Recycling and disposal of electronic waste

Health hazards and environmental impacts

REPORT 6417 • MARCH 2011

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SWEDISH ENVIRONMENTAL
PROTECTION AGENCY

Orders
Phone: + 46 (0)8-505 933 40
Fax: + 46 (0)8-505 933 99
E-mail: natur@cm.se
Address: CM Gruppen AB, Box 110 93, SE-161 11 Bromma, Sweden
Internet: www.naturvardsverket.se/publikationer

The Swedish Environmental Protection Agency
Phone: +46 (0)8-698 10 00 Fax: +46 (0)8-20 29 25
E-mail: registrator@naturvardsverket.se
Address: Naturvårdsverket, SE-106 48 Stockholm, Sweden
Internet: www.naturvardsverket.se

ISBN 978-91-620-6417-4
ISSN 0282-7298

Print: CM Gruppen AB, Bromma 2011
Cover photos: Top left: Modern recycling facility in Norway (© Stena Metall), Bottom left:
E-waste burning in Ghana (© DanWatch), To the right: Unsorted e-waste piled up on a road in Guiyu,
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Preface

Waste of electrical and electronic equipment is generated in enormous amounts around the globe today, and has become a global environmental issue. This is because the e-waste contains a multitude of hazardous substances that may be released as the waste is handled and processed. However, the risks for humans and the environment vary depending on how the e-waste is processed. Sometimes it is treated as general municipal solid waste, and is thus incinerated in incineration facilities or just put on landfills. Often, however, e-waste is recycled with the aim to take care of its hazardous components and/or to recover its valuable materials. In modern recycling facilities these two aims are usually combined, but during the recycling activities that are carried out by poor people in many developing countries, the efforts are usually directed towards the valuable materials. Consequently, such activities may result in huge emissions of hazardous compounds and thereby substantial risks for the recycling workers and the environment. This report, which was compiled for the Swedish Environmental Protection Agency (Naturvårdsverket), summarizes and compares the risks that may arise during different end-of-life treatment processes for electronic waste. These include traditional waste handling (landfilling and incineration), recycling in facilities designed for its purpose, as well as the rudimentary recycling activities occurring in many developing countries.

Although the information in this report has been funded wholly or in part by the Swedish Environmental Protection Agency, it may not necessarily reflect the views of the Agency and no official endorsement should be inferred.

Author: Staffan Lundstedt, Department of Chemistry, Umeå University.

Swedish Environmental Protection Agency, March 2011

Anders Johnson
Head of a Environmental Assessment Department

1 List of abbreviations

ABD	Acute beryllium disease
ADD	Average daily dose
As	Arsenic
ATSDR	Agency for Toxic Substances and Disease Registry (USA)
Ba	Barium
BAN	Basel Action Network (USA / global)
BBP	Butylbenzyl phthalate
BDE	Brominated diphenyl ether (mono-deca or polybrominated)
Be	Beryllium
BFR	Brominated flame retardants
BLL	Blood lead level
CBD	Chronic beryllium disease
Cd	Cadmium
CF4	Carbontetrafluoride
CFC	Chlorofluorocarbon
Cl-PAHs	Chlorinated polycyclic aromatic hydrocarbons
CNS	Central nervous system
COF2	Carbonyl fluoride
CP	Chlorinated paraffins
Cr	Chromium
Cr[VI]	Hexavalent chromium
CRT	Cathode ray tube
Cu	Copper
DBP	Dibutyl phthalate
DBT	Dibutyltin
Defra	Department for environment, food and rural affairs (United Kingdom)
DEHP	di(2-ethylhexyl)phthalate
DEP	Diethyl phthalate
DFA	Difluoroacetic acid
DHHS	Department of Health and Human Services (USA)
DINP	Diisononyl phthalate
dl-PCB	Dioxin like PCBs (for which TEFs are present)
DMP	Dimethyl phthalate
DNA	Deoxyribonucleic acid
DnOP	Di-n-octyl phthalate
EEE	Electrical and electronic equipment
EC	European commission (Europe)
Empa	Swiss federal laboratories for materials testing and research (Switzerland)
EPA	Environmental protection agency (various countries, e.g. USA, Sweden)

EPR	Extended producer responsibility
EPS Canada	Electronic product stewardship Canada (Canda)
ERP	European recycling platform (Europe)
ETBC	The electronic TakeBack coalition (USA)
ETC/SCP	European topic centre on sustainable consumption and production (Europe)
EU	European Union (Europe)
E-waste	Electronic waste
EWG	Environmental Working Group (USA)
GaAs	Gallium arsenide
HBCD	Hexabromocyclododecane
HCB	Hexachlorobenzene
HCFC	Hydrochlorofluorocarbon
HF	Hydrofluoric acid
HFC	Hydrofluorocarbon
Hg	Mercury
HPF	Hexafluoropropene
IARC	International Agency for Research on Cancer (WHO / global)
ICER	Industry Council for Electronic Equipment Recycling (United Kingdom)
IDLH	Immediately dangerous to life and health concentration
IGES	Institute for Global Environmental Strategies (Japan/Asia)
I-PCB	Indicator PCBs (seven of the most abundant PCBs in the environment)
IPCS	International Programme on chemical safety (UNEP / global)
I-TEF	Toxic equivalency factors according to NATO/CCMS 1988.
I-TEQ	Toxic equvalents according to I-TEFs
LCCP	Long chain chlorinated paraffins
LCD	Liquid crystal display
LED	Light emitting diode
LPCL	Low POP Content Limit
m3	kubic meter (1000 litres)
MBT	Monobutyltin
MCCP	Medium chain chlorinated paraffins
MEHP	Mono(2-ethylhexyl) phthalate
MFA	Monofluoroacetic acid
mg	milligram
MMIC	Microwave frequency integrated circuit
MSW	Municipal solid waste
NEPSI	National Electronics Product Stewardship Initiative (USA)
ng	nanogram
Ni	Nickel
Ni-Cd	Nickel-Cadmium
NiMeH	Nickel metal hydride
NIOSH	National Institute for Occupational Safety and Health (USA)

NMHSPE	The Netherlands Ministry of Housing, Spatial Planning and the Environment (The Netherlands)
NP	Nonylphenol
NPE	Nonylphenol ethoxylate
NSC	National Safety Council (USA)
OECD	Organization for Economic Co-operation and Development (global)
OFCB	Octafluorocyclobutane
OSHA	Occupational Safety and Health Administration (USA)
OSPAR	Oslo/Paris Convention (western Europe and EU)
PAH	Polycyclic aromatic hydrocarbon
Pb	Lead
PBB	Polybrominated biphenyl
PBDD	Polybrominated dibenzo-p-dioxin
PBDF	Polybrominated dibenzofuran
PBDD/Fs	Polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans
PCDD	Polychlorinated dibenzo-p-dioxin
PCDF	Polychlorinated dibenzofuran
PCDD/Fs	Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans
PBCDD/Fs	Polybrominated/chlorinated dibenzo-p-dioxins and furans
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyl
PC-board	Printed circuit board
PCN	Polychlorinated naphthalene
PFB	Perfluorobutane
PFIB	Perfluoroisobutane
PFOA	Perfluorooctanoic acid
pg	pikogram (1pg = 0.001 ng)
ppm	parts per million (e.g. microgram/gram)
POP	Persistent organic pollutants
POPRC	Persistent Organic Pollutants Review Committee (UNEP)
PTFE	Polytetrafluoroethylene, a polymer commonly known as Teflon
PVC	Polyvinyl chloride
SCCP	Short chain chlorinated paraffins
Seco	Swiss state secretariat for economic affairs (Switzerland)
SENS	Swiss foundation for waste management (Switzerland)
Sb	Antimony
Se	Selenium
Sn	Tin
StEP	Solving the e-waste problem (United Nation-led initiative)
SVTC	Silicon Valley toxic coalition (USA)
SWICO	Swiss association for information, communication and organization technology (Switzerland)

TBT	Tributyltin
TCLP	Toxicity characteristic leach profile
TEF	Toxic equivalency factor
TEQ	Toxic equivalent
TFA	Trifluoroacetic acid
TFE	Tetrafluoroethylene
TMT	Trimethyltin
TPP	Triphenyl phosphate
RoHS	Restriction of the use of certain hazardous substances in EEE (EU-directive)
TBBPA	Tetrabromobisphenol-A
UNEP	United Nations Environment Programme
µg	microgram
WEEE	Waste electrical and electronic equipment
WHO	World Health Organization
WHO-TEF	Toxic equivalency factors according to WHO (two sets issued, 1998 and 2006)
WHO-TEQ	Toxic equivalents according to one of the WHO-TEF sets
WRAP	Waste and Resources Action Programme (United Kingdom)
Y	Yttrium
Zn	Zinc

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2 Sammanfattning

Elektronikskrot är ett samlingsnamn för all kasserad elektrisk och elektronisk utrustning och innefattar allt från stora hushållsapparater, som kylskåp, mikrovågsugnar, TV-apparater och datorer, till bärbara digitala apparater, mobiltelefoner och leksaker. Elektronikskrot utgör idag ca 5 % av det fasta hushållsavfallet, och är också den avfallsfraktion som för närvarande växer snabbast. Uppskattningsvis genereras mellan 20-50 miljoner ton elektronikskrot runt om i världen varje år. Dessa enorma mängder i kombination med att elektroniska produkter innehåller ett flertal farliga ämnen har gjort att elektronikskrot idag anses vara ett globalt miljöproblem. När de kasserade apparaterna tas om hand, vare sig det gäller traditionella avfallsprocesser eller återvinningsprocesser, finns det en risk att de farliga ämnena frigörs och på så sätt blir tillgängliga för att orsaka skador på människor och miljö. I vissa processer kan dessutom nya giftiga ämnen bildas (t.ex. dioxiner) samtidigt som de ursprungliga komponenterna i elektronikskrotet bryts ned. För att undvika allvarliga konsekvenser på människor och miljö är det därför nödvändigt att säkerställa att elektronikskrot tas om hand på ett miljöriktigt sätt, hela vägen från insamling och lagring till återvinning och deponering.

Elektronikskrot innehåller dock även ett flertal värdefulla material, t.ex. ädelmetaller och olika plaster, som kan vara lönsamma att återvinna. Detta medför att det, förutom miljöaspekten, även finns ekonomiska anledningar att samla in och återvinna elektronikskrot. Det bästa alternativet, både i fråga om utsläpps-minimering och återvinningsoptimering, är utan tvivel att ta hand om kasserad elektronik i specialiserade återvinningsanläggningar som använder modern teknik och effektiva emissionskontrollsystem. På grund av bristande lagstiftning och insamlingssystem i många länder, är det dock bara en liten del av världens elektronikskrot som tas om hand på detta sätt. En stor del exporteras istället (oftast olagligt) till u-länder som Kina, Indien, Nigeria och Ghana, där skrotet tas isär av fattiga människor, med hjälp av mycket enkla metoder, i jakten på värdefulla material som går att sälja vidare. En annan stor andel av världens elektronikskrot följer samma väg som det vanliga fasta hushållsavfallet, vilket betyder att det förbränns i förbränningsanläggningar eller deponeras på soptippar. Faktum är att bara ca 10 % av allt elektronikskrot behandlas i riktiga återvinningsanläggningar. Även om samtliga nämnda processer resulterar i utsläpp som kan leda till negativ miljö- och hälsoeffekter, så är vissa processer värre än andra. I denna rapport beskrivs och jämförs de risker som kan uppkomma i olika avfalls- och återvinningsprocesser som används för omhändertagande av elektronikskrot.

Ett flertal farliga ämnen är av betydelse i sammanhanget, både organiska och oorganiska. De organiska inkluderar flera bromerade flamskyddsmedel, bromerade och klorerade dioxiner (PCDD/F och PBDD/F), bromerade och klorerade bensener och fenoler, polyklorerade bifenyler (PCB) och naftalener (PCN), polycykliska aromatiska kolväten (PAH), nonylfenol, organofosfatestrar, ftalatestrar och freoner. De oorganiska ämnena inkluderar antimon, arsenik, asbest, barium, beryllium, kadmium, krom, koppar, bly, kvicksilver, nickel, selen, tenn, yttrium zink. Vissa är av betydelse för att de är väldigt giftiga medan andra är av betydelse för att de finns närvarande i så stora mängder. Elektronikskrot innehåller även en del mer komplexa kemikalier som kan vara miljö- och hälsofarliga. Dessa är t.ex. flytande kristaller från LCD-skärmar, tonerpartiklar från skrivarkassetter samt nanopartiklar från ett flertal produkter. De elektronikdelar som innehåller mest giftiga ämnen och som därmed utgöra störst fara är kretskort, batterier, katodstrålerör (CRT-bildskärmar), plattskärmar (LCD), plaster, PCB-innehållande kondensatorer, freoninnehållande utrustning, tonerkassetter och olika kvicksilverinnehållande utrustning.

Störst risker uppkommer i samband med den okontrollerade återvinningen av elektronikskrot som utförs i fattiga länder, och är en följd av sättet återvinningen utförs på. Metoderna som används är manuell demontering och sortering; upphettning och syralakning av kretskort; fragmentering, smältning och varmpressning av plaster, öppen förbränning av plastisolerade kablar och andra komponenter; samt uppsamling av toner från tonerkassetter. Återvinningen utförs mestadels direkt på marken utomhus eller i dåligt ventilerade verkstäder. Personlig skyddsutrustning och reningssystem för att förhindra utsläpp är sällsynta. Som en konsekvens utsätts människor och miljö i omgivningen för stora mängder farliga ämnen. Människorna som arbetar med återvinningen liksom den lokala befolkningen utsätts framförallt för damm från demonterings- och fragmenteringsprocesserna, samt ångor och rök från syralakningsprocesserna och olika högtemperaturprocesser, som t.ex. öppen förbränning, upphettning, smältning och varmpressning. Miljön förorenas framförallt genom den öppna förbränningen samt genom läckage från dumpade rester från de olika återvinningsprocesserna, t.ex. rester av bildrör och kretskort, använda syror från lakprocesserna och askor från förbränningsprocesserna.

Vilka ämnen som är mest bekymmersamma vid de okontrollerade återvinningsprocesserna varierar beroende på vilka komponenter och material som återvinns och beroende på vilka metoder som används. Generellt verkar dock bly vara särskilt problematiskt bland metallerna, och dioxiner (klorerade och bromerade) och polybromerade difenyletrar (PBDE) bland de organiska ämnena. Dessa ämnen är alla mycket giftiga och kan potentiellt sett släppas ut i mycket stora mängder vid okontrollerad elektronikskrotsåtervinning. Bly och PBDE för att dessa ämnen utgör stora beståndsdelar i elektronikskrot, och dioxiner för att betingelserna för bildning av dessa ämnen många gånger är ideala under processerna som används. Till följd av detta har man i ett flertal studier kunnat mäta upp extremt höga halter av dessa ämnen (i vissa fall de högsta som någonsin mätts upp), både i mänsklig vävnad och olika miljöprover som samlats in runt platser där sådana här processer används. De höga halterna har också kunnat kopplas till olika negativa hälsoeffekter som har observerats i områdena. Vad det gäller dioxinerna så verkar det som att de bromerade och de blandade bromerade/klorerade kongenerna bidrar till den dioxinlika toxiciteten i minst lika stor utsträckning som de enbart klorerade kongenerna. Detta är viktigt att komma ihåg eftersom de flesta provtagningsprogram endast inkluderar analys av klorerade dioxiner. Publicerade data tyder också på att utsläppen från den okontrollerade återvinningsindustrin ger betydande bidrag till den regionala liksom den globala föroreningen av miljön, åtminstone för vissa ämnen.

Risker uppkommer även när elektronikskrot hanteras som vanligt fast avfall. Förbränning kan således leda till att en mängd farliga ämnen släpps ut till atmosfären via rök och avgaser, både i gasform och bundna till partiklar. Dels kan flertalet av alla de giftiga ämnena som finns närvarande i det ursprungliga elektronikskrotet släppas ut under förbränningen, men förmodligen ännu viktigare är de ämnen som kan bildas under processens gång, t.ex. PCDD/F och PBDD/F. Detta på grund av att elektronikskrot, som ett komplext bränsle, kan fungera som prekursorer (byggstenar) i bildningsprocessen för många olika ämnen under förbränningen. Faktum är att bildningsförhållandena för dioxiner många gånger är ideala vid förbränning av elektronikskrot, vilket beror på närvaron av PVC-plast och bromerade flamskyddsmedel som dioxin-prekursorer, och koppar och antimon som mycket effektiva katalysatorer i omvandlingsprocesserna. I moderna förbränningsanläggningar kan emissionerna av dessa ämnen oftast minimeras genom processoptimering och effektiv rökgasrening, men vid öppen förbränning, som den som används vid okontrollerad elektronikskrotsåtervinning, kan utsläppen vara betydande. Förutom dioxiner släpps även ett flertal andra miljöfarliga ämnen ut från förbränningsprocesser, t.ex. PAH, olika klorerade och bromerade ämnen samt ett flertal metaller (bly, koppar, antimon, zink, tenn, arsenik, nickel, krom, kadmium, barium och beryllium). Vidare resulterar förbränningsprocesser i askor som potentiellt kan läcka gifter till mark och vattendrag i omgivningen. Detta har dock än så länge undersökts i relativt liten utsträckning.

När elektronikskrot deponeras på soptippar kan farliga ämnen spridas till miljön genom läckage till yt- och grundvatten i omgivning, samt genom avdunstning till atmosfären. Läckage kan förväntas ske för de flesta ämnen i materialet eftersom deponering berör så långa tidsperioder, men särskilt problematiskt är läckaget av bly, ett antal andra metaller samt PBDE och ftalatbaserade mjukgörare. Avdunstning sker naturligtvis mest för flyktiga ämnen, och här är det kvicksilver och dess metylerade derivat som är mest problematiska. Hur stort läckaget och avdunstningen är beror på de aktuella föroreningarnas egenskaper, men också på deponins utformning (dvs. om den är öppen eller sluten), det deponerade materialets egenskaper (typ av skrot, om det har förbehandlats på något sätt etc.) samt på ett antal miljöfaktorer (t.ex. omgivningstemperatur samt pH och mängd humus i infiltrerande vatten).

Återvinning som sker under kontrollerade förhållanden i särskilda återvinningsanläggningar är avsevärt bättre ur ett riskperspektiv, för både återvinningsarbetarna, lokalbefolkningen och miljön. Risker uppkommer dock även vid dessa aktiviteter. För arbetarna utgörs de största riskerna av dammet som uppkommer vid demontering, fragmentering och sortering samt vid de efterkommande pyrometallurgiska processerna. Vidare så kan arbetarna exponeras för flyktiga ämnen, t.ex. kvicksilver, som en följd av att komponenter som innehåller dessa ämnen går sönder. För miljön och människor i allmänhet, uppkommer dock de största riskerna vid de pyrometallurgiska processerna samt vid andra högtemperaturprocesser, som t.ex. de som används vid plaståtervinning och förbränning av restprodukter (rättfärdigat som energiåtervinning inom återvinningsindustrin). Vid dessa processer kan stora mängder PCDD/F och PBDD/F liksom andra klorerade och bromerade ämnen släppas ut. Och när det gäller de pyrometallurgiska processerna, även stora mängder metaller, liknande de som släpps ut från okontrollerade återvinningsprocesser. Även om utsläppen är möjliga att minimera, genom processoptimering i kombination med dammuppsamling och effektiv rökgasrening, tyder existerande utsläppsdata på att detta sällan nyttjas i tillräcklig utsträckning, då man har hittat betydligt förhöjda halter av flera ämnen i sådana här anläggningars närhet.

Sammanfattningsvis kan man säga att det idag inte finns någon helt säker metod för att ta hand om elektronikskrot. Återvinning under kontrollerade former är mycket bättre än okontrollerad återvinning, men miljö- och hälsorisker uppstår i alla processer. Detta är helt enkelt en följd av att elektronikskrot innehåller så stora mängder giftiga ämnen. För att minska riskerna ytterliggare krävs att mängden giftiga ämnen i de ursprungliga elektronikprodukterna minskas ytterligare. Samtidigt krävs också att mängderna elektronikskrot i stort minskas, för att vi ska komma till rätta med problematiken på ett mer långsiktigt sätt. Detta kan vi uppnå, förutom genom en allmänt minskad konsumtion, genom utvecklandet av produkter med längre livslängd, som är enklare och säkrare att reparera, uppdatera och återvinna. För att uppnå en hållbar elektronikskrotshantering, måste vi först och främst sträva efter att minska elektronikskrotsmängderna som genereras, och sedan återvinna och ta hand om det som ändå genereras på bästa möjliga sätt för att minimera den negativa inverkan på människor och miljö.

3 Summary

E-waste is a generic term comprising all electrical and electronic equipment (EEE) that have been disposed of by their original users, and includes everything from large household appliances, such as refrigerators, microwave ovens, television sets, and computers, to hand-held digital apparatuses, cell phones and toys. E-waste is today the fastest growing sector of the municipal solid waste stream and currently comprises more than 5% of its total flow, which is equivalent to 20-50 million tones a year worldwide. These enormous quantities in combination with the fact that e-waste contains a wide range of hazardous compounds have turned e-waste into a global environmental issue. When the e-waste is taken care of, either in general waste processes or in recycling processes, these hazardous compounds may be released and thereby become a threat to humans and the environment. In addition, in some processes used, new hazardous compounds, such as dioxins, may be formed as the original e-waste components are degraded. Consequently, to avoid serious impacts on human health and the environment it is crucial to ensure that e-waste is properly taken care of, all the way from collection and handling through recycling and disposal.

However, e-waste also contains several valuable components, such as precious metals and various plastics that may be profitable to extract during the end-of-life treatment processes. This adds an economical incentive to process e-waste adequately. The best option, both from an environmental and a recovery efficiency point of view, is unquestionably to recycle the e-waste in modern recycling facilities using state-of–the–art technologies with efficient emission control systems. However, due to insufficient legislation and recycling collection systems in many countries, this option is seldom practiced, when seen on a global scale. Instead a large part of the e-waste generated in the world is sent, mostly illegally, to developing countries such as, China, India, Nigeria and Ghana, where the e-waste is disassembled by poor people using rudimentary methods, in the hunt for valuable materials. Another large fraction of the e-waste generated in the world is treated as general municipal solid waste, and is thus incinerated in waste incineration facilities or just put on landfills. Only a minor fraction (around 10%) is treated in recycling facilities adapted for its purpose. Even if all end-of-life treatment processes creates emissions of hazardous compounds, that may have negative impacts on human health and the environment, some processes are worse than others. This report summarizes and compares the hazards and risks that may arise in different processes.

The compounds of concern are several and include organic as well as inorganic compounds. The organic compounds include various brominated flame retardants, brominated and chlorinated dioxins (PCDD/Fs and PBDD/Fs), brominated and chlorinated benzenes and phenols, polychlorinated biphenyls (PCBs) and naphthalenes (PCNs), polycyclic aromatic hydrocarbons (PAHs), nonylphenol, organophosphorus flame retardants, phthalate esters and freons. The inorganic compounds include antimony, arsenic, asbestos, barium, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, tin, yttrium, and zinc. Some are of concern because they are very toxic and other mainly because they are very abundant in e-waste. There are also some more discrete chemicals present in e-waste that may be of concern. These are liquid crystals from liquid crystal displays (LCDs), toner dust from toner cartridges and nanonparticles from various products. The components and materials that are of most concern are: printed circuit boards (PC-boards), batteries, cathode ray tubes (CRTs), LCDs, plastics, PCB-containing capacitors, equipment containing freons, toner cartridges and various mercury containing components.

Most risks arise during the uncontrolled e-waste recycling activities that occur in developing countries, and are results of the rudimentary methods used. These include manual disassembly and sorting; heating and acid leaching of printed circuit boards (PC-boards); shredding, melting and extrusion of plastics; open burning of plastic coated wires and other components; and sweeping and collection of toners from toner cartridges. These activities are mostly carried out directly on the ground in open air or in poorly ventilated workshops, and involve minimal emission control systems and personal protection for the workers. Humans and the environment in the areas where this is carried out may therefore be highly exposed to the emissions generated. The recycling workers and the local residents are particularly exposed via dust generated during dismantling and shredding processes, and fumes and smoke generated during acid digestion processes and various high temperature processes, such as open burnings and heating, melting, and extrusion processes. The environment is mainly contaminated from the open burning processes and through leakage from dumped residues of various recycling activities, e.g. stripped cathode ray tubes (CRTs) and PC-boards, spent acids from the digestion processes and residual ashes.

The compounds of most concern during these activities vary depending on the material being recycled and the methods used. However, on the whole, lead seems to be particularly problematic among the metals, and dioxins (chlorinated and brominated) and polybrominated diphenyl ethers (PBDEs) among the organic compounds. These compounds are all very toxic and may potentially be emitted in large amounts during rudimentary e-waste recycling activities. Lead and PBDEs because they both are highly abundant in e-waste, and dioxins because the formation conditions many times are ideal in the processes used. As a consequence, extremely high levels (in some cases the highest ever measured) of these compounds have been measured in environmental as well as human samples collected in areas where uncontrolled e-waste recycling is taking place. These have also been connected to various negative health effects observed among the people in these areas. Regarding the dioxins, it seems like the brominated and the mixed brominated/chlorinated congeners contribute to the total dioxin-like toxicity to at least the same extent as the purely chlorinated congeners, which is important to remember as most monitoring campaigns only include analyses of chlorinated dioxins. Furthermore, there are convincing evidences that the emissions from the uncontrolled e-waste recycling industry are contributing significantly to the regional as well as the global pollution for some compounds.

Risks also arise when e-waste is treated as general municipal solid waste. During incineration, a wide variety of hazardous compounds may be emitted to the atmosphere via the smoke and exhaust gases, both in gaseous form and bound to particles. The compounds emitted may be those that were present in the original waste, but probably more important are those compounds that may be formed during the incineration processes, e.g. PCDD/Fs and PBDD/Fs. This is because the e-waste, being a complex fuel, may function as precursors for many different compounds in thermal processes. In fact, the conditions for dioxin formation are many times ideal when e-waste is incinerated, which is partly due to the presence of PVC-plastics and BFRs as dioxin precursors and partly due to the presence of copper and antimony as very potent catalysts in the transformation reactions. In modern incineration facilities the emission of these and other compounds may be minimized by process optimization and flue gas treatment systems. However, during open burning of e-waste, as occurs in many developing countries, the emissions may be substantial. Besides dioxins, a number of other pollutants are emitted in large quantities, e.g. PAHs, various chlorinated and brominated compounds and several metals, including lead, copper, antimony, zinc, tin, arsenic, nickel, chromium, cadmium, barium and beryllium. In addition to the atmospheric emissions, hazardous compounds may leak from the residual ashes to the ground and to aquifers in the surroundings. However, this has so far been scarcely investigated.

During landfilling, hazardous compounds may leak to the surrounding environments, including nearby surface water and groundwater reservoirs, and also evaporate to the atmosphere. Leakage may occur for most compounds in the waste due to the long time spans involved, but of particular concern are the leakage of lead and various other metals, as well as PBDEs and phthalate plasticizers. Evaporation mainly occurs for volatile compounds, of which mercury and its methylated derivatives are of most concern. The extent of leakage and evaporation from a landfill depends on the properties of the contaminants in question, but also on the design of the landfill (i.e. if it is open or sealed), the properties of the material being stored (e.g. type of waste, if it has been pre-treated in some way etc.), and on various environmental factors (such as the ambient temperature and pH and humic content in the infiltrating water).

Recycling under controlled conditions that are carried out in facilities adapted for its purpose is much better from a risk perspective point of view, both for the recycling workers, the local residents, and for the environment. However, risks may occur during these activities as well. For the workers, the largest risk is to be exposed to dust during dismantling, shredding and separation of the e-waste as well as during the subsequent pyrometallurgical processes. In addition, workers may be exposed to volatile compounds, such as mercury, that may be accidentally released during breakage of components in which these compounds are encapsulated. For the environment and the general population, the largest risks arises during the pyrometallurgical processes and during other high temperature processes, such as those used during plastic recycling and incineration of residual waste (justified in the recycling industry as energy recovery). During these, substantial amounts of PCDD/Fs and PBDD/Fs as well as other chlorinated and brominated compounds may be emitted, and in case of the pyrometallurgical processes, a wide range of metals (similar to the once emitted from uncontrolled processes) may also be emitted. Even if these emissions should be possible to minimize by using optimized processes together with modern dust containment and flue gas treatment systems, existing emission data indicate that this is not always satisfactorily done. Significant levels of several compounds have thus been found in and around some of these facilities.

From this, it can be concluded that there is no completely safe end-of-life process available to deal with the e-waste of today. Controlled recycling is much better than uncontrolled recycling, incineration or landfilling, but hazards and risks will occur in all cases. This is simply a consequence of the multitude of hazardous compounds that are present in e-waste. To reduce the risks further, cleaner products containing less hazardous compounds have to be produced. Furthermore, to solve the e-waste problem in a wider perspective, the quantities of e-waste generated have to be reduced. Besides by decreasing the consumption, products with greater life-spans that are safer and easier to repair, upgrade and recycle have to be developed. The ultimate goal must be to ensure that the quantities of e-waste generated are minimized, and that the e-waste which does arise is recycled and disposed of in the best achievable manner to minimize impacts on human health and the environment.

4 Introduction

Electronic waste (e-waste) or waste electrical and electronic equipment (WEEE) has become an emerging global environmental issue. It is the fastest growing sector of the municipal solid waste stream and it can be considerably hazardous. UNEP estimates that 20-50 million tones of e-waste is generated around the world every year, which is more than 5% of the total municipal solid waste stream, and nearly the same amount as all the plastic packaging [UNEP 2005]. The e-waste stream is also estimated to increase by 3-5% every year, which is nearly three times faster than the municipal waste streams' general growth [Arensman 2000]. This is a result of our constant desire for newer and more efficient technology, as well as the intense marketing by the producers, that make us replace our electronic devices more and more frequently. For example, cell phones have now an average life span of less than two years in the industrial world, and computers two to four years [BAN & SVTC 2002, UNEP 2005].

When new equipment are procured, the old ones are becoming obsolete and are eventually being discarded, leading to these enormous amounts of wastes. For example, it has been estimated that, in USA alone, over 30 million computers and 100 million cell phones are being discarded every year. Only these phones will contribute with more than 10 000 tones of e-waste annually [BAN 2004, Cobbing 2008]. Within EU, every citizen leaves behind 14-24 kg of e-waste every year, which in total gives nearly 10 million tones annually [Huismann *et al.* 2007], and numbers from Japan says that by year 2010, among others, 610 million cell phones are to be disposed of in their country [Uryu *et al.* 2003]. In addition, the new industrial countries in the world are contributing to the global e-waste generation to an increasing extent. In China, for example, at least 4 million computers, 70 million cell phones, 5 million TVs, 4 million refrigerators and 6 million washing machines have been abandoned annually since 2003 [Li *et al.* 2007, Cobbing 2008].

The problem is that only around 10% of all this e-waste is collected and taken care of in adequate recycling facilities [La Dou & Lovegrove 2007, Cobbing 2008], despite the well known fact that it contains a wide variety of hazardous components, such as heavy metals and persistent organic pollutants, as well as many valuable materials, such as metals (including several precious metals) and plastics. In fact, e-waste can both be considered as hazardous waste that potentially can cause serious pollution and health damage upon disposal, and as a huge resource that can provide the industry with valuable materials using less energy and less natural resources compared to using virgin materials in the production of new products. The use of recycled materials instead of virgin materials will also, in total, cause less pollution during extraction and further processing of the materials [Cui & Forsberg 2003, Cui & Zhang 2008].

So where does all the e-waste end up? First of all, it often takes a while before it actually is considered as waste. Consumers tend to keep obsolete electrical and electronic equipment (EEE) for a while before discarding it, which may be particularly true for computers and cell phones. For example, in USA, it has been estimated that each household has, on average, 4.1 small and 2.4 large obsolete EEE in their storage spaces [Saphores *et al.* 2009], while previous estimates says that the same households have an average of two to three obsolete computers in storage [NSC 1999]. In Sweden, similar numbers have been estimated for obsolete cell phones stored in homes [SwedWatch 2009]. Furthermore, outdated EEE may be resold for re-use to consumers with lower demands or lower economical resources. Some are thus traded nationally, while some are shipped to developing countries where old EEE like computers and cell phones normally can be used a few more years. This re-use in developing countries may be a good way to lengthen the life-span of the products as well as to help the poor world to keep up with the technological development in the developed world. At the same time it constitutes a great environmental, social and economical problem. The dividing line between re-usable and charity on the one hand, and waste and dumping on the other hand is very fine. Even if the equipment is working and possibly will be used a few more years in the developing world, the exports will also transfer the waste problem to the recipient countries.

Besides this, a large fraction of the obsolete EEE in the developed world is also deliberately exported as waste to developing countries, where it is recycled under very primitive conditions. Some of this trading, though deliberate waste export, is still phrased as or hidden under the umbrella of charity (“computers for the poor”), since e-waste export is banned in most countries today. This is because the rudimentary recycling methods used in the developing countries are not very effective in terms of recovering the valuable materials, and because the activities also lead to huge emissions of hazardous compounds resulting in sever exposure of the workers as well as pollution of the surrounding environments. However, since e-waste export is a very cost-effective option, due to the lower labour costs and less stringent environmental regulations in many developing countries, it still occurs to a very large extent [BAN & SVTC 2002, Cobbing 2008, SwedWatch 2009]. In fact, of all the e-waste generated in the industrial world, between 50-80% are probably exported to countries like China, India, Nigeria and Ghana [BAN &SVTC 2002, UNEP 2005].

Within EU, it is estimated that only 25% of the e-waste generated is collected and treated, while the remaining 75% is lost in a “hidden flow” [Huisman et al 2007]. In the US, this “hidden flow” is even larger, accounting for about 80% of all the e-waste generated [US EPA 2007], and in some developing nations, like India, it may account for more than 99% of the total e-waste flow [Cobbing 2008]. The fate of this “lost” waste is not very clear, although it is known that a large part of it end up in developing countries, where it is recycled under very primitive conditions. The rest is probably stored in homes, put on landfills and incinerated in municipal solid waste incineration facilities. In addition, it is known that even some of the collected e-waste described above, through inscrutable ways, eventually finds its way to the recycling areas in the developing world, making the hidden flow even larger [BAN & SVTC 2002].

Only a small part (around 10%) of the e-waste generated in the world is thus being recycled in adequate facilities [LaDou et al 2007, Cobbing 2008]. Some of these facilities are very efficient and may recover up to 80% of the materials in the e-waste, while another 15% can be used for energy production through incineration. Only 5% of the material thus finishes as waste in these facilities [LaDou et al 2007]. It is possible that the fraction of e-waste that is recycled properly will increase in the coming years, as a result of the more stringent legislation that is established in many countries, although the reverse effect of such legislation has also been suggested [SwedWatch 2009]. The EU, Japan, South Korea, Taiwan, China and several states of the USA have introduced legislation making producers (financially) responsible for their end-of life products. This Extended Producer Responsibility (EPR) is characterized by the shifting of responsibility away from the municipalities to include the costs of treatment and disposal into the price of the product, reflecting the environmental impact of the product [OECD 2001, Widmer *et al.* 2005]. The underlying assumption is that the producers will become more interested to develop more easily recyclable products that leave less waste and pollution behind [UNEP 2005].

4.1 The WEEE and the RoHS directive by the European Commission

Within EU the e-waste problem have been addressed by the Directive on Waste electrical and electronic equipment (WEEE, EU Directive 2002/96/EC), approved in October 2002 [European Commission 2003a], which is based on the producer-pays-principle. The scope of this directive includes producers, distributors, consumers, and all parties involved in the treatment of WEEE. Producers are requested to finance the collection, treatment, recovery, and environmentally sound disposal of WEEE. The directive imposes a high recycling rate for all targeted products, varying from 50% to over 80% depending on the type of WEEE. The objective of the directive is to reduce the amount of e-waste going to landfill and to improve the overall environmental performance of EEE products during their life cycle. Accompanying the WEEE directive, the EU directive on the Restriction of certain Hazardous Substances in electrical and electronic equipment (RoHS, EU Directive 2002/95/EC) was also approved in October 2002 [European Commission 2003b]. This directive bans the presence of certain hazardous substances in EEE being traded within EU. RoHS ensures that new EEE does not contain mercury, lead, cadmium, hexavalent chromium or the brominated flame retardants PBBs and PBDEs. It aims to control the environmental impact of EEE by implementing clean production.

4.2 The Basel Convention and the Basel Ban Amendment

The e-waste problem has also been tackled on a global level. Thus, in 1989, during a diplomatic conference in Basel, Switzerland, a global agreement aiming to limit the export of hazardous waste, including e-waste, to developing countries was adopted. This “Basel Convention on the Control of the Transboundary Movement of Hazardous Waste and Their Disposal” [Basel Convention], was mainly created to prevent the economically motivated dumping of hazardous wastes from richer to poorer countries. The convention currently has 172 parties, of which three, viz. Afghanistan, Haiti and the United States, only have signed the agreement but not yet ratified it. In 1995 an amendment to the convention was adopted. This Basel Ban Amendment called for a prohibition of all export of hazardous wastes from Parties that are member states of the EU, OECD and Liechtenstein to all other Parties to the Convention. However, the Basel Ban Amendment has not yet entered into force, as it has not been ratified by the pre-determined limit of 62 Parties, which probably is one of the reasons why e-waste continues to flow in large quantities into many Asian and African countries [BAN & SVTC 2002, UNEP 2005]. However, in a meeting in 2006 the parties to the Basel Convention agreed to accelerate the efforts to solve the global e-waste problem as it was emphasized as a particularly urgent matter. This agreement was announced by the Nairobi declaration [UNEP 2006]. Furthermore, in 2002 and 2009 the parties to the Basel Convention initiated partnerships with manufacturers and various stakeholders of the mobile phone and computing industry respectively, to develop and promote the environmentally sound management of their end-of-life products [Basel Convention].

These and some other initiatives that have been taken to tackle the global e-waste problem are listed in Table 1.

Table 1. Some initiatives that have been taken to tackle the global e-waste problem [Widmer et al 2005].

Initiative	Description
The Basel Convention on the Control of Transboundary movements of Hazardous Wastes and their Disposal. -came into force in 1992-	The most comprehensive global environmental agreement regulating movements of hazardous wastes, including WEEE, between nations, and specifically to prevent transfer of hazardous waste from developed to less developed countries.
The Basel Ban Amendment -not yet into force-	An amendment to the Basel Convention that completely prohibits the export of hazardous waste from a list of developed (mostly OECD) countries to developing countries. The Basel Ban Amendment has, however, not yet come into force.
The Mobile Phone Partnership Initiative (MPPI) -launched in 2002-	A partnership initiative between the Basel Convention, 12 mobile phone manufacturers and other stakeholders, to develop and promote the environmentally sound management of end-of-life mobile phones
The Nairobi declaration -signed in 2006-	An agreement by the parties to the Basel Convention to accelerate the efforts to solve the global e-waste problems.
Partnership for Action on Computing Equipment (PACE) -approved in March 2009-	A multi-stakeholder partnership under the Basel Convention aiming to tackle the environmentally sound management of end-of-life computing equipment.
The StEP initiative (Solving the E-waste problem) -initiated in 2004-	A UN-led initiative started at the ‘Electronic Goes Green’ Conference in Berlin to build an international platform to exchange and develop knowledge on WEEE systems among countries to enhance and coordinate various efforts around the world on the reverse supply chain.
Silicon Valley Toxic Coalition (SVTC) and computer take back campaign -formed in 1982-	A diverse organization engaged in research, advocacy and grassroots organizing to promote human health and environmental justice in response to the rapid growth of the high-tech industry.
The Electronics TakeBack Coalition (ETBC) -formed in 2001-	A coalition of non- governmental organizations in the US working together to urge the electronics industry to launch take back programs for their products, according to the extended producer responsibility (EPR).
WEEE forum -founded in 2002-	Founded in 2002, the WEEE forum is a group of representatives of voluntary collective WEEE take-back systems in Europe, taking care of individual producers’ responsibility in Europe.
National Electronics Product Stewardship Initiative (NEPSI) -created in 2001-	A multi-stakeholder dialogue to develop the framework of a national WEEE management system in the USA. The NEPSI dialogue includes representatives from electronics manufacturers, retailers, state and local governments, recyclers environmental groups, and others.
Electronic Product Stewardship Canada (EPS Canada)	EPS Canada was created to work with both industry and government to develop a flexible and workable Canadian solution. An industry-led organization. Founded by 16 leading electronics manufacturers.
European Recycling Platform (ERP) -Initiated in 2002-	Set up at the end of 2002 by Hewlett Packard, Sony, Braun and Electrolux to enable the producers to comply with the WEEE directive. It aims to evaluate, plan and operate a pan-European platform for recycling and waste management services.
Seco/Empa e-waste programme (Swiss State Secretariat for Economic Affairs, Seco) (Swiss Federal Laboratories for Materials Testing and Research, Empa)	A project set up by Seco and implemented by Empa in cooperation with a number of local partners and authorities, to assess and improve WEEE recycling systems in different parts of the world by analyzing the systems and by exchanging knowledge on recycling techniques and frameworks.

5 Objectives

The objective of this report is to summarize the current knowledge concerning health hazards and environmental impacts associated with the handling and end-of-life treatment of electronic waste. This include hazards and risks that may arise during traditional waste handling, such as landfilling and incineration, as well as those arising during directed recycling activities. The latter both include recycling in modern recycling facilities as well as the more informal and primitive recycling activities that are taking place in many developing countries. Furthermore, the review both includes hazardous compounds that deliberately have been added to the products at some stage, and therefore may be released during the end-of-life treatment, and compounds that may be formed during the disposal or treatment processes.

Figure 1. Chinese workers sorting e-waste on a truck in Guiyu, China (Photo: © Natalie Behring-Chisholm, Greenpeace).

6 Electronic waste – what is it and what does it consist of?

E-waste is a generic term of all EEE that have been disposed of by their original users, and includes everything from large household appliances, such as refrigerators, microwave ovens, televisions sets, and computers, to hand-held digital apparatuses, cell phones and toys. E-waste may, however, be divided into different categories that to some extent describes what they consist of. In table 2 the categories used by the European Union in the WEEE Directive is shown together with the average compositional breakdown for the e-waste generated by the EU 27 member states in 2005 [Huismann *et al.* 2007]. It should be noted though, that the numbers would probably look a bit different today as new electronic products are developed all the time, which of course affects the composition of the waste. For example, we would probably see a larger share of flat monitors and screens in the e-waste today. Nevertheless, of the categories listed in table 2, categories 1-4 account for almost 95% of the total e-waste generated, and category 1 "Large household appliances" account for almost half the total weight, which of course is due to these appliances' heavy weight.

Table 2. E-waste categories used by the European Union, and the average compositional breakdown for the e-waste generated by the EU 27 member states in 2005.

Category	% of total e-waste	Sub-categories	% of total e-waste
1. Large household appliances Washing machines, dryers, refrigerators, air-conditioners etc.	49	1A. Large household appl. Excl. 1B and 1C	27.7
		1B. Cooling and freezing	17.7
		1C. Smaller items	3.6
2. Small household appliances Vacuum cleaners, coffee machines, irons, toasters, etc.	7.0		7.0
3. IT and telecom. equipment PCs, Laptops, cell phones, telephones, fax machines, copiers, printers, etc.	16	3A. IT and telecom. equip. excl. 3B and 3C	8.0
		3B. CRT monitors	8.3
		3C. LCD monitors	0.0
4. Consumer electronics Televisions, VCR/DVD/CD players, Hi-Fi sets, Radios, etc.	21	4A Consumers electronics excl. 4B and 4C	7.8
		4B. CRT TV’s	13.3
		4C. Flat Panel TV’s	0.0
5. Lighting equipment Fluorescent tubes, sodium lamps etc. (Except: bulbs and halogen bulbs)	2.4	5A. Luminaries	0.7
		5B. Lamps	1.7
6. Electrical and electronic tools Drills, Electric saws, sewing machines, lawn mower etc. (Except: large stationary tools/machines)	3.5		3.5
7. Toys, leisure and sports equipment Electric train sets, coin slot machines treadmills, etc.	0.1		0.1
8. Medical devices	0.1		0.1
9. Monitoring and control equipment	0.2		0.2
10. Automatic dispensers	0.2		0.2

The discarded products constituting the e-waste are made of a wide variety of components and sophisticated materials containing thousands of individual substances. Most are, by weight, bulk materials, such as iron, aluminium, plastics and glass but there may also be wood, ceramics and rubber for instance. Figure 1 shows the average composition of materials found in e-waste according to European Topic Centre on Sustainable Consumption and Production [ETC/SCP]. As seen, iron and steel dominates, constituting almost half of the weight of the e-waste, while copper, aluminium and other metals contribute with another 13%. Plastics is another large component, representing approximately 21% of the e-waste weight.

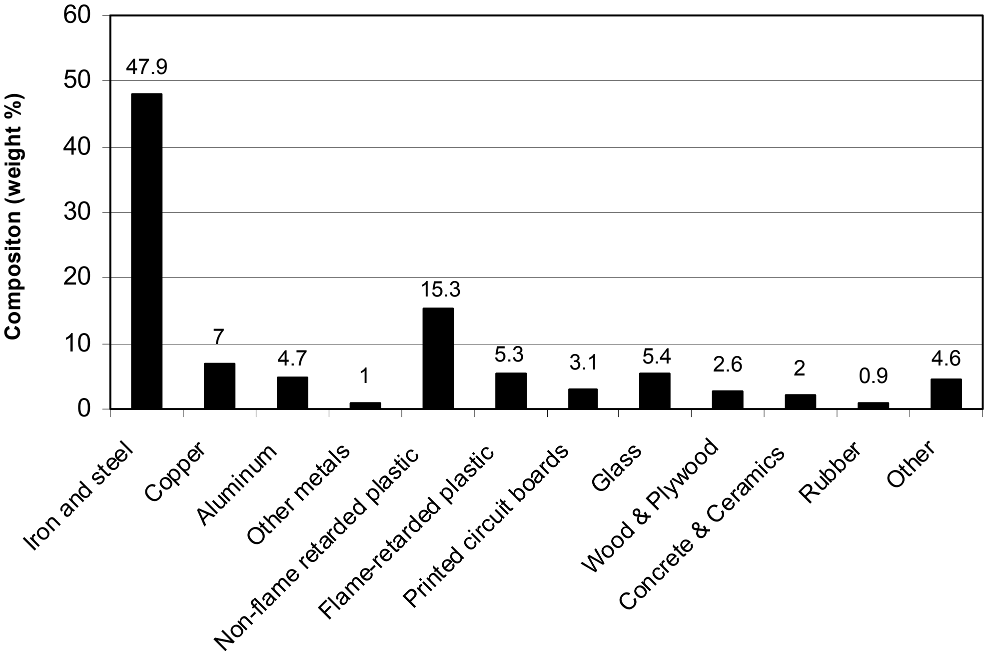


Figure 2. Average composition of materials found in e-waste according to European Topic Centre on Sustainable Consumption and Production (ETC/SCP, former ETC/RWM) [Widmer *et al.* 2005].

E-waste is also known to contain a wide variety of toxic or otherwise hazardous components that may constitute a serious risk for human health and the environment if they are released during processing, recycling or disposal [UNEP 2005]. For example, e-waste contains a wide range of heavy metals, such as lead, cadmium and mercury, and also persistent organic compounds, such as brominated flame retardants (BFRs) and phthalates. In another compositional breakdown of e-waste, compiled by the Swiss Federal Laboratories for Materials Testing and Research (Empa), it was estimated that e-waste on average contains 2.7% pollutants (Figure 2). However, it should be noted that many of these pollutants are not present as pure compounds in the e-waste, but are constituents of complex materials, e.g. flame retardants in plastics, or are hidden inside electrical components, such as mercury in switches, and are therefore difficult to isolate and separate from the other components. These facts make the recycling of e-waste very complicated and costly, although it is obvious that it is necessary from an environmental point of view. To avoid serious environmental pollution and human exposure, adequate treatment of e-waste is crucial, particularly considering the huge amounts of e-waste we are producing globally.

On the other hand, e-waste can also be considered as a resource, as it contains many valuable components that actually may be beneficial to recover. For example, it usually contains substantial amounts of copper (often 5-20% by weight), and also relatively high levels of several precious metals, such as gold (0.1%), silver (0.2%) and palladium (0.005%), which originally have been included in the EEE because of their resistant to oxidation and superior conductivity. These metals together make up the major economical incentive for recycling of e-waste, as they may constitute over 95% of its total value. However, also other metals and materials may be worth recycling from an economical point of view, e.g. lead, nickel and various plastics [He et al 2006, Cui and Zhang 2008]. Recycling of e-waste is thus important, not only from a waste management point of view, but also from the view of material and resource recycling.

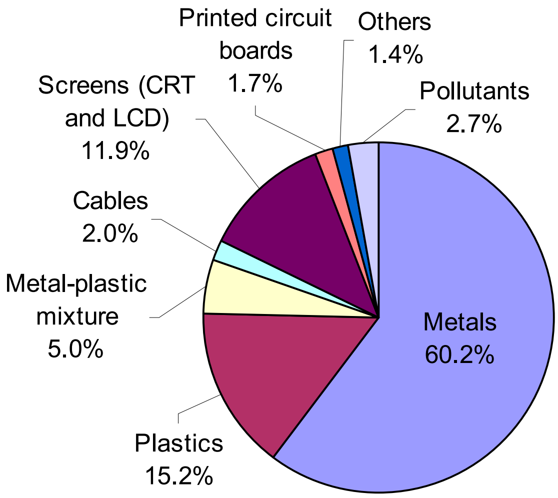


Figure 3. Average composition of materials found in e-waste according to the Swiss Federal Laboratories for Materials Testing and Research for industry (Empa), [Widmer et al 2005].

Figure 4. E-waste, such as these obsolete mobile phones, contains a variety of materials including plastics, metals, and glass (Photo: © Juraj Rizman, Greenpeace).

7 Hazardous components of e-waste

Hazardous compounds are found at various places in electronic equipment. However, there are certain components and materials that more frequently contain these substances. In Annex II of the WEEE Directive, a list of EEE components that, as a minimum, have to be removed from any separately collected e-waste are presented [European Commission 2003a]. This list is also shown in Table 3. Those components that are of particular concern and occur frequently in EEE [AEA 2004, EPS Canada 2006, IGES 2009] are further described below, and are also listed in Table 4.

Table 3. Components and materials that, as a minimum have to be removed from any separately collected e-waste according to Directive 2002/96/EC (the WEEE Directive) of the European Union [European Commission 2003a].

- Capacitors containing polychlorinated biphenyls (PCBs).
- Mercury-containing components such as switches or backlighting lamps.
- Batteries.
- PC-boards of mobile phones and of other devices if the surface area of the circuit board is greater than 10 cm^2.
- Toner cartridges.
- Plastics containing brominated flame retardants (BFRs).
- Asbestos waste and components that contain asbestos.
- Cathode ray tubes
- Freons and hydrocarbons
- Gas discharge lamps.
- LCDs, together with their casing where appropriate, of a surface area greater than 100 cm2 and all those back lighted with gas discharge lamps.
- External electrical cables.
- Components containing refractory ceramic fibers
- Components containing radioactive substances above exemption thresholds.
- Electrolyte capacitors containing substances of concern.

7.1 Printed circuit boards

A printed circuit board, or a PC-board, is the piece of hardware that acts as a base in electronic equipment, and provides electrical connections to the mounted components. PC-boards are present in almost all types of e-waste, including cell phones, computers, TVs and printers. PC-boards are made of woven glass fibre sheets hardened with a flame retarded epoxy resin. Most commonly, brominated flame retardants (BFR), such as tetrabromobisphenol-A (TBBPA) and polybrominated diphenyl ethers (PBDE), are incorporated into the resin, but chlorinated and inorganic compounds also occur. The glass in the glass fibre sheets mainly contains oxides of common base elements, such as silicon oxide, calcium oxide and aluminium oxide. The PC-board is layered with copper traces facilitating the conductivity [AEA 2004, Eswaraiah et al 2008, IGES 2009], and it is generally the most valuable parts of e-waste that are most beneficial to recycle due to their substantial contents of copper and precious metals [OECD 2003, AEA 2004].

Components such as switches, resistors and capacitors are mounted on the boards and connected to the copper circuitry by solder, which usually consists of a mixture of tin and lead (in the ratio 60/40 tin-lead) [Geibig & Socolof 2005], but sometimes also antimony or an alloy of copper and beryllium (typically containing 2% beryllium). The typical solder content in scrap PC-boards ranges between 4-6% by weight, or approximately 50g/m2 of PC-board [AEA 2004]. The components soldered to the PC-boards vary a lot and may contain many different substances. Relay and switches often contain mercury. Switches may also contain small amounts of cadmium, which also is the case for plated contacts. Light emitting diodes (LEDs) contain gallium arsenide (GaAs), and resistors, capacitors and microchips may contain various metals, although copper and aluminium is most common [IGES 2009].

7.2 Batteries

Batteries are present in all portable electronic devices, such as laptops, cell phones and portable power tools. They are produced in many shapes, sizes and types. From an environmental perspective, mercury containing batteries and rechargeable batteries containing cadmium, nickel and lead are of most concern. Mercury-containing batteries are banned in many countries due to concerns over their hazardous properties. Rechargeable batteries include nickel-cadmium (Ni-Cd), nickel metal hydride (NiMeH), lithium ion and lead acid batteries. About 80% of the rechargeable batteries world wide is Ni-Cd batteries [IGES 2009].

7.3 Other mercury containing components

Mercury has been widely used in EEE due to its unique properties including uniform volumetric thermal expansion and good electric conductivity. Therefore, mercury may be found in various components of e-waste. For example, thermostats, sensors, relays and switches in space heaters, ovens, air-handling units, levelling devices, pumps and electric ranges may all contain mercury. Also cold-cathode lamps (or gas discharge lamps) used for backlighting in liquid crystal displays (LCDs), some medical equipment and telecom-equipment may contain mercury [IGES 2009].

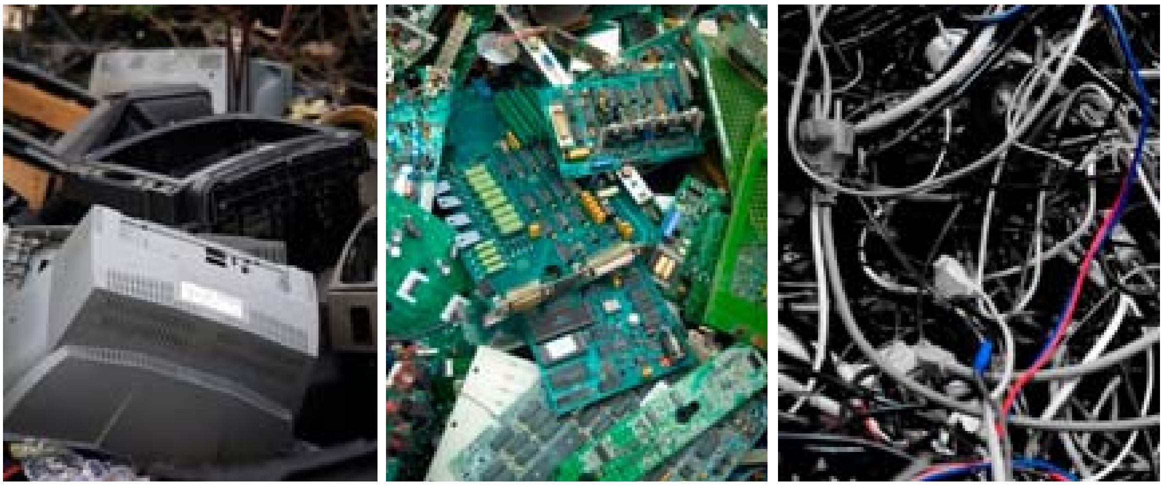


Figure 5. Common components of e-waste, including computer monitors, printed circuit boards and cables. (Photo from left to right: © Kristian Buus, Greenpeace, © Natalie Behring-Chisholm, Greenpeace, and © Lars Eklund, Swedish EPA).

7.4 Cathode ray tubes

Cathode ray tubes (CRTs) contain the greatest amount of all substances of concern in older desk top computers and TV sets [OCED 2003]. The hazardous compound that is present in largest amounts is lead, as it is used in the glass to shield people from the x-rays produced as a by-product during the electron acceleration [Menad 1999]. An older polychrome CRT can contain 2-3 kg of lead, while a new one typically contains about 1 kg of lead [OECD 2003]. The cone glass (or funnel glass) thus contains about 20-24% lead oxide (PbO), the neck glass about 28-30% PbO, and the glass frit about 80% PbO, whereas the screen glass (or panel glass) normally contains no lead. The lead is encapsulated in glass and, thus, immobilized unless and until the glass is broken. However, the glass most be broken in relatively small pieces before significant levels of lead would be available for release into the environment. The inside of the CRT panel is coated with a fluorescent phosphor layer, containing various metals, which presents an inhalation hazard if managed in dry state. Some older CRT screens may be coated with cadmium sulphide [Menad 1999]. In addition, the screen and/or cone glass may contain antimony. The electron gun of the CRT contains a small getter plate, weighing approximately 1-2 g including its frame, that contains barium and barium compounds [OECD, 2003].

7.5 Liquid crystal displays

Liquid crystal displays (LCDs) are found in all kind of electronic equipment containing a flat display, e.g. cellular phones and notebook PCs. As the name reveals LCDs contain liquid crystals that are embedded between display glass and electrical control elements. The liquid crystals are suspected to be hazardous even though studies on their toxicity are scarce [AEA 2004]. It should also be pointed out that LCDs are often back lighted with cold-cathode fluorescent lamps that contain mercury (see above) [BAN & SVTC 2002].

7.6 Plastics and polymers

Plastics, constituting more than 20% of e-waste [Schlummer *et al.* 2007], can be of concern in themselves or contain substances of concern as additives. Polyvinyl chloride (PVC) is one of the most widely used polymers, which also is common in EEE and thereby in e-waste. Among others, it is commonly used as coatings on wires and cables [OECD 2003]. The reasons for concern are both the fact that the PVC-polymer contain chlorine (up to 56% by weight) and that most PVCs are loaded with additives. Although the polymer in itself is not hazardous, as the chlorine is bound to the polymer, it may function as a source for chlorinated dioxins (see below), and also irritating hydrochloric acid as the plastic is incinerated. The additives may be of great variety, but most concerns have been raised regarding the use of metals, particularly cadmium, lead and organotin, as stabilizers, phthalates as plasticizers and brominated compounds (e.g. PBDE and TBBPA) as flame retardants [IGES 2009]. These additives may be present in other types of plastics as well, which therefore also are of concern. Another polymer that needs special attention is polytetrafluoroethylene (PTFE) or Teflon (DuPont's brand name). Although, Teflon generally is present in much lower amounts than other polymers in EEE, it is of concern because it can give rise to a wide range of toxic and persistent compounds during thermal degradation processes [EWG 2003]. This is, however, further discussed in section 7.2.13 below.

7.7 PCB containing capacitors

A capacitor is a passive electronic component that is widely used in electronic circuits for purposes such as blocking the flow of direct current while allowing alternating current to pass, to filter our interferences, and to smooth the output of power supplies. It consists of a pair of conductors separated by an isolating "dialectric", which in some older capacitors consisted of PCB-oil (polychlorinated biphenyls). Because PCBs have adverse effects on humans and the environment (see below), these capacitors are of environmental concern, and they have also been banned in a large part of the world since the 70s. However, PCB-containing capacitors are still present to some extent, although rarely, and they are difficult to distinguish from other capacitors, even for qualified personnel [SENS & SWICO 2008].

7.8 Equipment containing freons

Refrigerating circuits in refrigerators, freezers and air-conditioners may contain freons, i.e. chlorofluorocarbons, hydrochlorofluorocarbons and fluorocarbons, which after emissions to the atmosphere have deleterious effects on the ozone layer [Solomon 1999].

7.9 Toner cartridges

Toner cartridges are found in all laser printers, photocopying machines, faxes etc. Toner cartridges contain toner, which is an extremely fine powder, consisting mainly of carbon particles and polymers. Toners may also contain up to 7% carbon black, which is a material produced by the incomplete combustion of heavy petroleum products [IARC 1996].

Table 4. Components and materials that frequently occur in electrical and electronic equipment and that contain hazardous compounds.

Components	Applications	Compounds of concern
Printed circuit boards (PC-boards)	Ubiquitous, from beepers to PCs.	Pb, Sb in solder Cd, Be in contacts and switches Hg in switches and relays GaAs in LEDs BFR in plastics
Batteries	In various portable electronic devices.	Ni and Cd in Ni-Cd batteries Pb in lead acid batteries Hg in Hg batteries
Various Hg containing components	Thermostats, sensors, relays, switches, gas discharge lamps, medical equipment and telecom equipment.	Hg
Cathode ray tubes (CRTs)	Old TV sets, PC monitors, oscilloscopes.	Pb and Sb in CRT glass Various metals (e.g. Cd) in the glass phosphor Ba in electron gun getter
Liquid crystal displays (LCDs)	Most devices with a screen, e.g. cell phones, laptops etc.	Liquid crystals in the screen
Plastics and polymers	Wire insulation, plastic housing, circuit boards etc.	PVC and Teflon as polymers BFRs, Cd, Pb, org-Sn and phthalates as additives
PCB-containing capacitors	In various electronic circuits	PCB
Refrigerating circuits	Refrigerators, freezers, air-conditioners.	Freons
Toner cartridges	Laser printers, copying machines, faxes.	Toner, including carbon black

8 Hazardous compounds in e-waste

The majority of the hazardous compounds that are associated with EEE and e-waste are found in the components listed above. However, there are other e-waste components that may contain hazardous compounds, and there may also be other hazardous compounds present than those found in the components listed above. Below follows an extensive list of hazardous compounds that, in one way or another, can be associated with EEE and e-waste. Included are compounds that may be present in EEE as well as those that may be formed as e-waste is handled, deposited or recycled. The compounds are also listed in Table 5.

8.1 Metals and inorganic compounds

8.1.1 Antimony (Sb)

Antimony and its compounds have a number of uses in EEE. For example, antimony compounds are used in semiconductor manufacture (antimony trihydride), and in flame retardant formulations in plastics (antimony trioxide). In the latter case it is normally combined with brominated flame retardants, especially PBDE [Lau *et al.* 2003], though there are also reports of use in combination with phosphorus based flame retardants. Antimony is also used in the manufacture of lead acid starter batteries [Kentner et al 1995] and can occur as a component of electrical solders as well as in CRT glass.

Antimony shows many chemical similarities to arsenic [Andrews *et al.* 2004]. Like arsenic, it can undergo methylation as a result of microbiological activity (i.e. to form its trimethylated derivative, often called trimethylstibine), albeit at slower rates than for arsenic [Jenkins *et al.* 2000, Patterson *et al.* 2003]. It also shows some similarities in its toxic effects, especially to skin cells [Patterson *et al.* 2003]. However, unlike arsenic, there are relatively few studies concerning the toxicity and ecotoxicity of antimony and its compounds. Those studies which are available indicate that the toxicity of antimony depends greatly on its particular form (i.e. its oxidation state). Trivalent antimony, such as is present in antimony trihydride and antimony trioxide, is the most toxic state whereas its pentavalent form is far less toxic [Flynn et al 2003, Patterson et al 2003]. Some organic antimony compounds (including trimethylstibine) are very toxic [Andrews et al 2004]. Antimony compounds have been associated with dermatitis (skin problems) and irritation of respiratory tract, as well as interfering with normal function of the immune system [Kim et al 1999]. Antimony trioxide and antimony trisulphide have been listed by the International Agency for Research on Cancer as “possibly carcinogenic to humans”, with inhalation of dusts and vapours being the critical route of exposure [IARC 1989].

8.1.2 Arsenic (As)

Arsenic is a naturally occurring element that is widely distributed in the earth's crust. It is frequently referred to as a metal but it is chemically classified as a metalloid or a semi-metal. Arsenic has predominantly been used in wood preservatives and pesticides, but also for some other applications. In EEE and e-waste, arsenic is mainly found in the form of gallium arsenide, which is an important semi conductor used to make devices such as microwave frequency integrated circuits (MMICs), infrared light emitting diodes (LEDs), laser diodes and solar cells [Flora 2000, Uryu *et al.* 2003].

Arsenic may occur in many different forms, e.g. elemental arsenic, arsenide (As3-) arsenate (HAsO42-), and arsenate (H3AsO3). Several of these are classified as toxic and dangerous for the environment and are also confirmed carcinogens [IARC 1973, ATSDR 2007a]. Acute exposure to arsenic will cause disturbance of the metabolism and energy productions in cells, which may lead to death via multi-system organ failure. Chronic exposure to arsenic can lead to various diseases of the skin and decrease nerve conduction velocity. It may also cause tumour formation in the lungs, urinary bladder, kidneys and on the skin, which often is fatal [IARC 1973, ATSDR 2007a]. The toxicity of GaAs specifically is however unknown [Flora 2000, Flora et al 2009].

8.1.3 Asbestos

Asbestos is a group of natural occurring silicate minerals that consist of long, thin fibrous crystals. Asbestos have previously been widely used in our society due to its strength, flexibility and heat resistant properties. In electronic equipment it was formerly used in products such as coffee pots, toasters, irons, heaters and other items that benefit from the heat resistance of the material [AEA 2004]. Today, however, the use of asbestos is very limited, as it has been banned in a large part of the world, due to its negative health effects. The asbestos fibres may thus get stuck in the lungs and cause serious illness, including malignant lung cancer (mesothelioma), when inhaled [Arbetsmiljöverket 2009].

8.1.4 Barium (Ba)

Barium is a metallic element that occurs in the environment mainly as barium sulphate and barium carbonate. Barium and its compounds have a variety of uses. In the electronic industry it is mainly used in sparkplugs, fluorescent lamps and "getter plates" in vacuum tubes. Being highly unstable in its pure form, barium is oxidized when in contact with air. In the natural waters, most barium is then precipitated as sulphate or carbonate compounds. Barium sulphate is not very toxic as it is poorly available for uptake in the body. However, barium carbonate can dissolve in the stomach fluids and thereby become available for uptake, which consequently may lead to harmful effects. All water soluble forms of barium, e.g. barium acetate, barium chloride, barium hydroxide, barium nitrate and barium sulphide, may also be toxic [ATSDR 2007b].

Short-term exposure to large amounts barium can cause disturbed heart rhythm, paralysis or even death in humans. Short-term exposure to smaller amounts can cause vomiting, abdominal cramps, diarrhea, difficulties in breathing, increased or decreased blood pressure, numbness around the face and muscle weakness. Long-term effects in humans are less known, but animal studies reveal heart and kidney damages, increased blood pressure as well as decrease in body weight and survival [ATSDR 2007b].

8.1.5 Beryllium (Be)

Beryllium is used in EEE as copper-beryllium alloys, typically containing 2% beryllium, which increases it strength to six times that of pure copper. The alloy is used in springs, relays and solders, and historically also in computer motherboards [OECD 2003, Taylor 2003]. Beryllium may also be found in power supply boxes and x-ray lenses.

Beryllium is both acutely and chronically toxic to humans, mainly affecting the lungs. The primary health concern is inhalation of dust, fumes or mists of beryllium or beryllium oxide [Field 2001]. Breathing high concentrations of beryllium dusts or fumes can result in acute beryllium diseases (ABD), with a range of effects including shortness of breath, coughing, chest pain, rapid heart rate and death in extreme cases. Beryllium has also been classified as a human carcinogen, based upon the increased rates of lung cancer in beryllium production workers [IARC 1993]. Long term exposure to beryllium, even at very low levels, can lead to beryllium sensitization, which may lead to development of what is known as Chronic Beryllium Disease (CBD or berylliosis) [Infante & Newman 2004]. This debilitating and currently incurable disease gives symptoms including emphysema and fibrosis of the lungs that can sometimes be fatal [Field 2001]. Furthermore, exposure to beryllium can cause a form of skin disease that is characterized by poor wound healing and wart-like bumps. Studies have shown that people can still develop beryllium diseases even many years following the last exposure [Newman *et al.* 1996].

8.1.6 Cadmium (Cd)

Cadmium and its compounds are used in a number of applications within electrical and electronic products [OECD 2003]. Cadmium metal is used in some contacts, switches and solder joints. Many devices contain rechargeable nickel-cadmium (Ni-Cd) batteries, which contain cadmium oxide. Cadmium compounds have also been used as stabilizers within PVC formulations, including those used as wire insulation [Burstall 1997, Matthews 1996]. In addition, cadmium sulphide has been used in cathode ray tubes (CRTs) as a “phosphor” on the interior surface of the screen to produce light [OECD 2003].

Cadmium is highly toxic to plants, animals and humans, having no known biochemical or nutritional function [ATSDR 1999, WHO 1992]. Like lead, cadmium can accumulate in the body over time, with long-term exposure causing damage to the kidneys and bone structure. For the general population and for animals, cadmium exposure through diet primarily affects the kidneys [Elinder and Jarup 1996, WHO 1992, Olsson *et al.* 2005]. Recent studies have demonstrated kidney damage in humans at lower levels of exposure than previously anticipated [Hellstrom et al 2001]. Other health effects from cadmium exposure include disruption to calcium mechanisms causing bone effects, as well as the development of hypertension (high blood pressure) and heart disease. In the short term, inhalation of cadmium oxide fumes or dusts can also affect the respiratory system [ATSDR 1999, Elinder and Jarup 1996, WHO 1992]. Furthermore, cadmium and its compounds are known to be human carcinogens, primarily for lung cancer following inhalation of contaminated fumes and dusts [DHHS 2005]. When cadmium is released to aquatic environment it is more mobile than most other metals [ATSDR 1999].

8.1.7 Chromium (hexavalent in particular, Cr[VI])

Chromium is widely used in steel alloys because of its hardness, anti corrosive properties and high conductivity. In EEE and e-waste it is commonly found in metal housings among others.

While some forms of chromium are non-toxic, and may actually be trace nutrients for animals and humans, hexavalent chromium (Cr[VI]) is highly toxic even at low concentrations [ATSDR 2008]. It is easily absorbed in the human body and can produce various toxic effects within cells. Most Cr[VI] compounds are irritating to eyes, skin and mucous membranes, and chronic exposure to Cr[VI] can actually cause permanent eye injury, unless properly treated. Cr[VI] may also cause damage to kidney and liver, and is considered a human carcinogen that causes lung cancer among others [ATSDR 2008, IARC 1990]. Hexavalent chromium is far more reactive and soluble in water than other forms of chromium, making it more mobile in the environment [Mukherjee 1998].

8.1.8 Copper (Cu)

The copper content in e-waste may exceed 10%. This is because copper is one of the base elements in electronic products, and is used in a wide variety of applications and components. It is mainly used because of its excellent conductivity of heat and electricity. Among others, copper is used in wires and cables, PC-boards, relays, switches, electromagnetic motors and lead free solders [OECD 2003].

Copper is essential in all plants an animals, and because of its role in facilitating iron uptake, copper deficiency can often produce anaemia like symptoms in humans. However, at high concentration copper may become toxic and produce a number of adverse health effects, including gastrointestinal distress (nausea, vomiting, abdominal pain), respiratory tract irritation, liver and kidney damage, anaemia, immunotoxicity, and developmental toxicity. Many of these effects are consistent with oxidative damage of membranes and macromolecules [ATSDR

2004]. Furthermore, it is believed that copper and zinc compete for adsorption in the digestive tract so that the diet that is excessive in one of these metals may result in deficiency in the other. In the environment, the solubility of copper increases with decreasing pH, leading to higher mobility and bioavailability. Under these conditions, copper is considerably toxic to a wide range of aquatic animals and plants [ATSDR 2004, Gerhardt 1993, Mance *et al.* 1984]. Copper associated with e-waste may be of concern just because its abundance.

8.1.9 Lead (Pb)

Lead is widely used in electronic goods as a major components of solders on PC-boards (in alloy with tin), as lead oxide in the glass of cathode ray tubes (TVs and monitors), as well in lead-acid batteries [OECD 2003]. Lead compounds have also been used as stabilizers in some PVC cables and other products [Matthews 1996].

Lead is highly toxic to humans, as well as to animals and plants, and it has non known biochemical or nutritional function [ATSDR 2007c, Goyer 1996]. Short-term exposure to high levels of lead can cause vomiting, diarrhea, convulsions, coma or even death. Repeated low-level exposure, leads to accumulation of lead in the body, which potentially can result in irreversible effects on the brain and the nervous system. Particularly the developing nervous system in children is of concern, as the effects may lead to intellectual impairment [Canfield et al 2003]. However, lead can also damage the blood system, have negative impact on the kidneys and on reproduction. It is currently thought that there may be no level of blood-lead that does not produce a toxic effect, particularly in the developing central nervous system [ATSDR 2007c, Canfield et al 2003]. Similar toxic effects are seen in animals, and lead is also toxic to all aquatic life [WHO 1989a, Sadiq 1992]. The effects of exposure to lead are the same whether through ingestion or inhalation, and some appear to be irreversible [ATSDR 2007c, Bellinger & Dietrich 1994, Goyer 1996]. Following release to the environment, lead has low mobility compared to most metals.

8.1.10 Mercury (Hg)

Mercury is one of the most toxic yet widely used metals in the production of EEE. It is still used in some batteries and lighting devices for flat screen electronic displays, and was formerly also used in switches and relays among other things (see above) [OECD 2003].

Mercury and its compounds are highly toxic, and have no biochemical or nutritional value [WHO 1989b]. Inhalation of high levels of mercury vapour may cause a range of effects including impact to the brain and the central nervous system (CNS) [ATSDR 2000, Goyer 1996]. Long-term exposure to lower levels of mercury vapour can also cause damage to the brain and the CNS, particularly during early development. In addition, it can have negative impact on the liver and the kidneys [Ratcliffe et al 1996, Goyer 1996]. Once in the environment, mercury can be converted, by bacteria, to its organic methylated forms, which is the mercury form the general population primarily is exposed to [UNEP 2002]. Methyl-mercury can accumulate in the body and cause damage to the nervous system. Furthermore, methyl-mercury can readily pass through the placental barrier and the blood-brain barrier, potentially causing adverse effects on the developing brain and CNS in foetuses and children, even at very low levels [Mahaffey *et al.* 2004).

8.1.11 Nickel (Ni)

In electrical equipment and e-waste nickel is mainly found in nickel-cadmium and nickel metal hydride batteries, and also to some extent in the electron guns of CRTs.

When ingested in high doses, nickel can cause stomach aches as well as adverse effects in blood (increase blood cells) and kidneys (increased protein in urine). However, the most serious harmful effects from nickel exposure have occurred in people who have breathed dust containing nickel compounds while working in nickel refineries or nickel processing plants. These effects include chronic bronchitis, reduced lung function as well as lung and nasal sinus cancer [ATSDR 2005]. Nickel sulphide fumes and dust is thus believed to be carcinogenic, which also may be the case for various other nickel compounds [Kasprzak *et al.* 2003, Dunnick *et al.* 1995]. Furthermore, sensitized individuals may show an allergy to nickel affecting their skin, also known as dermatitis, and nickel is therefore an important cause of contact allergy [ATSDR 2005].

8.1.12 Selenium (Se)

The largest use of selenium worldwide is to colorize glass and ceramics during manufacturing. However, selenium is also used in the electronic industry, which is mainly due to its photovoltaic and photoconductive properties. Selenium is thus used in photocopying machines, photocells, light meters and solar cells as well as in some rectifiers and x-ray cameras

Although selenium is an essential micronutrient for most organisms including mammals, it is toxic in large doses [Goldhaber 2003]. Exposure to high concentration of selenium compounds cause selenosis [ATSDR 2003]. The major signs of selenosis are hair loss, nail brittleness, and neurological abnormalities (such as numbness and other odd sensations in the extremities). Extreme cases of selenosis can result in cirrhosis of the liver, pulmonary oedema and death [ATSDR 2003]. The toxicity is dependent on form of selenium. Elemental selenium and most metal selenides (Se2-) are relatively non-toxic, while most selenates (SeO42-) and selenites (SeO32-) are very toxic. Hydrogen selenide (H2Se) is extremely toxic as well as corrosive [Wilber 1980, Olson 1986]. Several organo-selenium compounds are also toxic.

8.1.13 Tin (Sn) and organo-tin

Metallic tin is widely used in electronic products, in the form of lead-tin alloys, in solders. However, this is of little concern as metallic tin is relatively non-toxic. When bound to an organic moiety, on the other hand, the toxicity of tin increases dramatically. The best know example of this is tributyltin (TBT), which, as a result of its widespread use in antifouling paints on ships and boats, has led to widespread changes in sexual development in marine snails. In consumer products, including electronic equipment, organotin compounds are mainly found in PVC plastics, in which they are added as stabilizers, and in certain glass coating applications. Mono- and dibutyltin (MBT and DBT) are most common for these applications. In PVC, the orgaotin compounds may comprise 2% by weight of the finished product [Matthews 1996, Sadiki & Williams 1999].

Organotins are known to be toxic at relatively low levels of exposure, not only in marine invertebrates but also for mammals. For marine invertebrates the effects are acute and lethal. In mammals, immunotoxic and teratogenic (developmental) effects have been demonstrated [Kergosien and Rice 1998]. DBT is neurotoxic and causes increased incidence of cell death (apoptosis) in certain brain tissues of rats exposed during development [Jenkins et al 2004]. Furthermore, exposure to trimethyltin (TMT) during development have been observed to affect the memory and cause impaired learning [Jenkins and Barone 2004], as well as having toxic effects on testes development in mice [Kumasaka et al 2002].

8.1.14 Yttrium (Y)

Yttrium is a metal that most importantly is used to make phosphors in CRTs and LEDs, to generate the red colour. Other uses include the production of electrodes, electrolytes, electronic filters, lasers and superconductors; various medical applications; and as properties enhancing traces in several materials [Cotton 2006]. In EEE it is mainly found in CRTs.

Yttrium has no known biological role, but exposure to some of its compounds may cause lung disease. Workers exposed to airborne yttrium europium vanadate dust experienced mild eye, skin, and upper respiratory tract irritation—though this may have been caused by the vanadium content rather than the yttrium [OSHA 2007]. Acute exposure to yttrium compounds can cause shortness of breath, coughing, chest pain, and cyanosis [OSHA 2007]. National Institute of Occupational Safety and Health (NIOSH) recommends a time-weighted average limit of 1 mg/m3 and an IDLH (Immediately dangerous to life or health concentration) of 500 mg/m3 [NIOSH 2005]. Yttrium dust is also flammable [OSHA 2007].

8.1.15 Zinc

Zinc is a metal that is widely used as an anti-corrosive agent. The most common use is for galvanization of iron and steel. However, zinc is also found in electronic products, and then mainly as zinc sulphide, which is used in luminescent pigments on the interior of CRT screens.

Although zinc is an essential requirement for good health of both animals and plants, excess zinc can be harmful. Excessive absorption of zinc suppresses copper and iron absorption [Fosmire 1990]. If ingested, zinc may also cause damage to the stomach lining due to the high solubility of the zinc ion in the acid stomach fluids, resulting in corrosive zinc chloride. [Bothwell 2003].The free zinc ion in solution is highly toxic to plants, invertebrates, and even vertebrate fish [Eisler 1993]. Levels of zinc in excess of 500 ppm in soil interfere with the ability of plants to absorb other essential metals, such as iron and manganese [Emsley 2001].

8.2 Organic compounds

8.2.1 Brominated flame retardants (BFR, e.g. PBDE, TBBPA, and HBCD)

Brominated flame retardants (BFRs) are a diverse group of brominated organic compounds that are used to prevent materials and products from catching fire [D'Silva et al 2004]. In electronic equipment, BFRs are mainly found in plastics and foams, in which the content may exceed 20% [Alaee et al 2003]. Although more than 75 different brominated compounds or groups of compounds have been used as BFRs, three chemicals dominate the current usage, viz. polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), and tetrabromobisphenol-A (TBBPA) [Birnbaum & Staskal 2004]. Of these, TBBPA and HBCD are single compounds, while the PBDEs consist of a group of 209 individual compounds that all contain the diphenyl ether molecule but differ in their degree of bromination. The chemical structures for the PBDEs, TBBPA and HBCD are shown in Figure 6. TBBPA is generally used as a reactive component, being chemically bound to the polymer, whereas PBDEs and HBCD are used as additives, simply blended with material and therefore more likely to leach out of the products [Alaee et al 2003]. In electronic goods TBBPA is used primarily in PC-boards, while PBDEs and HBCD are found to a larger extent in other plastic details, such as casings etc. [Alaee et al 2003, OECD 2003].

As mentioned above, there are many other brominated compounds that are used as flame retardants besides PBDEs, TBBPA and HBCD, e.g. hexabromobenzene (hexaBBz), decabromo diphenylethane (DBDPE) and 1,2-bis-2,4,6-tribromophenoxyethane (BTBPE). Some of these compounds are in fact gaining importance as they are more and more frequently used as substitute for the traditional BFRs in many applications. This is because many of the traditional

BFRs have been shown to cause serious negative effects on both human health and the environment (as discussed below), which have led to restrictions of the use of these compounds. However, some of the new, emerging BFRs may actually be as bad as the traditional ones, but they have been much less studied [SFT 2009, Watson *et al.* 2010].

While the acute toxicity of BFRs is considered to be low, the long-term effects seem to be more serious. Chronic exposure to certain PBDEs (especially in the womb) has been shown to interfere with brain and skeletal development in animals [Eriksson *et al.* 2001, 2002], which may lead to permanent neurological effects such as impaired learning and memory functions, as well as behavioural effects [Darnerud 2003, Eriksson *et al.* 2001, 2002, Viberg *et al.* 2004]. There are concerns that similar effects may also be of relevance in humans, especially after neonatal exposure to PBDEs via mother's milk [Herbstman et al. 2010, Branchi et al. 2003]. There is also some evidence that PBDEs, HBCD and TBBPA are neurotoxic [Mariussen and Fonnum 2003], and that they may exhibit endocrine (hormone) disrupting properties. At least PBDEs and TBBPA, may thus interact with both the oestrogen and thyroid hormone systems either as the parent compound or as metabolites [Meerts et al. 1998, 2001, Legler & Brouwer 2003], which may result in delayed onset of puberty, altered ciculating levels of estradiol and reduced reproductivity for women [Harley et al. 2010]. Effects of BFRs on the immune system have also been reported, as well as adverse effects on the liver and on foetal development [Birnbaum & Staskal 2004, Darnerud 2003].

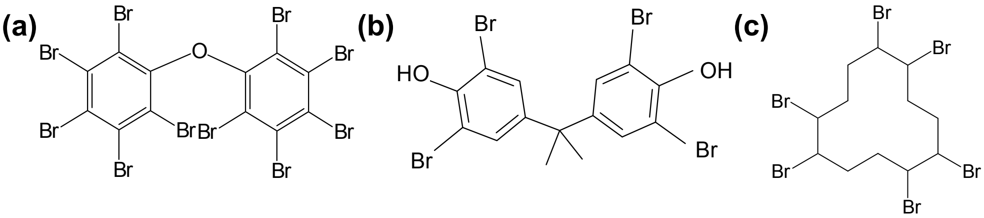


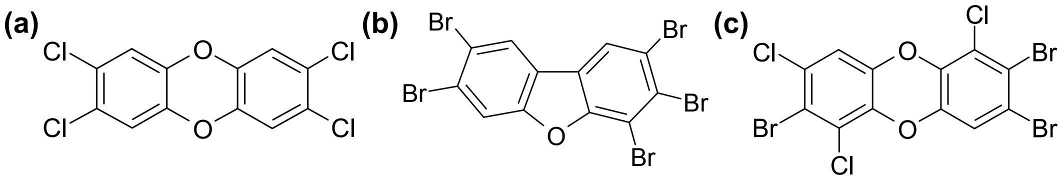
Figure 6. Molecular structures of (a) the polybrominated diphenylether, decaBDE or BDE#209, (b) tetrabromobisphenol A (TBBPA) and (c) hexabromocyclododecane (HBCD).

In addition to these direct effects of BFRs, there is also a risk that these compounds may be transformed into even more toxic dioxins during handling and recycling of the material in which they are present, e.g. e-waste [IPCS 1998]. This may happen during thermal processes, such as combustion, pyrolysis and gasification [Weber & Kuch 2003], during which the bromine in all BFRs may give rise to brominated dioxins. However, the dioxin formation is particularly prevalent if PBDEs are present, which easily may be transformed into dioxins in such way [Lundstedt 2009]. This is, however, further discussed below.

8.2.2 Dioxins, chlorinated (PCDD/F), brominated (PBDD/F) and mixed (PBCDD/F)

Dioxins is a generic term commonly used for chlorinated dibenzo-p-dioxins (PCDDs) and chlorinated dibenzofurans (PCDFs), but may also included the brominated analogs of these compounds (PBDD/Fs). The dioxins and furans all contain the dibenzo-p-dioxin and the dibenzofuran molecules, respectively, as a backbone structure, but with different numbers and patterns of chlorine and bromine atoms (Figure 7). In total, there are 210 so called congeners each of PCDD/Fs and PBDD/Fs. In addition, there are dioxins and furans containing both chlorine and bromine (PBCDD/F), which theoretically amounts to 4600 additional congeners [D'Silva et al. 2004, Stanmore 2004].

Brominated dioxins (or actually mainly furans) may be present in flame retarded plastics as a BFR impurity [Lundstedt 2009]. However, the main concern about dioxins during e-waste handling is because these compounds may be formed during combustion and other high temperature processing of chlorinated and brominated materials, including PVC coated wires and flame retarded plastics [Andersson 2004, Stanmore 2004, Gullet et al 2007, Hedman et al 2005]. PVC may thus act as a precursor for chlorinated dioxins [Takasuga et al 2003], and BFRs (PBDEs in particular) as very potent precursors for brominated dioxins [Weber & Kuch 2003]. The processes are catalyzed by copper and antimony, respectively [Shibata et al 2003, Weber & Kuch 2003], which makes e-waste a very good starting material for dioxins.

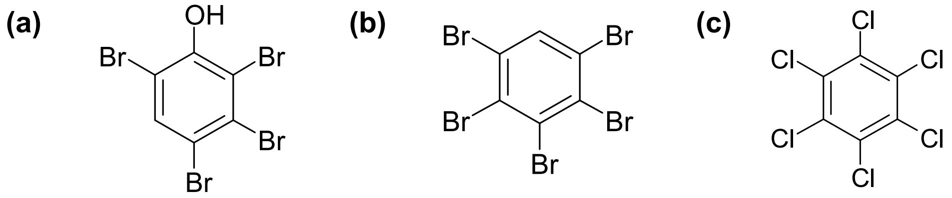


Dioxins are highly persistent in the environment and are able bioaccumulate, so that the concentrations in organisms may become higher than in the surrounding media. Dioxins have also shown a wide spectrum of toxic effects. Human exposure to high levels of dioxins results in the acute skin disease chloracne, while long-term effects include teratogenicity, carcinogenicity, reproductive disturbance and lymphoid disorders [Schecter et al 2006, ATSDR 1998, IARC 1997]. Other mammals and organisms are also affected, although the effects are strongly species dependent. The effects of dioxins are also highly dependent on the number and position of the chlorine and bromine atoms on the molecules. PCDD/Fs with chlorine atoms at the 2,3,7 and 8 positions have the most pronounced toxic properties, and the vast majority of toxicity data reported for PCDD/Fs relates to the effects of the 17 congeners with chlorines at these positions, using toxic equivalence factors (TEFs) and toxic equivalents (TEQs) [van den Berg et al. 2005]. 2,3,7,8-tetrachloro dibenzo-p-dioxin (TCDD) is the most toxic congener.

The toxicity of the brominated dioxins is much less studied than that of the chlorinated analogs. However, studies that have been performed indicate that their toxicity patterns are similar [Birnbaum et al. 2003, 2004, Olsman et al. 2007].

8.2.3 Various brominated compounds such as brominated phenols and benzenes

The abundance of BFRs and bromine in e-waste will, besides the PBDD/Fs, also lead to the formation of various other brominated compounds during combustion and high temperature processes. For example, it has been observed that brominated benzenes and phenols (Figure 8) may be formed in substantial amounts [Heeb et al 1995, Schüler & Jager 2004]. Although, the toxicity of these compounds have been poorly studied there are some evidences that they have negative effects on humans and the environment [Szymańska 1998, Kammann et al. 2006]. In addition, these compounds may act as precursors for further dioxin formation [Weber & Kuch 2003].



8.2.4 Polychlorinated biphenyls (PCB)

Polychlorinated biphenyls (PCBs) are a group of organic chemicals that contain 209 individual compounds (known as congeners), all containing the biphenyl molecule in the backbone structure, but with different numbers and positioning of chlorine atoms (Figure 9). PCBs have been used in a wide variety of applications, including transformer oils (as insulating fluid), capacitor dielectrics, hydraulic fluids, plasticizers and printing inks [ATSDR 2000]. The use in transformer oils, frequently with tri- and tetrachlorobenzenes as solvents [Swami et al. 1992], and capacitors accounted for the greatest tonnages [de Voogt & Brinkman 1989]. Production of PCBs was banned in 1977 when their ability to accumulate in the environment and to cause harmful effects became apparent [ATSDR 2000]. At least one third of the PCBs that have been produced are now estimated to have entered the environment [Swedish EPA 1999], while the rest either remain in old electrical equipment and other materials, or have been destroyed through incineration or other processes. The PCBs that remains in equipment and materials will unfortunately continue to leach into the environment, including when obsolete electrical equipment is dismantled, recycled and/or disposed of. Furthermore, PCBs can be formed during the combustion of chlorinated organic materials such as PVC, similarly as dioxins [Hedman et al. 2005, Wikstrom & Marklund 2001].

PCBs are highly persistent, and may bioaccumulate in organisms, leading to higher levels in the organism than in the surroundings. For aquatic organisms and fish, levels can reach many thousands of times higher than the concentration in the surrounding water [ATSDR 2000, Jones et al. 1988]. PCBs can both be absorbed through the skin as well as through ingestion and inhalation. For the general population today, food is undoubtedly the primary route of exposure to PCBs [Allsopp et al. 2000], although dermal exposure may be dominant amongst those directly handling PCBs or PCB-contaminated materials [Lees et al. 1987].

PCBs exhibit a wide range of toxic effects in animals, including immunosuppression, liver damage, tumour promotion, neurotoxicity, reproductive toxicity, endocrine disruption and behavioural changes [Seegal and Shain 1992, Safe 1993, Brouwer et al. 1999, Rice 1999]. The PCBs show dioxin like toxicity and are therefore contributing to TEQs calculated for dioxins. Although it is difficult to assess the impact on animal populations in the wild, not least because they are exposed to complex mixtures of chemical contaminants, some immunological and reproductive disorders in marine mammals have nevertheless been linked to elevated levels of persistent organochlorines, in particular the PCBs [Allsopp et al. 1999, 2001, Haave et al. 2003]. Studies on the general populations of the Netherlands and the Arctic and families of Swedish fishermen suggested that even relatively low levels of exposure to PCBs can result in impacts on the immune system, growth retardation and neurological effects [Allsopp et al.1999, 2001, Weisglas-Kuperus et al. 2004].

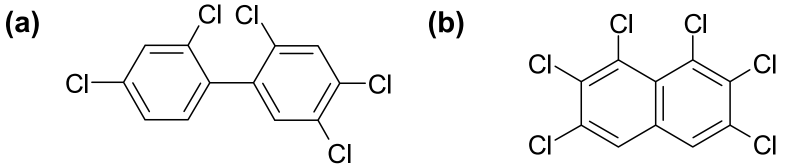


Figure 9. Molecular structures of (a)2,2',4,4',5-pentachloro biphenyl (PCB#99), and (b) 1,2,3,6,7,8-hexachloronaphthalene (PCN#70).

8.2.5 Polychlorinated naphthalenes (PCN)

The PCNs (Figure 9), which also comprises a group of compounds, were the predecessors to the PCBs, once used extensively in capacitors and as insulating compounds in wiring, among many other uses [Hayward 1998, Kimbrough & Grandjean 1989, Falandysz 1998]. PCNs may still be present in some old electronic equipment from which they may leak during recycling and disposal [Weistrand et al. 1992]. In addition, they may, like the PCBs, be formed during combustion of chlorine containing materials, such as PVC [Falandysz 1998]. The PCNs share many properties with the PCBs and the PCDD/Fs, including environmental persistence [Safe 1989], bioaccumulative properties [Falandysz and Rappe 1997] and toxicity, which include effects on the skin, liver, digestive tract, nervous system and reproduction [Hayward 1998, Kimbrough & Grandjean 1989, Morrissey & Schwetz 1989]. Like PCBs, PCNs also have dioxin-like toxicity.

8.2.6 Chlorinated paraffins (CP)

Polychlorinated paraffins (CPs) or polychlorinated n-alkanes are chlorinated derivatives of paraffinic hydrocarbons, i.e. alkanes, with 10-30 carbon atoms and a chlorine content of 30-70% by weight (Figure 10). The CPs may be subdivided into three categories: short chain (SCCP), medium chain (MCCP) and long chain (LCCP) compounds, containing 10-13, 14-17, and 18-30 carbons, respectively [Muir et al. 2000]. CPs have been produced in large amounts around the world for usages such as lubricants in metal working fluids, and as flame retardants and plasticizers in plastics, rubbers, paints, adhesives and sealants. In EEE and e-waste CPs (particularly MCCP) are mainly found in PVC and other plastic materials [Feo et al. 2009], from which they may leak during handling and disposal of the EEE [Tomy et al. 1998]. The leakage and emission of CPs may be particularly high during thermal destruction and modification of the materials. In these processes, the CPs may also be transformed into PCDD/Fs, similarly to other chlorinated compounds [Bergman et al. 1984].

Although, the acute toxicity of CPs seem to be low [WHO 1996], they share many properties with other organochlorine compounds (e.g. PCDD/Fs, PCBs, PCNs, etc.) meaning that they are highly lipophilic and persistent and thereby have potential for bioaccumulation [Muir et al. 2000]. This may possibly lead to long term effects instead, even if this area has been poorly investigated for the CPs. However, there are studies showing that SCCPs have severe negative effects on aquatic biota after chronic exposures [Tomy et al. 1998, POPRC 2007], and that SCCPs may cause tumours and cancers in rodents [OSPAR 2001a]. The SCCPs have also been categorized in group 2B by IARC [WHO 1996], i.e. compounds that are possibly carcinogenic to humans.

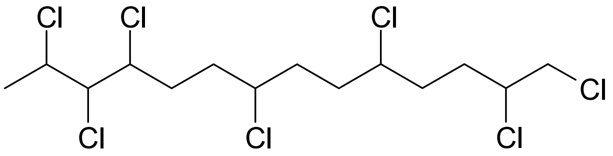


Figure 10. Example of a medium chain chlorinated paraffin, C14H23Cl7, containing 56% chlorine by weight.

8.2.7 Chlorinated benzenes, e.g. hexachlorobenzene (HCB)

Chlorinated benzenes, or chlorobenzenes, are chlorinated derivatives of benzene (Figure 8), possessing between one and six chlorine atoms (i.e. mono- to hexachlorobenzene). Chlorobenzenes, especially mono-, di-, tri- and hexachlorinated forms, have had a variety of uses, including as solvents (e.g. in commercial PCB formulations) and intermediates in the manufacture of other chemicals such as antioxidants, dyes and pigments, pharmaceuticals and agricultural chemicals [Budavari et al. 2000, ATSDR 2002]. Today only mono- and dichlorobenzenes continue to be manufactured in substantial quantities. Although, chlorinated benzenes are not present in electronic equipment, they may be emitted during the combustion of PVC plastics and other chlorine containing materials [Grimes et al. 2006].

Chlorobenzenes are relatively persistent in the environment and can bioaccumulate in both terrestrial and aquatic systems. Both acute and chronic effects have been reported in a wide range of aquatic organisms and mammals. The effects vary depending on the chlorobenzene in question, though common impacts include those on the liver, thyroid and CNS, as well as on developing foetus. In general terms, toxicity tends to increase with increasing degree of chlorination [WHO 2004, Giddings et al. 1994a, b, c]. Hexachlorobenzene (HCB), the most toxic of the chlorobenzenes, is both toxic to plants, animals and humans [Newhook & Meek 1994, van Birgelen 1998, ATSDR 2002]. It is listed, by the IARC, as a possible carcinogen to humans (Group 2B), and it appears to have tumour promoting properties. Furthermore, HCB has been shown to be an endocrine disruptor in laboratory animal studies [Ralph et al. 2003], and to have dioxin-like toxicity [van Birgelen 1998] that contribute substantially to the overall dioxin-type toxic effects in humans and wildlife [Pohl et al. 2001].

8.2.8 Polycyclic aromatic hydrocarbons (PAH)

Polycyclic aromatic hydrocarbons (PAHs) is a large group of non-halogenated organic compounds that consist of fused benzene rings in linear, angular or clustered arrangements (Figure 11). PAHs are, as dioxins, not present in EEE or other consumer products, but are formed as the products are subjected to combustion processes [Howsam & Jones 1998, WHO 1998]. Poor combustion conditions, including low temperature and oxygen supply, result in larger amounts of PAHs as well as other products of incomplete combustion [Richter & Howard 2000]. Although the physicochemical properties of PAHs differ substantially from the smallest to the largest compound, they are generally considered as lipophilic compounds with low water solubility and high affinity for organic matter [Howsam & Jones 1998]. This means that they are strongly sorbed to particles in the environment, which make them unavailable for degradation processes. As a consequence, PAHs show high persistency in the environment, and may also accumulate in some invertebrates. However, most animals, including humans, have the capability to metabolize PAHs leading to low bioaccumulation in general [WHO 1998].

PAHs show a wide range of toxic effects, including acute toxicity, reproductive and developmental toxicity, endocrine disruption, and immunotoxicity [Delistraty 1997, WHO 1998]. However, the main cause of concern has been due to their genotoxic and carcinogenic properties. Several PAHs have thus been shown to cause genotoxic effect in laboratory cellsystems as well as tumour formation and carcinogenicity in laboratory animals. These PAHs are also most likely carcinogenic to humans [IARC 1983, WHO 1998]. The genotoxicity and carcinogenicity varies among the PAH, and the individual potencies are often related to that of benzo[a]pyrene, which is one of the most carcinogenic PAHs known. This compound has also been most extensively studied of all PAHs [Boström et al 2002]. The genotoxic effects of PAHs arise when the compounds are metabolized in the body of higher organisms, leading to highly reactive epoxide-intermediate. These epoxides may react with DNA to form adducts that subsequently may result in mutations and cancer [Pickering 1999].

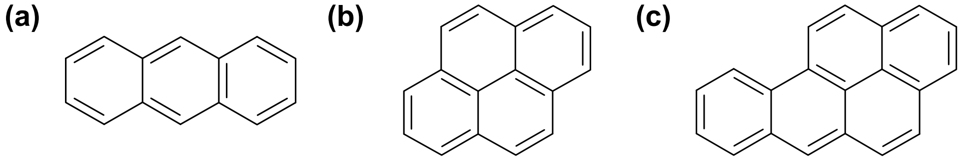


Figure 11. Molecular structures of the PAHs (a) anthracene, (b) pyrene and (c) benzo[a]pyrene.

8.2.9 Freons

Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), commonly known as freons, are compounds composed of carbon, fluorine, chlorine and sometimes also hydrogen and bromine (Figure 12). Freons have mainly been used as refrigerating agent in cooling units and during the production of insulation foam. However, today the freons have been more or less phased out due to their deleterious effects on the ozone layer and their contribution to the global warming, when released into the atmosphere [Solomon 1999]. The depletion of the ozone layer has resulted in increased incidence of skin cancer in humans and in genetic damage in many organisms [de Gruijl et al. 2003]. The freons are very stable compounds that may survive in the environment for more than hundred years.

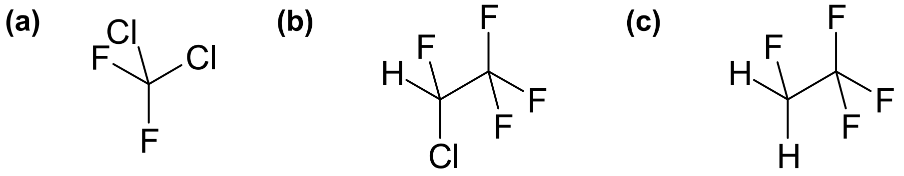


Figure 12. Molecular structures of the freons (a) CFC-12, (b) HCFC-124 and (c) HFC-134a.

8.2.10 Nonylphenol and nonylphenol ethoxylates

Nonylphenol (NP) is a chemical most widely known as a breakdown product of nonylphenol ethoxylates (NPEs) surfactants (Figure 13) that have been used as detergents, emulsifiers, and wetting agents in a variety of industrial and consumer applications [OSPAR 2001b]. However, NPEs has reportedly also been used as an antioxidant in some plastics [Guenther et al. 2002]. The main hazard associated with NPEs result from their partial degradation to shorter chain ethoxylates and to NP, both of which are toxic to aquatic organisms and to higher organisms through secondary poisoning (i.e. resulting from the accumulation through the food chain).The most widely recognised effects are undoubtedly oestrogenic activity, i.e. the ability of nonylphenol to mimic natural oestrogen hormones, leading to altered sexual development in some organisms, most notably the feminisation of fish [Jobling et al. 1995, 1996, 2002]. Hazards to human health remain unclear, although recent studies have highlighted concerns directly relevant to humans. For example, Chitra et al. [2002] and Adeoya-Osiguwa et al. [2003] describe effects on mammalian sperm function, while DNA damage in human lymphocytes has also recently been documented [Harreus et al. 2002].

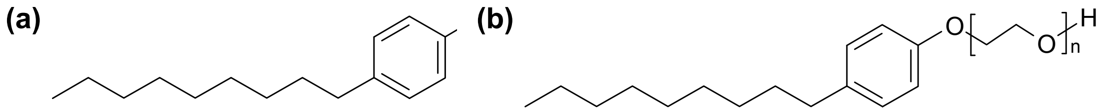


Figure 13. Molecular structures of (a) nonylphenol and (b) nonylphenol ethoxylates.

8.2.11 Organophosphorus flame retardants, e.g. triphenyl phosphate

Triphenyl phosphate (TPP, Figure 14), one of a number of so-called triaryl phosphates, has long been used as a flame retardant in polymers and resins of electronic equipment [IPCS 1991]. Other applications include use as a plasticizer in photographic films and as a component of hydraulic fluids and oils. Loss of TPP to the environment as a result of leaching from polymers in which it is incorporated has long been recognized [Carlsson et al. 1997, 2000].

All triaryl phosphates in common use are acutely toxic to aquatic life, but TPP shows the highest toxicity [IPCS 1991]. TPP has been reported as a contaminant in human blood [Jonsson et al. 2001] and is a strong inhibitor of a key enzyme (monocyte carboxyl esterase) in human blood cells [Amini & Crescenzi 2003]. Recent research has also indicated that TPP is a probable endocrine disruptor that may inhibit human androgen hormone reception [Honkakoski et al. 2004]. Furthermore, contact dermatitis following exposure to TPP has been reported by several authors, with some cases dating back to the 1960s [Carlsson et al. 1997 and Sanchez et al. 2003].

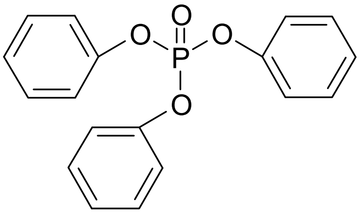


Figure 14. Molecular structures of tripheyl phosphate (TPP).

8.2.12 Phthalates

Phthalates (or more accurately, phthalate diesters) are non-halogenated esters of phthalic acid (Figure 15) that are widely used in a range of industrial and consumer applications. The dominating use is as plasticizers (or softeners) in plastics, especially PVC (e.g. in coated wires and cables and other flexible components). Other applications include uses as components of inks, adhesives, sealants, surface coatings and personal care products. Some phthalates are discrete chemicals, such as the well known di(2-ethylhexyl) phthalate (DEHP), while others are complex mixtures of isomers, such as diisononyl phthalate (DINP). All uses of phthalates, especially the major use as PVC plasticizers, result in large-scale losses to the environment (both indoors and outdoors) during the lifetime of products, and again following disposal. Within the EU alone, this amounts to thousands of tones per year (CSTEE 2001). As a result, phthalates are among the most ubiquitous man-made chemicals found in the environment, including in air and dust [Otake et al 2001, Butte and Heinzow 2002, Fromme et al 2004].

Substantial concerns exist with regard to the toxicity of phthalates to wildlife and humans. For example, DEHP, one of the most widely used to date, is a known reproductive toxin, capable of (after metabolization to its monoester form, MEHP) interfering with development of the testes in early life. In addition, adverse impacts on female reproductive success in adult rats and on development of the young have been reported following exposure to this chemical [Lovekamp-Swan and Davis 2003]. Butylbenzyl phthalate (BBP) and dibutyl phthalate (DBP) have also been reported to exert reproductive toxicity [Ema and Miyawaki 2002, Mylchreest et al 2002], and both DEHP and DBP are classified as “toxic to reproduction” within Europe [Langezaal 2002]. Recent research has revealed a correlation between phthalate exposure during pregnancy and decreased ano-genital index (distance from the anus to the genitals) in male children [Swan et al 2005], which indicate that phthalate exposure can lead to “undermasculinization”. Phthalates in indoor environment have been associated with allergic symptoms in children, including rhinitis, eczema and asthma [Bornehag et al 2004]. Furthermore, effects of phthalates have been observed on the liver and kidneys in humans as well as on the physiology and morphology of crops during growth [Liao 2006].

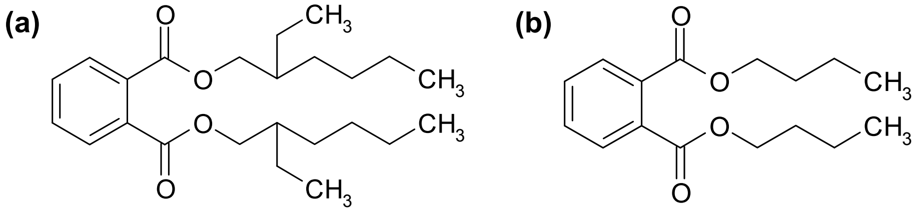


Figure 15. Molecular structures of (a) di(2-ethylhexyl)phthalate (DEHP), and (b) dibutyl phthalate (DBP).

8.2.13 Fluorinated compounds originating from Teflon

Teflon is a brand name of the polytetrafluoroethylene (PTFE) polymer which today is used in numerous applications, due its low friction and inertness. The most well known use is as a non-stick coating for pans and other cookware, but it has also found widespread use in bearings, gears, slide plates and other applications where low friction is needed. In addition, PTFE has excellent dielectric properties which make it useful as insulator in some high performance cables and connector assemblies and as a material for PC-boards used at microwave frequencies. Other fields of applications for PTFE in EEE are as measuring heads in radiometers and as low friction feet for computer mice.

PTFE is not a cause of concern in itself, but during thermal degradation of the polymer a wide range of hazardous compounds may be formed (Figure 16) [Arito & Soda 1977, Ellis et al. 2001, EWG 2003, Ochi et al. 2008]. This includes several fluorinated alkenes, such as tetrafluoroethylene (TFE) and hexafluoropropene (HPF); fluorinated alkanes, such as octafluorocyclobutane (OFCB), perfluorobutane (PFB), perfluoroisobutane (PFIB) and carbon tetrafluoride (CF4); fluorinated acetic acids, such as mono-, di- and trifluoroacetic acid (MFA, DFA and TFA); long chain fluorinated acids, such as perfluorooctanoic acid (PFOA); as well as hydrofluoric acid (HF), carbonyl fluoride (COF2) and various fluorinated fine particulates. At least four of these compounds are extremely toxic to animals and humans; PFIB, which have been used as chemical warfare agent; COF2, which is the fluorinated analog to the warfare gas phosgene; MFA, which can kill people at low doses and HF, which is a highly corrosive gas [EWG 2003]. Birds seem to be particularly sensitive to these compounds, but other animals and humans are affected as well, humans initially by developing a flu-like symptom called polymer fume fever [Arito & Soda 1977, Johnston et al. 2000]. Other decomposition products of PTFE, that may be less acutely toxic, are instead extremely persistent in the environment and can withstand most (or virtually all) natural degradation processes [Boutonnet et al. 1999, Trudel et al. 2008]. These compounds, which include PFOA, TFA, CF4, PFB as well as some of the particulates produced, may accumulate in the environment and thereby potentially cause serious effects on a long term basis. Some of these, e.g. CF4 and PFB, are also very potent greenhouse gases [EWG 2003].

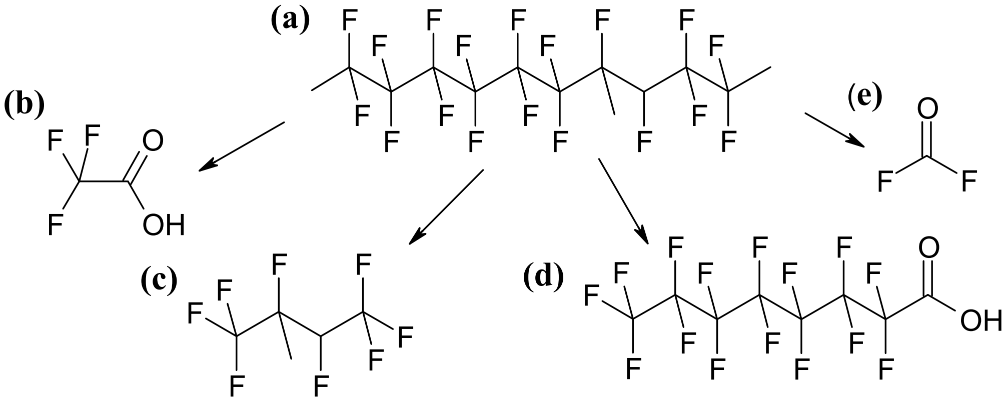


Figure 16. Molecular structures of the PTFE-polymer (a), and and a selction of its thermal decomposition products; (b) trifluoroacetic acid (TFA), (c) perfluorobutane (PFB), (d) perfluorooctanoic acid (PFOA), and (e) carbonyl fluoride (COF2).

8.2.14 Liquid crystals

Liquid crystals are found in LCD-screens between the display glass and electric control elements. Commercially available liquid crystals are mixtures of 10-20 substances, which belong to groups of substituted phenylcyclohexanes, alylbenzenes and cyclohexylbenzenes. About 250 substances are used for formulating more than a thousand marketed liquid crystals. Studies conducted so far have not found any carcinogenic potential or acute oral toxicity, although a few substances showed corrosive, irritant or sensitizing properties to the skin [AEA 2004]. A cell phone can contain about 0.5 mg of liquid crystals, and a notebook PC display about 0.5 g.

8.2.15 Toner dust

Photocopiers and laser printers use toner as part of the printing process. The toner is an extremely fine powder, which in itself is not classified as a hazardous substance, but as any dust in substantial concentration it may cause respiratory tract irritation resulting in coughing and sneezing [Koskela et al. 2005, Cormier et al 2006]. Toners may also contain up to 7% carbon black. Carbon black became a cause for concern when a group of Swedish scientists noticed that certain toners caused genetic changes in bacterial test systems, and it was later regarded as a possible carcinogen for humans [IARC 1996]. After this was noticed, the manufacturers of carbon black changed their process, leading to a much less genotoxic product. Since then, numerous studies have been carried out to determine the effects of exposure to carbon black. In all instances, there was no evidence of cancer production and no unusual death rates. The small content of carbon black is therefore probably not a cause for concern today.

8.2.16 Nanoparticles

Nanoparticles are small particles in the nanometre range (one billionth of a meter) that have attracted a lot of attention the last few years. The nanotechnology is growing steadily and nanomaterials are constantly finding new areas of usage [Whatmore 2006]. In electronics, a number of different nanomaterials are already being used commercially or are being used for research and development purposes. Most common are carbon nanotubes in semiconductor chips, quantum dots in lasers and silver nanoparticles as surface coatings [Allsopp et al. 2007].

The concerns about nanoparticles and their impacts on human health and the environment are mainly based on the particle's tiny size, the shape of some particles and their properties (e.g. reactivity) [Allsopp et al. 2007, Oberdörster et al. 2005]. It is already known that ultrafine particle in polluted air may cause respiratory illness and adverse cardiovascular effects in humans [Koskela et al. 2005, Cormier et al.2006]. It is plausible that synthetically produced nanoparticles can give the same effects. Another concern has arisen specifically about possible impacts of carbon nanotubes on human health [Greenpeace Environmental Trust 2003]. This is because carbon nanotubes are structurally similar to asbestos fibres, which are known to cause serious impacts on health. Indeed, exposure of rodents to carbon nanotubes has shown such effects [Lam et al. 2004, Warheit et al 2004]. Furthermore, due to the nanoparticle's large surface area, they have often increased potential for interaction with other substances and organisms compared to larger-scale materials [Donaldson et al 2004, Nel et al. 2006]. For example, silver nanoparticles have anti-microbial effects, which is of concern because they are likely to kill microbes that are beneficial to living beings and ecological processes besides killing harmful microbes [Allsopp et al 2007].

Table 5. Hazardous compounds that may be present in electrical and electronic equipment (EEE) and e-waste, as well as those that may be formed during end-of-life treatment of the e-waste. The primary locations of the compounds in the EEE are also shown.

Hazardous compound	In electrical and electronic equipment (EEE) and e-waste
Metals	
Antimony (Sb)	Semiconductors (SbH_3), flame retarded plastic (Sb_2O_3), solders, CRT-glass, Pb-acid batteries
Arsenic (As)	As GaAs in MMICs, LEDs, laser diodes and solar cells
Asbestos	In some old items that have to resist heat (coffe pots, heaters etc.)
Barium (Ba)	Sparkplugs, fluorescent lamps, getter plates in vaccum tubes
Beryllium (Be)	Cu-Be alloy in springs, relays and solders. Power supply boxes and x-ray lenses
Cadmium, (Cd)	Contacts, switches, solder joints, Ni-Cd batteries (CdO), stabilizers in PVC, CRT phosphors
Chromium (Cr[VI])	Coating on metal surfaces, steel alloys
Copper (Cu)	Wires, cables, PC-boards, relays, switches, electromagnetic motors, lead free solders
Lead, (Pb)	Solders, CRT glass (PbO), stabilizers in PVC, lead-acid batteries
Mercury, (Hg)	Hg-batteries, cold cathode lamps, switches, relays, thermostats, sensors, medical equipment, telecom equipment.
Nickel (Ni)	Ni-Cd batteries, electron guns of CRTs
Selenium (Se)	Photocopying machines, photocells, light meters, solar cells, rectifiers and x-ray cameras
Tin and organo-tin	Stabilizers in PVC, glass coatings
Yttrium	Phosphors in CRTs and LEDs. Also in lasers, superconductors etc
Zinc (Zn)	ZnS in luminiscent pigments of CRTs
Organic compounds	
Brominated flame retardants (BFRs)	Plastic details, e.g. TBBPA in PC-boards, and PBDEs and HBCD in casings etc.
Dioxins (PCDD/Fs, PBDD/Fs, PBCDD/Fs)	Formation during thermal processes PBDD/F as an impurity in BFR-treated materials.
Various Br-compounds (benzenes and phenols)	Formation during thermal processes, some are also used as flame retardants
Polychlorinated biphenyls (PCBs)	Old capacitors and transformers. Formation during thermal processes.
Polychlorinated naphthalenes (PCNs)	Old capacitors and insulated wires. Formation during thermal processes.
Chlorinated paraffins (CPs)	Plasticizer and flame retardant in PVC and other plastics.
Chlorinated benzenes (e.g. hexachlorobenzene, HCB)	Formation during thermal processes
Polycyclic aromatic hydrocarbons (PAHs)	Formation during thermal processes.
Freons (CFCs, HCFCs, HFCs)	Cooling units of refrigerators and freezers
Nonylphenol (NP) and nonylphenol ethoxylate (NPE)	Antioxidant in plastics
Organophosphorus flame retardants (e.g. TPP)	Plastic details, e.g. casings of computer monitors
Phthalates (e.g. DEHP, DBP)	Plasticizers in PVC wires, cables etc.
Fluorinated comp. from Teflon	Formation during thermal decomposition of Teflon (PTFE)
Liquid crystals	LCDs
Toner dust	Toner cartridges of photocopiers, laser printers and faxes
Nanoparticles	Nanotubes in semiconductor chips, quantum dots in lasers, Ag-nanoparticles as surface coatings

9 Recycling and end-of-life treatment of e-waste

After an electrical or electronic product has been abandoned by its owner and thereby become e-waste, it may encounter various fates. It may be treated as any municipal solid waste and thus be incinerated or just put on landfills, or it may be recycled with the objectives to recover its content of valuable materials and energy and/or to remove hazardous components and thereby reduce the impacts on human health and the environment. End-of life treatments thus include landfilling and incineration as well as reuse and recycling. It should be noted that incineration sometimes also is considered as recycling, as it may be used for heat and energy recovery as well as a first step in the metal recovery process. However, many times incineration is only used to reduce waste volumes prior to landfilling.

The processes and methods used for recycling differ a lot depending on where and under what circumstances they are carried out. In the developed world, the economy has allowed the development of more comprehensive solutions to the e-waste problem, and therefore a significant fraction of the e-waste generated (even if this fraction could be much larger) is collected and sent to authorized recycling facilities, in which both valuable materials and hazardous compounds are separated and treated appropriately. In the developing world this system has not yet had a chance to thrive, due to the competition from the informal recycling industry, through which many poor people earn their only income. Here, the primary goal is to recover the valuable materials in the e-waste, and consequently little or no regard is paid to the impacts on the environment and human health. Sadly, the processes used by the informal recycling industry are also much less efficient than the processes used by the formal recycling industry in terms of recovering valuable materials.

In the following sections, the processes used for recycling of e-waste are described. This includes processes carried out in controlled recycling facilities as well as the more rudimentary methods used in many developing countries.

9.1 Recycling of e-waste under controlled conditions.

The recycling of e-waste under controlled conditions generally engages two types of facilities according to the nature of the methods involved. In the first one the e-waste is dismantled and mechanically processed so that materials can be separated and further recovered. In the second type of facilities, metallurgical processes are used to recover metals, and various other processes to recover plastics and other materials.

9.1.1 Manual dismantling and sorting

The first step in the recycling process is manual dismantling, which allows the recovery of whole homogenous parts that may be reusable, valuable or recyclable, e.g. whole components, metal, plastic or glass parts, and hazardous components that require further special treatment, e.g. mercury containing components, batteries, CRT-glass and LCDs [Cui and Forsberg 2003, UNEP 2009]. Following separation, mercury containing components are normally sent to specialized mercury recovery facilities or authorized hazardous waste incinerators with modern flue gas cleaning systems [OECD 2003]. Batteries are normally sent for processing to recover cadmium, nickel, mercury and lead; the former three through heating of the batteries in a furnace, leading to evaporation of the metals that later can be collected through condensation [IGES 2009], and lead by smelting the whole batteries or parts of them in a metallurgical process [UNEP 2003]. The leaded CRT glass may be used in the production of new leaded glass, for the recovery of lead or may just be put on landfill [ICER 2004]. LCDs may be sent for glass recovery or destruction in authorized incineration facilities [OECD 2003].

9.1.2 Mechanical shredding and separation

Further liberation and size reduction of the recyclable materials, e.g. PC-boards, is usually achieved by some kind of shredding or crushing process. After the size reduction, the materials are sorted into defined output fractions based on their specific physical characteristics, such as weight, size, shape, density, and electrical and magnetic characteristics. Typical sorting processes used are screening, magnetic separation of ferrous parts, eddy current separation (electric conductivity) of non-ferrous metals (e.g. copper and aluminium), and density or gravity separation (water or airflow tables, heavy media floating, sifting) of plastics. Alternatively or in addition, manual sorting or new optical sorting techniques are also used. Furthermore, the sorting may sometimes be supported by screening as well as further size reduction steps. Final output streams are usually components taken out as a whole (for reuse or further treatment), a magnetic fraction (going to steel plants), an aluminium fraction (going to aluminium smelters), a copper fraction (going to copper smelters), and in some cases various plastic fractions. Usually a waste fraction is also generated at this stage, which among others consists of a mixture of plastics, glass, wood and rubber. This fraction, which often is called “the shredder light fraction”, is sent for further processing, incineration or landfilling [Cui and Forsberg 2003, Zhang and Forsberg 1998, Veit et al 2005].

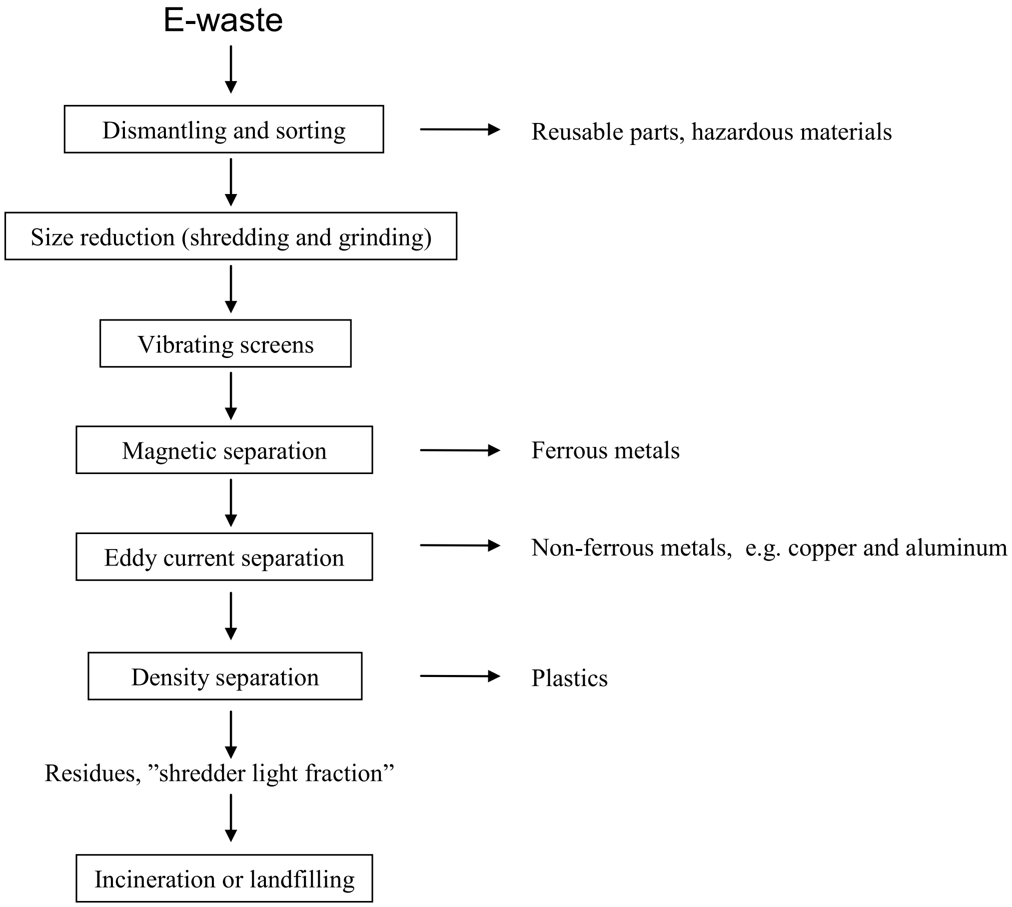


Figure 17. Schematic of the first steps in a typical e-waste recycling process.

The facilities that are doing the dismantling and separation vary in throughput, from relatively small to quite large operations, and also in degree of automation (from manual labour based to highly automated operations). Figure 17 shows a schematic of the processes used at typical e-waste recycling plant [Kang and Schoenung 2005].

9.1.3 Metallurgical processes

Further upgrading and refining of the metal containing fractions are performed by metallurgical processes. Both pyrometallurgical processes, in which the metals are melted, and hydrometallurgical processes, in which the metals are dissolved, are used, and often in combination. Pyrometallurgical processing in copper smelters followed by electrolytic refining has thus become the dominant method to recover non-ferrous metals, including precious metals as well as other valuable metals, from e-waste in the last two decades [Cui and Zhang 2008]. In the process, the crushed scraps are burned in a furnace or in a molten bath to remove plastics. At the same time metals such as iron, lead and zinc are converted into oxides that will become fixed within a silica based slag. The melt that mainly contains copper (but also silver, gold, palladium, nickel, selenium, tellurium and zinc) is further refined in a converter and an anode furnace where it is cast into anodes with copper content exceeding 99%. The remaining 0.9% contains the other recoverable metals, including the precious metals. The metals in the anodes are then typically refined and recovered by electrolysis in acidic solution.

The metallurgical processes may be carried out by the general metallurgical industry, which usually are designed to extract metals from ores, where electronic scrap only represents a small part of the feedstock. There are however a few large metallurgical industries in the world that are processing larger quantities of e-waste. These so called “integrated” smelters, which recycle many different kinds of copper containing materials, include Boliden in Sweden, Umicore in Belgium, Noranda in Canada, Norddeutsche Affinerie AG in Germany [Allsopp et al 2006] and Dowa Eco-System in Japan [IGES 2009]. The term “integrated” is used to define the smelters, as they represent a sophisticated combination of several metallurgical and chemical units that are closely interlinked and designed to work together [Cui and Zhang 2008, Antrekowitsch et al 2006]. A schematic of the process used at Boliden’s Rönnskär Smelter is shown in Figure 18.

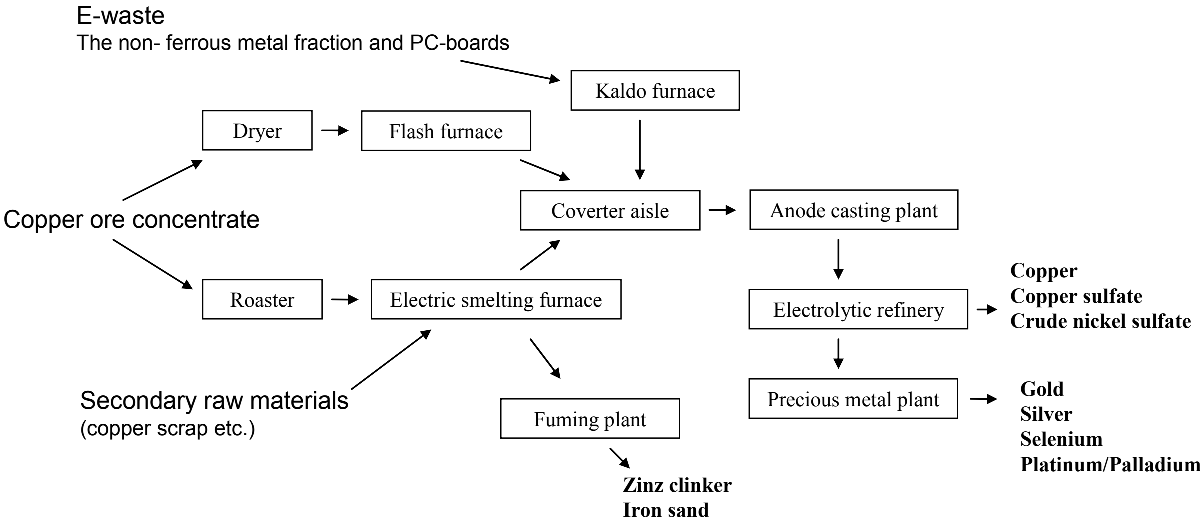


Figure 18. Schematic of the processes used to recover copper and precious metals from ore concentrate, copper scrap and e-waste at Boliden’s Rönnskär smelter in Sweden [Boliden 2010].

Hydrometallurgical processes are normally used for the final refining of the metals, following the pyrometallurgical processes, but they may also be used as an alternative to the pyrometallurgical processes. Although not yet widely used, hydrometallurgical processes have many advantages over pyrometallurgical processes, including being much less energy consuming as well as being more exact, more predictable and more easily controlled. The main steps in the hydrometallurgical processing consist of a series of acid or caustic leaches of solid material, which normally requires a small grain size to increase the metal yield. Leaching solvents are commonly solutions of cyanide, thiourea, thiosulfate, and sodium hydroxide and acids such as aqua regia, sulfuric acid, nitric acid, and hydrochloric acid. From the solutions, the metals of interest are then isolated and concentrated via processes such as solvent extraction, precipitation, cementation, adsorption, ion exchange, filtration and distillation [Cui and Zhang 2008, Antrekowitsch et al 2006].

9.1.4 Recycling of plastics

After metals, the plastics in e-waste have the greatest potential recycling value [Kang & Schoenung 2005]. Still, only a minor fraction (less than 25%) of all the collected e-waste plastics is actually being recycled. This is because plastics are very complex materials, consisting of numerous polymers and additives that make the recycling process very complicated [Schlummer et al 2007]. Different qualities thus have to be separated and unrecyclable fractions have to be removed before the recyclable plastics can be turned into new products, which today often mean low-grade products such as traffic cones, road material, outdoor furniture etc. The separation is usually performed by techniques such as sieving, density separation (in various aqueous or non-aqueous media), electrostatic separation (e.g. tribo-electric separation) and air-separation, in combination with various size reduction steps, such as grinding, milling and granulation [Kang & Schoenung 2005]. Paint and coatings are removed by further grinding, abrasion, solvent stripping and washing in high-temperature aqueous solutions, while other foreign materials are removed by similar methods as used for fragmented e-waste in general, i.e. magnetic separation, eddy current separation and air-separation. The separated plastics that are deemed recyclable may then be turned into new plastic products through processes such as melting, moulding and extrusion. There have also been attempts to develop alternative recycling methods for plastic materials such as pyrolysis and depolymerisation techniques with which the plastics are converted into coke, coke oven gas as well as other chemicals [Kang & Schoenung 2005]. However, it is uncertain to what extents these alternative recycling techniques have been used in larger scale applications.

However, as mentioned, the majority of the e-waste plastics are not being truly recycled. Much is instead incinerated in municipal waste incinerators with heat and energy recovery systems, while some are just dumped on landfills. In addition, a significant fraction is following the metal fraction to the smelter where it is combusted and thereby decomposed. This latter option may be justified by the argument that the plastic acts both as a fuel and a reducing agent in the smelter process, and thereby replaces some of the coke that normally is used [Kang & Schoenung 2005, Schlummer et al. 2007]. On the other hand, this activity contravenes with the current waste management practice, as well as the WEEE Directive of the EU, which stipulates that materials in e-waste (as well as in other waste fractions) should as far as possible be separated, recovered and reused in the production of new products [Allsopp 2006].

A report commissioned by the Swedish take-back system for electronic products (El-Kretsen) studied whether the ‘direct smelter route’ for mobile phones was environmentally and economically better or worse than the ‘disassembly route’ where the casing was manually removed for recycling [Huismann 2004]. The calculations in the report were based around sending the phones to Boliden's Rönnskär smelter for processing, considering transport costs and the costs for recycling. The report concluded that the 'direct smelter route' was the most eco-efficient process. However, it has later been criticized on a number of points by Ökopol, Institute for Environmental Strategies [Sander 2004]. This critic noted that the environmental effects of emissions from burning BFRs in the plastics were not considered, and that there were uncertainties with regard to the economic calculation because of a lack of transparency. In addition, it was questioned whether the calculations would be transferable to other smelters and whether the transport costs would be transferable to other countries.

9.2 Recycling of e-waste under uncontrolled conditions

The informal recycling sector in developing countries has one primary goal; to recover valuable materials in the e-waste, including copper, steel, plastics, aluminium, printer toner and PC-boards. The activities are often carried out in small workshops or just outdoors, using rudimentary methods [BAN & SVTC 2002]. In the processes used there is no real control over the materials processed, the performance of the processes or the emission generated. The typical processes used are:

9.2.1 Manual disassembly and recovery of valuable materials

The first step in the recycling process is the disassembly of the e-waste, which most often is carried out manually using tools such as hammers, chisels, screwdrivers, and bare hands. According to a report by the Basel Action Network and the Silicon Valley Toxic Coalition [BAN & SVTC 2002], the following components are separated for further recycling:

- Materials containing copper (including motors, wires and cables, CRT yokes).
- Steel (including internal computer frames, power supply housings, printer parts etc.)
- Plastics (including housings of computers, printers, faxes, monitors, keyboards etc.)
- Aluminium (printer parts, etc.)
- Printer toners (from spent toner cartridges)
- PC-boards

At this stage, the disassembly and recovery of valuable components from CRTs and PC-boards are of particular concern. The lead loaded CRTs are thus broken to remove copper yokes that are collected for further treatment and copper recovery. The broken CRTs are often dumped on open land after removal of the yokes [BAN & SVTC 2002]. In India, CRTs were reportedly smelted for recovery of glass, but prior to the treatment they were stored in an open area [Brigden 2005]. The common method to recover solder and other valuables from PC-boards is by heating the boards until the connecting solder is melted. Heating is normally done using coal grills, propane torches, kerosene burners, or other simple devices. Melted solder is then collected and individual components attached to the PC-boards are manually removed with pliers. Chips and other components are then sorted between those valuable for re-sale and those to be sent to the acid chemical strippers for precious metal recovery. Often the pins of the components to be re-sold are straightened and dipped in fresh solder to make them look new before they are traded. The collected solder is also sold. Waste boards stripped of chips are further burnt or acid digested in order to recover the remaining metals [BAN & SVTC 2002].

Figure 19: Collection, sorting and manual dismantling of electronic waste as it is performed in many developing countries, e.g. in China and Ghana (Photos: Top left: © Natalie Behring-Chisholm,Greenpeace, Bottom left: ©2006 Basel Action Network, Top right and bottom right: © Kate Davison, Greenpeace).

9.2.2 Acid extraction of metals

In both China and India, primitive hydrometallurgical processes are used to recover metals from e-waste [BAN & SVTC 2002, Brigden et al 2005]. PC-boards and other components are dissolved in strong acid solutions that are heated over small fires. The workers are then usually swirling the mixture for hours before the valuable metals can be precipitated and recovered from the solution. Common acids used are concentrated nitric acid and concentrated hydrochloric acid, either alone for extraction of copper and other metals, or in a 1:3 combination (giving aqua regia) for extraction of gold. The waste acids and sludges generated during these processes are often poured out and dumped on the open ground or into the water stream along which these facilities often are situated [BAN & SVTC 2002].

9.2.3 Shredding, melting and extrusion of plastics

Plastics are normally shredded into smaller pieces, where after it is separated (e.g. by color or density) and further grinded. Usually, children are employed for these tasks. The plastics may then be melted and extruded in order to be used for new applications. These operations are often carried out in rooms with insufficient ventilation by workers using no respiratory protection [Brigden et al 2005, BAN & SVTC, 2002]. A large portion of the e-waste plastics are deemed unrecyclable because of impurities and unmatched colors. These are dumped on piles or burnt on open fires [BAN & SVTC 2002].

9.2.4 Burning of plastics and residual materials

Some e-waste parts are burned on open fires to recover metals from the plastics in which they are encased. This includes plastic coated wires as well as other complex components [Brigden et al 2005]. This method is common by recyclers in both China and India, but is also used in African countries, such as Ghana [Brigden et al 2008], and also to some extent illegally in industrial countries [van Wijnen et al. 1992]. In Ghana, it was reported that the main fuel used to sustain these fires was insulation foam, primarily polyurethane, from obsolete refrigerators [Brigden et al 2008], which likely in itself will contribute to the emissions from these fires. Open burning of other wastes, unwanted scrap, and residues is also a common practice in many developing countries.

8.2.5 Toner sweeping

Toner cartridges are taken apart with screwdrivers to get hold of the residual toner inside them. The toner is collected in buckets using paint brushes, where after the empty cartridges usually are discarded directly on the ground. The activity usually creates clouds of toner that surrounds the unprotected workers [BAN & SVTC 2002].

9.2.6 Dumping of residual materials

A large portion of the e-waste is not recycled but is dumped on fields and other open areas as well as along rivers and wetlands. This dumped material consists of leaded CRT glass, burned and acid-reduced PC-boards, toner cartridges, dirty or mixed plastics, residues from recycling operations (including ashes from open burning operations) and spent acid baths and sludges [BAN & SVTC 2002].

Figure 20. Recovery of valuable materials in e-waste by manual sorting, heating and burning of the electronic equipment, as carried out in many developing countries, e.g. India, China and Ghana. (Photos from left to right: © Prakash Hatvalne,Greenpeace, ©2006 Basel Action Network, and © Kate Davison, Greenpeace).

10 Risks associated with end-of-life treatment of e-waste

End-of-life treatment of e-waste always leads to potential risks to human health and the environment. This is simply a consequence of the multitude of hazardous compounds that are present in EEE, and of the methods used to treat the waste. Landfilling and incineration of unsorted e waste are options that do not allow the removal of hazardous (or valuable) components, and may therefore potentially lead to leaching and emissions of all hazardous compounds in the e-waste. Recycling, involving the removal of hazardous compounds and recovery of valuable components, represents an opportunity both from environmental and resource conservation perspectives. However, since recycling processes seldom are perfect and completely removes all hazardous compounds from the waste, these processes are also associated with potential hazards and risks, and not least during the uncontrolled recycling activities carried out in many developing countries. In the following sections the risks associated with various end-of-life treatments of e-waste are discussed. The risks identified are also summarized in Table 6 below.

10.1 Risks associated with landfilling of e-waste

The risks associated with placing e-waste on landfills are due to leaching and evaporation of hazardous substances. The main problems in this context are the wide variety of substances the EEE contains as well as the long time spans involved. The hazardous compounds present in e-waste possess a wide range of properties, which means that their behaviours in the environment differ substantially. Consequently, it is difficult to avoid evaporation and leaching of all compounds at the same time, and it has therefore become a common knowledge that all landfills leak [BAN & SVTC 2002]. It is no guarantee that controlled landfills with liners and leachate collection systems completely eliminates the risks of pollution, even if the potential environmental impacts are considerably higher when e-waste is put on uncontrolled landfills [Jang &Townsend 2003]. In the latter case contaminated leachate may go directly to the soil, groundwater and surface water in the surroundings, and volatile compounds are exposed in open air. In addition, uncontrolled fires may begin at such landfills, posing additional threats to human health and the environment.

It is, however, difficult to assess the environmental consequences of e-waste in landfills due to the extreme complexity of the waste and long time spans of the processes involved. This may be the reason for the limited number of scientific studies available on this topic. However, the studies that are available show that leachate of e-waste, produced under simulated as well as natural conditions, often contain lead levels that exceed 5 mg/L, which is the toxicity characteristic limit for hazardous waste used in the U.S. [Townsend et al. 2008, Musson 2006, Jang &

Townsend 2003], and that other metals, i.e. copper, nickel antimony and zinc, also may leach to a relatively large extent [Lincoln et al. 2007]. Furthermore, high levels of BFRs as well as a number of unknown brominated compounds (possibly BFRs or breakdown products of such) have been found in landfill leachates [Townsend et al. 2003, Osako et al. 2004, Choi et al 2009], and also phthalate plasticizers such as DEHP, DBP and diethyl phthalate (DEP) [Slack et al. 2005]. In the studies by Osako et al. and Choi et al., it was also shown that the concentrations of BFRs were higher in leachates from landfills storing crushed e-waste compared to those storing uncrushed e-waste [Osako et al 2004], and that the leaching increased significantly in the presence of dissolved humic matter [Choi et al 2009].

Figure 21. Dump site for electronic waste in Accra, Ghana (Photo: © Kate Davison, Greenpeace).

Regarding the risk for vaporization of hazardous compounds from landfills, mercury is of particular concern. In fact, mercury has both the potential to leach as inorganic mercury compounds, and to evaporate as metallic mercury or as methylated mercury species [Lindberg et al. 2001]. Highly elevated levels of metallic mercury (or total gaseous mercury), monomethyl mercury and dimethyl mercury have thus been measured in landfill gases at various sites [Lindberg et al 1999, 2001, 2005]. The levels of total gaseous mercury were in many samples in the same range as the levels found in the plume gases from coal-fired power plants. The levels of monomethyl and dimethyl mercury were about 1000 times higher than the levels normally found in background air. The metallic mercury in these studies was probably to a large extent originating from discarded EEE, as it is estimated that about 70% of the heavy metals (including mercury and cadmium) found in US-landfills comes from discarded EEE [US EPA 2001]. Once buried, some of the inorganic mercury in the landfill is converted by inherent bacteria into the more toxic organic mercury compounds, which then also can be released into the atmosphere [Lindberg et al. 2001].

Overall, these studies suggest that various substances may leach from e-waste dumped in landfills, and considering the complex materials and processes involved as well as the long time spans implicated, long-term environmental effects can not be excluded. Indeed, toxic effects of e-waste leachates have been observed [Dagan et al. 2007]. For these reasons, landfilling of e-waste has been prohibited in many countries in the world, but is still commonly used in many other countries, e.g. USA [Kahhat et al. 2008].

10.2 Risks associated with incineration of e-waste

The risks associated with incineration of e-waste both involve the emissions of gaseous and particle bound pollutants (metals as well as organic compounds) via the exhaust gases, as well as leaching of pollutants from the residual ashes. These issues have received considerable attention in the scientific literature [Stanmore 2004, Lönnermark & Blomqvist 2005, Gullet et al 2007], and lots of efforts have been spent on trying to understand and minimize these emissions. It is no doubt that a multitude of pollutants are formed and released during the combustion process. However, it seems like at least the flue gas emissions are possible to control in modern incineration facilities by using process optimization and adequate flue gas treatment systems [Allsopp et al 2006, IGES 2009]. In these facilities, the ashes (and not least the bottom ashes) are probably of greater concern [Wang et al 2009].

Several studies have thus shown that incineration of e-waste leads to a substantial formation of both chlorinated and brominated, as well as mixed brominated-chlorinated, dioxins in the combustion zone, at the same time as the BFRs are destroyed, but also that the post combustion steps and flue gas treatment systems, that exist in modern incineration facilities, will remove or decompose most of these compounds before the flue gases reach their final exit [Funcke & Hemminghaus 1997, Menad et al. 1998, Söderström & Marklund 2002, Schüler & Jager 2004, Lai et al 2007, Watanabe et al 2008]. In some studies, however, no clear formation have been observed in the combustion zone either, indicating that the combustion process itself also can be optimized to efficiently decompose the pollutants in the original material without forming any new ones [Vehlow et al 2000, Sakai et al 2001, Tange & Drohmann 2005].

In addition to the dioxins, a wide variety of other organic pollutants are formed and emitted from combustion processes. This include other chlorinated and brominated compounds, such as chlorinated and brominated benzenes and phenols, as well as a large number of non halogenated compounds, such as PAHs [Lönnermark & Blomqvist 2005, Cormier et al. 2006, Gullett et al 2007]. Furthermore, a wide range of metals may be emitted during e-waste combustion. For example, in a study by Steward and Lemieux [2003] substantial amounts of copper, lead and antimony, as well as lesser amounts of cadmium, manganese, nickel, barium, arsenic, chromium, cobalt and beryllium were emitted during incineration of chipped PC-boards in a rotary kiln incinerator. Also, in studies by Gullett et al [2007], and Lönnermark & Blomqvist [2005] a similar set of metals were found in the fly ash and exhaust gases during combustion of e-waste in open burning and simulated accidental fire experiments, respectively. Large amounts of lead, copper and antimony, in particular, but also of zinc, tin, arsenic, nickel and chromium, were thus emitted. In addition, both Steward & Lemiuex [2003] and Gullett et al. [2007] found high levels of several metals in the residual ashes, e.g. copper, lead and tin, and in both these studies the ashes failed a toxicity characteristic leach profile (TCLP) leaching test because of soluble lead.

Similarly to the dioxins, the emissions of these other pollutants may be minimized in modern incineration facilities by process optimization and adequate flue gas treatment systems, at least if we ignore the potential leaching from the bottom ashes. However, during open burning activities none of these precautionary measures are taken and consequently the emissions are usually much larger. In fact, due to the poor and variable combustion conditions and the complexity of the e-waste as a fuel, the conditions for formation and emission of pollutants are often optimal in such fires [Evans & Dellinger 2003, Gullett et al 2007]. Indeed, very high emissions of PCDD/Fs and PBDD/Fs were observed in the study by Gullett et al. [2007]. The PCDD/F emissions were in this case particularly high during the open burning of insulated wires (around 12 000 ng TEQ/kg of wire), likely due its high PVC content, while the PBDD/F emissions were higher during the burning of PC-boards, possibly due to its BFR content. Very similar results were also obtained by Leung et al. [2006] during open burning tests, i.e. high emissions of PCDD/Fs from PC-boards and extremely high emissions from insulated wires. The latter was about three orders of magnitude higher than the emissions measured during open burning of household waste. Regarding PBDD/F, extremely high emissions have been observed during open burning of TV-sets [Zelinski et al 1993, Lundstedt 2009]. In the study by Lundstedt, the total levels of PBDD/F in the soot were 10 000-100 000 times higher than the total levels of PCDD/Fs.

In summary, incineration of e-waste, and especially if it is carried out under uncontrolled conditions, may lead to large emissions of a variety of hazardous substances that may pose a risk to humans and the environment directly exposed to the emissions, and also contribute to the global spreading of some compounds. Furthermore, even if the results indicate that e-waste can be incinerated efficiently in modern incineration facilities, with relatively low emissions as a result, this is no longer an available option in many countries due to the regulations that demand recycling of materials. In EU, for example, the recycling and recovery quotas set by the WEEE directive, ranging from 50-75% for recycling and 70-80% for recovery, can not be achieved without including combustible fractions such as plastics into the recovery or recycling systems. On the other hand, incineration with energy recovery is a good alternative when other recycling techniques are not possible, e.g. for the last residual fraction, and could also be considered as a complement to mechanical recycling of plastics.

Regarding health effects on humans, emissions from incineration processes may, among others, result in respiratory and pulmonary effects (including decreased lung function as well as inflammatory and immune responses), cardiovascular effects (including inflammation and increased cardiovascular mortality), genotoxic effects, reproductive effects as well as estrogenic effects [Cormier et al. 2006, Owens et al. 2007].

10.3 Risks associated with recycling of e-waste under controlled conditions

Although the risks associated with recycling of e-waste in controlled recycling facilities are limited and probably also decreasing, due to new regulations, new technical development and decreasing amounts of hazardous substances in the e-waste, several risks still exist as many hazardous compounds still are present.

10.3.1 Risks associated with collection and dismantling

The risks that appear during collection of e-waste are mainly that hazardous substances are accidentally released or spilled due to breaking of components that exposes previously encapsulated material. During dismantling substantial amounts of dust, containing hazardous substances, may also be generated and released [IGES 2009]. Of particular concern is:

- Release of mercury as a result of breakage of components such as light sources (e.g. fluorescent tubes in scanners and photocopiers, and backlights in LCDs) and switches. A study carried out in the US found that 17-40% of the mercury in broken low-mercury fluorescent bulbs is slowly released to the air over a two-week period following breakage, and almost one third of it is lost the first 8 hours [Aucott et al 2003]. Depending on the incoming waste supply, persistently elevated airborne levels of mercury are likely to exist in the vicinity of broken bulbs, and it is conceivable that the levels could exceed occupational exposure limits for inhalation.
- Release of fine dust containing phosphors of various compounds as well as barium oxide and lead as a result of CRT breaking, which pose inhalation hazards to the workers. First of all, the phosphor coating on the inner side of the CRT glass may be dispersed and inhaled if managed in dry state. Wet processes are therefore often used to remove the phosphors. Second, barium oxide dusts may be released if not the electron gun getter is carefully removed prior to shredding. Finally, glass dust containing lead is produced as the CRT glass is crushed, by mistake or for further recycling. Besides this, there is also a physical risk associated with the handling and dismantling of CRTs, due to the vacuum inside the CRTs that may cause implosions [IGES 2009].

- Release of various hazardous compounds due to the use of pneumatically operated power tools, mobilizing dust accumulated within the EEE. For example, elevated air-concentrations of PBDEs and TBBPA have been measured at two dismantling/recycling facilities in Sweden [Sjödin et al 2001, Hovander et al 2001]. In one of the facilities it was also shown that the workers had elevated blood levels of these compounds [Sjödin et al 1999]. However, this may also be due to exposure to dust generated during the subsequent shredding process (see below).

Besides these direct risks arising during collection and dismantling, a poor accomplished dismantling step, with incomplete removal of the hazardous components, will give problems at later stages in the recycling chain.

10.3.2 Risks associated with mechanical shredding and separation

The mechanical shredding and separation steps will always generate dusts to some extent, and sometimes also fumes, of the components being processed. Dusts of plastics, metals, ceramics, glass, and silicon may thus be emitted during these processes [MJC & Associates 2004].

The dust may pose risk of inhalation and dermal exposure to workers as well as risk of environmental contamination. The inhalation of dusts may, as a minimum, lead to aggravation of respiratory difficulties (e.g. a person pre-disposed with emphysema, chronic obstructive pulmonary disease, etc.), but also to intoxication as a result of the exposure to the chemicals in the dusts [Koskela et al.2005, Cormier et al. 2006]. For example, shredding of plastics will give rise to dust containing various organic compounds, such as BFRs, but also metals that may be present in the plastic as additives.

There is scientific evidence that hazardous substances are released during mechanical processing of e-waste. For example, in a study by Peters-Michaud et al. [2003], cadmium and lead levels as high as 0.27 and 1.4 µg/m3, respectively, were measured in the vicinity of the shredders in a modern US based e-waste recycling facility. Morf et al. [2005] found milligrams per gram of various BFRs (particularly PBDEs) in the fine dust fraction recovered in the off-gas purification system of a Swiss recycling plant engaged in mechanical treatment of e-waste. Takigami et al. [2006] found elevated levels (as compared to background) of BFRs (PBDEs, TBBPA and HBCD) and PBDD/Fs in the air of a TV recycling facility, and the levels were particularly high (two orders of magnitude higher) in the vicinity of the shredder. Sjödin et al. [2001] found a similar distribution of both BFRs and organophosphorus flame retardants in the air of one of the aforementioned e-waste recycling facilities in Sweden, i.e. elevated levels in the whole facility but highest in the vicinity of the shredder. Finally, Sjödin et al. [2001, 2003] found higher blood levels of PBDEs in workers of various e-waste recycling facilities in Europe than in other workers, which they concluded was a result of inhalation of contaminated dust.

10.3.3 Risk associated with pyrometallurgical processing

The emissions from pyrometallurgical processes are in many ways similar to the emissions from incineration processes. A wide spectrum of hazardous compounds, including both organic compounds and metals, may thus be released to the atmosphere from these processes. Of particular concern are the emissions of lead, cadmium, mercury and beryllium, as well as BFRs and brominated and chlorinated dioxins [Allsopp 2006]. The organic compounds are formed because the metal scrap generally contains considerable amounts of plastics as well. Although, the emissions are possible to control through process optimization and off-gas treatment, similarly to regular incineration processes, very few of today's smelters are designed in that way [IGES 2009]. This is particularly true for standard copper smelters, designed for refining mining concentrates and simple copper scrap, while new integrated metal smelters, designed for treating e-waste, are better suited as they are using high temperature burning (1200-1300°C) in combination with rapid gas cooling, and efficient flue gas treatment systems [Allsopp et al. 2006].

The emission of metals has, among others, been assessed in two studies at the copper smelter of Noranda Inc. in Quebec, Canada, which uses e-waste as one of its feedstock. Telmer et al. [2004] monitored the levels of 35 different elements in snow up to a radius of 50 km around the smelter, and found the concentrations of many of the elements to be elevated, compared to background levels, even at the longest distance from the smelter.

The concentrations were, however, higher closer to the smelter, where the levels of copper, lead and zinc for instance, were 500, 200 and 100 times higher than regional background concentrations, respectively. Zdanowicz et al. [2006], measured the elemental composition of particulate matter in air and snow near the same smelter, and found that 58% of the particles in the smelter plume were metal-bearing, which should be compared to around 15% in ambient air and snow. The dominant metal-bearing particle type in snow was iron-sulphur-copper, but zinc sulphide, iron sulphide and copper sulphide were also common. Lead was dominant in air-filtered particles, even those collected far (>60 km) from the smelter.

Regarding organic compounds, emission data in the scientific literature are scarce for large scale pyrometallurgical recycling facilities that use e-waste as one of its feedstocks. However, one study from China [Du et al 2009], in which fly ash from an electric arc furnace have been analyzed, show that the emissions of both PCDD/Fs and PBDD/Fs can be significant (1.6 and 0.29 ng I-TEQ/g fly ash, respectively). In addition, in a study from Taiwan [Wang et al. 2008], it was shown that the atmospheric concentrations of PCDD/Fs and PBDD/Fs were higher in an industrial area, in which several metallurgical industries were situated, as compared to concentrations measured in urban areas in general as well as in rural areas. On the other hand, in that study, even higher PBDD/F-levels were measured in a science park area where several electronic manufacturing industries were situated. Besides that, very little data exist regarding emission of organic compounds from metallurgical processes, but as discussed above, there are many studies showing that thermal treatments of bromine and chlorine containing materials (e.g. flame retarded plastics) in general, may lead to substantial release of both chlorinated and brominated dioxins and also of BFRs (see section above regarding risks associated with incineration).

10.3.4 Risks associated with hydrometallurgical processing

The hydrometallurgical processes generate acid fumes, liquid acid wastes and other toxic aqueous solutions (e.g. cyanide) [Cui & Zhang 2008]. Acid fumes, which mainly is an occupational problem, are hazardous to human health because they are generally irritating to the upper respiratory system, and because they may cause direct damage to the pulmonary tissue if reaching the lungs [MJC & Associates 2004]. The liquid wastes are often highly corrosive, and are also of environmental concern as they may cause severe metal pollution if disposed improperly [Cui & Zhang 2008].

10.3.5 Risks associated with recycling of plastics

For a complete recycling of plastics, including the production of new plastic products and various chemicals, some kind of thermal treatment is generally needed, e.g. melting, extrusion, moulding, depolymerisation, and pyrolysis. During such processes there is a risk that BFRs are transformed into highly toxic brominated dioxins. This has been shown in a number of studies reviewed by Ebert & Bahadir [2003] and by Weber & Kuch [2003]. The extent of PBDD/F-formation seems to be influenced by the temperature and the duration of the process, as well as by the presence of precursors such as PBDEs. Much less PBDD/Fs are thus formed if the BFR in the plastic consist of TBBPA for instance. The PBDD/Fs formed, may leak and evaporate from the plastics (possibly together with BFRs and other compounds) during the recycling processes as well as during the use and disposal of the new products.

Recycled plastics may thus end up in various products, and even in children’s toys. Indeed, in a study by Chen et al. [2009], a number of BFRs were found in children’s toys, of which some probably originated from recycled plastics. In the same study, it was also shown that significant amount of the BFRs present may be transferred to the children as the toys are used.

10.4 Risks associated with recycling of e-waste under rudimentary conditions

As the main goal with the e-waste recycling in developing countries is to recover the valuable components and materials, little regard is paid to impacts on the environment and human health. The rudimentary methods used are highly uncontrolled and consequently the emissions of toxic compounds may be large [BAN & SVTC 2002, Brigden et al 2005, 2008].

10.4.1 Risks associated with manual dismantling and the recovery of valuable materials

The risks associated with the manual dismantling processes used in developing countries are in many ways similar to those in developed countries, but differ in that the processes in the developing countries seldom are carried out in facilities adapted for its purpose, and that the workers most often are lacking protective clothing [BAN &SVTC 2002]. The workers as well as the environment may thus be exposed to large amounts of fumes and dusts containing hazardous compounds. For example, during the breakage of the CRTs the workers may be exposed to the phosphor powder covering the inner surface of the front panel, the barium oxide in the electron gun and the lead present in the glass. Since the broken CRTs often are dumped directly on the ground, there is also a risk that large amounts of lead, zinc and other compounds may leach to the environment [Musson et al. 2000]. Indeed, elevated levels of lead, zinc and yttrium have been reported in soil at CRT recycling sites in India [Brigden et al. 2005].

The heating of PC-boards is another manual dismantling activity that undoubtedly will expose the workers as well as the environment to a wide range of hazardous compounds. As the PC-boards are heated, fumes of metals, particularly lead and tin present in the solder, and other hazardous compounds, e.g. BFRs, will evaporated from the boards, and directly expose the workers carrying out this activity. Furthermore, when the stripped PC-boards are dumped on the ground afterwards, they may continue to leach hazardous compounds to the environment. In fact, PC-boards may be as bad as or even worse than CRT-glass in terms of lead leachability [Jang & Townsend 2003].

The breakage of toner cartridges and toner recovery activities are also of concern, even if this activity mainly constitutes an occupational problem. The workers that are doing this toner sweeping are constantly surrounded by a cloud of black toner, but are seldom wearing any protective clothing or respiratory protection [BAN & SVTC 2002]. Although the dust doesn’t contain any direct toxins, besides the black carbon that may be carcinogenic [IARC 1996], it will as any fine dust cause respiratory tract irritation [Koskela et al.2005, Cormier et al. 2006].

The emissions of toxic compounds during rudimentary component separation and solder recovery have been shown in a study by Brigden et al. [2005]. Dust samples collected from the floors of several workshops in China and India were found to contain high levels of a variety of metals, as compared to background levels, particularly lead and tin, but also copper, antimony and in some cases cadmium and mercury. The lead levels were many times hundreds of times higher than typical levels found in indoor dusts in other parts of the world. One extreme sample from China contained 29% by weight tin, 7.6% lead and 1.1% copper, and another one from a battery dismantling workshop in India 8.8% by weight of lead and 20% cadmium. This last figure is around 40 thousand times higher than levels typical for indoor dust samples. PCBs and PBDEs were also found in some samples. Even in the home of the solder-workers the levels of certain metals found in dust, i.e. copper, lead, tin and antimony, were elevated compared to houses with no connection to this activity. Similarly, Leung et al. [2008] found highly elevated levels of lead, copper, zinc and nickel in dusts from PC-board recycling workshops and adjacent roads in the e-waste recycling village Guiyu in China. For example, the concentrations in the dust exceeded the New Dutch List action values by 43-389 times for lead, 6-188 times for copper and 1.4-14 times for zinc. In addition, they found elevated levels of several of the metals at a local food market and a school yard in the village showing that public places were also adversely impacted. Both lead and copper were in this case predicted to potentially pose a serious health risk to the workers and local residents of Guiyu, especially children.

10.4.2 Risks associated with acid extraction of metals

The primitive acid treatment processes used to extract metals from e-waste in developing countries will expose the workers to fumes of acids and various volatile compounds as they lean over their solutions while swirling them for hours. The fumes will cause irritation to the respiratory tract as well as intoxication by various compounds. The environment will also be affected by this activity since the waste acids and sludges generated during the processes often are poured out or dumped on the open ground or into streams and rivers along which these facilities often are situated [BAN & SVTC 2002]. This cause severe pollution as the waste generally contains a wide range of hazardous compounds as well as partly disintegrated electrical components.

The environmental contamination from acid leaching activities has been documented in a number of studies [Brigden et al. 2005, Leung et al. 2007, Wong et al. 2007b, 2007c]. For example, in a study by Brigden et al. [2005], samples of acidic solid waste collected from open pits within two facilities located in Longmen village in China, engaged in acid processing/leaching of e-waste, contained very high levels of several heavy metals, including lead, tin, copper, antimony, and nickel. The levels of copper, lead and tin were more than 100 times higher than typical background values for uncontaminated soils and sediments. Some sediments were also found to contain residues of chlorinated benzenes, PCBs, PBDEs and phthalate esters. Furthermore, highly acidic wastewater from the same source was found to contain phthalate esters, derivatives of TPP and high levels of several metals. The river water downstream one of the facilities was also found to contain elevated levels of both metals and organic contaminants. For example, the levels of antimony, mercury and nickel were 20 times higher downstream the facility than upstream the same facility, and for cadmium the difference was 10 times. Similar contamination was also seen in river sediments adjacent to two other acid leaching facilities in China, i.e. with metal concentration reaching 100 times the concentration found in an unpolluted river in the region. Also, in India, a similar contamination pattern was seen at an acid leaching facility in the Mandoli industrial area in New Dehli [Brigden et al 2005]. Furthermore, in a study by Leung et al. [2007], soil at an acid leaching site in Guiyu was found to be heavily contaminated with both PBDEs and PCDD/Fs, i.e. the levels were about 1000 times higher than background levels.

Another set of samples worth mentioning were collected adjacent to an acid leaching facility along the Lianjiang river in the Guiyu region [BAN & SVTC 2002]. These revealed lead levels in the water that were 2400 times higher than the WHO Drinking Water Guidelines, and a sediment concentration of the same compounds that was 212 times higher than what would be treated as hazardous waste if it had been dredged from the Rhine River bottom in the Netherlands. Likewise, other heavy metals found in PC-boards and CRTs were found in very high quantities. Barium was found at levels almost 10 times higher than an EPA threshold for environmental risk in soil, and tin and chromium at levels 152 times and 1338 times the EPA threshold, respectively. Copper in one sample reached astounding 13.6% of the total.

Figure 22. Site in Guiyu, China, where metals are extracted from PC-boards and other components, using strong acids such as aqua regia. (Photo: ©2008 Basel Action Network).

10.4.3 Risks associated with shredding, melting and extrusion of plastics

The recycling of plastics may generate dust during shredding and toxic fumes during melting and extrusion. This may particularly expose the unprotected workers for hazardous compounds but the surrounding environment may also be contaminated. The melting and extrusion processes may, for example, generate both chlorinated and brominated dioxins, as discussed previously. Indeed, very high levels of PBDEs, PCDD/Fs, PBDD/Fs and PBCDD/F have been found in the soil at a PC-board smouldering site in Guiyu [Yu et al. 2008, Zennegg et al 2009]. Highly brominated PBDFs were particularly abundant at that site indicating that commercial decaBDE was responsible for a large part of the dioxin formation here [Weber & Kuch 2003].
Furthermore, sediments accumulating in discharge channels arising from mechanical shredding facilities in Guiyu generally contained very high levels of heavy metals as well as complex mixtures of organic contaminants [Brigden et al. 2005]. For copper, lead, tin, nickel and cadmium, the levels were between 400-600 times higher than would be expected for uncontaminated river sediments. For antimony, the levels were about 200 times higher than background. Waste water, consisting of thick slurry of particulates suspended in water, from these facilities were also found to contain high concentrations of metals. Several PBDEs, nonylphenol, phthalate esters (e.g. DBP and DEHP) and TPP and related compounds were also found in these samples. In one of the sediments, a number of chlorinated and mixed chlorinated/brominated benzenes and chlorinated naphthalenes were found as well.

In studies by Ma et al. [2008, 2009a, 2009 b], high levels of PCDD/Fs, PBDDFs, PBDEs and chlorinated as well as unsubstituted PAHs were found in electronic shredder waste, workshop dust, soil and vegetation from Taizhou in China. The samples from the e-waste recycling sites contained significantly higher levels of the contaminants than samples from a chemical-industrial complex in eastern China and those from agricultural areas at various places in China. Although the PCDD/F-levels were high in the samples, the TEQ calculated for both PBDD/Fs and chlorinated PAHs contributed more to the total dioxin like toxicity in dust and soil than the PCDD/Fs themselves. The profiles of cl-PAHs in dust and soil were similar to a profile that has been reported previously for fly ash from municipal solid waste incinerators, indicating that the emission source might be a thermal process as well as the shredding process.

10.4.4 Risks associated with burning of plastics and other materials

The open burning of plastics and other residues from the recycling process may lead to severe contamination of the environment. The compounds formed and emitted are potentially the same as the ones formed and emitted from controlled incineration facilities, but under uncontrolled conditions much larger amounts are normally emitted (see above).

Thus, in studies by Brigden et al. [2005, 2008], Labunska et al. [2008] and Wong et al. [2007a], high levels of a variety of pollutants have been found in soil and ashes collected at e-waste open burning sites in China, India, Ghana and Russia. The levels of individual compounds were variable depending on the components being burned and the techniques used. However, cadmium, copper, lead, zinc and antimony were common in many samples (sometimes the levels were more than 100 times higher than typical background levels), as well as PBDEs, PAHs, PCDD/Fs, PCBs and various other chlorinated and brominated compounds. Some of the latter probably originate from their use as flame retardants in certain plastics while other likely have been formed during the combustion process. Regarding PAHs, Yu et al [2006] also found high levels in soil from open burning sites in Guiyu, which is a result of incomplete combustion processes. In general, the levels of contaminants found at open burning sites were higher than the levels found at other sites.

In terms of dioxin contamination at open burning sites, high levels have been reported in several studies. For example, Leung et al. [2007] and Wong et al [2007a] reported concentrations ranging between 84-174 pg TEQ/g and 627-13900 pg TEQ/g (based on dry weight), respectively, in soil and combustion residues from open burning sites in the Guiyu region in China. This is far above the levels found in unpolluted soils, which commonly is below 1 pg TEQ/g and rarely above 10 pg TEQ/g, including lightly polluted urban and industrial soils [Zhu et al 2008]. High dioxin concentrations, 988 and 32 600 pg TEQ/g, have also been found in river sediments affected by open burning activities in Ghana [Brigden et al. 2008], and Guiyu [Luksemburg et al. 2002], respectively. These levels are far above the concentrations normally found in lake and river sediments in most countries, even at moderately polluted locations, which generally are below 20 pg/g TEQ [Liu et al 2007, El-Kady et al 2007]. The dioxin levels measured in soil and sediment at many of these open burning sites are also exceeding the 1000 pg TEQ/g threshold level defined as being indicative of serious contamination for soils and sediments in the Netherlands [NMHSPE 2000], and also the levels used for soil in the U.S. to assess the need for clean up of a site [USEPA 1998].

In addition to PCDD/F, high levels of PBDD/Fs and PBCDD/Fs have also been found at open burning sites. For example, Zennegg et al. [2009] and Yu et al [2008] found very high levels of PBDD/Fs and PBCDD/Fs, accompanying PCDD/Fs and PBDEs, in soil at e-waste open burning sites in Guiyu. The dioxin contamination was actually dominated by PBDFs and PBCDFs, with less contribution from purely chlorinated compounds as well as from dibenzo-p-dioxins in general, indicating a formation from PBDEs (as a direct PBDF precursor) as a major pathway, but also that chlorine-bromine substitution reactions have been important [Weber & Kuch 2003]. Moreover, the results show that brominated compounds most likely contribute significantly to the dioxin-like toxicity at these sites, which was further indicated in the study by Yu et al. [2008] by results from the DR CALUX assay, showing that the PCDD/F-levels in the soil only explained a small fraction of the toxic responses in the samples. However, the PCDD/F levels found in this study still exceeded international limits for dioxin contaminated soils where remediation is required, even for industrial sites.

Figure 23. Burning of e-waste directly on the on the ground to recover valuable metals, Accra, Ghana (Photo: © Kate Davison, Greenpeace).

Figure 24. Ashes from burned e-waste covered with sand and dumped besides the Langjiang river in Guiyu, China (Photo: ©2008 Basel Action Network).

10.4.5 Risks associated with the dumping of residual materials

The widespread dumping of residual materials of e-waste that are deemed unrecyclable, have undoubtedly also lead to severe contamination of the environment in and around the recycling districts in many developing countries. The evaporation and leaching of contaminants from these dump sites probably contribute significantly to the local as well as the global pollution for some compounds. For example, elevated levels of a number of hazardous substances, including PAHs, PBDEs, PCBs and various heavy metals, have been measured in the soil and sediments from a printer roller dump site and a burnt plastic dump site in the Guiyu region in China [Leung et al 2006]. The PBDE concentrations in the soil at the two sites were 1169 and 1140 µg/kg, respectively, which is 10-60 times higher than other PBDE-contaminated locations in the world, while the copper concentrations at the two sites were 496 and 712 mg/kg, respectively, which is above the new Dutch list action value of 190 mg/kg. Furthermore, the soil at the printer roller dumpsite contained 102 µg/kg PCB, which is above the allowable levels of 60 µg/kg for PCBs in ambient soil stipulated by the former USSR Ministry of Health in 1991, but below The Dutch action value of 1000 µg/kg. The river sediment adjacent to the dumping sites contained 743 µg/kg of PCBs, which exceed the Canadian probable effect level guideline by 2.7 times, and also high levels of PBDEs.

10.5 Other examples of pollution caused by rudimentary e-waste recycling

As a result of the huge amounts of e-waste processed in many developing countries in combination with the rudimentary methods used, the environment at many places in countries such as China, India and Ghana has become severely contaminated. This has been documented in a number of studies, some of which are reviewed below. As the situation has been particularly well documented for Guiyu, a town made up of several villages in the Chaozhou region of the Guangdong province in the southeast of China, the majority of the examples in the following as well as the preceding sections of this report are dealing with this region. However, examples from other places are also presented, as well as some evidence that the emissions are subject to long range transport that will make significant contributions to the regional as well as the global pollution.

10.5.1 Soil and sediment contamination connected to e-waste recycling

In the Guiyu region, elevated levels of a variety of pollutants, e.g. PBDEs, PCDD/Fs, PAHs, PCBs and various heavy metals, have been observed in soil and sediments at several places that are not directly connected to the e-waste recycling activities, e.g. rice fields, duck ponds, river tributaries and various remote areas [Leung et al. 2006, 2007, Wong et al. 2007a]. For example, in the rice fields the concentrations of the predominant PBDE congener, BDE#209, were 79-3973 times greater than background soil value measured in southern Sweden, and the dioxin and PAH-levels all exceeded the Canadian soil guideline value (4 pg TEQ/g d.w.) and the Dutch target value for unpolluted soil (20-50 µg/kg), respectively. Furthermore, concentrations of cadmium, copper, nickel and lead in sediments of the water gullies connected to the rice fields exceeded the New Dutch List Optimum Values for these metals, and PBDE levels in several sediment samples were higher than the levels found at many confirmed contaminated sites in the world.

In another study, Liu et al. [2009] found elevated levels of several phthalate esters, e.g. DEHP, DEP, DBP, dimethyl phthalate (DMP), and di-n-octyl phthalate (DnOP), in soil samples from Taizhou city in China, which is another major e-waste recycling centre in the country. The levels found were about one order of magnitude higher than previously measured levels in Denmark for instance.

10.5.2 Water contamination connected to e-waste recycling

Freshwater systems have also been affected by the intensive recycling activities in Guiyu. For example, Wong et al. [2007b, 2007c] found elevated levels of a number of metals, including cadmium, copper, nickel, lead and zinc in water and sediments in the Lianjiang and Nanyang rivers within the Guiyu region, as compared to a control reservoir outside the region. The elevated metal levels were suggested to be a result of the acid leaching processes used along the rivers, but the sources of the contaminants were probably diverse, although undoubtedly a result of the e-waste recycling activities. Furthermore, Luo et al. [2007] found elevated levels of PBDEs in sediments and fish of the same two rivers. The PBDE concentration in one of the fish species was around two orders of magnitude greater than that of the same fish species collected from a Hong Kong stream containing waste water. In a study by Wu et al. [2008], elevated levels of PBDEs and PCBs were found in water and a number of wild aquatic species, including Chinese mysterysnail, prawn, fish and water snake, collected from a reservoir surrounded by several e-waste recycling workshops in Longtang town in south China. Guan et al. [2007] found high levels of PBDEs in riverine runoff from eight major outlets within the Pearl River Delta in China. The sampling sites were in this case not in the direct vicinity of any large e-waste recycling area, but the elevated PBDE levels were still found to be connected to recycling activities in the region. The PBDE concentrations were in the high end of the global PBDE concentrations in aquatic environments. The annual input of the 17 measured PBDEs from all the outlets was estimated at 2140 kg/year, mainly originating from e-waste recycling activities.

The rudimentary e-waste industry is also deteriorating the local drinking water supply at many places. In Guiyu, drinking water have been trucked in from the town of Ninjing, 30 kilometres away, since the mid-1990ties [BAN & SVTC 2002], due to the pollution caused by the recycling activities. Among others, groundwater levels of lead exceeding the WHO drinking water guidelines by 6.3 times have been measured [Sepúlveda et al. 2009].

10.5.3 Air contamination connected to e-waste recycling

Many of the processes used within the informal e-waste recycling sector, including grinding, melting, roasting and open burning, certainly generates large amounts of dust, fumes and smoke that are emitted to the atmosphere. These emissions are contaminating the local environment, but are also subject to long-range transport and are thereby contributing to the regional as well as the global pollution. Indeed, elevated concentrations of both metals, PAHs and PBDEs have been reported in the air around Guiyu [Deng et al. 2006, 2007]. In these studies, the levels of chromium (1152 ng/m3), copper (126 ng/m3) and zinc (924 ng/m3) in the fine particulate fraction of air were 4-33 times higher than in other Asian metropolitan cities, such as Tokyo, Shanghai, Ho Chi Minh City, Taichung and Seoul. The PAH levels (11 PAHs) in the same particle fraction were 20 times higher than levels measured in Hong Kong and 1-6 times higher than the levels in Guangzhou, the latter being widely acknowledge as one of the most polluted cities in China. Furthermore, PBDE-levels (17 ng/m3 of 22 congeners) were 58-691 times greater than those found in Gaungzhou and Hong Kong, and at least 100 times greater than at other sites worldwide. In another study, Li et al [2007] measured the atmospheric dioxin concentrations around Guiyu, and the levels they found were actually the highest ever reported for these compounds in ambient air worldwide (64.9-2365 pg/m3 in total and 0.909-48.9 pg TEQ/m3). In addition these samples were found to contain high levels of PBDD/Fs. The severe dioxin pollution seen in this study was also found to influence adjacent areas in China, so that the atmospheric dioxin levels in the surroundings exceeded those of several common urban areas in the world. Likewise, Zhao et al. [2009] showed, by using leaves (Cinnamonum camphora) as biomonitors, that PBDEs are diffusing from the e-waste centres in the Taizhou region in China at least 74 km away.

10.5.4 Human exposures and health effects

There is no doubt that the unregulated recycling industry severely contaminates workplaces as well as the environment in the recycling centres in many developing countries, leading to exposure of particularly the recycling workers and the local residents in these areas. Inhalation of fumes and dust together with dust ingestion have been suggested as the most important routes of human exposure to hazardous compounds at these places [Leung et al. 2008], even if dermal exposure and exposure via dietary intake also may be significant [Leung et al. 2006]. Leung et al. [2008] conducted an assessment of the risk from ingestion of contaminated dust from recycling workshops and adjacent environments in Guiyu. The assessment was based on the metal concentrations in the dust, and it revealed that this exposure route may pose serious health risks to the workers and local residents in Guiyu, particularly because of the content of lead and copper in the dust. For a PC-board recycling worker, the estimated oral average daily dose (ADD) of lead exceeded the “safe” oral reference dose by 50 times, and for children the risk was estimated to be even higher. Furthermore, in the aforementioned study by Li et al. [2007], a risk assessment was conducted to estimate the risk from the inhalation of PCDD/Fs in ambient air in Guiyu. The assessment showed that the residents in the area are at high risk, as their intake of PCDD/Fs through inhalation are 15-56 times higher than WHOs recommended Tolerable Intake Level of 1-4 pg kg-1day-1.

The high exposure of the people living and working in the recycling areas in developing countries have also been verified by the contaminant levels found in their bodies. For example, in a study by Huo et al. [2007], 82% of the children younger than 6 years old living in Guiyu were found to have a blood lead level (BLL) that was greater than or equal to the Chinese average of 9.29 mg/L. The average in Guiyu was 15.3 mg/L and the highest measured was 32.7 mg/L. In the neighbouring Chendian, where textiles is the dominant trade and no e-waste processing occurs, the BLLs in a matching group of children was 9.94 mg/L on average. The highest mean level in Guiyu was found in a village housing several workshops specialized in dismantling, circuit board baking and acid bath leaching, indicating that some activities involve a greater exposure risk. Zheng et al. [2008] found similar elevated BLLs in children from Guiyu as compared to children from Chendian, and in this study cadmium was seen to follow the same trend. In a study by Li et al. [2008], neonates in Guiyu were found to have elevated levels of chromium in their blood and also higher rates of chromium induced DNA-damage of cord blood lymphocytes as compared to a control group in Chaonan where the fishing industry is dominating. In both the studies by Zheng et al. and Li et al. the high blood metal levels measured were found to correlate with their parent's engagement in the e-waste recycling business.

Elevated blood levels of PBDEs have also been observed in Guiyu [Bi et al. 2007, Qu et al. 2007]. Bi et al. found three times higher PBDE levels in the blood of Guiyu residents than in the blood of those from the nearby Haojiang region where the fishing industry dominates. Qu et al. found 11-20 times higher PBDE levels (when comparing the highly brominated congeners) in the blood of workers in Guiyu as compared to a control group with no known occupational exposure. In both these studies the levels of decaBDE (PBDE#209) were exceptionally high, peaking at 3100 and 3436 ng/g blood lipid, respectively, which are the highest levels ever reported in humans. Outside Guiyu, the highest reported levels worldwide for decaBDE is 270 ng/g blood lipid, found in a worker occupationally exposed to flame retarded rubber in Sweden [Thuresson et al 2005].

In terms of PCBs and dioxins, Zhao et al. [2007] and Chan et al. [2007] found elevated levels of these two compounds classes in maternal cord blood, meconium (the first faeces passed by a new born baby), human milk, placenta and hair in mothers and new born babies from the e-waste town Luqiao in China, as compared to those from other areas where no known e-waste industry exists. For example, the PCDD/F concentrations in hair and placenta (34 pg WHO-TEQ/g d.w. and 31 pg WHO-TEQ/g fat, respectively) were 6 and 3 times greater, respectively, in Luqiao than in the reference town Lin'an City. Still, the estimated daily intake of dioxins by breast fed babies in Lin'an city was exceeding the WHO tolerable daily intake by 11 times. In Luqiao, this reference value was exceeded by 25 times [Chan et al.

2007]. Elevated levels of PCDD/Fs in human hair have also been observed in Guiyu. Thus, Luksemburg et al. [2002] found 26 and 16 pg WHO-TEQ/g in hair samples from two individuals in the Chinese e-waste city, which far exceeds previously reported levels in people exposed to ambient air. Those all carried levels below 1 pg TEQ/g [Tirler et al. 2001, Miyabara et al. 2005].

In addition to all these high contaminant levels measured among the people living and working in the e-waste recycling centres in developing countries, a wide range of negative health effects have been observed. For example, residents of Guiyu have reported their children suffering from medical problems such as respiratory diseases, skin infections, and stomach problems [Leung et al. 2006, Sepúlveda et al. 2009]. There has also been a surge in cases of leukaemia.

Table 6. Risks associated with end-of-life treatment of electronic waste (e-waste).

End-of-life process	Occupational risks	Environmental risks
Traditional waste handling		
Landfilling		Leakage of metals (e.g. Pb, Cu, Ni, Sb, Cd, Zn) and organic compounds (e.g. BFRs, plastizicers). Evaporation of Hg and MeHg.
Incineration		Emission of various metals and organic compounds via exhaust gases (e.g. dioxins, BFRs, PAHs, Cu, Pb, Sb). Leakage of various compounds from ashes (e.g. dioxins, Cu, Pb, Sn)
Controlled recycling		
Collection and dismantling	Dust containing various compounds during dismantling activities. Dust containing Pb and Ba-oxide from broken CRTs. Cuts from CRT glass in case of implosion. Volatile compounds (e.g. Hg) from broken components.	Emissions of volatile compounds (e.g. Hg) from broken components.
Shredding	Dust containing various compounds (e.g. BFRs, TPP, phthalates, Cd, etc.).	
Pyrometallurgical processes	Dust and fumes of the shredded material and the melting process, containing various compounds (e.g. Pb, Cd, Hg, Be, BFRs, dioxins, TPP, phthalates).	Emissions of various metals (e.g. Pb, Cd, Hg, Be) and organic compounds from the melting process (e.g. BFRs and dioxins).
Hydrometallurgical process	Acid fumes containing various hazardous compounds	
Plastic recycling	Dust and fumes of various chlorinated and brominated compounds (e.g. BFRs and dioxins), and some metal additives (e.g. Cd)	Emissions of various chlorinated and brominated compounds (e.g. dioxins) from the thermal processes used.
Uncontrolled recycling		
Collection and dismantling	Dust containing various compounds during dismantling activities, e.g. Pb and Ba-oxide from broken CRTs. Cuts from CRT glass in case of implosion. Volatile compounds (incl. Hg) from broken components.	Emission of dust and fumes containing various metals (e.g. Pb, Zn, Cu, Sn, Sb, Cd, Ni, Hg) and organic compounds (e.g. BFRs) to the local environment.
PC-board heating	Exposure to fumes of various compounds from solder and PC-board components (e.g. Pb, Sn, BFRs and dioxins)	Leakage of various compounds (e.g Cu….) from dumped PC-board residues.
Toner sweeping	Exposure to toner dust including carbon black.	Leakage of various compounds from emptied and dumped toner cartridges.
Acid extraction	Exposure to acidic fumes containing various hazardous compounds.	Leakage of various metals (e.g. Pb, Sn, Cu, Sb, Ni, Hg, Ba, Cd) and organic compounds (BFRs, phthalates, TPP, dioxins) from dumped residues of the extraction process.
Shredding	Dust and fumes of various metals and organic compounds present in the plastics (e.g. BFRs, phthalates, TPP, Cd, etc.)	Emissions of dust containing various plastics components to the local environment.
Plastics and waste burning	Exposure to a wide range of metals (incl. Cd, Cu, Pb, Zn, Sb) and organic compounds (incl. PBDEs, PAHs, PCBs, dioxins) via the smoke.	Emissions of a wide range of metals (incl. Cd, Cu, Pb, Zn, Sb) and organic compounds (incl. PBDEs, PAHs, PCBs, dioxins) to the local, regional and global environment.
Dumping of residual materials	Exposure to dust and fumes, containing various compounds, from dumped materials. Secondary exposure via contaminated drinking water and food.	Leakage of various metals and organic compounds to the ground and water reservoirs in the surroundings

11 Case studies in Peru and Thailand

As shown in the previous chapters of this report there are numerous sites around the globe where hazardous compounds from e-waste are clearly contaminating the environment. However, there are probably even more sites where e-waste constitutes a potential risk, but where its significance is less clear. To investigate the width of the e-waste problem, contamination data from two such sites, where the contribution from e-waste is less obvious, was included in this report. The sites, the Zapallal waste site in Peru and the Phuket municipal solid waste incinerator in Thailand, were sampled within the framework of another project initiated by the Swedish Environmental Protection Agency. That study aimed to investigate whether the suggested 15 ppb (15 000 ng TEQ kg-1) Low POP Content Limit (LPCL) for dioxins in waste is low enough to protect humans from toxicological health risks, and included identification and quantification of risk scenarios where contaminants originating from wastes are transferred from the environment to human food chains. The study is currently summarized in the report “Evaluation of human health risks related to the suggested 15 ppb Low POP Content Limit for PCDD/Fs” [Swedish EPA 2010]. However, as considerable quantities of e-waste are handled at the studied sites, at least at the site in Peru and presumably also at the site in Thailand, the samples were also considered to be relevant for the present report. As a consequence, the originally analyzed set of compounds, i.e. PCDD/Fs indicator PCBs (I-PCBs) and dioxin like PCBs (dl-PCBs), were extended to include also PBDD/Fs, PBCDD/Fs and PBDEs. The results from the analyses are presented below.

The results are both presented as total concentrations and as TEQs according to the TEF-scale established by WHO in 2005 [van den Berg et al. 2005]. For the calculation of the PBDD/F-TEQs the TEFs for the corresponding PCDD/Fs were used, since no official TEFs are available for the PBDD/Fs so far. Furthermore, the TEQs for the PBDD/Fs are presented as a range, since some 2,3,7,8-substituted PBDD/Fs were unavailable as references compounds and could therefore not be identified separately in the samples. The lower value thus represent the sum of TEQs calculated for the truly identified compounds, and the higher value the TEQs with inclusion of the most abundant compounds that potentially also could be 2,3,7,8-substituted (like a worst case scenario). Among the PBCDD/F, only some tetra and penta-substituted congeners were analysed, viz. monobrom-trichloro, dibromo-dichloro and monobromo-tetrachloro dioxins and furans, and consequently the PBCDD/F-sums presented below are sums of these.

11.1 The Zapallal waste site in Peru

The Zapallal waste site is situated on the east side of the Chillon river in the Carabayllo district north of Lima in Peru. The area, which embraces 440 hectars, is used for dumping and recycling of a wide range of waste types, including urban house hold waste, industrial waste and hospital waste. The recycling activities that are carried out at and around the site include burning of cables and lead batteries and smelting of metals among others. The methods used can be described as everything from small and partly controlled industrial activities to completely uncontrolled private enterprises. The latter is carried out by poor people living in the absolute vicinity of the waste site, a zone that houses 54 consolidated urban allotments, in which the inhabitants both perform their rudimentary recycling activities and hold animals for egg and meat production, e.g. free range chickens, ducks and pigs. In total, it has been estimated that 30 000 people live in close proximity to the waste site and therefore might be affected by the environmental problems it causes. For examples, ashes from the combustion and recycling processes, which generally are dumped directly on the ground in open air or into the nearby Chillon River, are easily spread to the surroundings. Because the climate is extremely arid, the risk for wind spreading of particles from the ash piles is very high. Photos from the waste site are shown in Figure 25 and 26.

Figure 25. Photos from the Zapallal waste site showing a truck unloading waste to the left, and a view of the informal industrial allotments dealing with waste recycling to the right.
(Photos: © Viktor Sjöblom)

Table 7. Samples collected at and in the surroundings of the Zapallal waste site in Peru.

Sample	Sample/Site description
Ash 1	Ash from cable burning activities
Ash 2	Ash from a site where plastic film is burned
Ash 3	Ash from a site where lead batteries are burned
Soil 1:1,2,4,5	Soil collected close to the industrial allotments at Zapallal waste site.
Soil 2	Soil collected 200 m from the industrial allotments
Soil 3	Soil collected 300 m from the industrial allotments
Soil 5	Soil collected 1500 m from industrial allotments
Sediment 1	Sediment collected from the Chillon River, 2-3 km south (downstream) of Zapallal
Sediment 2	Sediment collected from the Chillon River, in Trapiche, 50 km upstream Zapallal (reference sample)
Plant 1:1,2,4	Plants collected close to the industrial allotments at Zapallal waste site (at the sample places as the soil samples).
Plant 2	Plant collected 200 m from the industrial allotments.
Plant 3	Plant collected 300 m from the industrial allotments.
Plant 4	Plant collected 500 m from the industrial allotments.
Plant 5	Plant collected 1500 m from the industrial allotments.
Plant 6	Plant collected 4000 m from the industrial allotments.
Egg 1	Eggs from free range chicken, 500 m west of industrial allotments
Egg 2	Eggs from free range ducks, 500 m west of industrial allotments
Egg 3	Eggs from free range ducks at the western parts of waste site
Egg 4	Eggs from free range chickens in Trapiche 50 km north of the waste site (reference samples)

Figure 26. Simple facility for recycling of copper cables, showing the whole facility to the left and the cable burning furnace to the right. Ash sample 1 was collected here
(Photos: © Viktor Sjöblom).

The sampling around the Zapallal waste site took place in May 2009. In total, 28 samples of soil, ash, eggs, plants and sediment were collected at the waste site and at places at increasing distance from the site. The sampling point furthest away was located more than 50 km from Zapallal (Table 7). However, four of the reference samples (of soil) were not included in the extended analysis scheme, since these samples were not available at that moment. Consequently, these samples are not included here.

11.1.1 Contaminants found at Zapallal

The results from the analyses are compiled in Table 8-11. The ash collected at the waste site contained considerable amounts of all the studied contaminants, particularly the ash from the cable burning site that contained 18 µg PCBs (Σ I-PCB), 880 µg PCDD/Fs, 310 µg PBDD/Fs, 94 µg PBCDD/Fs and 11 mg PBDEs per kg dry ash (Table 8). This is comparable to levels found at open e-waste burning sites in Guiyu, China [Wong et al. 2007a, Zennegg et al 2009, Yu et al 2008]. The extremely high levels of PBDEs in the ash can most likely be explained by a high degree of PBDE containing flame retardants in the cables being burned, which also would explain the high levels of PBDD/Fs and PBCDD/Fs in the ash. The high levels of PCDD/Fs are probably due to a high abundance of PVC-containing cables. The other ashes contained lower levels of all compounds, although still relatively high, and with a lower proportion of brominated compounds, indicating less BFRs in the materials being burned there. The calculated TEQ-values (Table 9) show that both the PCBs and PBDD/Fs are contributing significantly to the dioxin like toxicity of the ashes, particularly in the cable ash, and it is probable that also the contribution from the PBCDD/Fs would be significant. The total TEQs in the cable ash was in the high end of what Wong et al. [2007a] found in combustion residues at an open burning site for e-waste in Guiyu in China, while the TEQs in the other ashes were below the levels the group of Wong found [Table 9].

The soil collected close to the waste site (Soil 1:1, 1:2, 1:4, 1:5 and 2) and the downstream sediment contained higher levels of the contaminants than the soils collected further away from the site (Soil 3 and 5) and the upstream sediment, respectively (Table 8). This indicates that the environment around the waste site is affected by the site, even if other urban sources probably contribute to the elevated levels as well. Compared to previous studies, the levels were similar to levels found in the rice fields in the Guiyu region in China [Leung et al. 2007, Wong et al 2007a], i.e. not hotspot levels but strong indications of contamination. Accordingly, it seems like the waste site is a significant source of contaminants for the surroundings, which is further indicated by the PBDD/F-congener pattern found in the samples. All ash and nearby soil and sediment samples were thus strongly dominated by PBDFs, which indicate that they all originate from PBDE-mixtures [Weber & Kuch 2003]. The PBDF-dominance was greatest in the cable ash (as seen by the PBDD/PBDF ratios in Table 8) that also contained the highest levels of PBDEs, while the PBDD/PBDF ratios in the nearby soil and sediment samples were similar to an average of the ash samples. The samples collected further away from the site contained a somewhat higher proportion of PBDDs (Table 8 and Figure 27). Similarly to the PBDD/Fs, the PCDD/F-patterns in all samples were dominated by furans (Figure 28a), and particularly in two of the ash samples (see PCDD/PCDF ratios in Table 8), but in contrary to the PBDD/Fs, the PCDF dominance in the soil was relatively similar regardless of the distance from the site. As for the other contaminants, the highest PBDE-levels in the soil were found close to the waste site. However, for this compound class, the trend with decreasing levels with increasing distance from the site was less clear than for the other compound classes, which probably can be explained by the existence of multiple sources of PBDEs in the area. The congener patterns for PBDEs were generally dominated by highly brominated congeners, e.g. octa-decaBDE, but it varied quite a lot among the samples (Figure 28b).

As shown in Table 9, the PCDD/Fs were the main contributors (60-80%) to the total TEQs in most soil samples. The dl-PCBs generally contributed with 15-25% and the PBDD/Fs with another 2-20% depending on which PBDD/Fs that were included in the calculations (see above). However, in the sediment samples the PBDD/Fs contributed much more to the TEQs, viz. 37-61% in the downstream (Sed. 1) and 96% in the upstream sediment (Sed. 2). It should be noted though that the PBDD/F-TEQ in sediment 2 mainly originate from an unexpectedly high abundance of 2378-TBDD (which is considered as the most toxic congener according to the TEF-scale for PCDD/Fs), and this might need to be verified by further sampling in the area. Similarly to the ash samples, it can be assumed that the PBCDD/Fs would give another significant contribution to the TEQs, at least in some of the samples.

Table 8. Total concentrations of I-PCBs, PCDD/Fs, PBDD/Fs, PBCDD/Fs and PBDEs, as well as ratios for PCDDs/PCDFs and PBDDs/PBDFs in various abiotic samples from Zapallal waste site north of Lima in Peru. All concentrations are based on dry weight (d.w.) of the samples.

	Σ I-PCB (ng kg^{-1} d.w.)	**ΣPCDD/F (ng kg^{-1} d.w.)**	**Ratio PCDD/ PCDF**	**ΣPBDD/F (ng kg^{-1} d.w.)**	**Ratio PBDD/ PBDF**	**ΣPBCDD/F (ng kg^{-1} d.w.)**	**ΣPBDE (ng kg^{-1} d.w.)**
Ash 1	18 000	880 000	0.12	310 000	0.002	94 000	11 000 000
Ash 2	490	3400	0.53	250	0.019	150	1 500
Ash 3	2800	10 000	0.091	50	0.11	160	23 000
Soil 1:1	1000	1000	0.38	78	0.016	36	3500
Soil 1:2	1800	1300	0.38	99	0.015	48	2600
Soil 1:4	1200	1300	0.37	180	0.012	53	51 000
Soil 1:5	640	670	0.42	320	0.007	24	92 000
Soil 2	1800	420	0.41	217	0.008	17	17 000
Soil 3	410	390	0.37	69	0.027	16	3600
Soil 5	120	31	0.43	8.6	0.18	0.58	10 000
Sed. 1	820	170	0.82	74	0.016	15	6100
Sed. 2	120	21	0.49	12*	2.9*	8.1	3700

* The PBDD/F-content in this samples was of unknown reasons completely dominated by 2,3,7,8-TBDD.

Table 9. Concentrations of dioxin like PCBs (dl-PCBs), PCDD/Fs, and PBDD/Fs, given as toxic equivalents (TEQs) and the total TEQs, in various abiotic samples from Zapallal waste site and its surroundings north of Lima in Peru. All concentrations are based on dry weight (d.w.) of the samples.

	Σ dl-PCB (ng TEQ kg^{-1} d.w.)	**ΣPCDD/F (ng TEQ kg^{-1} d.w.)**	**ΣPBDD/F (ng TEQ kg^{-1} d.w.)**	**Total TEQs (ng TEQ kg^{-1} d.w.)**
Ash 1	1700	12 000	1300-8200	15 000-22 000
Ash 2	6.1	50	4.4-16	61-72
Ash 3	12	140	3.1-4.0	160
Soil 1	2.6	8.8	0.17-1.6	12-13
Soil 2	2.9	10	0.19-1.4	13-14
Soil 3	3.5	11	0.18-3.3	15-18
Soil 4	1.3	5.3	0.094-0.75	6.7-7.4
Soil 5	0.87	3.3	0.078-0.52	4.3-4.7
Soil 6	0.93	3.6	0.096-0.88	4.6-5.4
Soil 7	0.10	0.32	0.007-0.30	0.43-0.72
Sed. 1	0.41	1.3	1.0-2.7	2.7-4.4
Sed. 2	0.086	0.23	7.8*	8.1

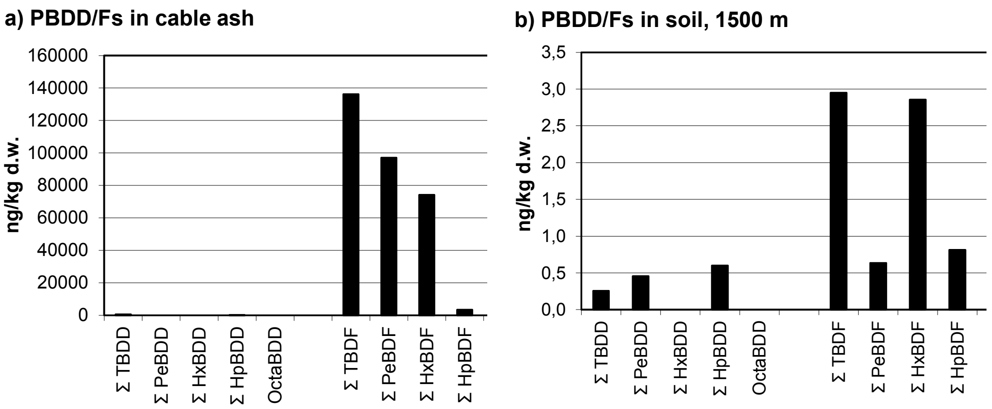


Figure 27. Congener patterns for PBDD/Fs in a) ash from a cable burning furnace at Zapallal waste site and b) a soil sample 1500 m away from the site.

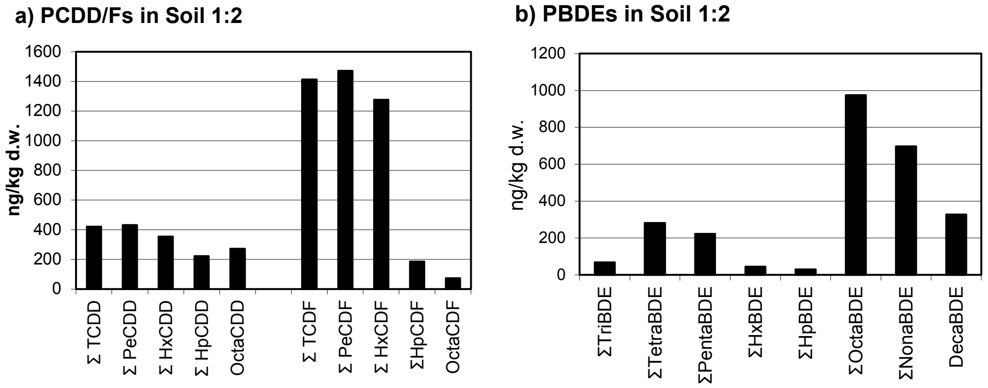


Figure 28. Congener patterns for a) PCDD/Fs and b) PBDEs in soil collected close to Zapallal waste site in Peru.

All compounds were found in higher concentrations in the eggs collected close to the waste site than in the eggs from the reference site (Table 10). The difference was most distinct for the PCDD/Fs that were found in 20-70 times higher concentrations close to the waste site than at the reference site, while PCBs, PBDD/Fs and PBDEs were found in 4-5, 1.5-6 and 3-10 times higher levels, respectively. PBCDD/Fs were only detected in the eggs from the waste site. Surprisingly, the eggs from the reference site contained three times as much PBDD/Fs as PCDD/Fs, while a reverse relation was seen in the eggs from the waste site. The contaminant levels in the plants varied, but in general the levels decreased with increasing distance from the waste site (Table 10). However, the contamination levels also seemed to be species dependent, which made the comparison highly uncertain. For example, the levels in the Yuccas and the Agave at the waste site differed up to three orders of magnitude.

Table 10. Total concentrations of I-PCBs, PCDD/Fs, PBDD/Fs, PBCDD/Fs and PBDEs, as well as ratios for PCDDs/PCDFs and PBDDs/PBDFs in eggs and plants from the Zapallal waste site and its surroundings north of Lima in Peru. The concentrations in the eggs are normalized against fat weight and in the plants against wet weight.

	Σ I-PCB (pg g^{-1} fat / w.w.)	**ΣPCDD/F (pg g^{-1} fat / w.w.)**	**Ratio PCDD/ PCDF**	**ΣPBDD/F (pg g^{-1} fat / w.w.)**	**Ratio PBDD/ PBDF**	**ΣPBCDD/F (pg g^{-1} fat / w.w.)**	**ΣPBDE (pg g^{-1} fat / w.w.)**
Egg 1	2400	92	0.39	19	0.20	37	150 000
Egg 2	3000	140	0.16	79	0.47	57	540 000
Egg 3	2900	290	0.31	76	0.12	34	330 000
Egg 4	640	4.0	0.30	13	0.076	<2	56 000
Plant 1:1	1600	690	0.57	31	0.008	24	14 000
Plant 1:2	640	390	0.44	29	0.008	14	1100
Plant 1:4	14	0.58	0.51	<0.5	-	<2	300
Plant 2	940	340	0.51	14	0.036	19	1700
Plant 3	1200	550	0.46	25	0.028	45	1700
Plant 4	1100	300	0.48	10	0.057	20	1500
Plant 5	660	74	0.56	6.1	-	4.3	950
Plant 6	450	62	0.65	4.4	-	2.2	890

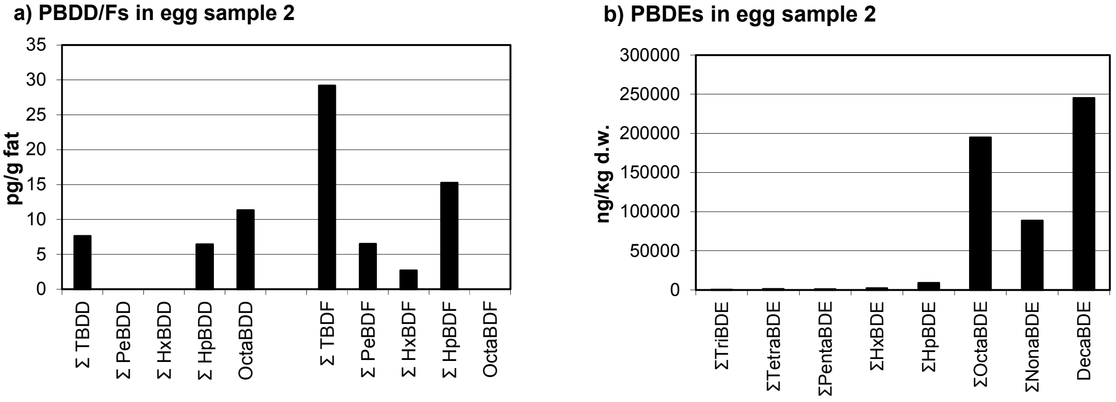


Figure 29. Congener patterns for a) PBDD/Fs and b) PBDEs in eggs collected close to Zapallal waste site north of Lima in Peru.

Like in the ash, soil and sediment samples, the congener patterns for dioxins in the eggs and the plants were dominated by furans (see ratios in Table 10). However, in the eggs the PBDF-dominance was less pronounced than in the abiotic samples (Figure 29a). This can be explained by a lower relative accumulation of PBDFs (as compared to PBDDs) in the eggs, or alternatively by the presence of another source of PBDD/Fs that at least partly gave rise to the elevated levels in the eggs. It is, however, difficult to say which of these processes that prevail. In terms of PBDE patterns, the eggs contained mainly octa-decaBDEs (Figure 29b), while the congener patterns in the plants differed. Nevertheless, the plant with the highest levels of contaminants (plant 1:1) contained mainly decaBDE.

The eggs from the waste site contained 6.1-8.5 pg TEQ g-1 fat with 50-60% contribution from PCDD/Fs, 30-40% from dl-PCBs and 5-10% from PBDD/Fs (Table 11). This value exceeds, by 2-3 times, the legislated maximum levels of 3 pg TEQ g-1 fat for eggs, set by the European Union [European Commission 2006].

Table 11. Concentrations of dioxin like PCBs (dl-PCBs), PCDD/Fs, and PBDD/Fs, given as toxic equivalents (TEQs) and the total TEQs, in eggs and plants from Zapallal waste site and its surroundings north of Lima in Peru. The concentrations in the eggs are normalized against fat weight and in the plants against wet weight (w.w.).

	Σ dl-PCB (pg TEQ g^{-1} fat / w.w.)	**ΣPCDD/F (pg TEQ g^{-1} fat / w.w.)**	**ΣPBDD/F (pg TEQ g^{-1} fat / w.w.)**	**Total TEQs (pg TEQ g^{-1} fat / w.w.)**
Egg 1	2.4	3.4	0.29-0.30	6.1
Egg 2	2.3	3.8	0.37-0.73	6.5-6.8
Egg 3	3.3	4.4	0.37-0.81	8.1-8.5
Egg 4	0.16	0.12	0.19-0.20	0.47-0.48
Plant 1:1	3.8	5.2	0.13-0.84	9.1-9.8
Plant 1:2	1.8	3.2	0.0077-0.14	5.0-5.1
Plant 1:4	0.0015	0.012	-	0.014
Plant 2	2.0	2.2	0.0035-0.052	4.2-4.3
Plant 3	3.1	4.4	0.0057-0.11	7.5-7.6
Plant 4	2.3	2.0	0.0021-0.041	4.3
Plant 5	1.1	0.58	0.0032-0.037	1.7
Plant 6	0.48	0.33	0.0040-0.0040	0.81

11.2 The Phuket Municipal Solid Waste Incinerator in Thailand

The Phuket municipal solid waste (MSW) Incinerator situated in the south of Thailand receives municipal solid waste of various origins (presumably also e-waste) from the whole Phuket city. The plant used to have problems with high PCDD/F emissions via the exhaust gases, but after improvement of the incineration process the emissions have now decreased. However, ash from the process is stored in open piles at the facility, which may lead to considerable spreading via airborne particles. A leachate water pond at the site is also connected to a lake outside the plant, where local inhabitants catch fish for consumption. Sampling at the Phuket MSW incineration plant took place in June 2009. A total of 12 samples of ash, soil, sediment and fish were collected at and in close proximity to the site. Besides that, two reference samples of soil were collected at Patong Beach, 15 km away (Table 12).

Table 12. Samples collected at and in the surroundings of the Phuket MSW incinerator in Phuket, Thailand.

Sample	Sample/Site Description
Soil 1 (ref)	City of Patong Beach, 15 km from Phuket MSW incinerator.
Soil 2 (ref)	City of Patong Beach, 15 km from Phuket MSW incinerator.
Soil 3	Soil sample collected in front of main office at Phuket MSW incinerator
Soil 4	Soil from the landfill area at Phuket MSW incinerator
Sediment 1	Sediment from ash deposit pond at Phuket MSW incinerator
Sediment 2	Sediment from lake just outside Phuket MSW incinerator area.
Ash 1	Ash from the incineration process, newly sampled by the staff at Phuket MSW incinerator. To be used for internal control.
Ash 2	Ash from ash deposit at Phuket MSW incinerator
Ash 3	Ash from the covered landfill at Phuket MSW incinerator
Ash 4	Older (grey) ash from the incineration process collected at the ash deposit at the Phuket MSW incinerator.
Ash 5	Ash samples (grey) collected close to a house where a family was living, adjacent to the incinerator site.
Fish 1-3	Fish from the lake just outside the Phuket MSW incinerator area.

Figure 30. Photos from the Phuket MSW incineration site, showing ash deposit with leachate water pond to the left (sampling point for sediment 1) and the lake outside the site to the right (sampling point for sediment 2 and the fish samples), Photos: © Lars Lundmark.

11.2.1 Contaminants found at Phuket MSW incinerator site

The results from the analyses are compiled in Table 13-16. As seen in Table 13, the soil collected at the MSW incineration site (soil 3 and 4) contained elevated levels of all the contaminants, as compared to the reference soils collected at Patong Beach, 15 km away. The difference was on average 9 times for PCBs, 2 times for PCDD/Fs, 7 times for PBDD/Fs, 9 times for PBCDD/Fs, and 5 times for PBDEs. Compared to other studies, the PCDD/F and PBDE levels were somewhat below those found in rice fields in the Guiyu region [Wong et al. 2007a], but considerably higher than those found in Swedish background soils, viz. about 10 times higher for PCDD/Fs and 100 times for PBDEs [Matscheko et al. 2002, Sellström et al. 2005]. These contaminants probably originate to a large extent from the ashes that are stored in open air at the site. The ashes that were sampled were also found to contain very high levels of the contaminants in question. The only exception was the ash that had been sampled by the staff at the facility a week earlier (ash 1), which contained much lower levels of all compounds except the PBDD/Fs. The explanation to this is unknown, but it seems like this sample was a poor representative of the ashes that had been dumped at the site. Furthermore, the sediment from the ash deposit pond contained almost as high levels of the contaminants as was found in the ash piles at the site, indicating that the sediment in the pond mainly consisted of ashes.

Table 13. Total concentrations of I-PCBs, PCDD/Fs, PBDD/Fs, PBCDD/Fs and PBDEs, as well as ratios for PCDDs/PCDFs and PBDDs/PBDFs in various abiotic samples from Phuket MSW incinerator in Phuket, Thailand. All concentrations are based on dry weight (d.w.) of the samples.

	Σ I-PCB (ng kg^{-1} d.w.)	**ΣPCDD/F (ng kg^{-1} d.w.)**	**Ratio PCDD/ PCDF**	**ΣPBDD/F (ng kg^{-1} d.w.)**	**Ratio PBDD/ PBDF**	**ΣPBCDD/F (ng kg^{-1} d.w.)**	**ΣPBDE (ng kg^{-1} d.w.)**
Ash 1	95	430	0.51	1700	0.0031	18	1800
Ash 2	1600	530 000	0.57	3400	0.0065	40 000	59 000
Ash 3	3700	610 000	0.55	9000	0.0025	46 000	69 000
Ash 4	2400	260 000	0.61	660	-*	20 000	13 000
Ash 5	1900	250 000	0.72	130	0.043	21 000	31 000
Soil 1	130	410	14	19	0.012	6.6	1800
Soil 2	130	400	18	20	0.010	6.9	2600
Soil 3	630	640	1.8	110	0.021	57	11 000
Soil 4	250	1000	0.68	160	0.0088	64	13 000
Sed. 1	2700	180 000	0.42	1500	0.014	18 000	58 000
Sed. 2	310	270	1.5	37	0.0066	6.8	3400

*No PBDDs were detected in this sample.

The sediment from the lake just outside the area (Sed. 2) contained much lower levels of the contaminants; levels that were comparable to the levels found in the soil at the reference site (Table 13). In comparison to other studies, as reviewed in Wong et al. [2007a], the PBDE-concentration in the sediment was lower than at several urban and known contaminated sites in the world but higher than in coastal sediments. Notably, however, the sediment from the lake outside the incineration plant, as well as all soil samples and also the ash collected by the local staff, contained a larger proportion of brominated dioxins than other dioxins, while the other ashes and the sediment from the ash deposit lake contained more of the chlorinated and mixed brominated-chlorinated dioxins. The samples can also be grouped similarly when comparing their congener patterns for PCDD/Fs. The ash samples and the sediment from the ash deposit pond were thus dominated by PCDFs, particularly penta- and hexaCDFs, while most soils and the sediment from the lake outside the area were dominated by PCDDs (see PCDD/F-ratios in Table 13). Furthermore, when studying the latter samples in more detail, the congener patterns for the two reference soils were completely dominated by OCDDs, which is typical for samples that mainly have been affected by diffuse sources and long range transport [Gaus et al. 2002, Prange et al 2002], while the two soils from the incineration plant and the lake sediment contained other congeners as well, and also a more even distribution of PCDDs and PCDFs (Figure 31). This indicates that the soil at the site and the lake outside the site is affected both by the ashes from the local incineration process as well as by PCDD/Fs from more diffuse sources. The PBDD/F patterns were strongly dominated by PBDF in all samples, which indicate that they originated from PBDE-containing flame retardants [Weber & Kuch 2003]. The PBDE-pattern was dominated by octa-decaBDEs in all samples except the ash collected by the local staff that contained mainly tri-heptaBDEs.

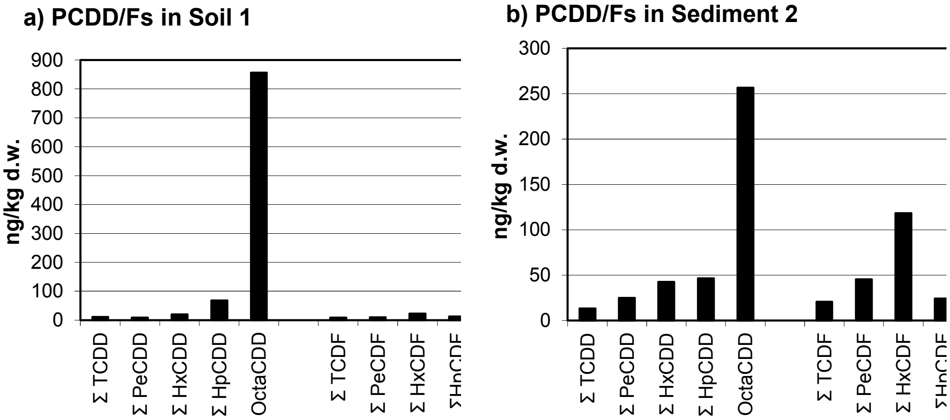


Figure 31. Congener patterns for PCDD/Fs in a) soil from Patong Beach 15km away from Phuket MSW incinerator (reference site), and b) sediment from the lake just outside the

Table 14. Concentrations of dioxin like PCBs (dl-PCBs), PCDD/Fs, and PBDD/Fs, given as toxic equivalents (TEQs) and the total TEQs, in various abiotic samples from Phuket MSW incinerator in Phuket, Thailand. All concentrations are based on dry weight (d.w.) of the samples.

	Σ dl-PCB (ng TEQ kg^{-1} d.w.)	**ΣPCDD/F (ng TEQ kg^{-1} d.w.)**	**ΣPBDD/F (ng TEQ kg^{-1} d.w.)**	**Total TEQs (ng TEQ kg^{-1} d.w.)**
Ash 1	0.35	6.2	4.8-27	11-34
Ash 2	210	7200	11-48	7400-7500
Ash 3	255	8000	30-130	8300-8400
Ash 4	68	3600	2.6-40	3700-3700
Ash 5	72	3300	0.83-2.6	3400-3400
Soil 1	0.022	0.66	0.027-0.75	0.71-1.4
Soil 2	0.028	1.0	0.037-0.51	1.1-1.5
Soil 3	0.2	4.7	0.066-0.80	5.0-5.7
Soil 4	0.42	11	0.30-4.8	12-16
Sed. 1	97	2700	5.6-41	2800
Sed. 2	0.066	1.8	0.11-0.91	2.0-2.8

The PCDD/Fs generally contributed most to the total TEQs (often by more than 95%). However, in the ash collected by the local staff, as well as in some of the soils and the lake sediment the PBDD/Fs also contributed significantly. The dl-PCBs contributed with less than 5% in all samples (Table 14).

The fish samples from the lake outside the area contained high levels of contaminants (Table 15 and 16), although not extremely high. The PCDD/F-levels were just below the 4 pg TEQ g-1 (w.w.) set by the European Commission as the maximum acceptable level in fish intended for food [European Commission 2006], and the PCBs and the PBDD/Fs also contributed significantly to the TEQs. Furthermore, the PCDD/F-levels found in the fish were in the higher range of what previously have been found in other countries in fish intended for food [Moon & Choi 2009 and references therein]. However, the PBDE-levels were relatively low compared to previous studies, both in relation to fish from contaminated areas as well as fish from un-contaminated areas [Luo et al 2007, Wu et al 2008 and references therein]. The congener patterns found in the fishes were like a mixture of the previously found patterns, with a fairly even distribution of PCDDs and PCDFs, a clear dominance of PBDFs over PBDDs, and the whole range of PBDEs occurring in the samples (Figure 32).

Table 15. Total concentrations of I-PCBs, PCDD/Fs, PBDD/Fs, PBCDD/Fs and PBDEs, as well as ratios for PCDDs/PCDFs and PBDDs/PBDFs in fish from the lake just outside the Phuket MSW incinerator area in Phuket, Thailand. All concentrations are normalized against wet weight (w.w.).

	Σ I-PCB (pg g^{-1}, w.w.)	**ΣPCDD/F (pg g^{-1}, w.w.)**	**Ratio PCDD/ PCDF**	**ΣPBDD/F (pg g^{-1}, w.w.)**	**Ratio PBDD/ PBDF**	**ΣPBCDD/F (pg g^{-1}, w.w.)**	**ΣPBDE (pg g^{-1}, w.w.)**
Fish 1	450	380	0.62	6.5	0.036	14	420
Fish 2	3400	41	0.99	3.9	0.015	<0.3	850
Fish 3	1600	63	0.88	3.2	-*	5.5	1000

*No PBDDs were detected in this sample.

Table 16. Concentrations of dioxin like PCBs (dl-PCBs), PCDD/Fs, and PBDD/Fs, given as toxic equivalents (TEQs) and the total TEQs, in fish from the lake just outside the Phuket MSW incinerator area in Phuket, Thailand. All concentrations are based on wet weight (w.w.).

	Σ dl-PCB (pg TEQ g^{-1}, w.w.)	**ΣPCDD/F (pg TEQ g^{-1}, w.w.)**	**ΣPBDD/F (pg TEQ g^{-1}, w.w.)**	**Total TEQs (pg TEQ g^{-1}, w.w.)**
Fish 1	0.26	5.3	0.031-0.18	5.6-6.0
Fish 2	0.45	1.1	0.013-0.17	1.6-1.7
Fish 3	0.25	1.0	0.019-0.17	1.3-1.4

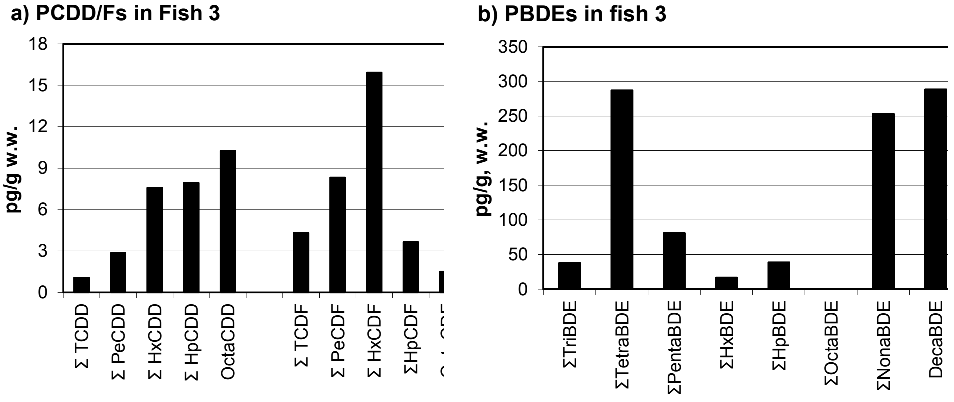


Figure 32. Congener patterns for a) PCDD/Fs and b) PBDEs in fish from the lake just outside the Phuket MSW incinerator area in Phuket, Thailand.

11.3 Conclusions from the case studies

The results from the analyses show that both the Zapallal waste site and the Phuket MSW incinerator give rise to significant, but moderate contamination of the environment. The concentrations of contaminants were higher close to the sites than far away from the sites. The results also indicate that e-waste, or at least flame retarded materials, contribute to the contamination. This is because relatively large proportions of brominated compounds were found at and around the sites. At the Zapallal waste site, it was already known that e-waste was handled and treated to some extent, which also was verified by the results from the cable ash analysis. However, the soil at the Phuket MSW incinerator site contained as high levels of the brominated compounds (as well as of PCDD/Fs) as the soil at Zapallal, which indicate that BFR-containing materials are handled even there. The congener patterns for PBDD/Fs and PBDEs added further evidence to this indication, as these were all clearly dominated by PBDFs and highly brominated PBDEs, respectively, which are typical patterns in combustion residues of decaBDE-mixtures. Accordingly, both sites seem to constitute sources for e-waste related contaminants that may be spread to the surroundings together with other contaminants from the sites. The results show that the closest surroundings to the sites are clearly affected by contaminants from the sites, giving rise to high levels in locally produced eggs and fish for example, while the influences at further distances from the sites are less clear. Particularly at Zapallal, other local sources seem to influence the results.

12 Conclusions

The data summarized in this report show that there are many risks associated with the handling, disposal and recycling of e-waste (Table 6). This is because electrical and electronic equipment generally are loaded with hazardous compounds (e.g. lead, cadmium, mercury and PBDEs) that may be emitted during the end-of-life processes, and because many of the processes also may result in the formation of new toxic compounds, (e.g. PCDD/Fs, PBDD/Fs, PBCDD/Fs, PAHs and HCB). Risks may thus arise during traditional waste handling processes, such as landfilling and incineration, as well as during processes that are conducted with the purpose to recycle the materials involved.

Most risks arise during the uncontrolled recycling activities occurring in many developing countries, which is a result of the rudimentary methods used, involving minimal emission control systems or personal protection for the workers. Humans and the environment in these areas are therefore highly exposed to a wide range of toxic compounds originating from these activities. The recycling workers and the local residents are particularly exposed via dust generated during dismantling and shredding processes (including breaking of CRTs), and fumes and smoke generated during acid digestion processes and various high temperature processes, such as open burnings and heating, melting, and extrusion processes. Humans in these areas are also indirectly exposed via contaminated food and drinking water. The environment is mainly contaminated from the open burning processes and through leakage from dumped residues of various recycling activities, e.g. stripped CRTs and PC-boards, spent acids from the digestion processes and residual ashes.

The compounds of most concern vary depending on the material being recycled and the recycling methods used. However, on the whole, lead seems to be particularly problematic among the metals, and dioxins (chlorinated and brominated) and PBDEs among the organic compounds. These compounds are all very toxic and may potentially be emitted in large amounts during rudimentary e-waste recycling activities. Lead and PBDEs because they both are highly abundant in e-waste, and dioxins because the formation conditions many times are ideal in the processes used. As a consequence, extremely high levels (in some cases the highest ever measured) of these compounds have been measured in environmental as well as human samples collected in areas where uncontrolled e-waste recycling is taking place. These have also been connected to various negative health effects observed among the people in these areas. Regarding the dioxins, it seems like the brominated and the mixed brominated-chlorinated congeners contribute to the total dioxin-like toxicity to at least the same extent as the purely chlorinated congeners. This is important to remember as most monitoring campaigns only include analyses of chlorinated dioxins. Furthermore, there are convincing evidences that the emissions from the uncontrolled e-waste recycling industry are contributing significantly to the regional as well as the global pollution for some compounds.

Other organic compounds that may be of concern as a result of uncontrolled e-waste recycling are various chlorinated and brominated compounds (including other BFRs, PCBs, PCNs, and chlorinated and brominated benzenes and phenols), PAHs, oganophosphorous compounds, nonylphenol and phthalate esters. Other metals that may pose a risk are cadmium, mercury, tin, antimony, nickel, barium, chromium, zinc, beryllium and copper. Some of these, e.g. cadmium and mercury, are generally present in low amounts in e-waste, but may be of concern due to their high toxicity. Others, such as copper, have low toxicity but may be problematic due to very high abundance in the materials.

Recycling under controlled conditions, that are carried out in facilities adapted for its purpose, is much better from a risk perspective point of view, both for the recycling workers, the local residents, and for the environment. However, risks may occur during these activities as well. For the workers, the largest risk is to be exposed to dust during dismantling, shredding and separation of the e-waste as well as during the subsequent pyrometallurgical processes. In addition, workers may be exposed to volatile compounds, such as mercury, that may be accidentally released during breakage of components in which these compounds are encapsulated. For the environment and the general population, the largest risks arises during the pyrometallurgical processes and during other high temperature processes, such as those used during plastic recycling and incineration of residual waste (justified in the recycling industry as energy recovery). During these, substantial amounts of chlorinated and brominated dioxins as well as other chlorinated and brominated compounds may be emitted, and in case of the pyrometallurgical processes, a wide range of metals (similar to the once emitted from uncontrolled processes) may also be emitted. Even if these emissions should be possible to minimize, by using optimized processes together with modern dust containment and flue gas treatment systems, existing emission data indicate that this is not always satisfactorily done. Significant levels of several compounds have thus been found in and around some of these facilities. However, it should be noted that there is a great paucity of data concerning emissions from these kinds of facilities.

The alternatives to e-waste recycling, i.e. to incinerate the material in waste incineration facilities or just to put it on landfills, are less attractive. Incineration will, as previously noted, give rise to a wide variety of toxic compounds, including those that were present in the original waste and those that may be formed during the incineration process (e.g. PCDD/Fs and PBDD/Fs). If the e-waste is incinerated in mixed form, the emissions will be even greater than the emissions arising during incineration of separated combustible fractions, and it will also lead to loss of the valuable materials that are present in the e-waste. The latter will, in turns, lead to increased consumption of virgin materials with further impacts and pollution of the environment as a consequence. Landfilling will lead to long term risks to the environment as leakage and evaporation from landfills may continue for ages. Leakage may occur for most compounds in the waste, but it seems like various metals, lead in particular, as well as highly abundant organic compounds, such as

PBDEs and phthalate plasticizers, are of particular concern. Evaporation mainly occurs for volatile compounds, of which mercury and its methylated derivatives are of most concern. Due to the long time spans involved, it is difficult to predict and completely prevent the emissions from landfills. Conditions may change over time, which may lead to altered behaviour of the pollutants.

From the discussion above it can be concluded that there is no completely safe disposal method for e-waste when considered from a health and environmental perspective. Although risks may be greatly reduced in controlled recycling facilities, they can not be completely avoided. To further reduce the risks, the amounts of hazardous compounds in the EEE have to be reduced, since the very presence of these compounds is one of the primary causes of the risks. At the same time the amount of e-waste generated in the world have to be reduced in order to solve the e-waste problem in a wider perspective. This can, at least partly, be achieved through the design of products with greater life-spans that are safer and easier to repair, upgrade and recycle. The ultimate goal must be to ensure that the quantities of e-waste generated are minimized, and that the e-waste that do arise are recycled and disposed of in the best achievable manner to minimize impacts on human health and the environment.

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Recycling and disposal of electronic waste

Health hazards and environmental impacts

REPORT 6417

SWEDISH EPA
ISBN 978-91-620-6417-4
ISSN 0282-7298

E-waste is today the fastest growing sector of the municipal solid waste stream and currently comprises more than 5% of its total flow, i.e. 20-50 million tones a year worldwide. These enormous quantities, in combination with the fact that e-waste contains a wide range of hazardous compounds, have turned e-waste into a global environmental issue.

When the e-waste is treated, in general waste processes or in recycling processes, hazardous compounds may be released and pose a threat to humans and the environment. In addition, in some treatment processes, hazardous compounds, such as dioxins, may be formed as the original e-waste components are degraded. This report summarizes and compares the hazards and risks that may arise in different processes.

Swedish EPA SE-106 48 Stockholm. Visiting address: Stockholm - Valhallavägen 195, Östersund - Forskarens väg 5 hus Ub, Kiruna - Kaserngatan 14. Tel: +46 8-698 10 00, fax: +46 8-20 29 25, e-mail: registrator@naturvardsverket.se Internet: www.naturvardsverket.se **Orders** Ordertel: +46 8-505 933 40, orderfax: +46 8-505 933 99, e-mail: natur@cm.se Address: CM Gruppen, Box 110 93, SE-161 11 Bromma. Internet: www.naturvardsverket.se/bokhandeln