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

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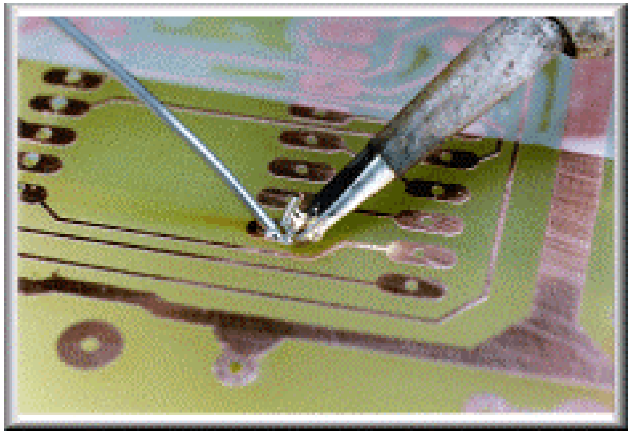
The challenge



- Tin (Sn)-Lead (Pb) solders (Sn63Pb37) used in electronics are assumed to pose threats to public health and the environment. Risks associated with alternative lead-free solders have not been studied.

- Rapidly growing municipal e-waste stream is creating concern for "end-of-life" disposal impacts on landfills, recyclers and incinerators. There are no uniform e-waste management guidelines, and infrastructures for proper disposal/recycling vary across regions.

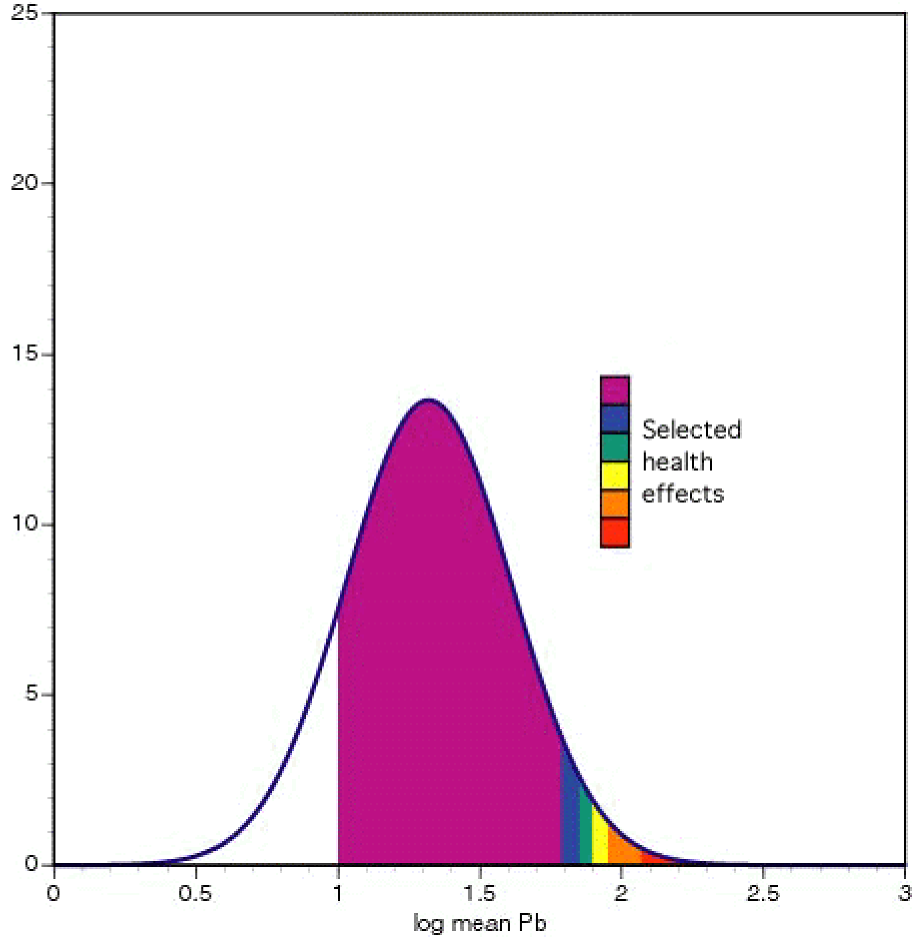
- International initiatives based on the "negative reputation" of Pb are driving the adoption of replacement metal alloy solders. Comparative life cycle analysis of the alternatives have not yet shown reduction in negative impacts on health and the environment.

Health effects or physiological changes associated with blood lead levels

Outcome	Blood lead levels [mg/dl]		Adjustment factor accounting for fraction of population affected when exceeding indicated levels
	Children	Adults	
IQ reduction (1-4 points, mean of 2.6)*	10 – 20	-	50%
IQ reduction (2-5 points, mean of 3.5)*	20	-	-
Increased systolic blood pressure (1.25 mm Hg)	-	10 – 15[1]	-
Increased systolic blood pressure (2.50 mm Hg)	-	15 – 20[1]	-
Increased systolic blood pressure (3.75 mm Hg)		Above 20[1]	-
Gastrointestinal effects	60	-	20%
Anaemia	70	80	20%
Nephropathy	80	120	20%
Encephalopathy	90	140	20%

[1]Only applied to men, aged 20-79, in current estimate; * In children aged 0-1 only (Fewtrell *et al.*, 2002)

Example probability density function showing individuals at risk of selected health effects

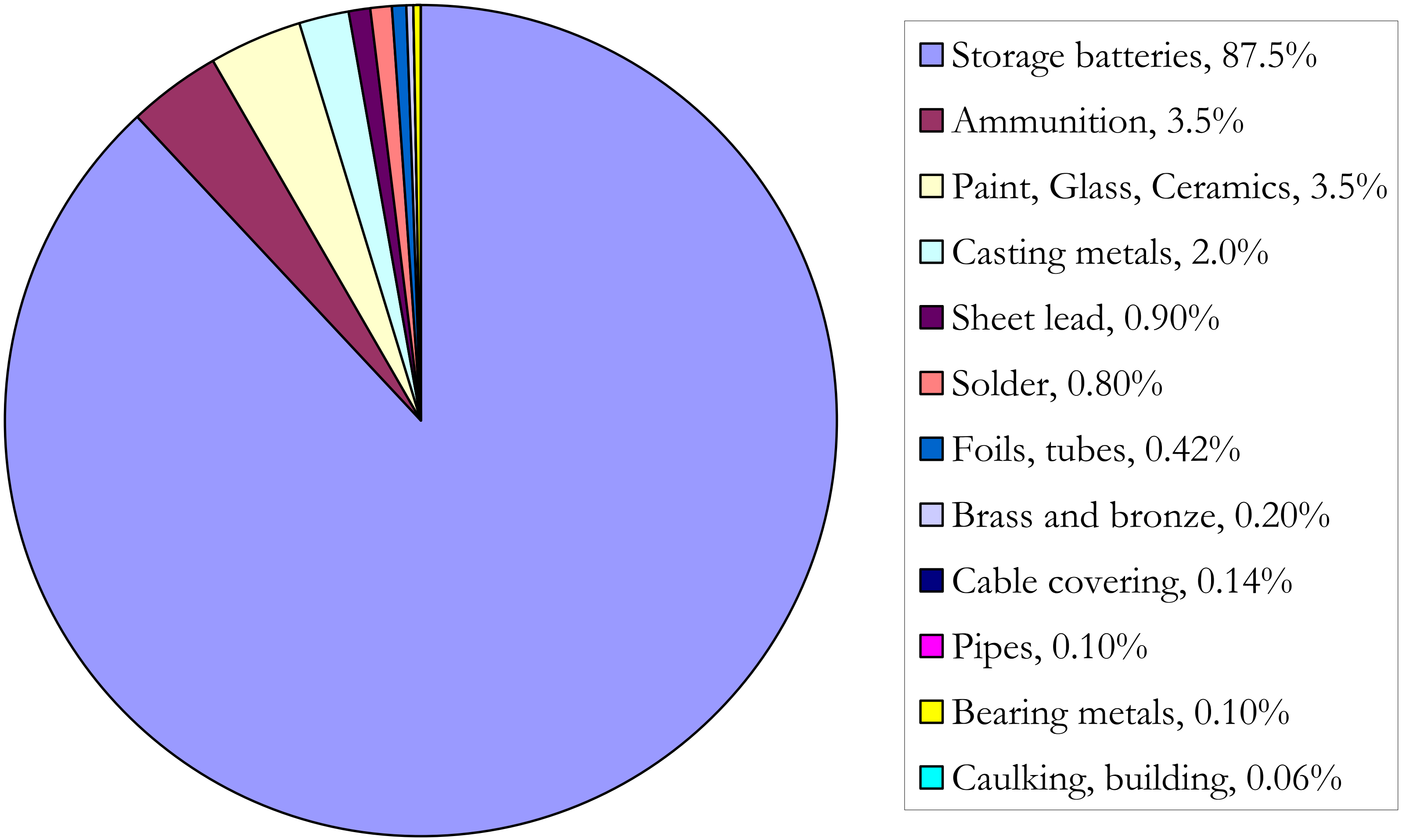


IQ reduction
Increased systolic blood pressure
Gastrointestinal effects
Anaemia
Nephropathy
Encephalopathy

Lead-phase out initiatives by sector in the United States

SECTOR	PRODUCTS	Pb USE	REGULATORY PROGRAM	REPLACEMENT/ ALTERNATIVE POLICY	REMARKS
ENERGY	Gasoline	Tetraethyl lead additive	National Phase-out 1975 - 1987	Manganese (MMT); MTBE	Incomplete global phase-out of Pb; Uncertainty about health and ecological impacts of alternatives
	Batteries	Lead electrodes and Lead oxide, red	State-regulated Recycling programs	"Green batteries" Nickel-Metal Hydride	Voluntary programs, incentives, Uncertain Impacts on transnational disposal
WATER	Distribution	Pb pipes, Brass faucets, & Cu Pipes With Pb (50%)-solder	National Phase-out June 1986 – June 1988	"Pb-free" pipes and fittings" (8% Pb); "Pb-free solder" (0.2% Pb)	Fixtures, old tanks remain hazardous for next decade
CONSTRUCTION	Paint	Lead pigments	Residential Lead-Based Paint Hazard Reduction Act of 1992 (PL 102-550)	Lead-free pigments	Persistent litigation; Paint Replacement hazards in old buildings.
ELECTRONICS	Cathode Ray Tubes	Lead oxide	State-regulated recycling	Flat panels; Hg	Premature collection programs. International trade. Uncertainty about Pb leaching conditions.
	Printed wire Boards	Tin-Pb solders	Europe/Japan phase-out programs	Pb-free solder, Silver, Bismuth	Uncertainty about risks of alternatives; costs and benefits of switching.

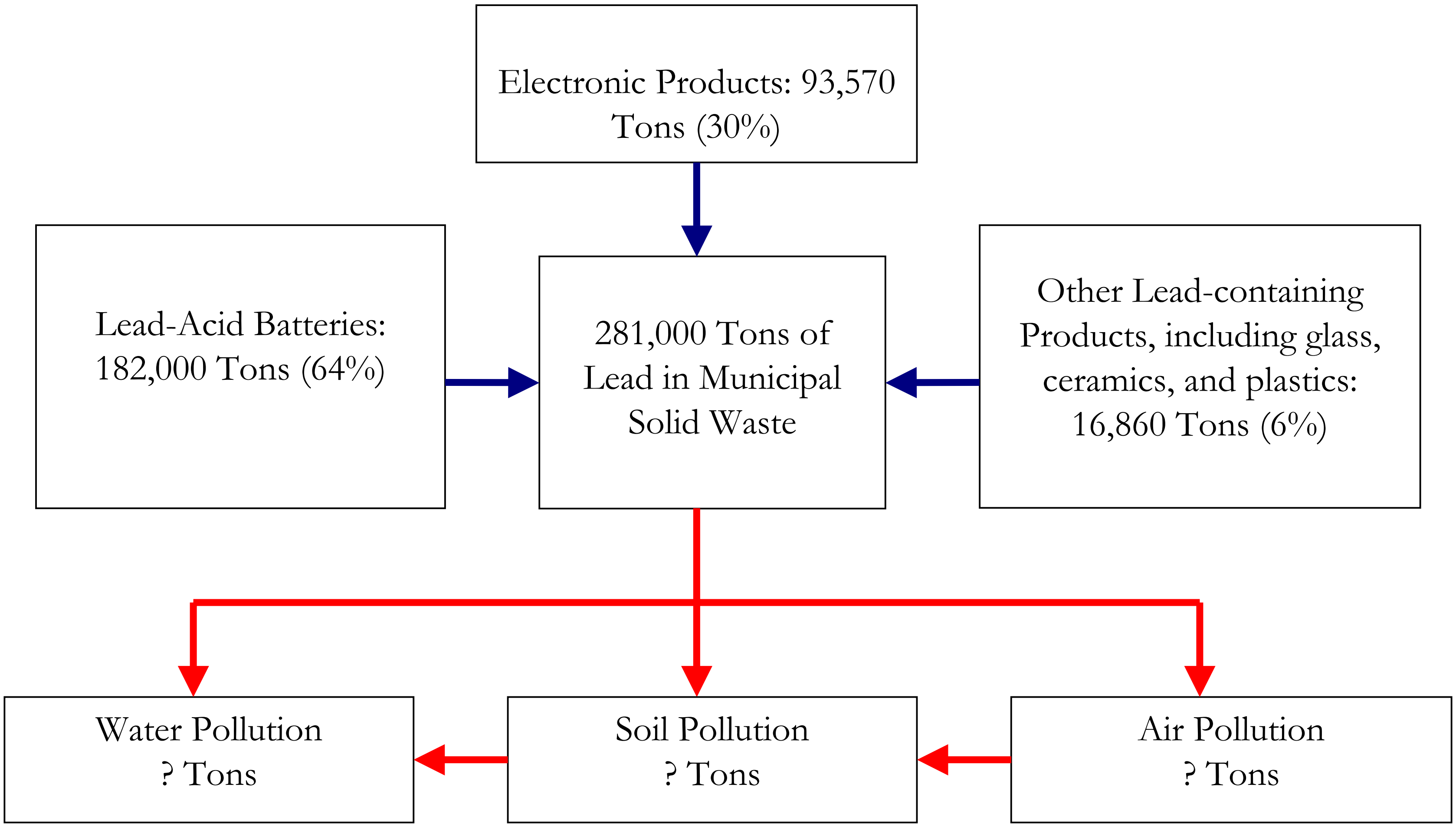
U.S. Lead Use by Sector in 1999. Total of 1.68×10^6 Tons



Year 2000 Toxic Release Inventory (TRI) Data for Pb, with Emphasis on Proportionate Contributions by California and Electronic and Electrical Industries.

	United States (lbs)	California (lbs)	% Contribution of California sources to total U.S. releases
Total Pb Releases (lbs)	3.87×10^8	5.09×10^6	1.29
Electrical Industries (SIC 36) Pb Releases (lbs)	2.22×10^6	5.01×10^4	2.25
% Contribution (SIC 36) to total releases	0.57	1.00	

Sources of lead in U.S. Municipal Solid Waste estimated for the year 2000

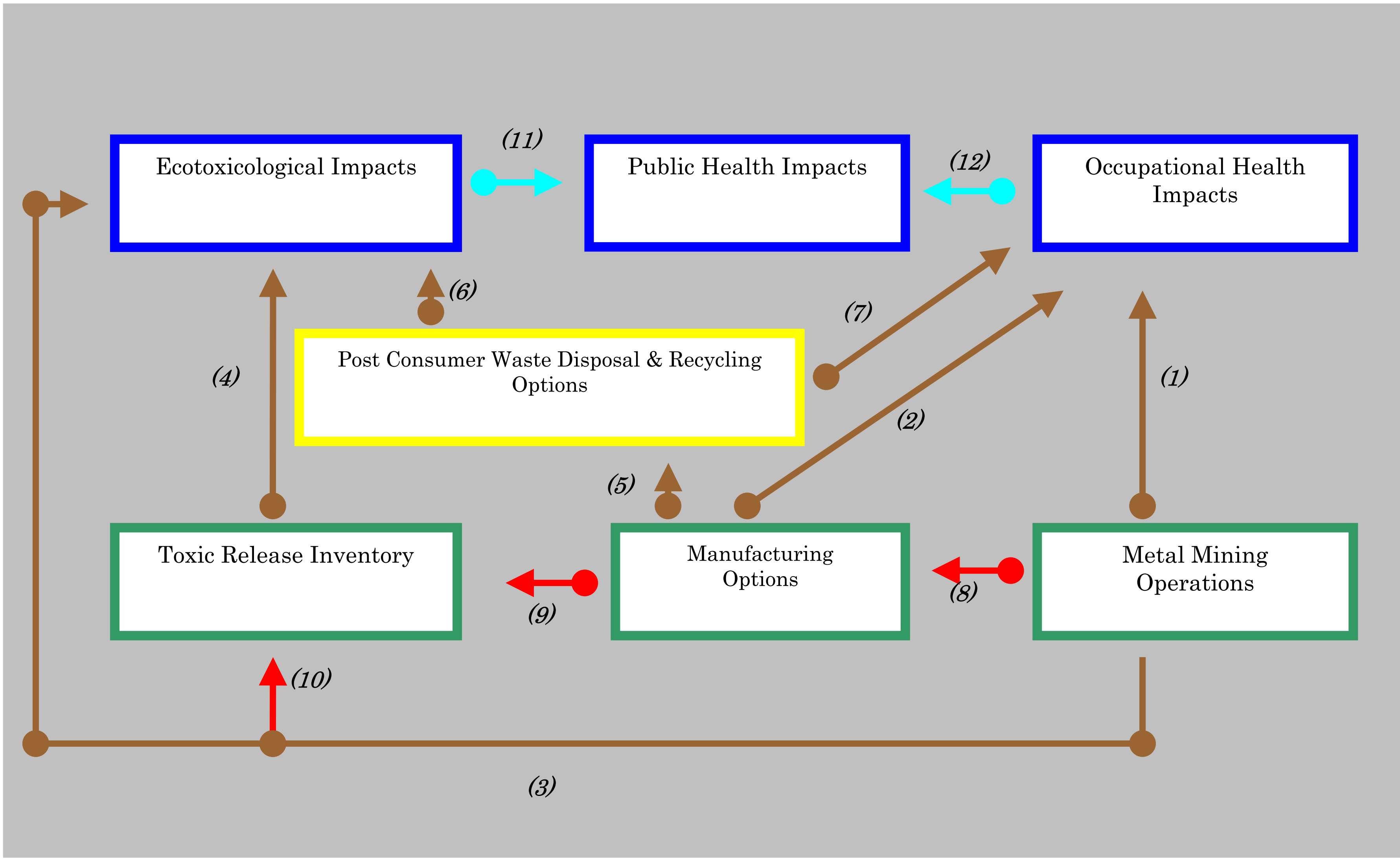


Data obtained from the United States EPA.

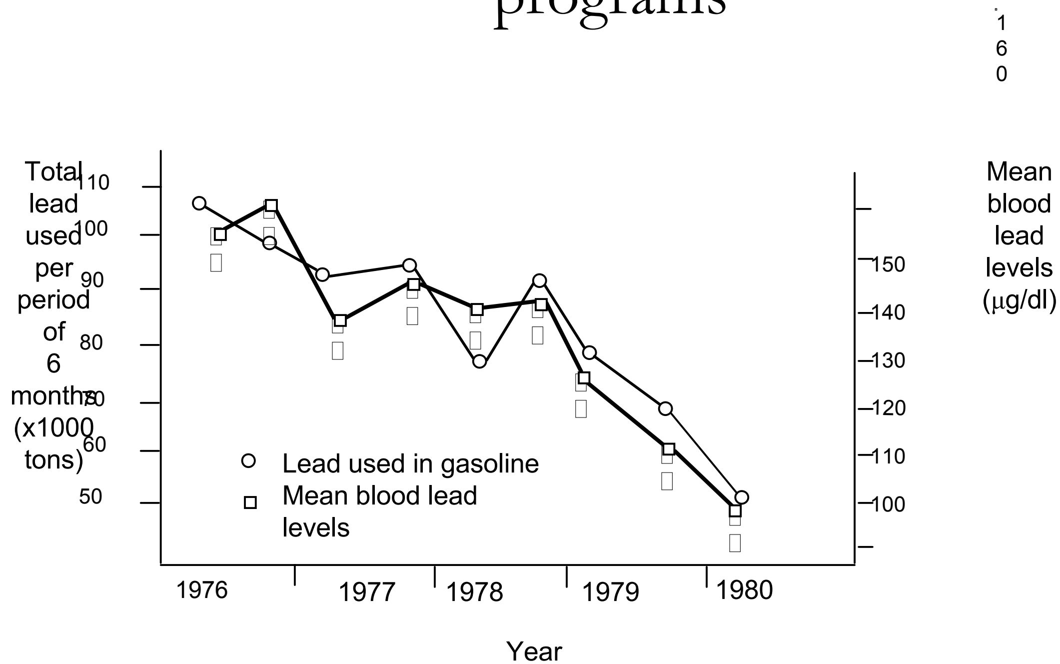
What can we learn from other Pb phase-out and recycling programs?

- Categories of uncertainty
  - Performance standards
  - Occupational exposure levels
  - Toxic release inventory thresholds and human health effects
  - Post-manufacture environmental release and ecotoxicological impacts
  - Consumer costs
  - End-of-life options
    - Parts recycling
    - Recovery and reuse
    - Disposal

Quantifying uncertainty

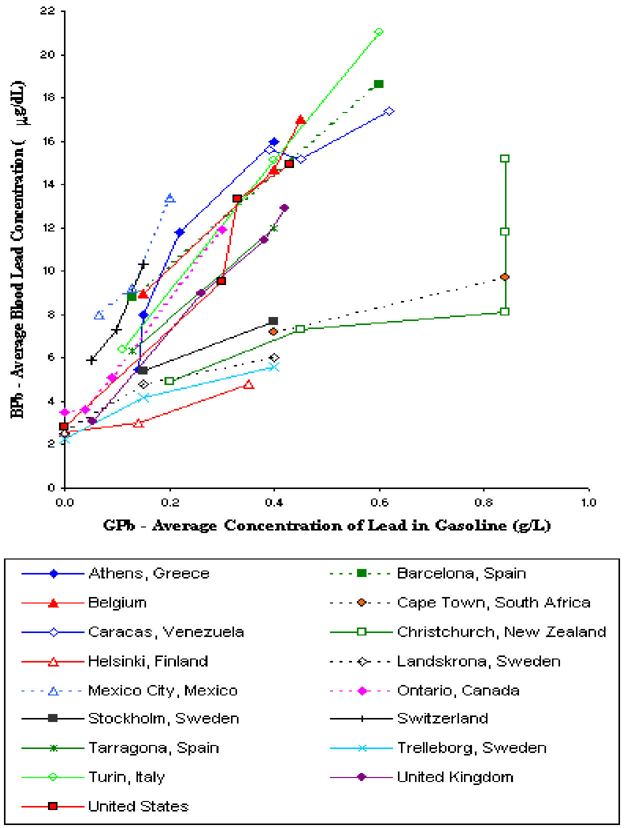


Reduction in blood lead levels in relation to a lead reduction programs



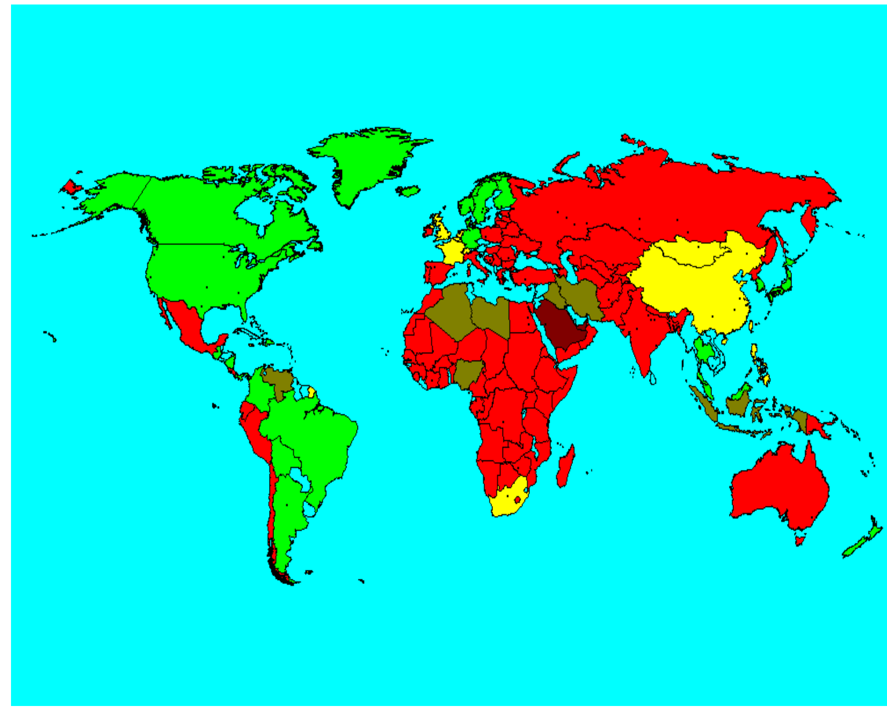
(based on Annest, 1983 - copied from Plomb dans l'environment, INSERM, 1999)

Global legacy of leaded gasoline



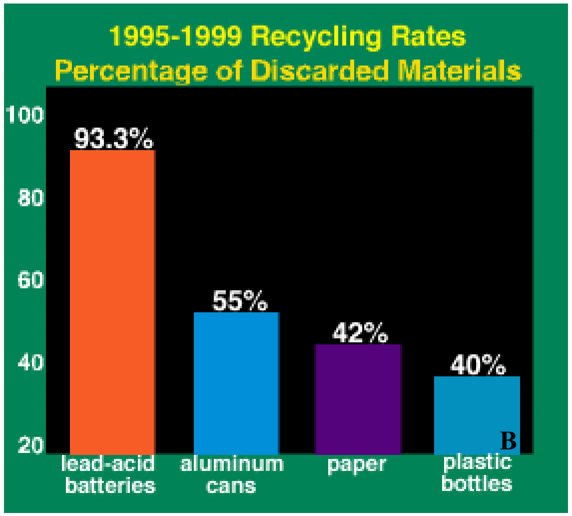
Thomas et al. "Effects of Reducing Lead in Gasoline,"
Envi. Sci. Technol. **33**(22):3942-3947, 1999

There is a clear correlation between the continued use of lead in gasoline and the internalized concentration of lead in humans at levels that have been shown to produce cognitive impairment and other symptoms of ill health in many countries. Reproduced with permission from Valerie Thomas, Princeton University [Thomas *et al.*, 1999].



Global map showing various outcomes of regulatory strategies to eliminate lead from gasoline in different countries. Countries highlighted in green are those in which 10-20 years of regulatory enforcement have reduced the environmental burden of lead. Countries highlighted in yellow, purple, brown, and red are those in which historical or contemporary use of leaded gasoline remains a major source of environmental lead and human exposure.

Lead-acid batteries



Ni-MH “Green Batteries

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.

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, NE, NM, NV, MA have banned disposal of leaded batteries in municipal solid waste landfills or incinerators.

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

SnZn	199°C
SnBiAg	210°C
SnBiAgCu	210°C
SnAgCu	217°C
SnAgCuSb	210-217°C
SnInBiAg	179-210°C
SnCu	229°C

Performance characteristics of alternative solder materials for electronics products

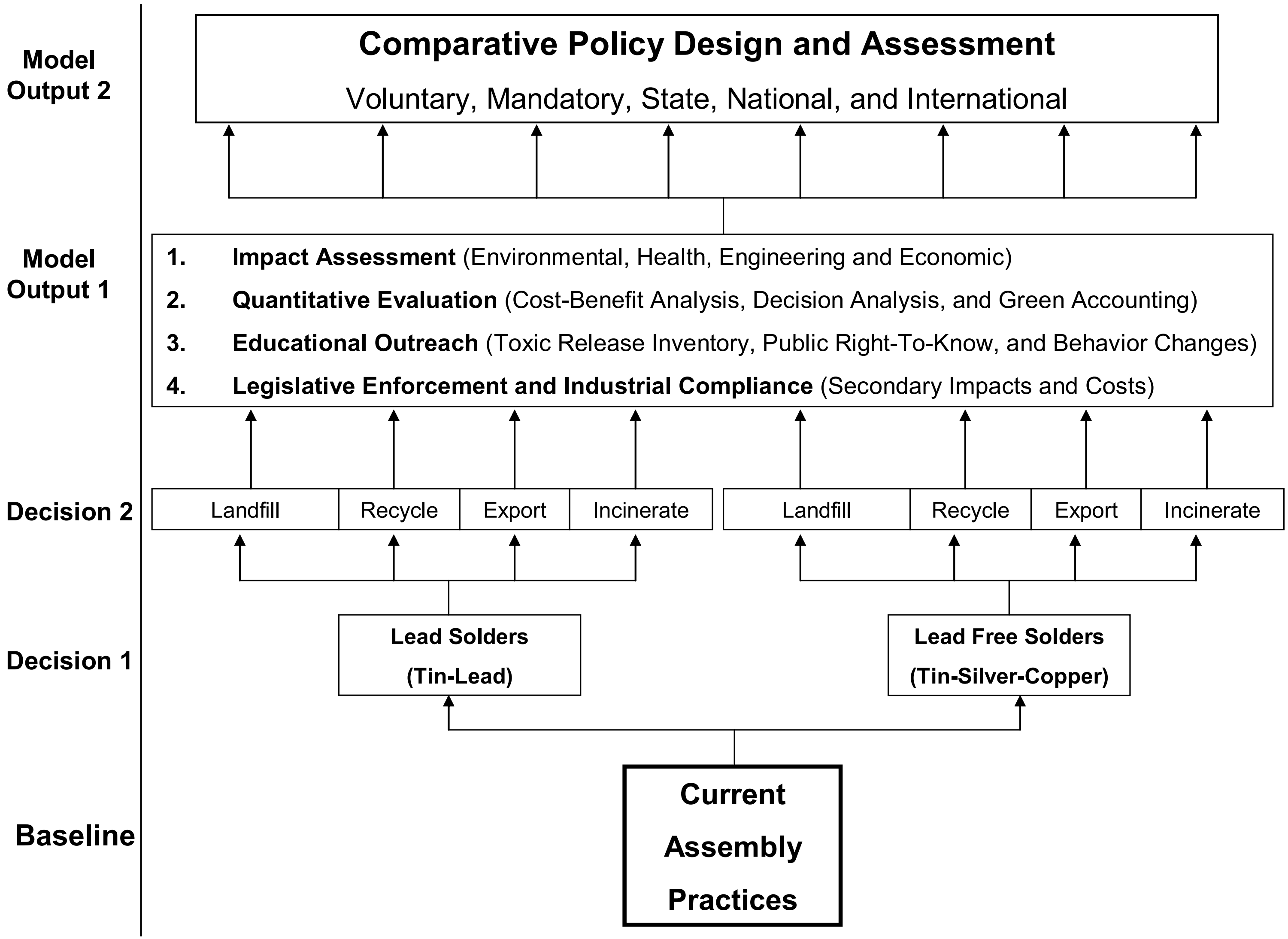
SOLDER COMPOSITION	T_m (°C)	ADVANTAGES	CONCERNS
Sn96.5Ag3.5 (eutectic)	221	(a) Good wetting characteristics and superior joint strength compared to Sn/Pb solder (b) Long history of use	(a) May exhibit structural weakness at solder connection (b) High T_m
Sn95.5Ag3.8Cu0.7	217 - 218	(a) Recommended by NEMI (b) Virtually no plastic range (c) Rapid solidification avoiding formation of cracks (d) Formation of intermetallics $Cu6Sn_5$ and Ag_3Sn provides greater strength and fatigue resistance	(a) High T_m
Sn96.2Ag2.5Cu0.8Sb0.5	217 - 218	(a) Addition of Sb improves thermal fatigue (b) Coating offers flatter pads and uniform coat (c) Works well with Ni/Au Ag/Pd and OSP boards (d) Sb reduces melting °C and refines grain structure	(a) Sb trioxide may exhibit toxicity at higher temperatures (b) High T_m
Sn77.2In20.0Ag2.8	175 (T_S)–187 (T_L)	(a) Compatible T_m to Sn/Pb (b) Good ductility, strength and creep resistance (c) Low dross in wave solder	(a) Low supply, high cost (b) 118°C eutectic point may deteriorate joints (c) Large plastic range

	Pb	Ag	Bi*	Cu	In	Sn
Permitted Exposure Level, 8 hour-Time Weighted Average**	50 μg/m^3	0.01 mg/m^3 h	5 (respirable fraction) – 15 (total dust) mg/m^3 h	0.1 (fume) – 1.0 (dust) mg/m^3 h	0.1 mg/m^3 h	2 (inorganic), (organic); 5 (respirable fraction) – 15 (total SnO dust) mg/m^3 h
Threshold Limit Value*** (mg/m^3)	0.15	0.1	No established standard	0.1	0.1	2.0
Total Maximum Daily Load (Number of Impairments)	480	47	No monitoring program	510	No monitoring program	No monitoring program
Maximum Contaminant Level in Drinking Water	Zero	0.1 mg/L	No established standard	1.3 mg/L	No established standard	No established standard
Toxic Release Inventory****	8.2 (Pb) 170 (Compounds)	0.04 (Ag) 2.1 (Compounds)	No monitoring program	10 (Cu) 630 (Compounds)	No monitoring program	No monitoring program
Health Impairment Levels	Blood Lead Level in Children = 10 μg/100g. Workers = 40 μg/100g	Oral reference dose = 0.005 mg/kg/day	Not established. Bismuth salts are used as pharmaceutical agents	Liver storage; 500 mg/kg	Not established. Indium 111 is used in therapy against Cancer	Not established
Toxicity Symptoms	Cognitive and Development impairment in children; Hypertension	Argyria or permanent discoloration of skin; Tissue degeneration	"Tellurium breath"; foul breath and stomatitis and may progress to malaise, nausea, weight loss, and depression	Gastrointestinal ailment; Kidney and Liver failure	Not established	Disturbance of immune function; Psychosis

Summary metric based on an equally-weighted scoring model of the results from the toxicity metric, the availability and supply metric, and the environmental impact of extraction metric (Ku *et al.*, 2003)

METAL	Toxicity Rank	Cost Rank	Extraction Impact Rank	Rank Sum	Final Rank
Lead	1	6	6	13	5
Antimony	3	4	4	11	3
Bismuth	5	2	5	12	4
Copper	6	7	7	20	7
Indium	4	1	3	8	2
Silver	2	3	1	6	1
Tin	7	5	2	14	6

Decision tree towards best management policy for leaded electronic products



Conclusions

- *The pessimistic view*
  - Experience with lead phase-out programs in other industries indicates that "leaded electronic products" are not likely to be phased out globally in the short term. International trade in defunct products and recyclable materials will likely sustain the flow of leaded microelectronic products into environmental compartments for the foreseeable future.

- *The optimistic view*
  - Science-driven agenda to select alternative alloys will include
    - Assessments of negative impacts to health and the environment are associated with manufacturing and end of life processes.
    - Analysis of trade-offs for each replacement being considered?
    - Decision analysis to support how industry, recyclers and the government best cooperate to define economically viable and sustainable end of life programs to protect public health and the environment.
    - Policy analysis to define alternatives to command and control policies for successful implementation of recovery and recycling programs at the State, national, and international levels?

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