The devil that we know: Lead (Pb) replacement policies under conditions of scientific uncertainty

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Abstract – Engineering and economic considerations are typical driving forces behind the selection of specific chemicals used in the manufacture of consumer products. Only recently has post-consumer environmental impact become part of the major considerations during the initial phases of product design. Therefore, reactive, rather than proactive strategies have dominated the consideration of environmental and health issues in product design. This study draws from case histories of national and international policies pertaining to lead (Pb) use in various industrial sectors, with the goal of producing guidelines for a predictive model of possible outcomes of international initiatives to phase out Pb from electronics products where it is primarily used in solder alloys. Data are scarce on the ultimate fate and hazards associated with Pb in discarded products, but the environmental and health effects of Pb exposure are well documented. Even less is known about the fate and effects of proposed alternatives such as silver and bismuth. Nevertheless, industrial convergence to a Pb-phase out strategy is deemed inevitable, with restrictions on the permissible local disposal of current stock of Pb-containing electronic products. To avoid the selection of hazardous alternatives, it is necessary to perform quantitative assessment of trade-offs in product reliability, recycling potential, economic costs, occupational health, and environmental quality. We identify key elements of the potential trade-offs and conclude with strategies to avoid the loop holes that have plagued similar international initiatives and legislation to phase out Pb from other industrial processes under conditions of scientific uncertainty about Pb and alternative metals.

INTRODUCTION

In the year 1999, industries in the United States consumed 1.68 million tons of lead (Pb), distributed unevenly over more than a dozen sectors (Figure 1). This is a surprisingly large amount of Pb, given that this element and its compounds have been phased out of several industrial sectors, including energy, water, and construction industries. For examples, lead is no longer used as an additive in gasoline or in paint sold in the United States. The uses of lead pipes and solder alloys in water distribution systems have also been phased out. In addition, the lead content of batteries has been highly scrutinized, causing the implementation of battery recycling programs [1]. Most recently, cathode ray tubes (CRTs) have now been categorized as universal waste because of their lead content, and can no longer be disposed of in California landfills [2]. In these cases, government regulation and policy enforcement have been necessary to coordinate industrial compliance with the phase out of lead. However, international endorsement of these regulations is spotty at best [See Table 1; 3, 4]. For instance, leaded gasoline is still used in a considerable number of countries despite the remarkable environmental health success that accompanied its restriction in the U.S. Similarly, regulatory strategies for recycling leaded batteries vary across State and national boundaries [Figure 2; 5]. The Pb content of water distribution pipes is only regulated not to exceed 8%, and faucets and fittings are allowed to contain 0.2% of Pb. Finally, litigation continues to plague the interactions between lead-paint manufacturers and consumers over the risks associated with childhood lead poisoning in old buildings.
Figure 1.

U.S. Lead Use by Sector in 1999. Total of $1.68 \times 10^6$ Tons

<table>
<thead>
<tr>
<th>Sector</th>
<th>Products</th>
<th>Pb Use</th>
<th>Regulatory Program</th>
<th>Replacement or Alternative Policy</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Gasoline</td>
<td>Tetraethyl lead additive</td>
<td>National Phase-out 1975 - 1987</td>
<td>Manganese (MMT); MTBE</td>
<td>Incomplete global phase-out of Pb; Uncertainty about health and ecological impacts of alternatives</td>
</tr>
<tr>
<td>Energy</td>
<td>Batteries</td>
<td>Lead electrodes and Lead oxide, red</td>
<td>State-regulated Recycling programs</td>
<td>“Green batteries” Nickel-Metal Hydride</td>
<td>Voluntary programs, incentives, uncertain impacts on transnational disposal</td>
</tr>
<tr>
<td>Water</td>
<td>Distribution</td>
<td>Pb pipes, brass faucets, and copper pipes with Pb (50%)-solder</td>
<td>National Phase-out June 1986 – June 1988</td>
<td>“Pb-free” pipes and fittings” (8% Pb); “Pb-free solder” (0.2% Pb)</td>
<td>Fixtures, old tanks remain hazardous for next decade</td>
</tr>
<tr>
<td>Electronics</td>
<td>Cathode Ray Tubes</td>
<td>Lead oxide</td>
<td>State-regulated recycling</td>
<td>Flat panels; Hg</td>
<td>Premature collection programs, International trade, Uncertainty about Pb leaching conditions.</td>
</tr>
<tr>
<td>Electronics</td>
<td>Printed wire Boards</td>
<td>Tin-Pb (37%) solders</td>
<td>Europe/Japan phase-out programs</td>
<td>Pb-free solder, Silver, Bismuth</td>
<td>Uncertainty about risks of alternatives; costs and benefits of switching.</td>
</tr>
</tbody>
</table>
Recent U.S. government-sponsored programs targeted at reducing lead exposure have mostly focused on lead in paint. However, there is increasing recognition of the need to diversify the coverage of protective policies against lead poisoning. At the federal level, the U.S. EPA has recently changed the reporting criteria for lead under the Toxic Release Inventory (TRI) “public right to know” program for facilities that manufacture, process or otherwise use more than 220 kg (100 lbs) of lead annually (down from 5,000 kg) [6]. Current estimates indicate that this new rule could affect more than 9,000 industrial facilities, many of them in California [7; See Table 2]. The U.S. EPA is also evaluating their list of “persistent, bioaccumulative and toxic” chemicals (PBTs). Lead is not on the currently approved list but has been added to the pending list that is now under discussion [8, 9]. The purpose of the PBT list is to “focus federal, state, industry, and public attention on actions that reduce the generation of these PBT chemicals in RCRA hazardous waste by 50 percent by 2005” [10]. However, the EPA has established an e-waste prevention campaign that is targeted at waste prevention, reuse and recycling [11]. The State of California has a similar campaign that is focused on reducing and recycling packaging materials, as well as computers and components [12]. Other states as well as industry organizations also have initiated such campaigns [13, 14]. Although these campaigns recognize that e-waste contains hazardous materials, their concerns over lead content focus on CRTs, not solder. These regional and national initiatives are emerging with limited integration of international phase-out agenda. More importantly, the initiatives have been sanctioned despite several scientific uncertainties regarding the comparative costs and benefits of proposed alternative “Pb-free” components, particularly in the context of other hazardous materials present in electronic products. The uncertainties surrounding Pb phase-out in the electronics industries can be bounded and better characterized through case studies of documented environmental and health risk assessment of Pb, and the implementation of phase-out or recycling programs in similar industrial sectors.

HEALTH AND ENVIRONMENTAL IMPACTS OF LEAD

Lead (Pb) is of great concern because it is widely recognized as one of the most ubiquitously distributed toxic metals used in industries across many sectors. The background concentration of lead in the Earth’s crust is 16 µg/g but human industrial activities have resulted in lead concentrations several orders of magnitude above background levels in soils (up to 5,000 µg/g), freshwater (up to 10 µg/L), and air (up to 10 µg/m³) [15]. The global distribution of lead, coupled with its well-documented deleterious effects on biological systems makes it one of the most hazardous environmental toxicants. The fact that lead is toxic has been known for more than 2,000 years, but there remains some uncertainty about knowledge of the complex relationship between lead exposure and human response. For example, considerable research is ongoing to define a threshold for safe levels of lead exposure, if in fact such thresholds exist. Similarly, the contribution of genetic susceptibility factors to the development of lead associated diseases is not clear. The impact of lead exposure on human health has been distributed into five major categories representing stages of human development: normal, physiological changes of uncertain significance, patho-physiological changes, overt symptoms (morbidity), and mortality. There are no clear distinctions, among these categories, and it is likely that an exposed victim experiences a continuum of effects. Exposure to lead is known to have several adverse health effects, such as neurological, reproductive, renal, and hematological disorders [15]. Children are especially at risk because play behavior increases the opportunity for exposure to lead through contaminated dust, and blood lead levels above 10 µg/dL have been linked to the impairment of cognitive development [15].

Although Pb used in the electronics industry accounts for less than 4.2% of the total amount of Pb used in the United States (Table 1), estimates indicate that a substantial portion of the Pb content of landfill leachate that pollutes the environment is from electronic products. There are no comparable data on the fate of discarded electronic products on Pb emissions from incinerators, but the environmental impact from this source is likely to be considerable. In contrast, the use of Pb in storage batteries accounted for 87.5% of total lead use, but there is a universal policy for battery recovery and recycling, which prevents environmental impacts. The year 2000 Toxic Release Inventory records show that electronics industries (SIC 36) accounted for 0.57% of total emissions of lead nationwide, and approximately 1.0% of the 5.0 million pounds of total Pb releases in California. Nevertheless, the targeting of Pb in specific electronic products among the wide array of commercially available components is
Table 2. Year 2000 Toxic Release Inventory (TRI) Data for Pb, with Emphasis on Proportionate Contributions by California and Electronic and Electrical Industries.

<table>
<thead>
<tr>
<th></th>
<th>United States (lbs)</th>
<th>California (lbs)</th>
<th>% Contribution of California sources to total U.S. releases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Pb Releases (lbs)</strong></td>
<td>3.87 x 10^8</td>
<td>5.09 x 10^6</td>
<td>1.29</td>
</tr>
<tr>
<td><strong>Electrical Industries (SIC 36) Pb Releases (lbs)</strong></td>
<td>2.22 x 10^6</td>
<td>5.01 x 10^4</td>
<td>2.25</td>
</tr>
<tr>
<td><strong>% Contribution of SIC 36 to total releases</strong></td>
<td>0.57</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

controversial because microelectronic products other than CRTs, which also contain Pb as Pb-Sn solder may pose an even greater threat to the environment and to public health if they are disposed of improperly. The resolution of this controversy calls for a comprehensive policy that takes into consideration, product design, manufacturing costs, sales and distribution in communities, product life expectancy, end-of-life options including recycling, land-filling or incineration, and exportation. Lead is not the only hazardous metal used in electronic products, but there is substantially more corporate, regulatory, and international attention to the elimination of Pb, than there are to other toxic components of electronics. This focus is due in part to the national health care costs attributable to lead poisoning, estimated at $4.3 billion annually, according to a 100% environmentally attributable fraction model [16]. A source apportionment study for this annual cost of lead poisoning has not been conducted, but all unnecessary sources of lead exposure need to be controlled to prevent human exposures that could significantly reduce costs to society. Therefore, it is imperative for the State of California, and indeed, the United States to formulate environmental policy that encompasses the concerns of manufacturers, consumers, occupational health agencies, and environmental protection agencies. By necessity, the emergent environmental policy will include substantive trade-offs across these sectors, but the health and environmental costs must be internalized in cost-benefit analysis.

The US has a long history of leading environmental initiatives to phase out or restrict the end-of-life disposal of lead-containing consumer products, including tetraethyl lead in gasoline, lead-acid batteries, lead-pigment paint, and the use of leaded solders in water distribution systems. However, in the case of electrical and electronic products, the US is currently behind the European Union and Japan in the design and implementation of legislative strategies to limit or eliminate the use of lead [17]. For instance, the Waste Electrical and Electronic Equipment and Reduction of Hazardous Substances (WEEE/ROHS) directives require that all electronic products made, sold, and imported into the European Union be lead-free by July 2006. Despite the fact that lead in solder represents less than one percent of all lead produced and that tin-lead solder has been the industry standard for decades, this directive is forcing the electronics industry to seriously evaluate lead-free alternative solders [Table 3].

Table 3. Current Pb-Free alloy alternatives and their respective melting temperatures.

<table>
<thead>
<tr>
<th></th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SnZn</td>
<td>199°C</td>
</tr>
<tr>
<td>SnBiAg</td>
<td>210°C</td>
</tr>
<tr>
<td>SnBiAgCu</td>
<td>210°C</td>
</tr>
<tr>
<td>SnAgCu</td>
<td>217°C</td>
</tr>
<tr>
<td>SnAgCuSb</td>
<td>210-217°C</td>
</tr>
<tr>
<td>SnInBiAg</td>
<td>179-210°C</td>
</tr>
<tr>
<td>SnCu</td>
<td>229°C</td>
</tr>
</tbody>
</table>
Several studies have been completed on various lead-free alternative solders and the extent to which they satisfy engineering, process and design requirements [18, 19, 20]. As a result of these studies, several alternative solders have been identified [21, 22]; the preferred choice for most applications is tin-silver-copper (SnAgCu). Several researchers, including members of our team, have studied the comparative impacts of tin-lead and a variety of the alternative solders [23, 24, 25]. All of these studies have demonstrated that although lead is a known toxicant, the alternative solder metals also present a variety of environmental impacts, especially when the entire life cycle is considered. For many of the alternative materials, data on environmental fate and regulatory standards are not available [Table 4]. Silver appears to be of particular concern.

Despite the consistency among these studies, the WEEE directive still stands, and the US electronics industry is being forced to either give up market share or evaluate alternative alloys that may present continued environmental and public health impacts. Moreover, US policy makers must now evaluate legislative strategies that not only address the ever-increasing quantity of toxic e-waste, but also account for industry’s response to foreign legislation. The results of the above studies provide limited guidance from a policy-making perspective, because they do not attempt to quantitatively combine different types of environmental and human health impacts. Furthermore, the economic impact of a change in solder composition, such as that caused by changes in manufacturing or testing procedures, is not considered in any of these studies. With increasing globalization and free trade agreements, poorly conceived environmental protection initiatives tend to leave loopholes that defeat the purpose of regulation or to erode the incentives for voluntary environmental initiatives by corporations.

LESSONS FROM LEAD-ACID BATTERIES

Battery manufacturers use 87.5% of the total amount of lead consumed by industries in the United States. However, battery manufacturing accounts for less than 1% of the environmental emissions of lead [26]. There is an effective take back recycling program for large automobile batteries, but existing regulations to recycle small sealed lead batteries (weighing less than 1 kg) have not been very effective. The use of small sealed lead batteries is increasing in popularity as the requirement for specialized power back-up systems in portable equipment increases. Take-back programs for these batteries exist in nine U.S. states and 16 countries worldwide, with the target of recycling 95% of these small lead batteries, including nickel-cadmium batteries [27]. However, corporations have complained about the expense of these take-back programs, costing $6,000 per metric ton in the U.S., and $1,500 - $7,000 per metric ton in Europe [27]. Manufacturers in the U.S. paid $9 million per year to recover batteries, although only 1.9 million kg of batteries were recovered, less than 60% of the number of units estimated to be defunct. Many U.S. states have not yet enforced battery-recycling laws, and not all corporations are contributing financially to the Rechargeable Battery Recycling Corporation (RBRC). This situation means that larger companies are subsidizing the collection of batteries for those corporations that are not paying. In the absence of mandates and clearly stated penalties, the number of non-paying corporations is increasing [27]. The 1996 Mercury-Containing and Rechargeable Battery Management Act (Battery Act) was the first major congressional strategy to deal with the problems associated with the environmental impacts of improperly disposed batteries. The Battery Act was passed following evidence of environmental impacts such as the report in 1995 by the U.S. Environmental Protection Agency that 65% of the lead found in municipal solid wastes can be traced to small sealed lead acid batteries [27].

ALTERNATIVE POLICIES FOR REGULATING Pb IN ELECTRONIC PRODUCTS

The U.S. electronics industry has a great deal at stake if it does not comply with the need to eliminate lead-based solder from its exported electronic devices. California, with a high technology job base of over 900,000 people, hosts the largest proportion of industries responsible for manufacturing lead-containing electronics products in the United States. California alone exported $67.5B in high tech goods in 1999, which represented over 56% of California’s total exports [28]. Thus, from the perspective of trade and economic strength, it is imperative that alternatives to lead-based solder be identified and used. However, from the perspective of disposal and occupational health, it is not clear that currently available alternatives are better for the environment, because they also rely on heavy metals that can impact human health [22, 29, 30]. In fact, an outright ban on lead-based solders may
Table 4. Comparative assessment of environmental and health standards for metals used in solder material. *Bismuth telluride; Undoped; **Occupational Safety and Health Administration; ***American Conference of Govt. Industrial Hygienists; ****National Data for year 2000 in million kg.

<table>
<thead>
<tr>
<th>Permitted Exposure Level, 8 hour-Time Weighted Average**</th>
<th>Pb</th>
<th>Ag</th>
<th>Bi*</th>
<th>Cu</th>
<th>In</th>
<th>Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 µg/m³</td>
<td>0.01 mg/m³ h</td>
<td>5 (respirable fraction) – 15 (total dust) mg/m³ h</td>
<td>0.1 (fume) – 1.0 (dust) mg/m³ h</td>
<td>0.1 mg/m³ h</td>
<td>0.1 (inorganic), 0.1 (organic); 5 (respirable fraction) – 15 (total Tin oxide dust) mg/m³ h</td>
<td></td>
</tr>
<tr>
<td>Threshold Limit Value *** (mg/m³)</td>
<td>0.15</td>
<td>0.1</td>
<td>No established standard</td>
<td>0.1</td>
<td>0.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Total Maximum Daily Load (Number of Impairments)</td>
<td>480</td>
<td>47</td>
<td>No monitoring program</td>
<td>510</td>
<td>No monitoring program</td>
<td>No monitoring program</td>
</tr>
<tr>
<td>Maximum Contaminant Level in Drinking Water</td>
<td>Zero</td>
<td>0.1 mg/L</td>
<td>No established standard</td>
<td>1.3 mg/L</td>
<td>No established standard</td>
<td>No established standard</td>
</tr>
<tr>
<td>Toxic Release Inventory ****</td>
<td>8.2 (Pb) 170 (Compounds)</td>
<td>0.04 (Ag) 2.1 (Compounds)</td>
<td>No monitoring program</td>
<td>10 (Cu) 630 (Compounds)</td>
<td>No monitoring program</td>
<td>No monitoring program</td>
</tr>
<tr>
<td>Health Impairment Levels</td>
<td>Blood Lead Level in Children = 10 µg/100g, Workers = 40 µg/100g</td>
<td>Oral reference dose = 0.005 mg/kg/day</td>
<td>Not established. Bismuth salts are used as pharmaceutical agents</td>
<td>Liver storage; 500 mg/kg</td>
<td>Not established. Indium 111 is used in therapy against Cancer</td>
<td>Not established</td>
</tr>
<tr>
<td>Toxicity Symptoms</td>
<td>Cognitive and development impairment in children; Hypertension</td>
<td>Argyria or permanent discoloration of skin; Tissue degeneration</td>
<td>“Tellurium breath”; foul breath and stomatitis and may progress to malaise, nausea, weight loss, and depression</td>
<td>Gastrointestinal ailment; Kidney and Liver failure</td>
<td>Not established</td>
<td>Disturbance of immune function; Psychosis</td>
</tr>
</tbody>
</table>
Figure 2. Panel A: Governmental regulation of recycling programs for lead-containing batteries has been successful in the United States, when compared with other recyclable products such as aluminum, paper, and plastics. Figures in both panels are reproduced by courtesy of the Battery Council International. http://www.batterycouncil.org/environment.html.

Panel B: The remarkable success story of lead-acid battery recycling was achieved through an even more remarkable variety of regulation and voluntary incentives across States as shown in the map, where 37 States highlighted in blue and 1 city adopted recycling programs with or without monetary deposits based on a trade-in model developed by Battery Council International (BCI). Highlighted in yellow are 7 States that require a $5 deposit in lieu of trade-in requirement, and 2 States that require a $10 deposit. Only 5 States, NE, NH, NM, NV, MA have banned disposal of leaded batteries in municipal solid waste landfills or incinerators.
not be the best policy to limit human exposure to lead; recycling policies similar to those for lead batteries or for general e-waste, which rely on economic instruments and education campaigns, may provide similar health benefits at a lower cost for both industry and society. With no current legislation pending at the federal level regarding the use of lead-based solders in the electronics industry, an investigation of the implications of national and foreign lead control initiatives for the U.S. economy and public health policy is urgently needed.

Our overall objective is to construct a practical framework that prospectively defines the range of environmental behavior and performance for United States corporations that are confronting the implementation of emergent international agenda to phase out electronic products manufactured with lead alloy solders. To achieve this goal, we have adopted a comparative case history approach that explores national and international regulatory programs developed to eliminate or reduce the environmental and public health impact of lead used in consumer products such as lead-acid batteries.

The two facets of electronic waste management (quantity and toxicity) are not naturally linked together in the US. Landfill disposal of lead-containing e-waste is not scientifically proven to pose any threat to human health. As a consequence, policy alternatives currently under consideration tend to highlight only one facet or the other [31]. Inability to link these two facets will not produce a net gain on total environmental impact. Incentives that encourage recycling could lead to the melting or shredding of lead-containing articles, thus causing a greater threat than if simply disposed of in landfills. Alternatively, legislation that bans the use of lead may not only result in the use of alternative materials that create a greater environmental threat, but may do nothing to reduce the quantity of e-waste.

Thus, we envision the two facets of e-waste interwoven in policy scenarios highlighted in the matrix presented in Table 5. The scenarios are presented as a matrix of interactions between the decision to retain lead or to replace it with alternative metals, and the decision regarding whether or not to promulgate specific recycling rules regarding electronic products that contain toxic metals. Hence, the first scenario describes a situation where lead would be banned and full recycling programs would be implemented (including the recycling of alternative alloys that are also likely to exhibit certain levels of toxicity). Under this scenario, the disposal of existing lead-containing inventory would also need to be taken into consideration. The second scenario describes a situation where lead would not be banned, but legislation would require full post-consumer recapture and recycling. Under this scenario, special consideration would need to be given to the implications for producing lead-free products for international consumers that have implemented a ban on lead. The third scenario describes the condition under which lead would be banned, but there would be no legislative imperative to capture and recycle electronic products containing the replacement metals. The fourth scenario represents the current status where lead is not banned, and there are no incentives to capture and recycle lead-containing solders used in microelectronics products.

Modeling trade-offs among these scenarios requires extensive analyses including, but not limited to, comprehensive environmental life cycle assessments where impact pathways are mapped for environmental quality and public health effects of toxic metals used in manufacturing electronic products (Figure 3). An implementation framework for such analyses is presented in Figure 4. The ultimate goal of our research team is to develop quantitative models that describe his scenario towards the formulation of the best management policy.

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Table 5. Matrix of Alternative Policy Scenarios for Electronic Device Solder.

<table>
<thead>
<tr>
<th>POLICY DECISION TO BAN LEAD IN MICROELECTRONICS</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLICY DECISION TO MANDATE COMPLETE RECYCLING AND REUSE OF TOXIC METALS IN ELECTRONIC WASTE</td>
<td>Yes</td>
<td>SCENARIO 1</td>
</tr>
<tr>
<td>No</td>
<td>SCENARIO 3</td>
<td>SCENARIO 4</td>
</tr>
</tbody>
</table>

Figure 3. Impact pathways for environmental quality and public health effects of toxic metals used in manufacturing electronic products. A comprehensive LCA must quantitatively determine stock for each “box”, and flow rates for the 12 transformations arrows.
Figure 4. Decision analysis tree for evaluating policy alternatives regarding phase-out, recycling, landfilling, or incineration of lead-containing electronic products.

Comparative Policy Design and Assessment
Voluntary, Mandatory, State, National, and International

1. Impact Assessment (Environmental, Health, Engineering and Economic)
2. Quantitative Evaluation (Cost-Benefit Analysis, Decision Analysis, and Green Accounting)
3. Educational Outreach (Toxic Release Inventory, Public Right-To-Know, and Behavior Changes)
4. Legislative Enforcement and Industrial Compliance (Secondary Impacts and Costs)

Baseline

Current Assembly Practices

Decision 1
Lead Solder (Tin-Lead)
Landfill Recycle Export Incinerate

Model Output 1

Decision 2
Landfill Recycle Export Incinerate

Model Output 2

Current Assembly Practices

References


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Analysis and Design at the University of California, Irvine (UCI). He also maintains an affiliation with the UC Irvine Center for Occupational and Environmental Health. His research involves the industrial output and post-consumer fate of toxic chemicals such as mercury, lead, pesticides, and polyaromatic hydrocarbon compounds in the environment. He has conducted research on risk assessment in genetic engineering, and on ecological bioremediation and health effects of environmental contaminants. Under a project supported by the Global Forum for Health Research at the World Health Organization, Prof. Ogunseitan used the composite measures of disease burden, HeaLY and DALY to assess the contribution of environmental risk factors, including lead, to the burden of disease in developing countries.

Julie Schoenung is a materials engineer with a strong background in materials systems analysis and process economics. Her faculty appointment is in the department of Chemical Engineering & Materials Science at the University of California, Davis. She has conducted important interdisciplinary research on the industrial use of various chemical elements such as germanium, gallium, and silicon in electronic and ceramic applications. She has also conducted material selection and cost-modeling analyses for materials use in key industries such as electronics, automotive, and aerospace. Prof. Schoenung also has experience with life cycle analysis and the application of decision trees in evaluating alternatives.

Jean-Daniel Saphores was trained as an economist, as a civil engineer and as an environmental systems engineer. His specialization is in environmental and resource economics, with an emphasis on decision-making under uncertainty using tools from finance (real options). His primary appointment is in the department of Urban and Regional Planning, Policy, and Design in the School of Social Ecology at UCI, but he also has joint appointments in the department of Economics in the School of Social Sciences, and in the department of Civil and Environmental Engineering. Prof. Saphores has conducted research on economic analysis and environmental impact of policy options in various industrial sectors, including transportation, agriculture, and energy.

Andrew Shapiro is a materials scientist in the department of Chemical Engineering and Materials Science at UCI. He has extensive experience in microelectronics fabrication industries such as Rockwell International, Hughes Aircraft, Broadcom, and VSK Photonics. He currently holds a position at the California Institute of Technology, Jet Propulsion Laboratory. Prof. Shapiro has seven patents on low temperature co-fired ceramic technology and electronics manufacturing.

Toni Stein is an environmental engineer in the department of Environmental Analysis and Design, School of Social Ecology at UCI. She has seven years working experience in Materials and Process Research and Development at General Electric Company, in Aircraft Engines Division and Medical Systems Division. She currently holds a position as a postdoctoral research fellow under the supervision of Prof. Julie Schoenung and Prof. Dele Ogunseitan. She possesses five innovative patents in process development of advanced material systems.

Amrit Bhuie is an environmental toxicologist in the department of Environmental Analysis and Design, School of Social Ecology at UCI. She has an extensive experience in identifying the heavy metal deposition in the terrestrial environment. She got her doctorate degree from University of Toronto, Ontario, Canada. Her research on MMT (gasoline additive) has led her to achieve several regional and national awards. She has also been appointed as a Council member of Natural Science of Engineering Research Council of Canada (NSERC). She currently holds a position as a postdoctoral research fellow under the supervision of Prof. Oladele Ogunseitan and continues to work on managing the toxic metals in electronic waste focusing on the future implications of alternative policies for the Health, Environment, and Economy Sectors in State of California.

Hai-Yong Kang is an environmental engineer in the department of Chemical Engineering & Materials Science at the University of California, Davis. He is currently continuing his doctoral degree under the supervision of Prof. Julie Schoenung at UCDavis. He holds a B.Sc in Metallurgical Engineering from Yonsei University and double M.Sc. in Metallurgical and Environmental Engineering from the Yonsei University and Colorado School of Mines.