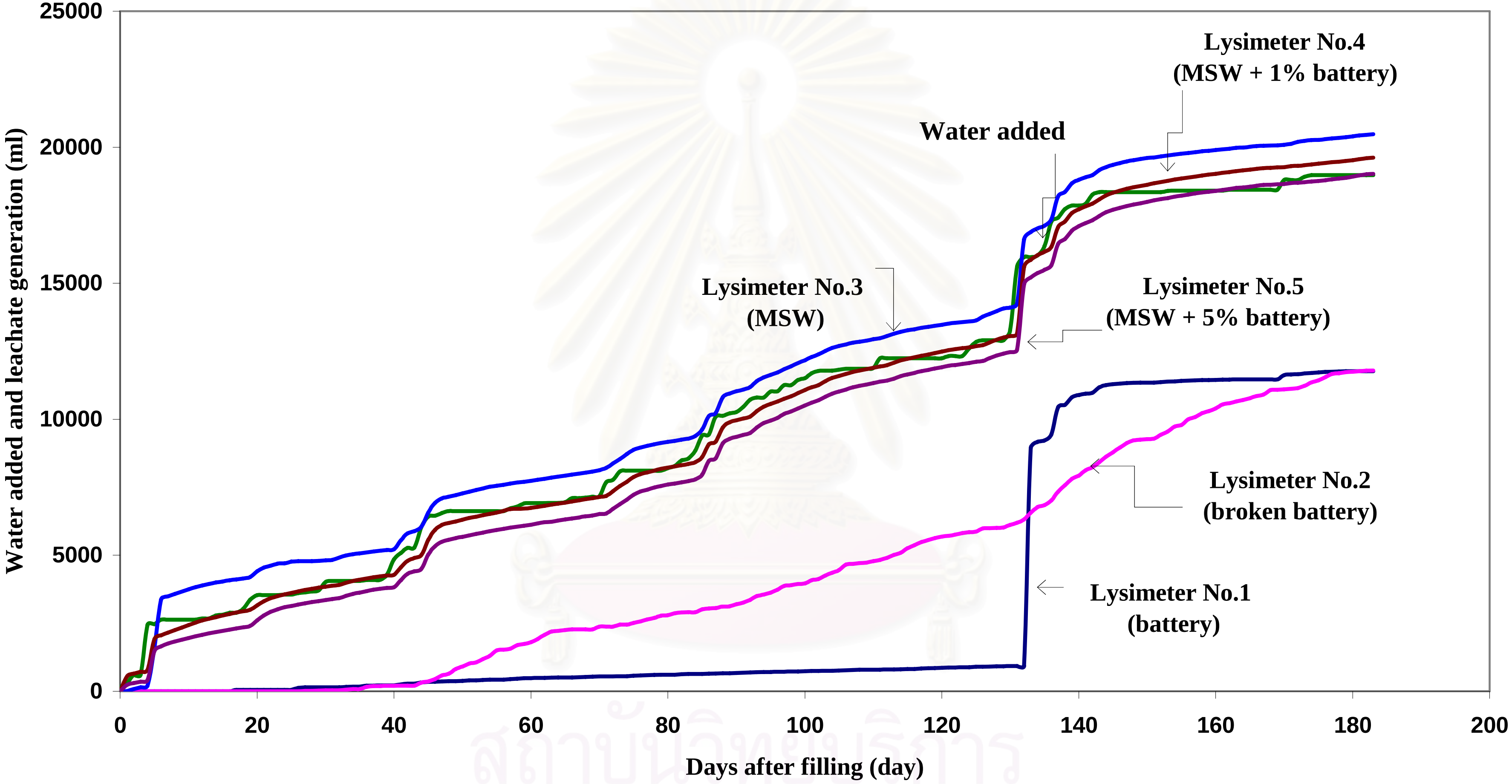


Figure 4.6 Cumulative leachate quantities

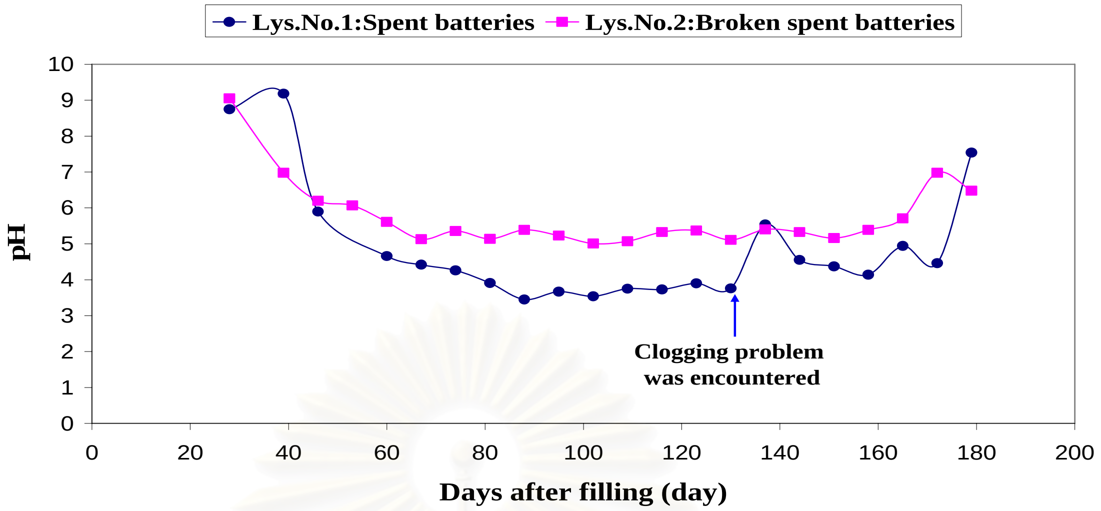


Figure 4.7 (a) pH variation over time from Lysimeters No.1 and No.2

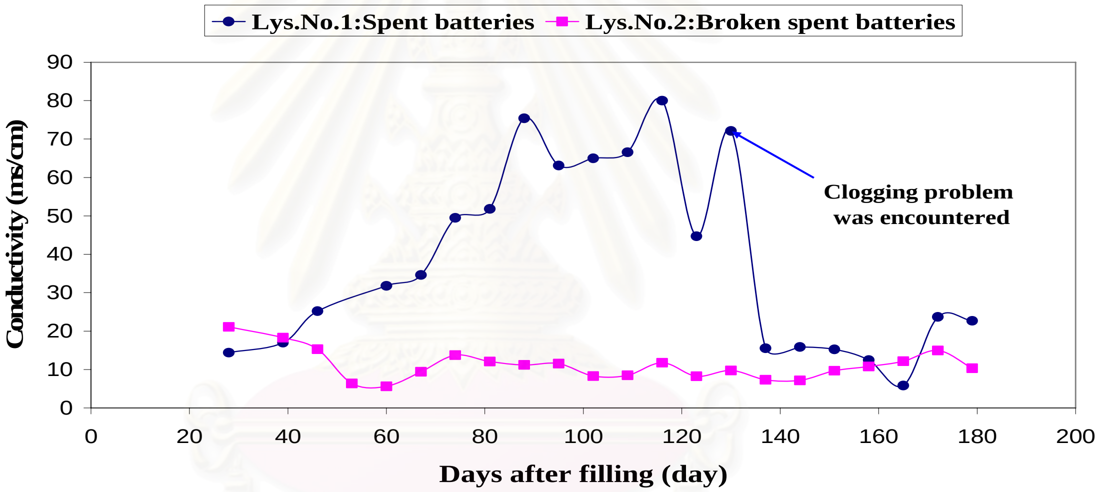


Figure 4.7(b) Conductivity variation over time from Lysimeters No.1 and No.2

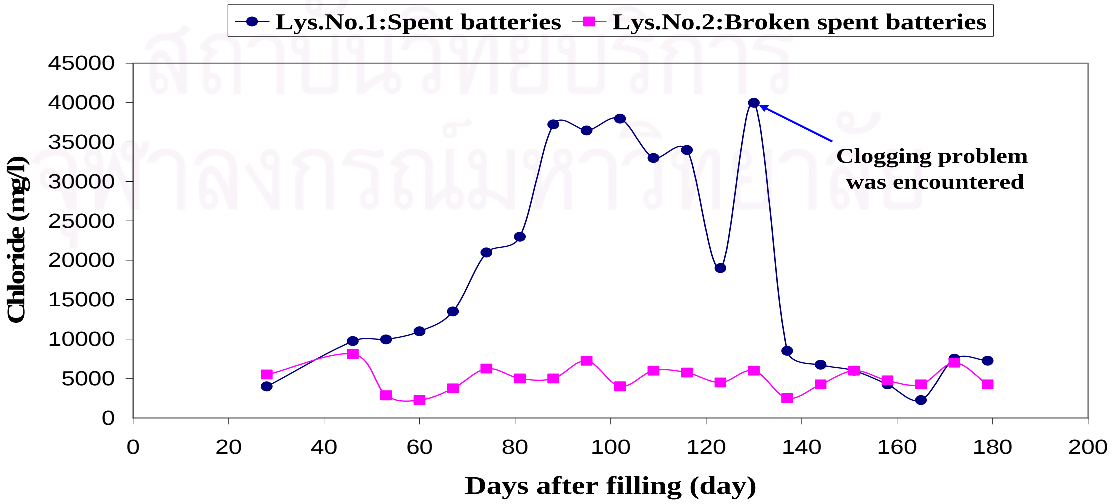


Figure 4.7(c) Chloride variation over time from Lysimeters No.1 and No.2

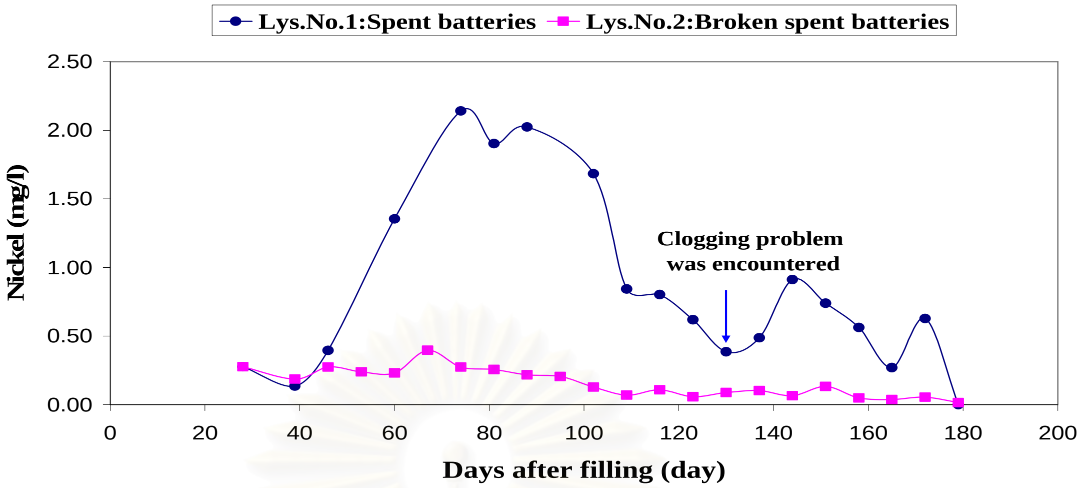


Figure 4.7(d) Nickel variation over time from Lysimeters No.1 and No.2

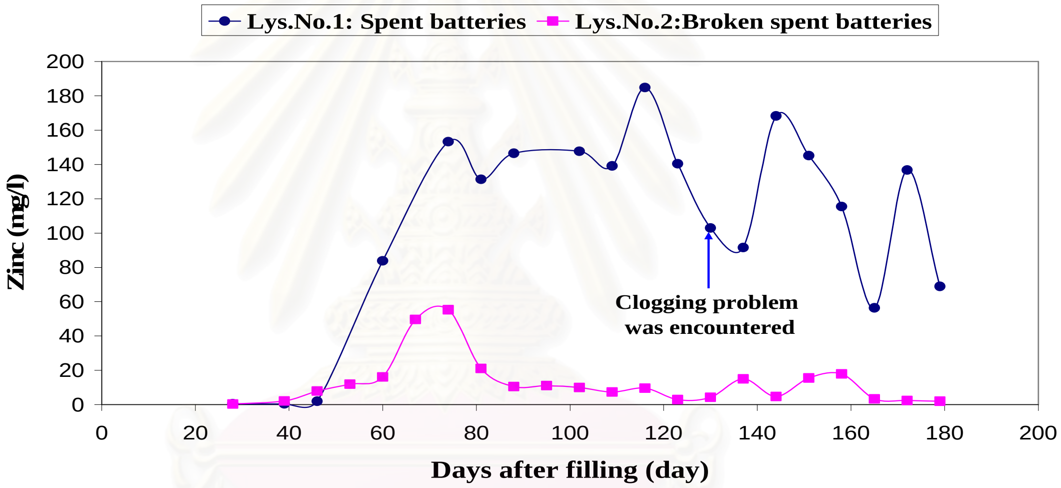


Figure 4.7(e) Zinc variation over time from Lysimeters No.1 and No.2

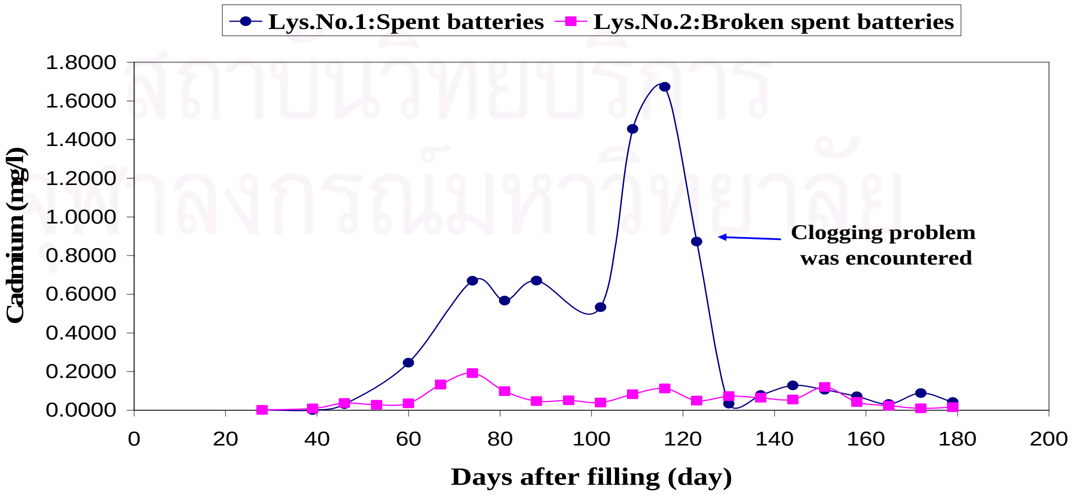


Figure 4.7(f) Cadmium variation over time from Lysimeters No.1 and No.2

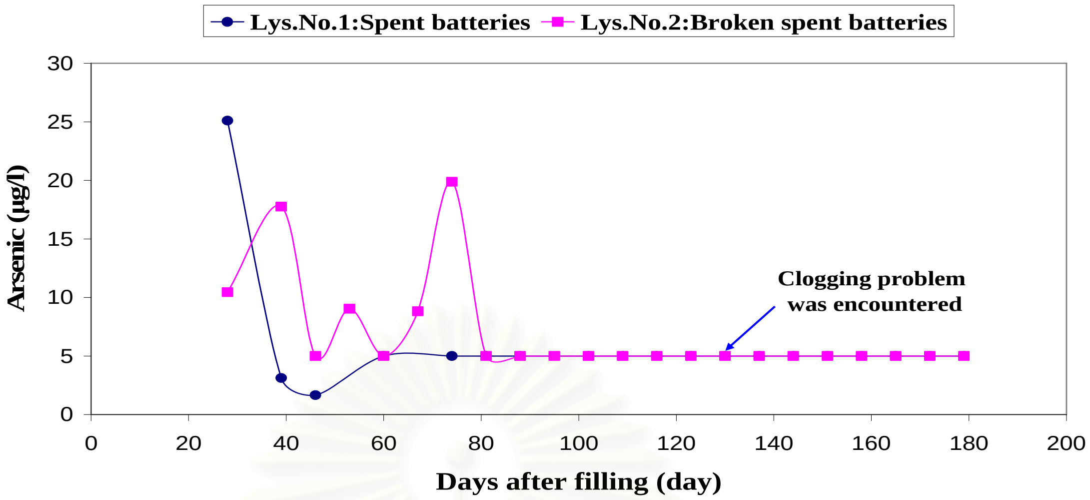


Figure 4.7(g) Arsenic variation over time from Lysimeters No.1 and No.2

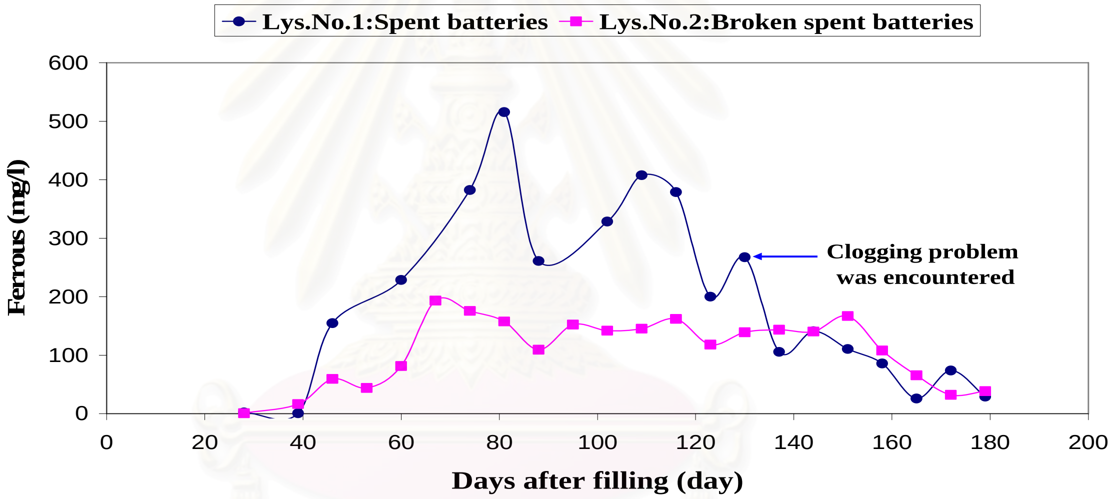


Figure 4.7(h) Ferrous variation over time from Lysimeters No.1 and No.2

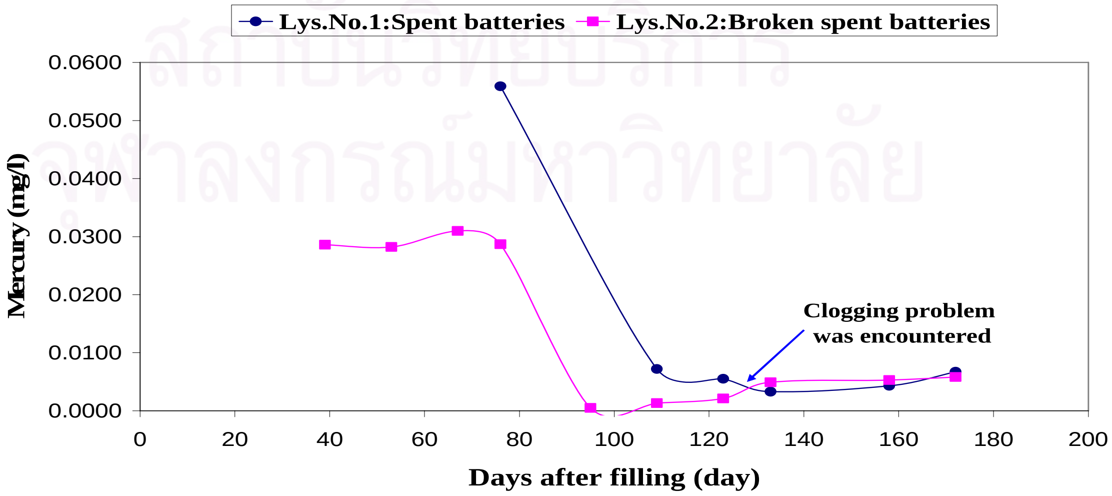


Figure 4.7(i) Mercury variation over time from Lysimeters No.1 and No.2

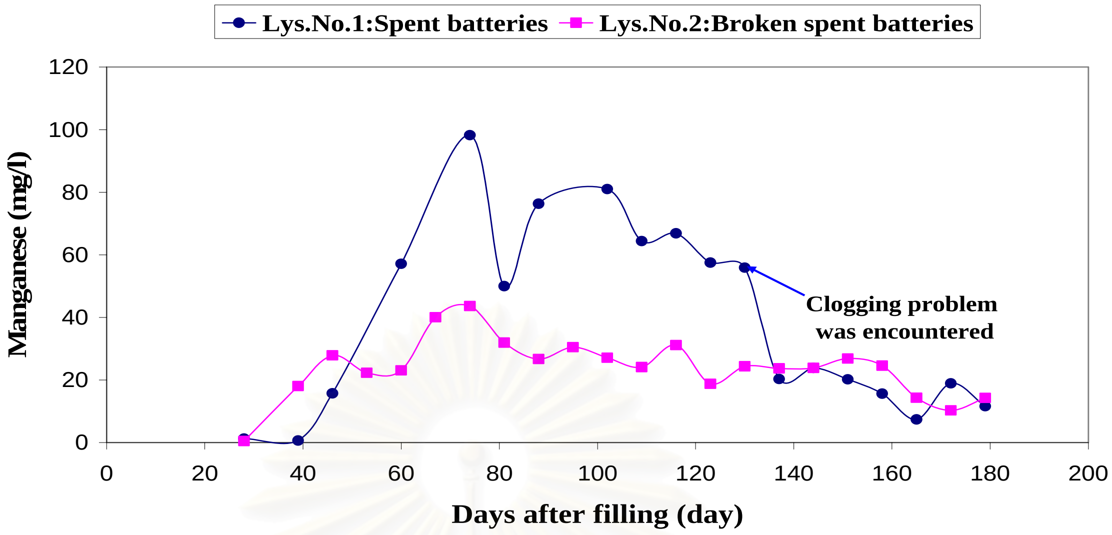


Figure 4.7(j) Manganese variation over time from Lysimeters No.1 and No.2

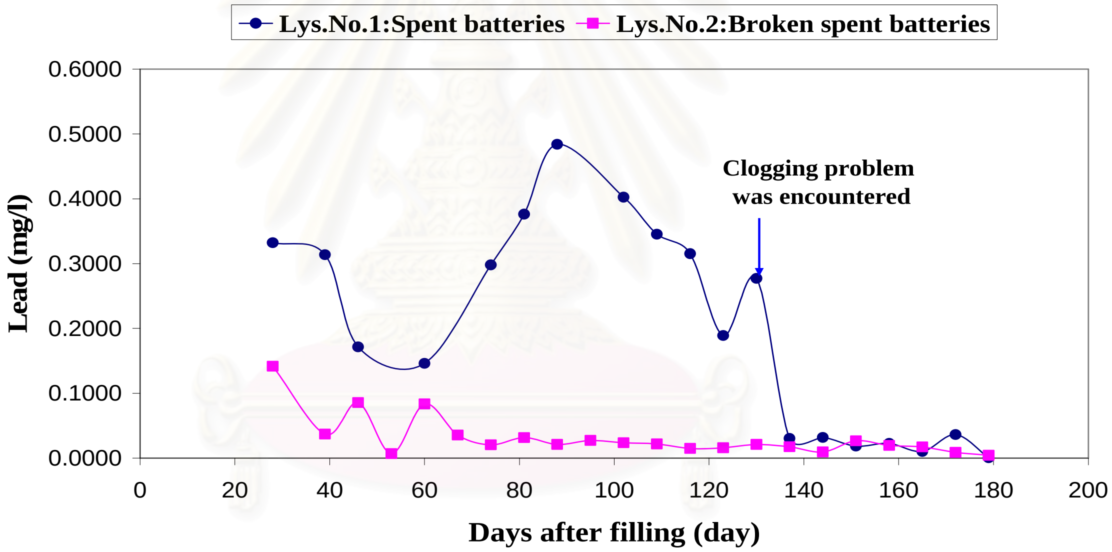


Figure 4.7(k) Lead variation over time from Lysimeters No.1 and No.2

4.2.3.1.1 Comparison between the batch leaching test and column test

Because the clogging problem occurred in Lysimeter No.1, only the results of the leachate characteristics from Lysimeter No.2 (broken batteries) were used in comparisons with the batch leaching test.

The ranges of heavy metals that leached out obtained from the batch leaching test and column test are concluded in Table 4.3.

Table 4.3 Range of heavy metal concentrations from the batch leaching test and lysimeter test

Parameter	**Heavy metal concentration (mg/l)**	
	Batch test	**Lysimeter test**
As*	5.31-6.19	9.48-11.60
Cd	0.0019-46.9	0.0014-0.1920
Fe	0.02-0.42	11-188
Hg	< 0.002	0.0056-0.0084
Mn	0.12-55.70	0.50-43.60
Ni	0.0253-53.3000	0.0132-0.3950
Pb	0.0067-0.3914	0.0019-0.1390
Zn	7-711	0.28-55.20

* µg/l

Generally, the batch test and column test were compared using the plot of the liquid to solid ratio. There were three scenarios that could be expected. The first is where the results agree with the batch test results. The second is where the batch tests over predict metal leachability. The third is where the batch test results under predict the lysimeter results at any given liquid to solid ratio (Townsend et al., 2002).

In this study, each type and size of battery was conducted in the batch leaching test and mixed types and sizes of battery were used to fill the lysimeter test. Therefore, the results from both tests might not be compared directly due to the different input materials. However, the plot of liquid to solid ratio against the cumulative amount of heavy metals that leached out can give remarkable information.

The plot of the liquid to solid ratio against the cumulative amount of heavy metals leached of As, Cd, Pb and Hg are presented in Figure 4.8. It should be noted that only As, Cd, Pb and Hg which were referred to in the US TC list, were compared using this pattern.

When the cumulative amounts of As, Cd, Pb and Hg leached from the batch leaching test (presented in Table 4.4) were compared with the results from Figure 4.8, it was found that the cumulative amounts of As, Cd and Pb leached in the batch leaching test were higher than those recorded in the lysimeter test. The significantly lower liquid to solid ratio in the lysimeter test compared with the batch leaching test was the cause of this discrepancy.

The maximum values of As, Cd and Pb's cumulative concentrations in the batch test were 0.0619, 469, 2.62 mg/kg battery, respectively: while the cumulative values in the lysimeter test were 0.0025, 0.270, 0.0132 mg/kg battery, respectively (Appendix A). In the case of Hg in the batch test, it could not be compared because the concentration was below the detection limit of 0.002 mg/l.

At any given liquid-to-solid ratio after 0.25, Hg were leached out at the same cumulative metal concentration. Thus, it can be concluded that these metals were leached at very small amounts when the liquid-to-solid ratio was increased

On the contrary, more Cd was leached out with the increasing liquid-to-solid ratio. It might have occurred due to the high amount of water added during the 73rd to 143rd days which resulted in the leaching of Cd into the leachates. When compared with the pH value during the above period, it was found that the pH was slightly acid. This might have been a resulted of the increase of Cd.

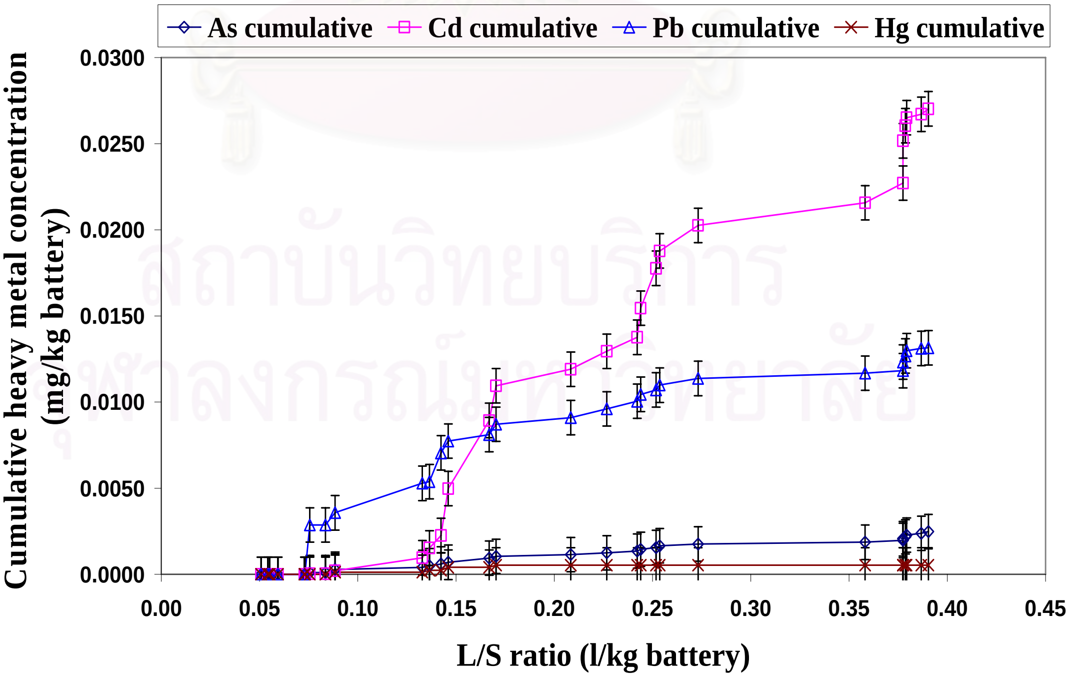


Figure 4.8 Cumulative heavy metal concentrations against the L/S ratio

Table 4.4 Cumulative As, Cd, Pb and Hg leached from the batch leaching test

Label	Battery type	L/S (l/kg)	Cumulative metal leached (mg/kg battery)			
			As	Cd	Pb	Hg
B1	Zinc-carbon	20:1	< 0.0500	0.019	0.465	< 0.02
B2	Zinc-carbon	20:1	< 0.0500	0.077	0.520	< 0.02
B3	Zinc-carbon	20:1	< 0.0500	0.034	0.674	< 0.02
B4	Zinc-carbon	20:1	< 0.0500	1.110	0.181	< 0.02
B5	Zinc-carbon	20:1	< 0.0500	0.990	0.454	< 0.02
B6	Zinc-carbon	20:1	< 0.0500	0.523	0.151	< 0.02
B7	Zinc-carbon	20:1	< 0.0500	0.002	0.261	< 0.02
B8	Zinc-carbon	20:1	< 0.0500	6.760	0.455	< 0.02
B9	Zinc-carbon	20:1	< 0.0500	0.098	0.468	< 0.02
B10	Zinc-carbon	20:1	< 0.0500	1.023	2.090	< 0.02
B11	Zinc-carbon	20:1	< 0.0500	0.475	3.910	< 0.02
B12	Zinc-carbon	20:1	< 0.0500	0.147	1.420	< 0.02
B13	Zinc-carbon	20:1	< 0.0500	0.173	0.188	< 0.02
B14	Zinc-carbon	20:1	< 0.0500	6.590	0.015	< 0.02
B15	Zinc-carbon	20:1	< 0.0500	0.136	0.015	< 0.02
B16	Zinc-carbon	20:1	< 0.0500	9.980	0.470	< 0.02
B17	Zinc-carbon	20:1	< 0.0500	0.426	0.086	< 0.02
B18	Zinc-carbon	20:1	< 0.0500	0.044	0.483	< 0.02
B19	Zinc-carbon	20:1	< 0.0500	0.174	2.400	< 0.02
B20	Zinc-carbon	20:1	< 0.0500	0.128	2.620	< 0.02
B21	Zinc-carbon	20:1	< 0.0500	1.370	0.179	< 0.02
B22	Zinc-carbon	20:1	< 0.0500	1.240	0.104	< 0.02
B23	Zinc-carbon	20:1	< 0.0500	0.106	<0.015	< 0.02
B24	Zinc-carbon	20:1	< 0.0500	0.454	0.211	< 0.02
B25	alkaline	20:1	< 0.0500	0.020	<0.015	< 0.02
B26	alkaline	20:1	< 0.0500	0.079	<0.015	< 0.02
B27	alkaline	20:1	< 0.0500	0.066	<0.015	< 0.02
B28	alkaline	20:1	< 0.0500	0.063	<0.015	< 0.02
B29	alkaline	20:1	< 0.0500	0.047	<0.015	< 0.02
B30	alkaline	20:1	< 0.0500	0.103	<0.015	< 0.02
B31	alkaline	20:1	< 0.0500	0.076	0.104	< 0.02
B32	alkaline	20:1	< 0.0500	0.028	0.131	< 0.02
B33	Ni-cd	20:1	< 0.0500	469.000	0.258	< 0.02
B34	Ni-cd	20:1	0.0619	84.800	<0.015	< 0.02
B35	Ni-MH	20:1	0.0531	9.980	<0.015	< 0.02
B36	Ni-MH	20:1	0.0566	1.340	0.067	< 0.02

It has been observed that battery labels B8, B14 and B16 which are zinc-carbon type generated the higher concentration of Cd than other labels of zinc-carbon batteries. It might have been a result of the different battery manufacture and the different battery size.

The battery label B8, brand name “power” with AA size was made in China while other brand names were made in Japan, Malaysia, Indonesia, Singapore, Thailand and USA. The battery labels B14 and B16 were the largest sizes (D size) that might resulted in the high concentration of Cd in the leaching solution.

4.2.3.2 Landfill lysimeter test

The characteristics of landfill leachate depends on the variation, type, and rate of decomposition of the waste. Major mechanisms of pollutant production in leachate can be attributed to the entrainment of extractable pollutants from waste components itself that are easily soluble substances in percolating water. The mechanisms are the dissolution of soluble materials and decomposition of biodegradable substances that would be transformed to gaseous and soluble forms (Ikeguchi, 1991).

Leachate characteristics of the leachate generated from Lysimeters No. 3 to No.5 are summarized in Appendix E.

Generally speaking, the concentration curve of pollutants is accompanied by an initial peak at the onset of leachate production, followed by a slight decrease. Some parameters show the gradual increase of pollutants from the beginning followed by a decrease and a second increase afterward. These different trends do not matter, however, because the concentration of pollutants in leachate during early time period is strongly influenced by the amount of readily extractable waste substance and the amount of percolation water.

During this period, concentration curves cross each other and no definite trends of concentration difference among the lysimeters can be recognized graphically, especially in Lysimeters No. 3, 4 and 5. It is noteworthy that some parameters such as COD, TA, VFA, TOC and DOC decreased their concentrations slightly around days 140-160 in all lysimeters. This might have occurred due to the dilution effect as a result of the high amounts of flushing water added during days 121-143 and followed by the very low amount of water added during days 144 -168.

The study of Karnchanawong et al. (2004) on the investigation of leachate and gas generation from batch filling lysimeter test was examined. It was found that the hydrolysis phase covered the first two months and the methane phase started after waste filling at around day 250. It can be conclusively stated that the acidogenesis phase in this study was terminated nearly at the end of the experiment.

Table 4.5, gives the range of leachate characteristics from the three lysimeters. Figure 4.9 shows the variation of leachate characteristics from Lysimeters No.3 to 5 over time during the study period.

Table 4.5 Range of analytical parameters from Lysimeters No. 3 to 5

Parameter	**Unit**	**Lysimeter No. 3**	**Lysimeter No. 4**	**Lysimeter No. 5**
pH		3.91-5.94	3.86-6.09	3.84-6.62
Conductivity	ms/cm	8.2-30.5	10.2-29.5	11.0-29.6
Chloride	mg/l	1500-7750	1750-7500	1750-8750
TA	mg/l CaCO3	1860-17700	1930-17600	991-18100
VFA	mg/l	2500-27500	3260-23200	4190-28000
COD	mg/l	21000-121000	24100-129000	27200-146000
TOC	mg/l	4850-35800	6120-32900	6800-34200
DOC	mg/l	5100-26600	5650-27900	6740-29200
Cd	mg/l	0.0012-0.0350	0.0047-0.0412	0.0292-0.1690
As	μg/l	5.76-10.20	7.77-15.30	9.50-13.40
Fe	mg/l	4-80	25-76	104-188
Hg	mg/l	0.0077-0.0854	0.0156-0.1430	0.0006-0.2370
Mn	mg/l	3.89-12.00	3.55-10.20	6.18-17.50
Ni	mg/l	0.0168-0.2230	0.0838-0.7840	0.1120-0.8910
Pb	mg/l	0.0045-0.0509	0.0028-0.0448	0.0070-0.0525
Zn	mg/l	0.55-18.90	3.93-49.30	8.29-41.30

The pH values of the leachates from Lysimeters No. 3, No.4 and No.5 were slightly acid, and these tends continued until the end of the experiment. The initial anaerobic biodegradation processes (during which acid fermentation prevails) occurred upon completion of the short-term aerobic decomposition, nearly 40 days the beginning. The result from the statistic analyses indicated that the means differences of the pH were not significantly different, at 95% a confidence limit, among the three lysimeters. For more details, see Appendix D.

It was observed that the conductivity was higher in the first three months due to the high levels of pollutants in the leachate, and then it slightly decreased thereafter until the end of the experiment. It can be seen that the value obtained from Lysimeter No. 3 was higher when compared with those of the other two lysimeters. However, the mean values were not significantly different, at a 95% confidence limit, among the three lysimeters. For more details, see Appendix D.

The chloride concentration was high during the first three months, and then it decreased thereafter until the end of experiment. The organic content of the landfill leachate was measured as COD (Chemical Oxygen Demand), TOC (Total Organic Carbon) and DOC (Dissolved Organic Carbon). A variation of those organic contents in the leachates generated from the three lysimeters had a similar pattern where the values increased and reached their peaks at around the days 40 – 70, and then gradually decreased with time. The results from the statistical analyses also showed that the mean concentration of Cl^-, COD, TOC and DOC were not significantly different, at a 95% confidence limit, among the three lysimeters.

Total Alkalinity (TA) started to reach its maximum concentration during during the first two months and then decreased continuously until it reached a minimum level and then slightly increased on the following day.

VFA (Volatile Fatty Acid) is the product of decomposition in acidogenesis. VFA is also classified as a water-soluble fatty acid that can be distilled at atmospheric pressure. A high concentration of VFA indicated a high rate of decomposition in the acidogenesis phase. A low concentration of VFA can be used to indicate that the waste inside the landfill lysimeter is stabilized and shifted to the methanogenesis phase (Johansen et al., 1976). Referring to Table 4.4 and Figure 4.9, the VFA concentrations in the leachate from the three lysimeters were high in the first

4 months and slightly decreased after 140 days of filling waste. The statistic analysis results indicate that the means of TA and VFA in the leachates from the three lysimeters were not significantly different. For more details, see Appendix D.

For the heavy metals, there are no standards in Thailand related to leachate. Therefore, the Groundwater Standards for drinking purposes from the Notification of the Ministry of Industry was selected in order to evaluate the potential risk to human health and the environment. This standard was used as a reference for comparison with the results of heavy metal contents in the leachate from the lysimeter test.

The results show that Fe, Mn, and Hg concentrations from all three lysimeters were higher than the Maximum Allowable Groundwater Standards stated at 1.0, 0.5 and 0.001 mg/l, respectively. When the comparison of their concentration among the three lysimeters using statistical analyses was conducted, it was found that the mean concentrations of Fe and Mn from Lysimeter No.5 were significantly higher than those of Lysimeters No.3 and No.4. Hg concentrations from all lysimeters however were not significantly different.

The concentrations of As and Pb were very low and did not exceed the Standards set at 0.05 mg/l, in all the lysimeters. The results from the statistical analyses also indicated that the means of the As concentrations were not significantly different among the three lysimeters.

For the Zn concentration, it was found that Lysimeters No. 4 and No. 5 generated leachates with significantly higher concentrations than that of Lysimeter No.3, and also exceeding the Groundwater Standards set at 15 mg/l. A similar trend in Ni concentration was observed, Lysimeters No. 4 and No.5 generated leachates containing significantly higher Ni concentrations than that of Lysimeter No. 3.

Cd was found in the highest concentration in the leachate from Lysimeter No. 5 and its mean concentrations were significantly higher than those of Lysimeters No.3 and No. 4 at a 95% confidence limit. When the compared to the Groundwater Standards, it was noted that the Cd concentration of leachate generated from Lysimeter No.5 was higher than the allowance standard, stated at 0.01 mg/l.

In conclusion, Lysimeter No.5 (MSW+5%batteries) generated leachate with significantly higher concentrations of Fe, Mn, Pb, Zn, Ni and Cd than Lysimeters No. 3 (MSW) and No.4 (MSW+1%batteries). Lysimeter No. 4 (MSW+1%batteries) generated leachate with significantly higher concentrations of Fe, Ni and Zn than Lysimeter No. 3.

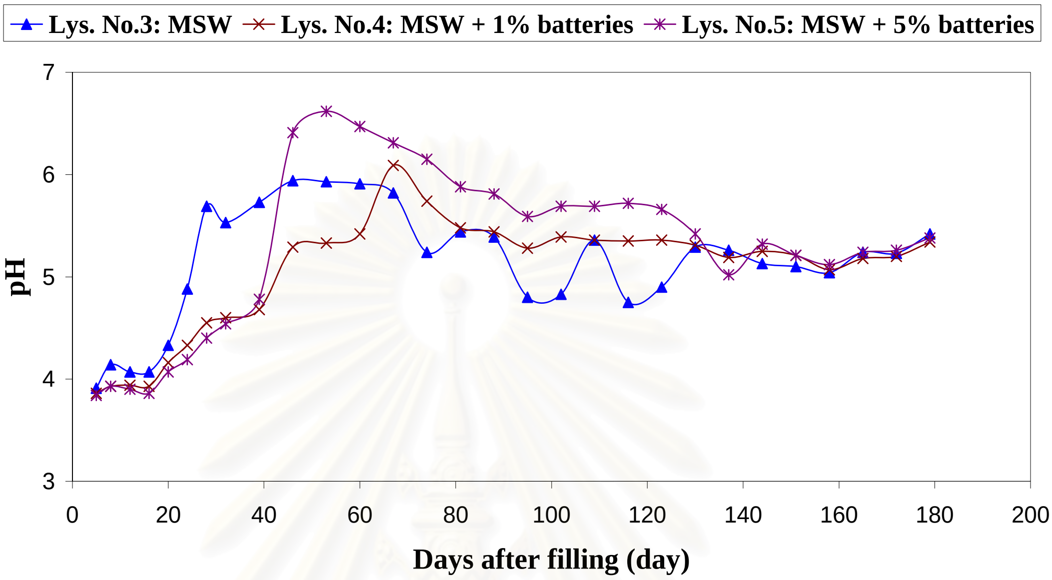


Figure 4.9(a) pH variation over time from lysimeters 3 to 5

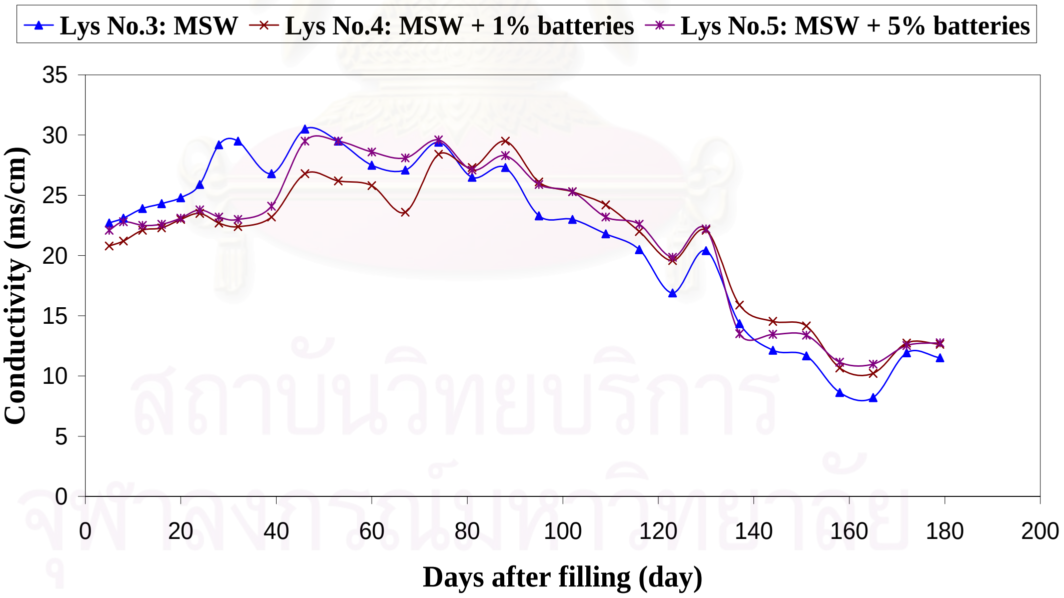


Figure 4.9(b) Conductivity variation over time from lysimeters 3 to 5

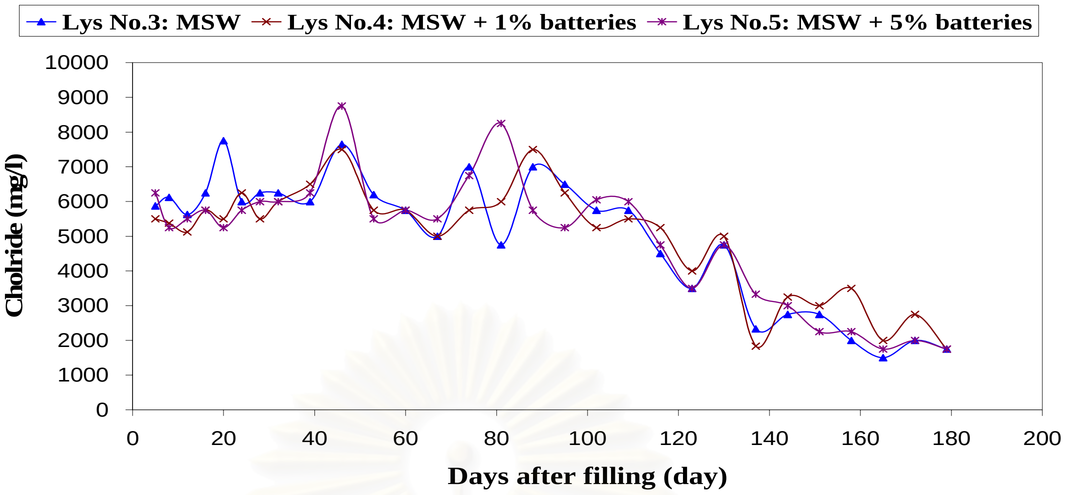


Figure 4.9(c) Chloride variation over time from lysimeters 3 to 5

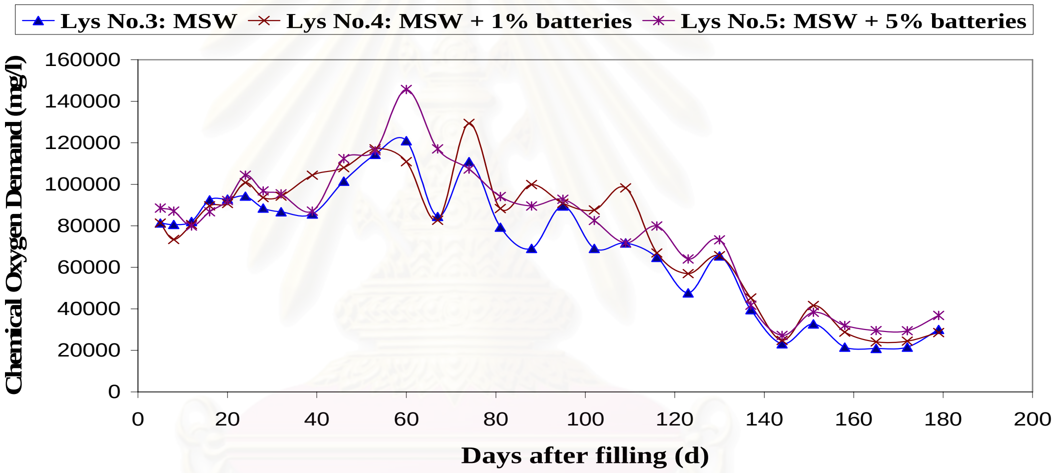


Figure 4.9(d) COD variation over time from lysimeters 3 to 5

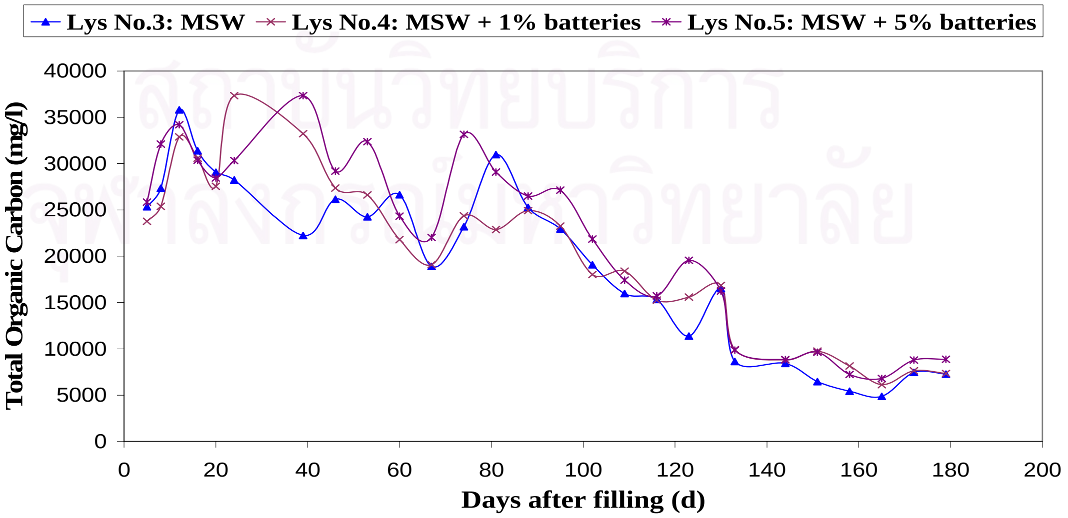


Figure 4.9(e) TOC variation over time from lysimeters 3 to 5

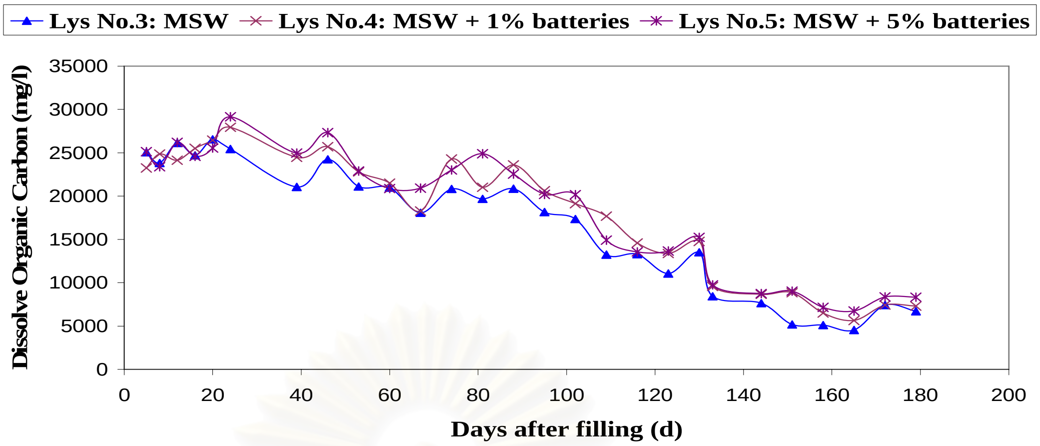


Figure 4.9(f) DOC variation over time from lysimeters 3 to 5

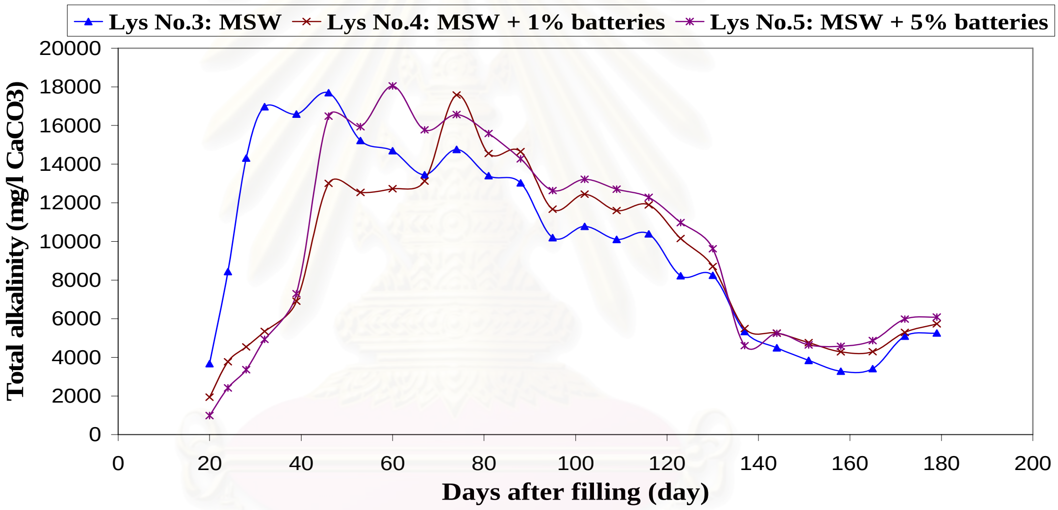


Figure 4.9(g) TA variation over time from lysimeters 3 to 5

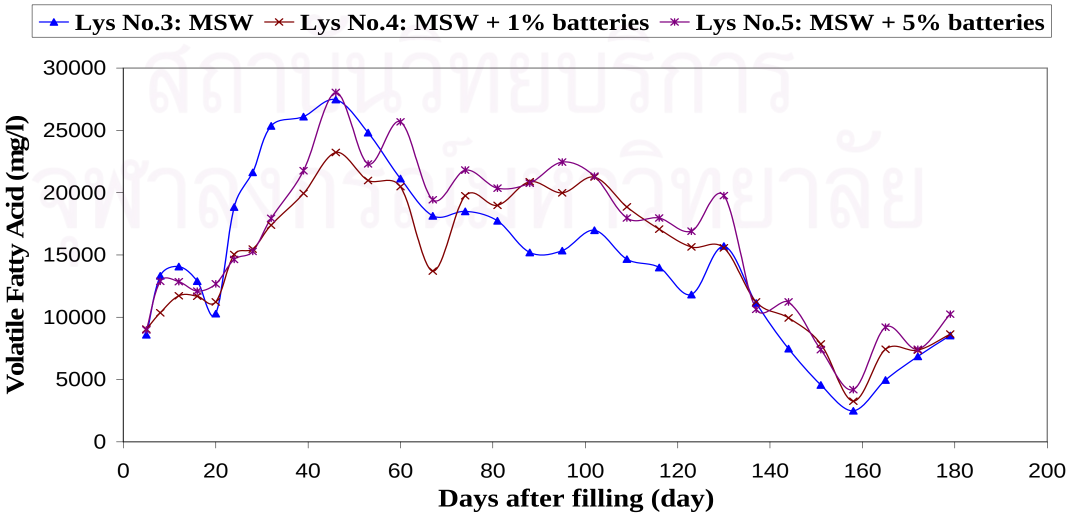


Figure 4.9(h) VFA variation over time from lysimeters 3 to 5

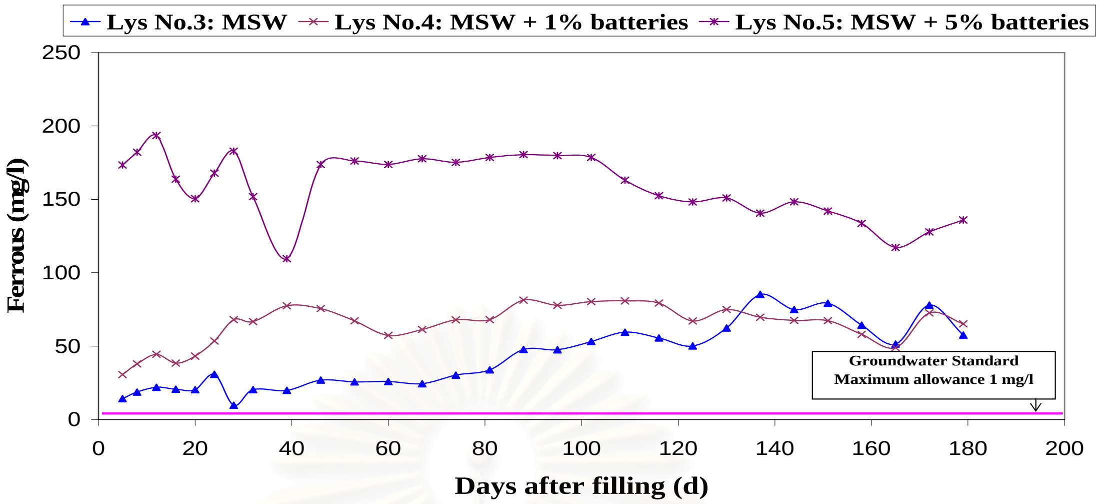


Figure 4.9(i) Ferrous variation over time from lysimeters 3 to 5

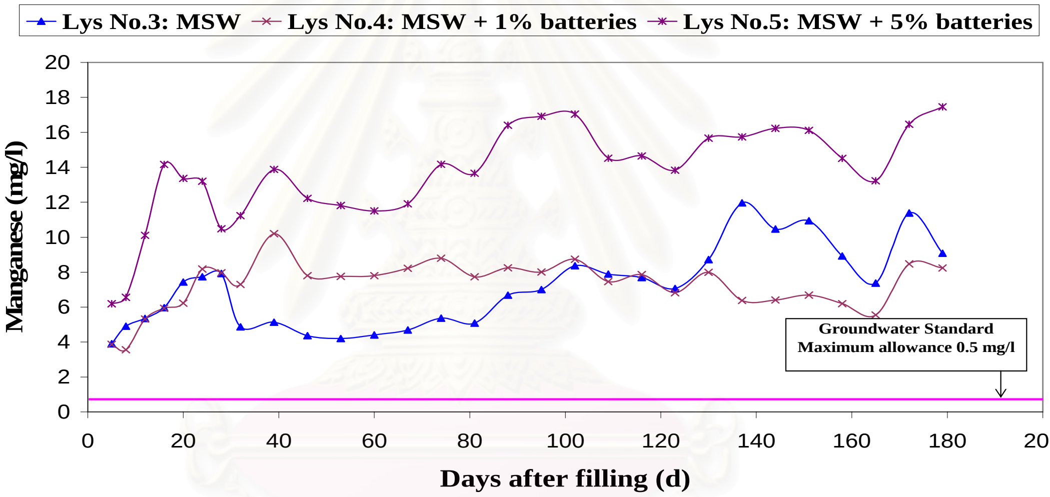


Figure 4.9(j) Manganese variation over time from lysimeters 3 to 5

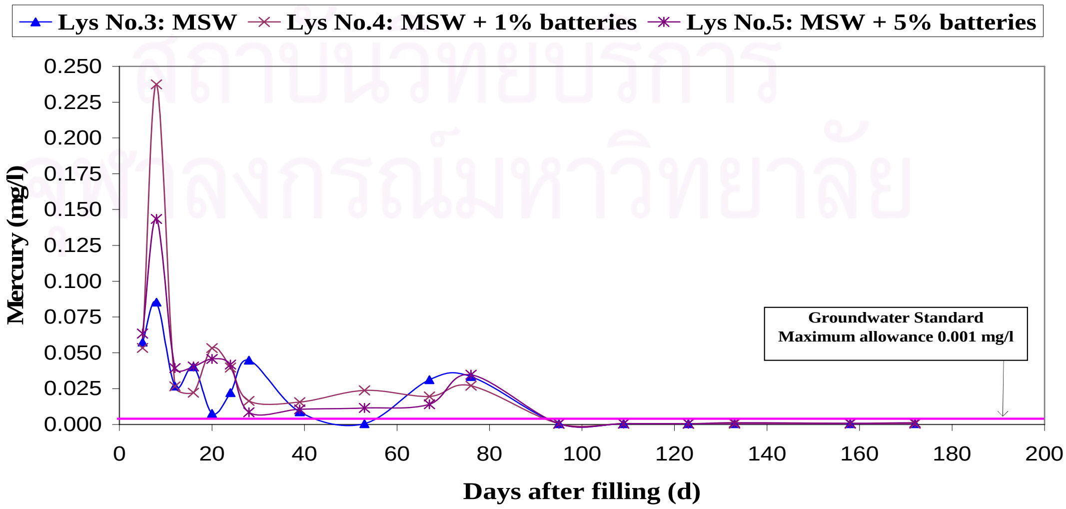


Figure 4.9(k) Mercury variation over time from lysimeters 3 to 5

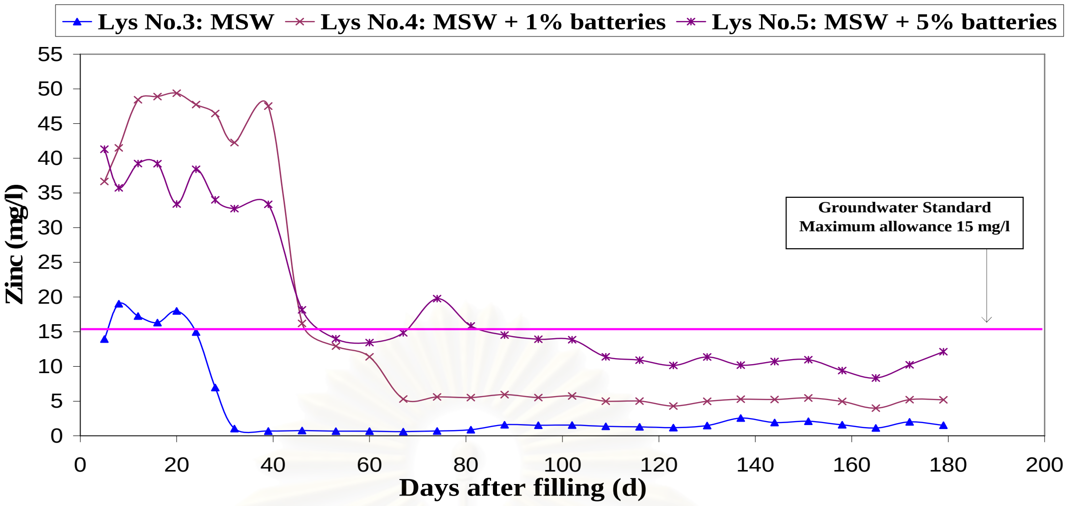


Figure 4.9(l) Zinc variation over time from lysimeters 3 to 5

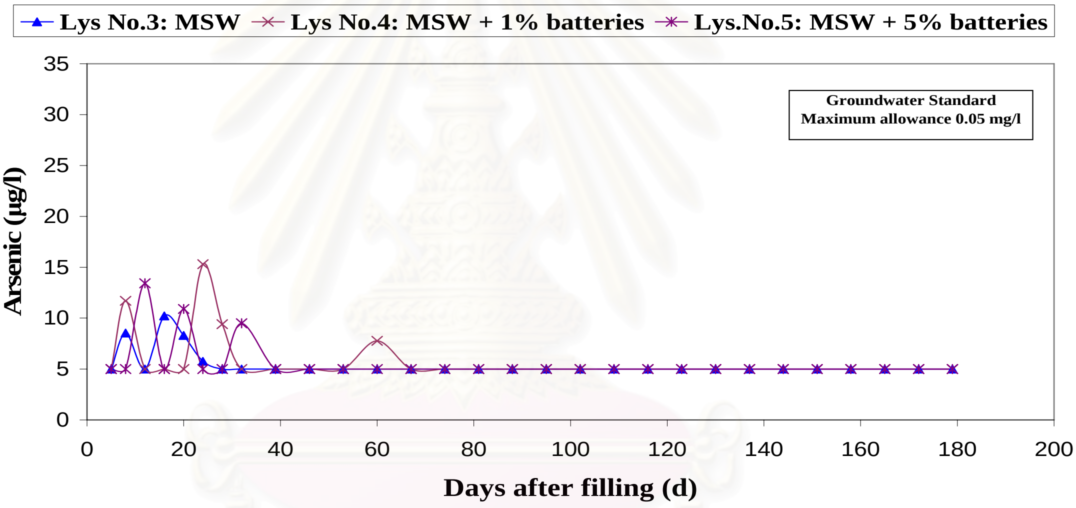


Figure 4.9(m) Arsenic variation over time from lysimeters 3 to 5

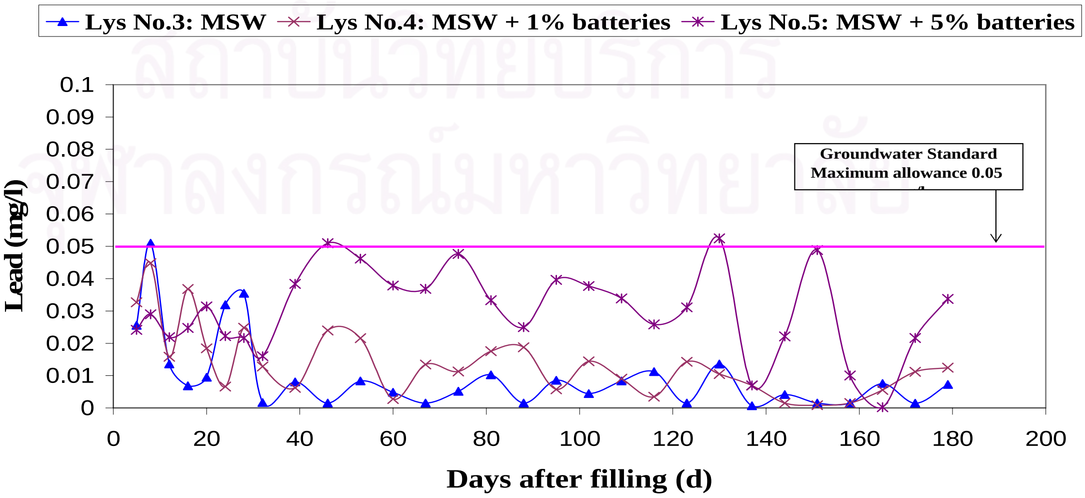


Figure 4.9(n) Lead variation over time from lysimeters 3 to 5

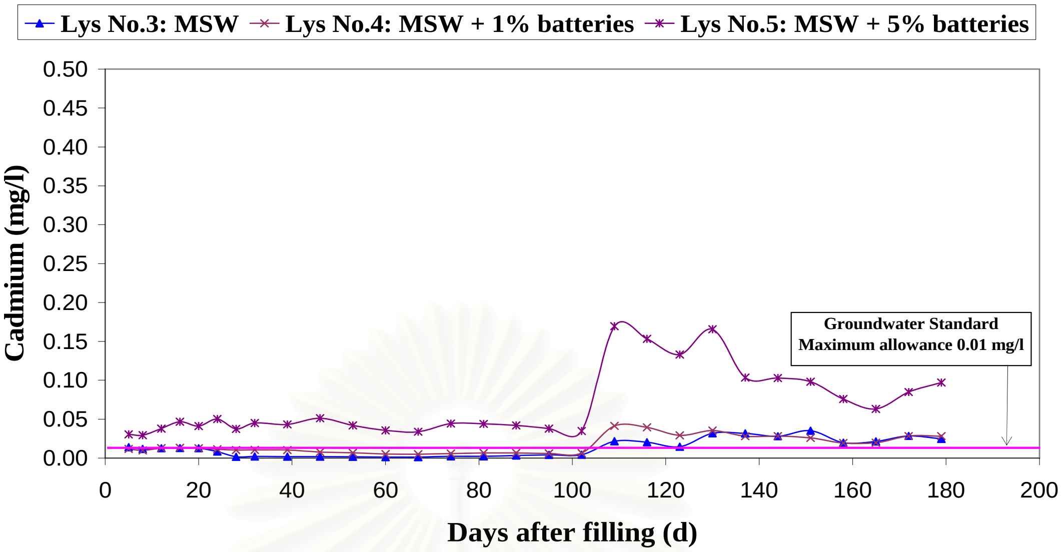


Figure 4.9(o) Cadmium variation over time from lysimeters 3 to 5

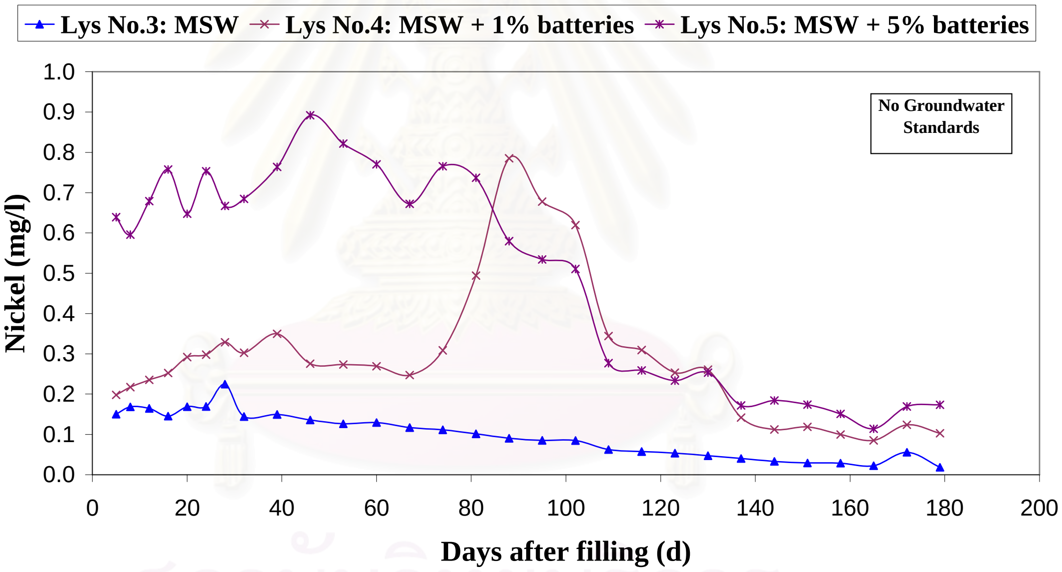


Figure 4.9(p) Nickel variation over time from lysimeters 3 to 5

From Figures 4.9k to 4.9m, it can be observed that the concentration of Hg, Zn and As were high during the first 20 days. It was because of during this period, the high amount of carbon dioxide generated from organic metabolism can dissolve in the water, forming a leachate that is rich in carbonic acids which in turn, lower the pH of the surroundings. The lower pH of leachate could increase the solubility of metal leaching.

4.3 Total mass of pollutants

Mass leach-out per kilogram unit of dry waste from each lysimeter was also determined to obtain a clear understanding of the leaching process. Table 4.6 shows a summary of the accumulated leachate volume and total mass of pollutants extracted per kilogram of dry waste.

It was found that all three lysimeters generated a similar quantity of leachate volume per dry weight of waste. Fe was found to be leached out to the largest extent among the metals in this study. High acidity in the leachates generated from the lysimeter had increased the leaching of Fe from both batteries and metals in the municipal solid waste. It was observed that Fe concentrations in Lysimeter No. 5 were very high, compared with Lysimeter No.3 and No.4. This was because of the high percentage of batteries filled into Lysimeter No.5.

It can be seen that the total mass of pollutants from Lysimeter No.3 and Lysimeter No.4 were not much different from each other. The exception was the Zn concentration in the leachate from Lysimeter No. 4, which was rather high, compared with that of Lysimeter No.3.

It was notified that the total mass of As generated from Lysimeters No.3 and No.4 were slightly higher than Lysimeter No.5. This might be because of the lower pH of the leachate generated from Lysimeters No.3 and No. 4, compared with Lysimeter No.5, which resulted in the leachability of As in the leachate.

Based on the filed survey of the Thailand Health Research Institute (1992) it was found that the people who lived in Bangkok generated spent batteries at 0.033 % of the total waste generation. The PCD (1998) also reported that spent batteries were found at 6.81% of total hazardous waste generation. And according to the data reported by the PCD (2005), the amount of hazardous wastes and total wastes generated from households in Thailand were estimated to be 0.4 and 14.3 million tons, respectively. As a result, the percentage of hazardous wastes was estimated to be 2.8 % of the total waste generated. If the percentage of batteries in the hazardous wastes at 6.81 % (as mentioned before) was used for the calculation, the percentage of batteries in the waste total would be around 0.19 %. The actual composition of batteries in municipal wastes at present is lower than the amounts of batteries put into the lysimeters in this study. However, it can be concluded from this study that the increasing of amount of spent batteries from 0 to 1 % and from 1 to 5 % gave the remarkable increasing of the heavy metals leaching out especially for Fe, Zn and Mn. In addition, the amount of spent batteries in municipal wastes is forecasted to increase every year. Therefore, it may be concluded from this study that the disposal of spent batteries creates a high potential risk of heavy metal contamination in landfill leachates.

Table 4.6 Generated leachate volume and extracted total mass of pollutants from the Lysimeters

Parameter	Lysimeter No.*		
	3	4	5
Leachate volume (l/kg dry waste)	0.77	0.80	0.78
Material extracted (g/kg dry waste)			
Chloride	3.72	3.82	3.78
COD	51.30	58.07	56.74
TOC	13.92	14.81	15.63
DOC	12.03	13.63	13.20
Volatile Fatty Acid	10.88	11.73	12.35
Total Alkalinity	6.43	6.25	6.60
Heavy metal (mg/kg dry waste)			
Hg	0.005	0.01	0.01
As**	0.31	0.51	0.17
Cd	0.01	0.01	0.03
Mn	2.94	2.76	5.41
Ni	0.03	0.12	0.18
Pb	0.003	0.01	0.01
Fe	16.98	23.90	60.24
Zn	1.51	5.74	6.67

Remarks: * Lysimeter No.3: Solely MSW
Lysimeter No.4: MSW mixed with 1% batteries
Lysimeter No.5: MSW mixed with 5% batteries
** *u*g/kg dry waste

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of the battery batch leaching tests and lysimeter tests were drawn as follows:

1. The results from the leaching tests showed that the concentration of As, Cd, Fe, Mn, Ni, Pb and Zn in the leaching solution ranged from 5.31-6.19 μg/l, 0.0019-46.9 mg/l, 0.02-0.42 mg/l, 0.12-55.7 mg/l, 0.0190-53.3 mg/l, 0.0067-0.391 mg/l and 7-711 mg/l, respectively. The exception was the Hg concentrations, which were below the detection limit of 0.005 mg/l.

2. The Ni-Cd batteries were classified as hazardous waste due to the Cd concentration in the leaching solution were 8.48-46.9 mg/l which above the US TC limit value of 1 mg/l. However, zinc-carbon, alkaline and Ni-MH batteries were not classified as hazardous wastes because the As, Cd, Hg and Pb concentrations in the leaching solutions of these three battery types were 5.31-6.19 μg/l, 0.0019-0.9980 mg/l, >0.005 mg/l and 0.0067-0.3910 mg/l which below the US TC limits at 5 mg/l, 1 mg/l, 0.2 mg/l and 5 mg/l, respectively.

3. The type of batteries influenced the concentration of heavy metals in the leaching solution. Even if zinc-carbon batteries and alkaline batteries are not classified as hazardous waste, those batteries must not be disposed directly into the municipal waste stream due to the high amounts of Zn and Mn leaching.

4. With regard to the lysimeter that contained solely of batteries, the As, Cd, Fe, Hg, Mn, Ni, Pb and Zn concentrations in the leachate generated from Lysimeter No.2 (broken batteries) ranged from 9.48-11.6 μg/l, 0.0014-0.192 mg/l, 11-188 mg/l, 0.0056-0.0084 mg/l, 0.50-43.6 mg/l, 0.0132-0.3950 mg/l, 0.0019-0.1390 mg/l and 0.28-55.2 mg/l, respectively.

5. In the lysimeter tests, the As, Cd, Fe, Hg, Mn, Ni, Pb and Zn concentrations in the leachate generated from Lysimeters No.3 (MSW), No.4 (MSW + 1% batteries) and No.5 (MSW + 5% batteries) ranged from 5.76-15.3 μg/l, 0.0012-0.1690 mg/l, 4-188 mg/l, 0.0006-0.2370 mg/l, 3.55-17.5 mg/l, 0.0168-0.891 mg/l, 0.0028-0.0525 mg/l, and 0.55-49.3 mg/l, respectively.

6. When the means of heavy metal concentrations generated from Lysimeters No.3 and No.4 were compared, it was found that the Cd, Mn, Hg, As and Pb contents were not significantly different among the three lysimeters. At the same time, the means concentrations of Zn, Ni and Fe in Lysimeter No.4 were significantly higher than those of Lysimeter No.3 at a 95 % confidence limit.

7. A comparison between the mean concentrations of the heavy metals from Lysimeters No.4 and No.5 showed that the Cd, Mn, Ni, Pb and Fe contents from Lysimeter No.5 were significantly higher than those of Lysimeter No.4. While the Zn, Hg and As contents were not significantly different from each other at a 95 % confidence limit.

8. It was observed that the Fe concentration was among the major elements found among the three lysimeters followed by Zn, Mn and Ni, respectively.

9. The effects of the batteries added in Lysimeters No. 4 and No. 5 on leachate characteristics resulted in the high concentrations of Fe, Mn, Zn, Hg, and Cd that were higher than the Groundwater Standards for drinking purposes as ruled under the Groundwater Act B.E.2520 (1977) at the maximum allowance levels of 1 mg/l, 0.5 mg/l, 15 mg/l, 0.001 mg/l and 0.01 mg/l, respectively.

10. The lysimeters containing one and five percent of batteries had the potential to release Fe, Zn and Ni into the environment. In addition, the lysimeter with a five percent battery content also had the potential to leach Cd, Mn and Ni into the landfill leachate.

Recommendations

1. At present, only a few local Thai governments have 100 % hazardous waste separation, so the regulation of dry cell battery separation from municipal solid waste should be raised as a national policy.

2. National uniformity in collection, storage, and transport of certain batteries should be discussed and carried out.

3. The use of certain Ni-Cd batteries should be phased out due to the high concentration of Cadmium.

4. In order to reduce the amount of spent battery contaminated in municipal solid waste, the campaign for using rechargeable battery instead of non-rechargeable battery should be implemented.

5. For the high contaminations of pollutants in the leachate generated from landfill mixed with battery at present, the leachate treatment should be enforced to implement in landfill of local government.

6. Due to the high concentrations of Cd and Ni from the leaching test results, the recycling of these kinds of heavy metals from spent batteries should be of concern to the government sector.

Suggestion for future work

1. Investigation into the long-term risks associated with spent batteries should be conducted in order to monitor the heavy metal concentrations in leachate over long periods of time.

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APPENDICES

APPENDIX A

TYPE OF BATTERIES
AND
LEACHING TEST DATA

Table A-1 pH leaching of batteries

Label	Battery Type	Battery Brand Name pH	after slurry	pH after added acid	Extraction Fluid Number	pH after extraction
B1	Zinc-carbon	Panasonic (black), National (black)	3.77	3.77	1	6.61
B2	Zinc-carbon	Panasonic (green), National (green)	5.78	5.78	2	6.62
B3	Zinc-carbon	Panasonic (red)., National (red)	2.18	2.18	1	6.76
B4	Zinc-carbon	Eveready (black)	4.90	4.90	1	6.76
B5	Zinc-carbon	Eveready (red)	4.63	4.63	1	6.75
B6	Zinc-carbon	Super power (black-silver)	5.35	5.35	2	6.42
B7	Zinc-carbon	Leader price	2.96	2.96	1	6.80
B8	Zinc-carbon	Power (black-goldbrown)	4.41	4.41	1	6.87
B9	Zinc-carbon	Panasonic (black), National (black)	6.70	6.70	2	6.41
B10	Zinc-carbon	Power (black-goldbrown)	7.40	7.40	2	6.40
B11	Zinc-carbon	White horse	6.34	6.34	2	6.40
B12	Zinc-carbon	Panasonic (black).National (black)	5.49	5.49	2	6.45
B13	Zinc-carbon	Panasonic (green).National (green)	5.31	5.31	2	5.42
B14	Zinc-carbon	Panasonic (red). National (red)	5.44	5.44	2	5.75
B15	Zinc-carbon	Eveready (black)	5.19	5.19	2	5.29
B16	Zinc-carbon	Eveready (blue)	5.13	5.13	2	6.01
B17	Zinc-carbon	Superay	4.52	4.52	1	6.78
B18	Zinc-carbon	Panasonic (black), National (black)	5.98	4.52	1	6.32
B19	Zinc-carbon	Panasonic (green), National (green)	5.86	3.39	1	6.49
B20	Zinc-carbon	Panasonic (red), National (red)	6.14	4.57	1	6.48
B21	Zinc-carbon	Eveready (black)	6.37	3.41	1	6.51
B22	Zinc-carbon	Eveready (red)	6.29	2.99	1	6.55
B23	Zinc-carbon	Panasonic (black), National (black)	6.01	3.98	1	6.12
B24	Zinc-carbon	Panasonic (red), National (red)	10.5	3.22	1	6.59
B25	Alkaline	Panasonic alkaline (black-yellow)	5.81	5.81	2	6.69
B26	Alkaline	Energizer alkaline	9.59	9.59	2	6.73
B27	Alkaline	Duracell	6.13	6.13	2	6.70
B28	Alkaline	Panasonic alkaline (black-yellow)	11.20	11.20	2	6.24
B29	Alkaline	Energizer alkaline	11.50	11.50	2	6.21
B30	Alkaline	Duracell	11.10	11.10	2	6.31
B31	Alkaline	Energizer alkaline	11.10	11.10	2	6.64
B32	Alkaline	Duracell	5.85	2.54	1	7.11
B33	Ni-cd	National recharge (Ni-cd)	2.24	2.24	1	6.41
B34	Ni-cd	Panasonic recharge (Ni-cd)	6.63	6.63	2	6.53
B35	Ni-MH	Sanyo twicell 1700 (Ni-MH)	2.49	2.49	1	5.91
B36	Ni-MH	SPA recharge (Ni-MH)	4.76	4.76	1	6.45

Table A-2 Leaching Test result

Label	Battery type	Battery size	Battery Brand name	Concentration of metals (mg/l)							
				As*	Cd	Fe	Hg	Mn	Ni	Pb	Zn
B1	Zinc-carbon	AA	Panasonic (black), National (black)	bdl	0.0019	-	bdl	38.30	0.0305	0.0465	301
B2	Zinc-carbon	AA	Panasonic (green), National (green)	bdl	0.0077	-	bdl	53.60	0.0602	0.0520	568
B3	Zinc-carbon	AA	Panasonic (red), National (red)	bdl	0.0034	-	bdl	38.80	0.0830	0.0674	318
B4	Zinc-carbon	AA	Eveready (black)	bdl	0.1110	-	bdl	25.80	3.1000	0.0181	276
B5	Zinc-carbon	AA	Eveready (red)	bdl	0.0990	-	bdl	27.90	0.0253	0.0454	241
B6	Zinc-carbon	AA	Super power (black-silver)	bdl	0.0523	-	bdl	50.00	0.1550	0.0151	472
B7	Zinc-carbon	AA	Leader price	bdl	bdl	-	bdl	30.40	0.0422	0.0261	293
B8	Zinc-carbon	AA	Power (black-goldbrown)	bdl	0.6760	-	bdl	14.80	0.2290	0.0455	285
B9	Zinc-carbon	AAA	Panasonic (black),National (black)	bdl	0.0098	-	bdl	50.00	0.0670	0.0468	505
B10	Zinc-carbon	AAA	Power (black-goldbrown)	bdl	0.1023	bdl	bdl	42.10	0.5470	0.2094	520
B11	Zinc-carbon	AAA	White horse	bdl	0.0475	-	bdl	54.80	0.4820	0.3910	559
B12	Zinc-carbon	D	Panasonic (black), National (black)	bdl	0.0147	-	bdl	55.70	0.0190	0.1420	611
B13	Zinc-carbon	D	Panasonic (green), National (green)	bdl	0.0173	-	bdl	53.60	0.6300	0.0188	679
B14	Zinc-carbon	D	Panasonic (red), National (red)	bdl	0.6593	-	bdl	41.50	0.1360	bdl	711
B15	Zinc-carbon	D	Eveready (black)	bdl	0.0136	-	bdl	47.80	0.0170	bdl	601
B16	Zinc-carbon	D	Eveready (blue)	bdl	0.9980	-	bdl	47.80	0.1740	0.0470	551
B17	Zinc-carbon	D	Superay	bdl	0.0426	bdl	bdl	10.80	0.0236	0.0086	239
B18	Zinc-carbon	C	Panasonic (black).National (black)	bdl	0.0044	-	bdl	45.40	0.0467	0.0483	283
B19	Zinc-carbon	C	Panasonic (green).National (green)	bdl	0.0174	-	bdl	23.10	0.0766	0.2400	265
B20	Zinc-carbon	C	Panasonic (red). National (red)	bdl	0.0128	-	bdl	28.30	0.0560	0.2620	317

Table A-2 Leaching Test result (continued)

Label	Battery Size	Battery Type	Battery Brand name	Concentration of metals (ppm)							
				As*	**Cd**	**Fe**	**Hg**	**Mn**	**Ni**	**Pb**	**Zn**
B21	Zinc-carbon	C	Eveready (black)	bdl	0.1370	-	bdl	36.60	0.0613	0.0179	253
B22	Zinc-carbon	C	Eveready (red)	bdl	0.1240	-	bdl	18.60	0.0429	0.0104	234
B23	Zinc-carbon	9V	Panasonic (black).National (black)	bdl	0.0106	-	bdl	52.70	1.2500	bdl	299
B24	Zinc-carbon	9V	Panasonic (red). National (red)	bdl	0.0454	-	bdl	51.80	1.2700	0.0211	311
B25	alkaline	AA	Panasonic alkaline (black-yellow)	bdl	0.0020	-	bdl	13.80	0.2020	bdl	365
B26	alkaline	AA	Energizer alkaline	bdl	0.0079	-	bdl	0.12	0.1330	bdl	349
B27	alkaline	AA	Duracell	bdl	0.0066	-	bdl	4.84	0.2810	bdl	323
B28	alkaline	AAA	Panasonic alkaline (black-yellow)	bdl	0.0063	0.02	bdl	17.00	0.2870	bdl	358
B29	alkaline	AAA	Energizer alkaline	bdl	0.0047	0.06	bdl	49.10	0.7140	bdl	378
B30	alkaline	AAA	Duracell	bdl	0.0103	-	bdl	14.90	1.0500	bdl	399
B31	alkaline	D	Energizer alkaline	bdl	0.0076	-	bdl	0.28	0.1230	0.0104	265
B32	alkaline	9V	Duracell	bdl	0.0028	-	bdl	4.21	0.0444	0.0131	158
B33	Ni-cd	AA	National recharge (Ni-Cd)	bdl	46.9000	-	bdl	11.90	9.1500	0.0258	207
B34	Ni-cd	AA	Panasonic recharge (Ni-Cd)	6.19	8.4800	-	bdl	6.40	0.6410	bdl	387
B35	Ni-MH	AA	Sanyo twicell 1700 (Ni-MH)	5.31	0.9980	0.42	bdl	13.10	39.1000	bdl	15
B36	Ni-MH	AA	SPA recharge (Ni-MH)	5.66	0.1340	-	bdl	13.70	53.3000	0.0067	7

* µg/l , bdl : below detection limit (As 5 µg/l, Cd 0.0002 mg/l, Fe 0.0003, Hg 0.002 mg/l, Pb 0.0003 mg/l)

Table A-3 Cumulative As, Cd, Pb and Hg leached from Lysimeter No.2

Days after filling (d)	L/S	Cumulative metal leached (mg/kg)			
		As	Cd	Pb	Hg
5	0.051	0.0000	0.0000	0.0000	0.0000
8	0.054	0.0000	0.0000	0.0000	0.0000
12	0.055	0.0000	0.0000	0.0000	0.0000
16	0.059	0.0000	0.0000	0.0000	0.0000
20	0.073	0.0000	0.0000	0.0000	0.0000
24	0.073	0.0000	0.0000	0.0000	0.0000
28	0.076	0.0001	0.0000	0.0029	0.0000
32	0.084	0.0001	0.0000	0.0029	0.0000
39	0.088	0.0003	0.0002	0.0036	0.0001
46	0.133	0.0004	0.0010	0.0053	0.0001
53	0.136	0.0005	0.0015	0.0054	0.0002
60	0.142	0.0006	0.0023	0.0071	0.0002
67	0.146	0.0007	0.0050	0.0077	0.0004
74	0.167	0.0009	0.0089	0.0081	0.0004
81	0.170	0.0010	0.0109	0.0087	0.0005
88	0.208	0.0011	0.0119	0.0091	0.0005
95	0.227	0.0012	0.0129	0.0096	0.0005
102	0.242	0.0013	0.0138	0.0100	0.0005
109	0.244	0.0015	0.0155	0.0104	0.0005
116	0.252	0.0016	0.0178	0.0107	0.0005
123	0.254	0.0017	0.0188	0.0110	0.0005
130	0.273	0.0018	0.0203	0.0114	0.0005
137	0.358	0.0019	0.0216	0.0117	0.0005
144	0.377	0.0020	0.0227	0.0118	0.0005
151	0.377	0.0021	0.0252	0.0123	0.0005
158	0.379	0.0022	0.0260	0.0127	0.0005
165	0.379	0.0023	0.0265	0.0130	0.0005
172	0.387	0.0024	0.0267	0.0131	0.0005
179	0.390	0.0025	0.0270	0.0132	0.0005

APPENDIX B

PRECIPITATION DATA

Table B-1 Monthly Rainfall (mm). Rain-days and Daily Maximum from station 327501 year 1995 to 2004

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Rain Days	Daily Maximum
1995	0.0	0.0	5.4	37.9	128.4	132.2	239.6	335.9	143.7	78.4	0.0	1135.4	1135.4	114.0	68.4
1996	0.0	40.6	9.2	213.8	84.3	106.9	123.8	215.5	24.0	222.7	73.6	73.6	1314.4	127.0	119.1
1997	0.0	0.0	6.7	85.1	64.5	31.1	211.6	210.4	135.3	150.1	13.8	0.0	908.6	105.0	65.2
1998	14.6	0.0	T	11.5	181.3	66.4	101.3	201.6	128.8	33.3	16.9	0.2	755.9	100.0	76.9
1999	31.7	66.4	22.6	31.3	330.8	94.9	105.8	150.4	164.9	104.4	35.7	2.6	1141.5	147.0	96.0
2000	0.0	57.4	41.2	107.7	189.5	180.5	68.3	147.0	132.3	195.0	10.1	4.1	1133.1	117	83.5
2001	0.0	0.0	75.4	22.8	171.6	107.8	167.6	330.9	129.1	176.4	21.5	17.3	1220.4	106	120.2
2002	9.0	9.9	1.4	11.2	221.8	123.8	77.0	254.7	309.7	145.2	332.3	116.3	1612.3	123	114.6
2003	17.6	.0	53.5	41.2	141.4	92.0	52.4	156.8	315.8	12.8	6.1	T	889.6	96	67.8
2004	2.8	4.9	0.0	0.5	249.1	178.8	218.0	115.7	371.4	38.8	28.9	0	1208.9	111	144.4

Source: Data Processing Sub-division, Climatology Division, Meteorological Department [2005, June 2]

Table B-2 Amount of daily rainfall added into the lysimeter from May to October

Date	**May**		**June**		**July**		**August**		**September**		**October**	
	mm	**cm^3**	**mm**	**cm^3**	**mm**	**cm^3**	**mm**	**cm^3**	**mm**	**cm^3**	**mm**	**cm^3**
1	9.5	154	2.5	41	.1	1.6	16.5	267	T		3.0	49
2	9.2	149	.0	-	.0	-	5.0	81	17.2	279	.7	11
3	18.4	298	.0	-	.4	6.5	.3	5	14.7	238	.0	-
4	.0	-	.0	-	.0	-	13.2	214	4.0	65	.0	-
5	113.8	1844	.0	-	1.7	28	.7	11	.0	-	.0	-
6	1.4	23	1.9	31	8.9	144	13.8	224	.0	-	.0	-
7	10.2	165	.3	5	T	-	.0	-	.0	-	.0	-
8	.0	-	.4	6.5	1.4	23	12.0	195	22.7	368	.0	-
9	.0	-	11.9	193	2.3	37	4.2	68	144.4	2340	.0	-
10	.0	-	34.1	553	1.0	16	11.0	178	21.0	340	1.9	31
11	.0	-	14.6	237	31.6	512	4.9	79	.1	1.62	T	-
12	.0	-	12.1	196	5.3	86	.8	13	4.1	66	T	-
13	2.8	45	.4	6.5	19.2	311	.0	-	21.5	348	.0	-
14	.0	-	46.6	755	1.6	26	2.0	32	55.7	903	.0	-
15	6.7	109	23.8	386	.0	-	2.4	39	8.2	133	.0	-
16	1.7	28	1.7	28	T	-	.0	-	19.6	318	.0	-
17	4.4	71	6.2	100	T	-	.0	-	7.8	126	.2	3.24
18	T	-	4.1	66	.0	-	T	-	.0	-	22.0	357
19	9.1	148	.4	6.5	.0	-	1.8	29	4.1	66	.0	-
20	22.2	340	.0	-	6.0	97	21.7	352	20.8	337	.0	-
21	10.1	164	T	-	4.7	76	.0	-	5.5	89	7.0	113
22	T	-	.0	-	12.7	206	.0	-	.0	-	4.0	65
23	.1	1.62	T	-	4.4	71	.0	-	.0	-	.0	-
24	.0	-	.0	-	17.7	287	.0	-	.0	-	.0	-
25	.8	13	.0	-	34.6	561	.0	-	.0	-	.0	-
26	.2	3.24	.0	-	2.1	34	.0	-	.0	-	.0	-
27	3.5	57	5.8	94	40.6	658	.0	-	.0	-	.0	-
28	1.3	21	4.0	65	1.6	26	.0	-	T	-	.0	-
29	2.5	41	7.3	118	5.8	94	T	-	.0	-	.0	-
30	2.4	39	.7	11	2.5	41	5.4	88	.0	-	.0	-
31	18.8	305			11.8	191	.0	-			.0	-
Total	249.1	4037	178.8		218.0		115.7	-	371.4	6017.62	38.8	
R-day	21	-	19	-	23	-	16		16		7	

T = Rainfall amount less than 0.1 mm

APPENDIX C

RAINFALL ADDITION AND LEACHATE GENERATION FROM LYSIMETER TEST

Table C-1 Rainfall added and Leachate generated

Days after filling (d)	**Rainfall added (ml)**	**Leachate generated from lysimeter (ml)**				
		Lysimeter No. 1	**Lysimeter No. 2**	**Lysimeter No. 3**	**Lysimeter No. 4**	**Lysimeter No. 5**
0	154	-	-	-	-	-
1	149	-	-	5	550	240
2	298	-	-	81	95	64
3	-	-	-	62	76	53
4	1844	-	-	64	60	54
5	23	-	-	1390	1140	1079
6	165	-	-	173	143	164
7	-	-	-	117	95	109
8	-	-	-	88	92	71
9	-	-	-	82	91	61
10	-	-	-	87	96	69
11	-	-	-	79	91	62
12	45	-	-	66	74	52
13	-	-	-	56	68	53
14	109	-	-	47	58	46
15	28	-	-	45	58	48
16	71	-	-	43	56	44
17	-	58	-	30	55	49
18	148	-	-	36	47	36
19	340	-	-	51	50	55
20	164	-	-	205	170	200
21	-	-	-	142	140	178
22	1.62	-	-	74	119	135
23	-	-	-	72	77	93
24	13	-	-	5	63	72
25	3.24	-	-	64	56	51
26	57	73	-	20	55	49
27	21	15	17	-	50	44
28	41	-	5	-	40	48
29	39	-	8	10	42	41
30	305	-	8	14	41	37
31	41	-	3	25	34	33
32	-	-	-	80	31	39
33	-	20	20	77	83	83
34	-	9	18	46	60	72
35	-	-	-	33	43	47
36	31	37	88	37	52	50
37	5	-	20	32	41	54
38	6.5	8	2	30	34	37
39	193	-	13	25	30	29
40	553	-	-	25	26	25

Table C-1 Rainfall added and Leachate generated (continued)

Days after filling (d)	Rainfall added (ml)	Leachate generated from lysimeter (ml)				
		Lysimeter No. 1	Lysimeter No. 2	Lysimeter No. 3	Lysimeter No. 4	Lysimeter No. 5
41	237	31	10	329	271	256
42	196	35	1	259	238	240
43	6.5	-	-	81	108	85
44	755	41	105	165	117	96
45	386	20	44	516	554	532
46	28	11	83	355	360	300
47	100	10	140	170	185	165
48	66	3	64	62	70	67
49	6.5	5	167	55	61	62
50	-	11	91	60	59	45
51	-	10	110	71	67	57
52	-	7	50	57	48	56
53	-	11	118	57	50	48
54	-	12	120	64	52	57
55	-	5	195	41	47	43
56	-	-	33	33	63	38
57	94	11	34	41	65	45
58	65	20	130	41	9	30
59	118	16	47	30	9	39
60	11	7	58	33	25	38
61	1.6	9	123	39	42	49
62	-	-	155	37	38	38
63	6.5	10	120	40	41	26
64	-	2	25	40	41	38
65	28	-	26	36	36	36
66	144	5	23	37	43	39
67	-	9	-	37	40	38
68	23	10	-	37	41	44
69	37	8	-	37	39	33
70	16	5	107	52	48	48
71	512	-	-	84	32	24
72	86	5	-	162	178	168
73	311	9	69	162	186	174
74	26	2	2	188	154	165
75	-	15	64	154	180	184
76	-	8	56	82	102	115
77	-	12	69	62	71	63
78	-	11	59	54	62	84
79	-	5	84	50	59	57
80	97	-	15	42	51	52
81	76	-	72	38	38	38

Table C-1 Rainfall added and Leachate generated (continued)

Days after filling (d)	**Rainfall added (ml)**	**Leachate generated from lysimeter (ml)**				
		Lysimeter No. 1	**Lysimeter No. 2**	**Lysimeter No. 3**	**Lysimeter No. 4**	**Lysimeter No. 5**
82	206	16	27	41	49	47
83	71	7	9	39	47	42
84	287	4	-	103	65	62
85	561	-	107	231	192	179
86	34	11	26	491	459	503
87	658	8	18	118	102	100
88	26	5	55	580	520	540
89	94	7	17	138	189	163
90	41	5	67	78	73	79
91	191	12	62	61	66	70
92	267	7	100	95	74	72
93	81	7	145	220	205	200
94	5	7	55	135	160	164
95	214	2	66	92	96	95
96	11	8	110	88	96	96
97	224	-	135	125	100	145
98	-	10	27	105	90	95
99	195	5	51	120	122	110
100	68	10	13	97	105	105
101	178	3	124	118	98	100
102	79	3	45	105	90	93
103	13	6	124	129	139	127
104	-	-	105	110	117	115
105	32	8	100	65	74	76
106	39	11	200	59	76	80
107	-	10	30	60	74	78
108	-	6	23	40	51	54
109	-	-	20	38	48	50
110	29	1	52	50	55	55
111	352	7	44	36	50	48
112	-	5	74	88	42	40
113	-	2	108	78	94	74
114	-	6	82	78	89	89
115	-	9	163	47	57	61
116	-	5	110	42	53	54
117	-	10	126	51	55	64
118	-	10	70	39	43	50
119	-	9	68	35	53	53
120	-	9	59	37	54	45
121	88	10	30	49	59	58
122	-	5	39	25	37	28

Table C-1 Rainfall added and Leachate generated (continued)

Days after filling (d)	Rainfall added (ml)	Leachate generated from lysimeter (ml)				
		Lysimeter No. 1	Lysimeter No. 2	Lysimeter No. 3	Lysimeter No. 4	Lysimeter No. 5
123	-	3	62	28	33	32
124	279	6	33	25	26	34
125	238	15	18	40	50	48
126	65	5	115	136	32	32
127	-	5	10	102	104	106
128	-	5	10	98	96	94
129	-	6	17	95	87	73
130	368	5	90	44	55	52
131	2340	5	82	143	85	87
132	340	-	123	2350	2450	2400
133	1.62	8000	242	270	260	255
134	66	240	210	145	178	170
135	348	50	78	97	120	118
136	903	230	167	233	185	165
137	133	990	320	843	720	775
138	318	89	244	163	213	190
139	126	276	236	315	305	307
140	-	80	118	135	137	165
141	66	46	190	88	115	110
142	337	37	120	84	100	110
143	89	200	175	180	154	155
144	-	84	205	107	140	130
145	-	34	167	87	100	99
146	-	23	170	63	74	66
147	-	22	162	58	72	64
148	-	5	100	53	56	59
149	-	5	30	40	49	48
150	-	3	20	35	48	52
151	-	4	18	26	52	51
152	-	17	144	35	41	45
153	49	14	118	31	45	41
154	11	15	185	40	48	49
155	-	13	56	25	37	38
156	-	9	208	25	39	35
157	-	10	79	35	36	52
158	-	7	144	30	36	30
159	-	6	80	25	34	28
160	-	6	92	24	31	31
161	-	6	150	27	39	37
162	31	5	45	22	25	33
163	-	6	63	30	38	38

Table C-1 Rainfall added and Leachate generated (continued)

Days after filling (d)	Rainfall added (ml)	Leachate generated from lysimeter (ml)				
		Lysimeter No. 1	Lysimeter No. 2	Lysimeter No. 3	Lysimeter No. 4	Lysimeter No. 5
164	-	-	53	14	20	22
165	-	-	66	22	28	27
166	-	5	81	26	34	34
167	-	-	60	15	20	23
168	-	-	158	9	14	16
169	3.24	-	10	10	15	13
170	357	150	20	15	10	10
171	-	25	15	35	40	35
172	-	17	30	75	10	12
173	113	20	86	32	23	19
174	65	21	120	29	28	29
175	-	17	73	13	26	20
176	-	22	120	23	28	25
177	-	7	118	27	29	33
178	-	7	30	25	22	30
179	-	7	34	20	22	30
180	-	7	20	35	30	45
181	-	-	20	30	35	45
182	-	-	18	25	35	30
183	-	-	10	20	20	25
Total	18972	11769	11795	20476	19614	19024

APPENDIX D

STATISTICAL DATA

Table D-1 Independent sample T-test for analyzed leachate generation from Lysimeters No. 1 and No. 2

Group Statistics

	Lysimeter	N	Mean	Std. Deviation	Std. Error Mean
Leachate generation	1	51	212.49	1122.142	157.131
	2	51	107.41	75.612	10.588

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Leachate generation	Equal variances assumed	3.421	.067	.667	100	.506	105.08	157.488	-207.373	417.529
	Equal variances not assumed			.667	50.454	.508	105.08	157.488	-211.174	421.331

(If the Sig. value is less than 0.05, the mean difference is significant at the 0.05 level)

Table D-2 Independent sample T-test for analyzed leachate characteristics from Lysimeters No. 1 and No. 2

Group Statistics

	Lysimeter	N	Mean	Std. Deviation	Std. Error Mean
pH	1	7	5.0771	1.17868	.44550
	2	7	5.7786	.68536	.25904
Conductivity	1	7	15.901	6.0677	2.2934
	2	7	10.351	2.7268	1.0306
Chloride	1	7	6069.57	2148.571	812.084
	2	7	4713.00	1438.832	543.827
Cadmium	1	7	.077671	.0338709	.0128020
	2	7	.046957	.0378386	.0143016
Ferrous	1	7	76.00	42.462	16.049
	2	7	93.71	54.061	20.433
Manganese	1	7	16.8557	5.70837	2.15756
	2	7	19.7043	6.50855	2.46000
Nickel	1	7	.562829	.2209162	.0834985
	2	7	.063686	.0401564	.0151777
Lead	1	7	.019557	.0118705	.0044866
	2	7	.012400	.0076546	.0028932
Zinc	1	7	111.7486	41.32635	15.61989
	2	7	8.6429	7.06961	2.67206

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
pH	Equal variances assumed	.855	.373	-1.361	12	.198	-.7014	.51534	-1.82425	.42139
	Equal variances not assumed			-1.361	9.641	.204	-.7014	.51534	-1.85549	.45264
Conductivity	Equal variances assumed	1.744	.211	2.207	12	.048	5.550	2.5143	.0718	11.0282
	Equal variances not assumed			2.207	8.329	.057	5.550	2.5143	-.2084	11.3084
Chloride	Equal variances assumed	1.084	.318	1.388	12	.190	1356.57	977.358	-772.908	3486.051
	Equal variances not assumed			1.388	10.480	.194	1356.57	977.358	-807.662	3520.805
Cadmium	Equal variances assumed	.048	.831	1.600	12	.136	.030714	.0191945	-.0111069	.0725355
	Equal variances not assumed			1.600	11.856	.136	.030714	.0191945	-.0111634	.0725920

Table D-2 Independent sample T-test for analyzed leachate characteristics from Lysimeters No. 1 and No. 2 (continued)

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Ferrous	Equal variances assumed	1.199	.295	-.682	12	.508	-17.71	25.982	-74.325	38.896
	Equal variances not assumed			-.682	11.362	.509	-17.71	25.982	-74.679	39.251
Manganese	Equal variances assumed	.849	.375	-.871	12	.401	-2.8486	3.27210	-9.97787	4.28073
	Equal variances not assumed			-.871	11.799	.401	-2.8486	3.27210	-9.99135	4.29421
Nickel	Equal variances assumed	7.895	.016	5.881	12	.000	.499143	.0848667	.3142342	.6840515
	Equal variances not assumed			5.881	6.396	.001	.499143	.0848667	.2945591	.7037266
Lead	Equal variances assumed	1.494	.245	1.341	12	.205	.007157	.0053386	-.0044746	.0187889
	Equal variances not assumed			1.341	10.254	.209	.007157	.0053386	-.0046981	.0190124
Zinc	Equal variances assumed	14.085	.003	6.506	12	.000	103.1057	15.84680	68.57851	137.63292
	Equal variances not assumed			6.506	6.351	.000	103.1057	15.84680	64.84342	141.36801

(If the Sig. value is less than 0.05, the mean difference is significant at the 0.05 level)

Table D-3 Data of Lysimeters No. 3 to No.5 from one-way anova (SPSS program)

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Leachate Generation	Between Groups	1656.971	2	828.486	.018	.982
	Within Groups	24988762.674	549	45516.872		
	Total	24990419.645	551			
pH	Between Groups	.667	2	.334	.716	.491
	Within Groups	39.110	84	.466		
	Total	39.777	86			
Conductivity	Between Groups	5.016	2	2.508	.067	.935
	Within Groups	3136.349	84	37.337		
	Total	3141.365	86			
Chloride	Between Groups	26783.721	2	13391.861	.004	.996
	Within Groups	258447358.043	84	3076754.262		
	Total	258474141.764	86			
TA	Between Groups	19897562.782	2	9948781.391	.329	.720
	Within Groups	2537751508.138	84	30211327.478		
	Total	2557649070.920	86			
VFA	Between Groups	33374865.816	2	16687432.908	.460	.633
	Within Groups	3046085623.793	84	36262924.093		
	Total	3079460489.609	86			
COD	Between Groups	1012207776.368	2	506103888.184	.553	.577
	Within Groups	76819983367.310	84	914523611.516		
	Total	77832191143.678	86			
TOC	Between Groups	93834046.840	2	46917023.420	.546	.582
	Within Groups	6705880650.741	78	85972828.856		
	Total	6799714697.580	80			
DOC	Between Groups	46219009.654	2	23109504.827	.434	.649
	Within Groups	4149868684.000	78	53203444.667		
	Total	4196087693.654	80			
Cadmium	Between Groups	.055	2	.027	40.300	.000
	Within Groups	.057	84	.001		
	Total	.112	86			
Arsenic	Between Groups	2.227	2	1.114	.295	.745
	Within Groups	317.130	84	3.775		
	Total	319.357	86			
Ferrous	Between Groups	227691.793	2	113845.897	294.681	.000
	Within Groups	32452.276	84	386.337		
	Total	260144.069	86			
Mercury	Between Groups	.001	2	.000	.272	.763
	Within Groups	.081	48	.002		
	Total	.082	50			
Manganese	Between Groups	795.543	2	397.772	77.709	.000
	Within Groups	429.973	84	5.119		
	Total	1225.517	86			
Nickel	Between Groups	2.370	2	1.185	35.971	.000
	Within Groups	2.767	84	.033		
	Total	5.137	86			
Lead	Between Groups	.007	2	.003	23.334	.000
	Within Groups	.012	84	.000		
	Total	.018	86			
Zinc	Between Groups	4172.167	2	2086.084	11.971	.000
	Within Groups	14638.253	84	174.265		
	Total	18810.421	86			

Table D-4 Data of Lysimeters No.3 to No.5 from Post Hoc Multiple comparisons

Multiple Comparisons: Scheffe

Dependent Variable	(I) Lysimeter	(J) Lysimeter	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Leachate Generation	3	4	-4.01	22.243	.984	-58.60	50.58
		5	-.80	22.243	.999	-55.40	53.79
	4	3	4.01	22.243	.984	-50.58	58.60
		5	3.21	22.243	.990	-51.39	57.80
	5	3	.80	22.243	.999	-53.79	55.40
		4	-3.21	22.243	.990	-57.80	51.39
pH	3	4	.1072	.17919	.836	-.3393	5538
		5	-.1072	.17919	.836	-.5538	3393
	4	3	-.1072	.17919	.836	-.5538	3393
		5	-.2145	.17919	.491	-.6610	2321
	5	3	.1072	.17919	.836	-.3393	5538
		4	.2145	.17919	.491	-.2321	6610
Conductivity	3	4	.463	1.6047	.959	-3.536	4.462
		5	-.082	1.6047	.999	-4.081	3.917
	4	3	-.463	1.6047	.959	-4.462	3.536
		5	-.546	1.6047	.944	-4.544	3.453
	5	3	.082	1.6047	.999	-3.917	4.081
		4	.546	1.6047	.944	-3.453	4.544
Chloride	3	4	42.34	460.641	.996	-1105.60	1190.28
		5	14.79	460.641	.999	-1133.15	1162.73
	4	3	-42.34	460.641	.996	-1190.28	1105.60
		5	-27.55	460.641	.998	-1175.49	1120.39
	5	3	-14.79	460.641	.999	-1162.73	1133.15
		4	27.55	460.641	.998	-1120.39	1175.49
TA	3	4	1171.41	1443.447	.720	-2425.73	4768.56
		5	590.86	1443.447	.920	-3006.28	4188.00
	4	3	-1171.41	1443.447	.720	-4768.56	2425.73
		5	-580.55	1443.447	.922	-4177.69	3016.59
	5	3	-590.86	1443.447	.920	-4188.00	3006.28
		4	580.55	1443.447	.922	-3016.59	4177.69
VFA	3	4	161.34	1581.421	.995	-3779.63	4102.32
		5	-1225.76	1581.421	.741	-5166.74	2715.22
	4	3	-161.34	1581.421	.995	-4102.32	3779.63
		5	-1387.10	1581.421	.682	-5328.08	2553.88
	5	3	1225.76	1581.421	.741	-2715.22	5166.74
		4	1387.10	1581.421	.682	-2553.88	5328.08
COD	3	4	-5692.69	7941.700	.774	-25483.80	14098.42
		5	-8142.62	7941.700	.593	-27933.73	11648.49
	4	3	5692.69	7941.700	.774	-14098.42	25483.80
		5	-2449.93	7941.700	.954	-22241.04	17341.18
	5	3	8142.62	7941.700	.593	-11648.49	27933.73
		4	2449.93	7941.700	.954	-17341.18	22241.04
TOC	3	4	-679.37	2523.561	.964	-6976.95	5618.21
		5	-2545.78	2523.561	.603	-8843.36	3751.80
	4	3	679.37	2523.561	.964	-5618.21	6976.95
		5	-1866.41	2523.561	.761	-8163.99	4431.17
	5	3	2545.78	2523.561	.603	-3751.80	8843.36
		4	1866.41	2523.561	.761	-4431.17	8163.99
DOC	3	4	-1400.19	1985.194	.780	-6354.26	3553.89
		5	-1747.63	1985.194	.680	-6701.71	3206.45
	4	3	1400.19	1985.194	.780	-3553.89	6354.26
		5	-347.44	1985.194	.985	-5301.52	4606.63
	5	3	1747.63	1985.194	.680	-3206.45	6701.71
		4	347.44	1985.194	.985	-4606.63	5301.52

Table D-4 Data of Lysimeters No. 3 to No.5 from Post Hoc Multiple comparisons (continued)

Multiple Comparisons : Scheffe

Dependent Variable	(I) Lysimeter	(J) Lysimeter	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Arsenic	3	4	-.3917	.51026	.746	-1.6633	.8799
		5	-.2072	.51026	.921	-1.4788	1.0644
	4	3	.3917	.51026	.746	-.8799	1.6633
		5	.1845	.51026	.937	-1.0871	1.4561
	5	3	.2072	.51026	.921	-1.0644	1.4788
		4	-.1845	.51026	.937	-1.4561	1.0871
Mercury	3	4	-.010376	.0140852	.764	-.045958	.025205
		5	-.005694	.0140852	.922	-.041275	.029887
	4	3	.010376	.0140852	.764	-.025205	.045958
		5	.004682	.0140852	.946	-.030899	.040264
	5	3	.005694	.0140852	.922	-.029887	.041275
		4	-.004682	.0140852	.946	-.040264	.030899
Cadmium	3	4	-.003559	.0068589	.874	-.020651	.013534
		5	-.055017*	.0068589	.000	-.072110	-.037925
	4	3	.003559	.0068589	.874	-.013534	.020651
		5	-.051459*	.0068589	.000	-.068551	-.034366
	5	3	.055017*	.0068589	.000	.037925	.072110
		4	.051459*	.0068589	.000	.034366	.068551
Ferous	3	4	-22.17*	5.162	.000	-35.04	-9.31
		5	-117.90*	5.162	.000	-130.76	-105.03
	4	3	22.17*	5.162	.000	9.31	35.04
		5	-95.72*	5.162	.000	-108.59	-82.86
	5	3	117.90*	5.162	.000	105.03	130.76
		4	95.72*	5.162	.000	82.86	108.59
Manganese	3	4	-.16690	.594151	.961	-1.64755	1.31376
		5	-6.49655*	.594151	.000	-7.97721	-5.01590
	4	3	.16690	.594151	.961	-1.31376	1.64755
		5	-6.32966*	.594151	.000	-7.81031	-4.84900
	5	3	6.49655*	.594151	.000	5.01590	7.97721
		4	6.32966*	.594151	.000	4.84900	7.81031
Nickel	3	4	-.188314*	.0476634	.001	-.307093	-.069534
		5	-.403966*	.0476634	.000	-.522745	-.285186
	4	3	.188314*	.0476634	.001	.069534	.307093
		5	-.215652*	.0476634	.000	-.334431	-.096872
	5	3	.403966*	.0476634	.000	.285186	.522745
		4	.215652*	.0476634	.000	.096872	.334431
Lead	3	4	-.004059	.0031140	.431	-.011819	.003702
		5	-.020114*	.0031140	.000	-.027874	-.012354
	4	3	.004059	.0031140	.431	-.003702	.011819
		5	-.016055*	.0031140	.000	-.023815	-.008295
	5	3	.020114*	.0031140	.000	.012354	.027874
		4	.016055*	.0031140	.000	.008295	.023815
Zinc	3	4	-13.87448*	3.466738	.001	-22.51377	-5.23520
		5	-15.38862*	3.466738	.000	-24.02790	-6.74934
	4	3	13.87448*	3.466738	.001	5.23520	22.51377
		5	-1.51414	3.466738	.909	-10.15342	7.12515
	5	3	15.38862*	3.466738	.000	6.74934	24.02790
		4	1.51414	3.466738	.909	-7.12515	10.15342

* The mean difference is significant at the .05 level.

Table D-5 Homogenous Subset analyses by SPSS Program

Leachate generation

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	184	102.59
5	184	103.39
4	184	106.60
Sig.		.984

Means for groups in homogeneous subsets are displayed.

pH

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
4	29	5.0090
5	29	5.1162
3	29	5.2234
Sig.		.491

Means for groups in homogeneous subsets are displayed.

Conductivity

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
4	29	21.341
3	29	21.804
5	29	21.886
Sig.		.944

Means for groups in homogeneous subsets are displayed.

Chloride

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
4	29	4966.69
5	29	4994.24
3	29	5009.03
Sig.		.996

Means for groups in homogeneous subsets are displayed.

Total Alkalinity

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
4	29	7664.41
5	29	8244.97
3	29	8835.83
Sig.		.720

Means for groups in homogeneous subsets are displayed.

Volatile Fatty Acid

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
4	29	14621.72
3	29	14783.07
5	29	16008.83
Sig.		.682

Means for groups in homogeneous subsets are displayed.

Chemical Oxygen Demand

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	29	71172.03
4	29	76864.72
5	29	79314.66
Sig.		.593

Means for groups in homogeneous subsets are displayed.

Total Organic Carbon

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	27	19426.78
4	27	20106.15
5	27	21972.56
Sig.		.603

Means for groups in homogeneous subsets are displayed

Dissolve Organic Carbon

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	27	16671.41
4	27	18071.59
5	27	18419.04
Sig.		.680

Means for groups in homogeneous subsets are displayed.

Cadmium

Scheffe

	N	Subset for alpha = .05	
Lysimeter		1	2
3	29	.012866	
4	29	.016424	
5	29		.067883
Sig.		.874	1.000

Means for groups in homogeneous subsets are displayed.

Table D-5 Homogenous Subset analyses by SPSS Program (continued)

Manganese

Scheffe

	N	Subset for alpha = .05	
Lysimeter		1	2
3	29	7.05586	
4	29	7.22276	
5	29		13.55241
Sig.		.961	1.000

Means for groups in homogeneous subsets are displayed.

Zinc

Scheffe

	N	Subset for alpha = .05	
Lysimeter		1	2
3	29	4.61207	
4	29		18.48655
5	29		20.00069
Sig.		1.000	.909

Means for groups in homogeneous subsets are displayed.

Mercury

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	17	.041329
5	17	.049394
4	17	.052000
Sig.		.764

Means for groups in homogeneous subsets are displayed.

Lead

Scheffe

	N	Subset for alpha = .05	
Lysimeter		1	2
3	29	.009931	
4	29	.013990	
5	29		.030045
Sig.		.431	1.000

Means for groups in homogeneous subsets are displayed.

Arsenic

Scheffe

	N	Subset for alpha = .05
Lysimeter		1
3	29	5.4417
5	29	5.6490
4	29	5.8334
Sig.		.746

Means for groups in homogeneous subsets are displayed.

Ferous

Scheffe

	N	Subset for alpha = .05		
Lysimeter		1	2	3
3	29	36.21		
4	29		58.38	
5	29			154.10
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

Nickel

Scheffe

	N	Subset for alpha = .05		
Lysimeter		1	2	3
3	29	.098966		
4	29		.287279	
5	29			.502931
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

APPENDIX E

LEACHATE CHARACTERISTICS
AND
DETECTION LIMIT OF THE INSTRUMENT

Table E-1 Characteristics of leachate from Lysimeter No.1

Days after filling (d)	**pH**	**Conducitivity (mS/cm)**	**Chloride (mg/l)**	**As (μg/l)**	**Cd (mg/l)**	**Fe (mg/l)**	**Hg (mg/l)**	**Mn (mg/l)**	**Ni (mg/l)**	**Pb (mg/l)**	**Zn (mg/l)**
28	8.75	14.4	4000	16.80	0.0014	bdl	-	1.25	0.2750	0.3300	0.49
39	9.18	17.0	-	bdl	0.0009	bdl	-	0.65	0.1330	0.3110	0.41
46	5.90	25.2	9750	bdl	0.0311	149	-	15.70	0.3940	0.1690	1.96
53	-	-	9950	-	-	-	-	-	-	-	-
60	4.66	31.8	11000	bdl	0.2450	223	-	57.10	1.3500	0.1440	83.80
67	4.42	34.6	13500	-	-	-	-	-	-	-	-
74	4.26	49.5	21000	bdl	0.6700	377	-	98.20	2.1400	0.2960	153.00
81	3.91	51.8	23000	bdl	0.5670	510	0.0333	50.00	1.9000	0.3740	131.00
88	3.45	75.4	37200	bdl	0.6700	255	-	76.30	2.0200	0.4820	147.00
95	3.67	63.1	36500	-	-	-	-	-	-	-	-
102	3.54	65.0	38000	bdl	0.5330	323	-	81.00	1.6800	0.4000	148.00
109	3.75	66.6	33000	bdl	1.4600	402	bdl	64.40	0.8420	0.3430	139.00
116	3.73	80.0	34000	bdl	1.6700	373	-	66.80	0.8010	0.3130	185.00
123	3.90	44.7	19000	bdl	0.8720	195	bdl	57.50	0.6180	0.1870	140.00
130	3.76	72.1	40000	bdl	0.0336	262	-	55.90	0.3840	0.2750	103.00
137	5.54	15.6	8500	bdl	0.0786	100	bdl	20.30	0.4860	0.0279	91.50
144	4.55	15.8	6750	bdl	0.1280	135	-	23.90	0.9100	0.0294	168.00
151	4.37	15.2	6000	bdl	0.1050	105	-	20.20	0.7380	0.0162	145.00
158	4.14	12.5	4250	bdl	0.0714	80	bdl	15.70	0.5610	0.0203	115.00
165	4.94	5.83	2250	bdl	0.0314	20	-	7.39	0.2690	0.0078	56.40
172	4.46	23.7	7500	bdl	0.0883	68	bdl	19.00	0.6280	0.0338	137.00
179	7.54	22.7	7250	bdl	0.0411	24	-	11.60	0.3490	bdl	68.90

bdl = below detection limit (As = 5 μg/l, Hg = 0.0005 mg/l, Pb = 0.0015 mg/l)

Table E-2 Characteristics of leachate from Lysimeter No.2

Days after filling (d)	pH	Conducitivity (mS/cm)	Chloride (mg/l)	As (μg/l)	Cd (mg/l)	Fe (mg/l)	Hg (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
28	9.05	21.1	5500	bdl	0.0014	bdl	-	0.50	0.2750	0.1390	0.28
39	6.98	18.3	-	9.48	0.0084	11	0.0060	18.00	0.1850	0.0345	2.10
46	6.20	15.3	8100	bdl	0.0368	54	-	27.90	0.2730	0.0832	7.87
53	6.07	6.4	2850	bdl	0.0274	38	0.0056	22.30	0.2380	0.0047	11.80
60	5.61	5.6	2250	bdl	0.0356	76	-	23.10	0.2300	0.0812	16.10
67	5.13	9.4	3750	bdl	0.1320	188	0.0084	40.10	0.3950	0.0332	49.60
74	5.36	13.7	6250	11.60	0.1920	170	-	43.60	0.2730	0.0181	55.20
81	5.14	12.1	5000	bdl	0.0981	152	0.0061	31.90	0.2550	0.0293	21.10
88	5.39	11.2	5000	bdl	0.0465	104	-	26.70	0.2160	0.0188	10.50
95	5.23	11.5	7240	bdl	0.0506	147	bdl	30.50	0.2040	0.0248	11.00
102	5.01	8.3	4000	bdl	0.0395	136	-	27.10	0.1270	0.0213	9.90
109	5.07	8.5	6000	bdl	0.0822	140	bdl	24.10	0.0681	0.0195	7.31
116	5.33	11.8	5750	bdl	0.1130	157	-	31.10	0.1070	0.0125	9.54
123	5.37	8.3	4500	bdl	0.0489	113	bdl	18.80	0.0561	0.0135	2.90
130	5.11	9.8	6000	bdl	0.0720	134	-	24.40	0.0878	0.0187	4.27
137	5.40	7.3	2500	bdl	0.0639	138	bdl	23.70	0.1010	0.0150	14.90
144	5.33	7.2	4250	bdl	0.0556	135	-	23.90	0.0636	0.0071	4.67
151	5.16	9.7	6000	bdl	0.1190	161	-	26.80	0.1320	0.0243	15.50
158	5.39	10.8	4750	bdl	0.0425	102	bdl	24.60	0.0477	0.0171	17.80
165	5.71	12.2	4250	bdl	0.0226	60	-	14.40	0.0356	0.0150	3.29
172	6.98	14.9	7000	bdl	0.0097	27	bdl	10.30	0.0534	0.0064	2.38
179	6.48	10.3	4250	bdl	0.0152	33	-	14.30	0.0132	0.0019	1.91

bdl = below detection limit (As = 5 μg/l, Hg = 0.0005 mg/l, Pb = 0.0015 mg/l)

Table E-3 Characteristics of leachate from Lysimeter No.3

Days after filling (d)	pH	Conducitivity (mS/cm)	Chloride (mg/l)	TA (mg/l)	VFA (mg/l)	COD (mg/l)	TOC (mg/l)	DOC (mg/l)	As (µg/l)	Cd (mg/l)	Fe (mg/l)	Hg (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
5	3.91	22.7	5870	-	8600	81400	25300	25100	bdl	0.0136	9	0.0574	3.89	0.1480	0.0255	13.90
8	4.14	23.1	6120	1860	13300	80600	27400	23800	8.53	0.0117	13	0.0854	4.89	0.1670	0.0509	19.00
12	4.07	23.9	5620	1960	14100	82100	35800	26100	bdl	0.0124	16	0.0268	5.35	0.1630	0.0136	17.20
16	4.07	24.3	6250	1500	12900	92500	31400	24700	10.20	0.0127	15	0.0403	5.96	0.1440	0.0068	16.30
20	4.33	24.8	7750	3680	10300	92900	29100	26600	8.30	0.0124	15	0.0077	7.42	0.1670	0.0095	18.00
24	4.88	25.9	6000	8440	18800	94300	28200	25400	5.76	0.0083	25	0.0222	7.72	0.1680	0.0319	14.90
28	5.69	29.2	6250	14300	21600	88600	-	-	bdl	0.0015	4	0.0449	7.92	0.2230	0.0355	6.92
32	5.53	29.5	6250	17000	25400	86800	-	-	bdl	0.0019	15	-	4.86	0.1430	0.0016	0.99
39	5.73	26.8	6000	16600	26100	85700	22200	21100	bdl	0.0018	14	0.0087	5.12	0.1480	0.0080	0.63
46	5.94	30.5	7650	17700	27500	102000	26200	24200	bdl	0.0018	21	-	4.36	0.1340	bdl	0.73
53	5.93	29.5	6200	15200	24800	114000	24300	21100	bdl	0.0016	20	bdl	4.19	0.1250	0.0083	0.61
60	5.91	27.5	5750	14700	21100	121000	26600	21000	bdl	0.0012	20	-	4.40	0.1280	0.0048	0.61
67	5.82	27.1	5000	13500	18100	84500	18900	18100	bdl	0.0012	19	0.0312	4.68	0.1150	bdl	0.55
74	5.24	29.4	7000	14800	18500	111000	23200	20800	bdl	0.0021	25	-	5.36	0.1100	0.0052	0.65
81	5.44	26.5	4750	13400	17700	79400	31000	19700	bdl	0.0021	28	0.0335	5.07	0.1000	0.0102	0.82
88	5.39	27.3	7000	13000	15200	69100	25300	20900	bdl	0.0030	42	-	6.67	0.0889	bdl	1.53
95	4.80	23.3	6500	10200	15300	89600	22900	18200	bdl	0.0038	42	bdl	7.00	0.0835	0.0086	1.46
102	4.83	23.0	5750	10800	17000	69100	19100	17300	bdl	0.0041	48	-	8.36	0.0831	0.0045	1.48
109	5.36	21.8	5750	10100	14700	71800	16000	13200	bdl	0.0216	54	bdl	7.88	0.0612	0.0083	1.31
116	4.75	20.5	4500	10400	14000	64800	15300	13300	bdl	0.0201	50	-	7.68	0.0558	0.0112	1.25
123	4.90	16.9	3500	8220	11800	47700	11400	11100	bdl	0.0144	45	bdl	7.05	0.0521	bdl	1.13
130	5.29	20.4	4750	8240	15700	65500	16500	13500	bdl	0.0318	57	-	8.71	0.0457	0.0136	1.43
137	5.26	14.3	2330	5340	11100	39700	8630	8420	bdl	0.0316	80	bdl	12.00	0.0386	bdl	2.51
144	5.13	12.1	2750	4500	7490	23200	8420	7650	bdl	0.0278	69	-	10.50	0.0315	0.0041	1.86
151	5.10	11.7	2750	3850	4570	32800	6470	5180	bdl	0.0350	74	-	10.90	0.0275	bdl	2.04
158	5.04	8.63	2000	3300	2500	21600	5410	5110	bdl	0.0195	59	bdl	8.92	0.0270	bdl	1.53
165	5.24	8.21	1500	3400	4960	21000	4860	4540	bdl	0.0213	46	-	7.36	0.0208	0.0075	1.08
172	5.23	11.9	2000	5100	6860	21600	7440	7420	bdl	0.0284	73	bdl	11.40	0.0543	bdl	1.95
179	5.42	11.5	1750	5300	8540	30100	7260	6710	bdl	0.0244	52	-	9.07	0.0168	0.0073	1.48

Table E-4 Characteristics of leachate from Lysimeter No.4

Days after filling (d)	pH	Conducitivity (mS/cm)	Chloride (mg/l)	TA (mg/l)	VFA (mg/l)	COD (mg/l)	TOC (mg/l)	DOC (mg/l)	As (µg/l)	Cd (mg/l)	Fe (mg/l)	Hg (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
5	3.86	20.8	5500	-	9050	81400	23800	23300	bdl	0.0116	25	0.0534	3.86	0.1970	0.0327	36.60
8	3.93	21.2	5370	-	10400	73400	25400	24900	11.70	0.0097	32	0.2374	3.55	0.2160	0.0448	41.50
12	3.94	22.1	5120	-	11700	80600	32900	24100	bdl	0.0127	39	0.0266	5.30	0.2340	0.0158	48.40
16	3.93	22.3	5750	-	11700	89600	30600	25500	bdl	0.0130	33	0.0222	5.92	0.2510	0.0368	48.80
20	4.16	23.0	5500	1930	11200	90700	27600	26500	bdl	0.0125	38	0.0533	6.22	0.2900	0.0184	49.30
24	4.33	23.5	6250	3770	15000	101000	37300	27900	15.30	0.0113	48	0.0397	8.17	0.2960	0.0066	47.70
28	4.55	22.7	5500	4550	15500	93600	-	-	9.40	0.0100	63	0.0164	7.95	0.3270	0.0248	46.40
32	4.60	22.4	6000	5340	17400	94300	-	-	bdl	0.0103	61	-	7.28	0.3010	0.0128	42.20
39	4.68	23.2	6500	6910	19900	104000	33200	24500	bdl	0.0102	72	0.0156	10.20	0.3480	0.0062	47.50
46	5.29	26.8	7500	13000	23200	108000	27400	25700	bdl	0.0074	70	-	7.80	0.2740	0.0240	16.20
53	5.33	26.2	5750	12500	21000	117000	26600	22800	bdl	0.0067	62	0.0238	7.75	0.2720	0.0216	12.90
60	5.42	25.8	5750	12700	20500	111000	21800	21500	7.77	0.0050	52	-	7.79	0.2680	0.0028	11.40
67	6.09	23.6	5000	13100	13700	82700	19100	18300	bdl	0.0047	56	0.0195	8.21	0.2460	0.0134	5.24
74	5.74	28.4	5750	17600	19800	129000	24400	24300	bdl	0.0057	63	-	8.79	0.3070	0.0113	5.56
81	5.48	27.3	6000	14600	19000	88300	22900	21000	bdl	0.0064	63	0.0271	7.73	0.4930	0.0176	5.46
88	5.44	29.5	7500	14600	20900	99800	24900	23600	bdl	0.0064	76	-	8.24	0.7840	0.0188	5.89
95	5.28	26.1	6250	11700	20000	90900	23300	20600	bdl	0.0057	72	bdl	8.00	0.6760	0.0057	5.48
102	5.39	25.3	5250	12400	21300	87700	18000	19100	bdl	0.0062	75	-	8.73	0.6180	0.0144	5.70
109	5.36	24.2	5500	11600	18900	98200	18400	17700	bdl	0.0412	75	bdl	7.45	0.3430	0.0090	4.94
116	5.35	22.0	5250	11900	17100	67000	15300	14600	bdl	0.0393	74	-	7.85	0.3080	0.0035	4.96
123	5.36	19.6	4000	10200	15600	57000	15600	13400	bdl	0.0290	62	bdl	6.82	0.2520	0.0143	4.24
130	5.31	22.1	5000	8710	15600	65600	16900	14800	bdl	0.0352	70	-	7.99	0.2590	0.0105	4.91
137	5.19	15.9	1830	5500	11200	45200	9900	9570	bdl	0.0278	64	bdl	6.37	0.1400	0.0069	5.23
144	5.25	14.5	3250	5260	9960	24800	8800	8670	bdl	0.0280	62	-	6.40	0.1110	bdl	5.17
151	5.21	14.1	3000	4760	7860	41600	9750	8850	bdl	0.0257	62	-	6.68	0.1170	bdl	5.41
158	5.07	10.7	3500	4290	3260	28800	8140	6510	bdl	0.0190	53	bdl	6.19	0.0981	bdl	4.90
165	5.18	10.2	2000	4290	7430	24100	6130	5650	bdl	0.0195	44	-	5.54	0.0838	0.0056	3.93
172	5.20	12.7	2750	5290	7360	24500	7630	7430	bdl	0.0281	67	bdl	8.46	0.1220	0.0112	5.17
179	5.34	12.6	1750	5730	8640	28600	7330	7310	bdl	0.0281	60	-	8.23	0.1010	0.0124	5.15

Table E-5 Characteristics of leachate from Lysimeter No.5

Days after filling (d)	pH	Conducitivity (mS/cm)	Chloride (mg/l)	TA (mg/l)	VFA (mg/l)	COD (mg/l)	TOC (mg/l)	DOC (mg/l)	As (µg/l)	Cd (mg/l)	Fe (mg/l)	Hg (mg/l)	Mn (mg/l)	Ni (mg/l)	Pb (mg/l)	Zn (mg/l)
5	3.84	22.1	6250	-	8990	88600	25800	25100	bdl	0.0302	168	0.0634	6.18	0.6380	0.0242	41.30
8	3.93	22.8	5250	-	12900	87100	32100	23400	bdl	0.0292	177	0.1434	6.55	0.5940	0.0290	35.70
12	3.90	22.5	5500	-	12900	79900	34200	26200	13.40	0.0377	188	0.0393	10.10	0.6780	0.0219	39.20
16	3.86	22.6	5750	-	12100	86800	30400	24600	bdl	0.0466	158	0.0405	14.20	0.7560	0.0247	39.20
20	4.07	23.1	5250	991	12700	92200	28500	25500	10.90	0.0410	145	0.0457	13.40	0.6460	0.0314	33.40
24	4.19	23.8	5750	2420	14600	104000	30300	29200	bdl	0.0499	162	0.0418	13.20	0.7520	0.0222	38.40
28	4.40	23.2	6000	3360	15300	96800	-	-	bdl	0.0373	177	0.0085	10.50	0.6650	0.0216	34.00
32	4.54	23.0	6000	4930	17900	95400	-	-	9.50	0.0449	146	-	11.20	0.6830	0.0160	32.70
39	4.78	24.1	6250	7300	21800	87100	37300	25000	bdl	0.0430	104	0.0106	13.90	0.7620	0.0384	33.30
46	6.41	29.5	8750	16500	28000	112300	29200	27300	bdl	0.0510	168	-	12.20	0.8910	0.0510	18.10
53	6.62	29.5	5500	15900	22300	116200	32400	22900	bdl	0.0417	171	0.0115	11.80	0.8200	0.0462	13.90
60	6.47	28.6	5750	18000	25700	146000	24300	20900	bdl	0.0353	168	-	11.50	0.7690	0.0378	13.40
67	6.31	28.1	5500	15800	19400	117000	22000	20900	bdl	0.0337	172	0.0141	11.90	0.6700	0.0368	14.80
74	6.15	29.6	6750	16600	21800	107400	33200	23000	bdl	0.0441	170	-	14.20	0.7640	0.0476	19.70
81	5.88	27.1	8250	15600	20400	94100	29100	24900	bdl	0.0438	173	0.0347	13.70	0.7350	0.0333	15.80
88	5.81	28.3	5750	14300	20800	89600	26500	22500	bdl	0.0418	175	-	16.40	0.5780	0.0250	14.50
95	5.59	25.9	5250	12600	22500	92800	27100	20200	bdl	0.0377	174	bdl	16.90	0.5320	0.0397	13.90
102	5.69	25.3	6050	13200	21300	82600	21900	20200	bdl	0.0346	173	-	17.00	0.5090	0.0377	13.80
109	5.69	23.2	6000	12700	18000	71800	17400	14900	bdl	0.1693	158	0.0006	14.50	0.2750	0.0339	11.30
116	5.72	22.6	4750	12300	18000	79900	15700	13600	bdl	0.1531	147	-	14.70	0.2570	0.0258	10.90
123	5.66	19.9	3500	11000	16900	64100	19600	13700	bdl	0.1329	143	bdl	13.80	0.2320	0.0311	10.10
130	5.42	22.2	4750	9620	19800	73200	16300	15200	bdl	0.1655	145	-	15.70	0.2520	0.0525	11.30
137	5.02	13.5	3330	4600	10600	41800	9850	9760	bdl	0.1033	135	0.0012	15.70	0.1700	0.0070	10.10
144	5.32	13.5	3000	5250	11200	27200	8840	8740	bdl	0.1026	143	-	16.20	0.1830	0.0221	10.70
151	5.21	13.4	2250	4650	7410	38400	9630	9030	bdl	0.0980	137	-	16.10	0.1730	0.0488	10.90
158	5.12	11.1	2250	4570	4190	32000	7230	7160	bdl	0.0757	128	0.0009	14.50	0.1490	0.0100	9.35
165	5.24	11.0	1750	4870	9200	29600	6800	6740	bdl	0.0630	112	-	13.20	0.1120	bdl	8.29
172	5.26	12.5	2000	5990	7430	29500	8790	8370	bdl	0.0848	122	0.0012	16.50	0.1680	0.0216	10.20
179	5.38	12.8	1750	6080	10300	36800	8860	8340	bdl	0.0969	130	-	17.50	0.1720	0.0337	12.10

Table E-6 Detection limit of the Instrument

Heavy Metal	Wavelenght (nm.)	Detection limit	Intrument
As	183.9	5 µg/l	AA: Hidride Generation
Cd	214.4	0.0002 mg/l	Inductively Couple Plasma
Fe	238.2	0.0003 mg/l	Inductively Couple Plasma
Hg	253.7	0.002 mg/l	AA: Cold Vapor Technique
Mn	257.6	0.0001 mg/l	Inductively Couple Plasma
Ni	231.6	0.0007 mg/l	Inductively Couple Plasma
Pb	220.3	0.0015 mg/l	Inductively Couple Plasma
Zn	334.5	0.0002 mg/l	Inductively Couple Plasma

AA : model GBC Avanta HG3000
ICP : model Varian Vista-MPX CCD simultaneous

Table E-7 Quality control for leaching test

Method blank	**Heavy Metal Concentration (mg/l)**						
	Cd	**As***	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
Extraction #1	0.0020	1.470	0.07	0.020	0.0080	0.0010	0.52
Extraction #2	0.0017	0.970	0.02	0.060	0.0070	0.0126	0.19

* µg/l

Table E-8 Quality control for lysimeter test

Method	**Heavy Metal Concentration (mg/l)**							
	Cd	**As***	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**	**Hg**
Method & reagent blank	0.0002	8.280	5.51	0.008	0.0016	0.0024	0.05	0.0226

* µg/l

BIOGRAPHY

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