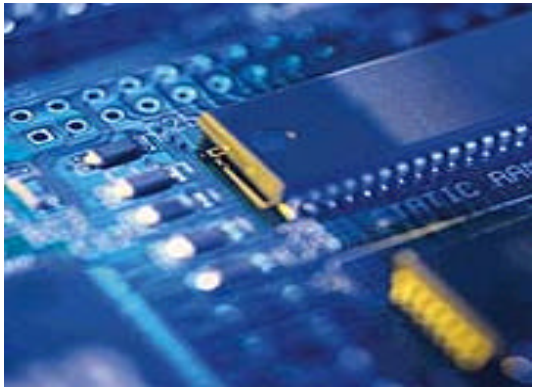
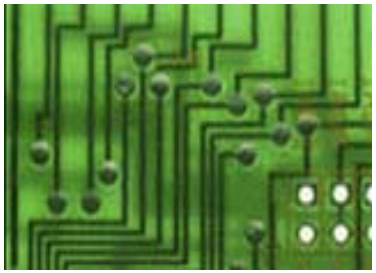


Life-Cycle Environmental Impact Evaluation *of* Tin-Lead and Lead Free Solders

Jack Geibig and Maria Socolof
University of Tennessee Center for Clean Products
jgeibig@utk.edu
April 14, 2005

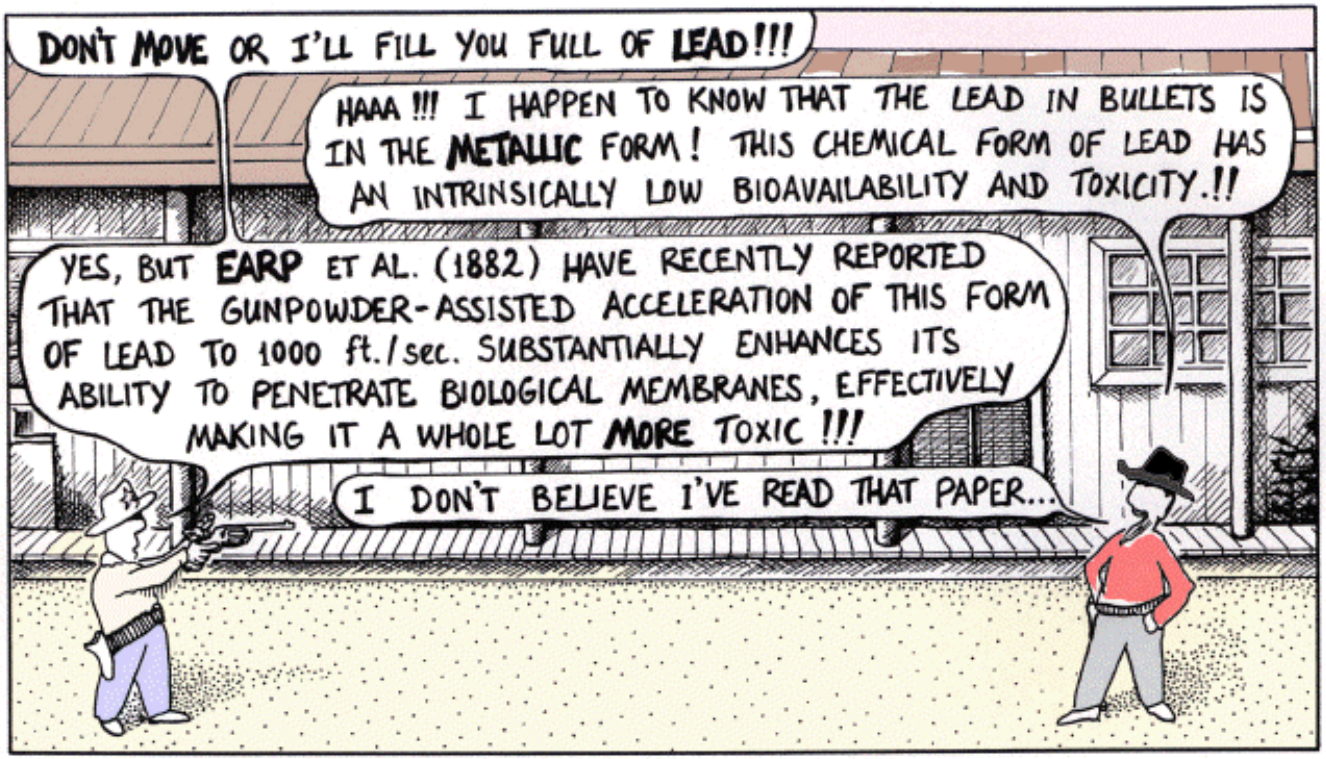
THE CENTER FOR CLEAN PRODUCTS AND CLEAN TECHNOLOGIES



EU WEEE/ROHS Directive

- WEEE sets a recycling goal of 6 kg/yr-person (2006)
  - Collection systems responsibility of mfg.'s
  - Free to consumer
  - Shared responsibility for historic waste
  - Fees and penalties
- Based on Precautionary Principle
- ROHS banned materials- Pb, Hg, Cd, Cr, PBB, etc.
- Sound policy? -- roughly 93% of lead in landfills exempted from ROHS

Lead toxicity

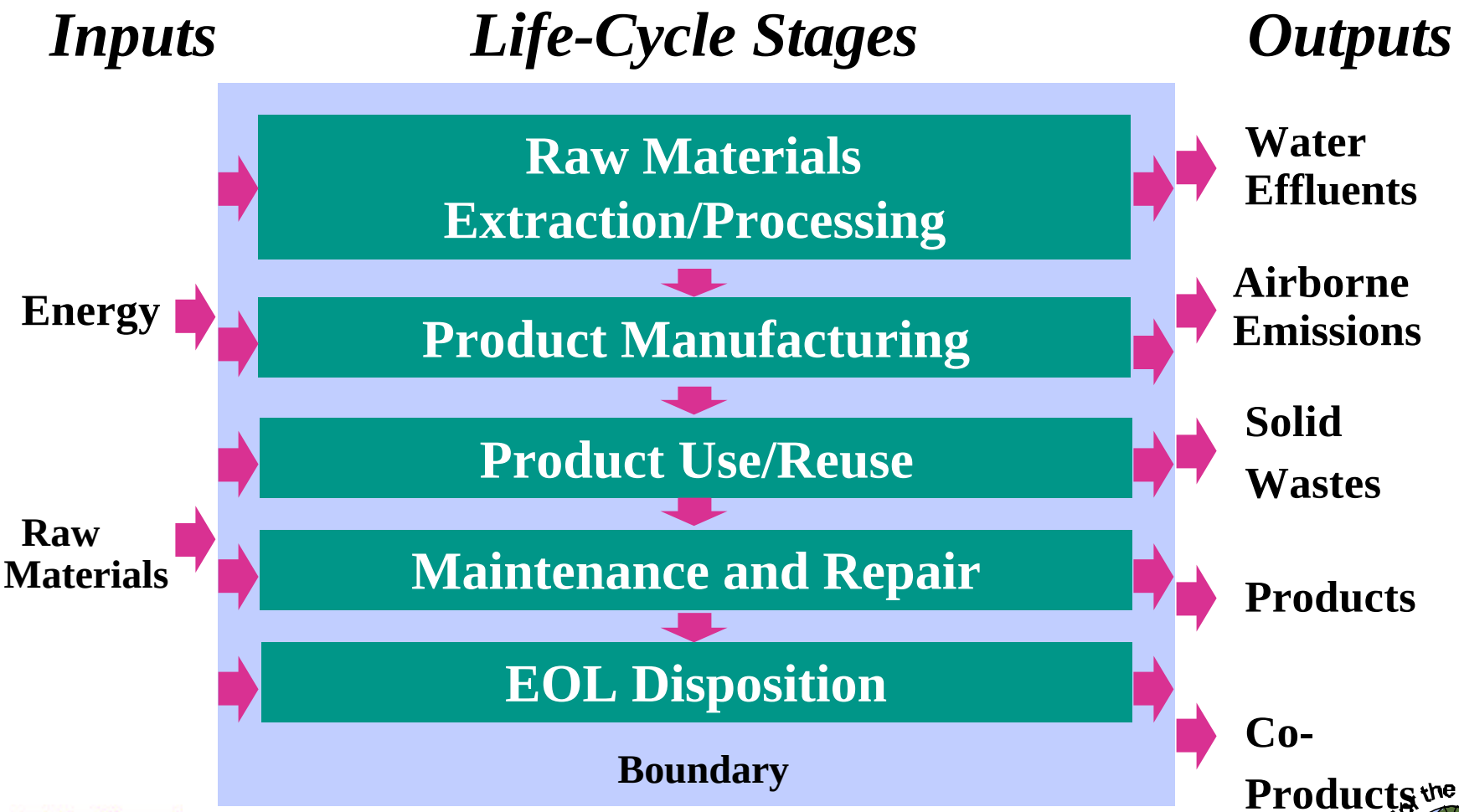


ENVIRONMENTAL SCIENTISTS IN THE WILD WEST

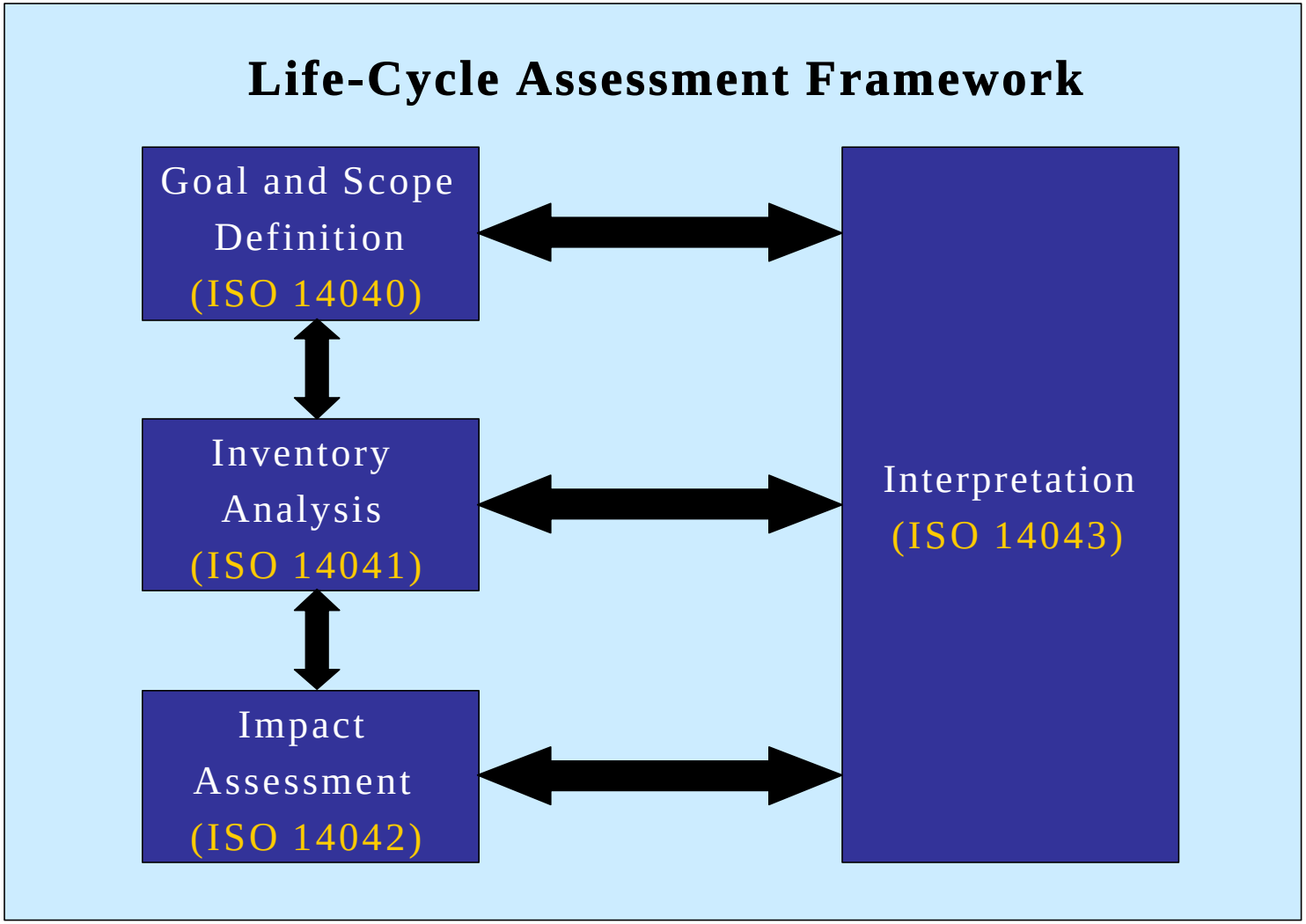
LFSP Scoping - Project Goals

- Primary goal:
  - Evaluate the relative life-cycle environmental impacts of Sn/Pb solder and selected Pb-free alternative solders
- Secondary goals:
  - Evaluate the effects of lead-free solder implementation on the manufacturing processes
  - Assess the leachability of Pb-free solders and their potential environmental effects

Life-Cycle Stages and General Materials Flow



ISO 1404x Definition of LCA



Goals and Scoping

Scoping- Solder Selection

Initial Solders

- Sn/Pb
- Sn/Ag
- Sn/Cu
- Sn/In
- Sn/Sb
- Sn/Ag/Bi
- Sn/Ag/Cu
- Sn/Ag/In
- Sn/Ag/Cu/Bi
- Sn/Ag/Cu/In
- Sn/Ag/Cu/Sb

Final Solder List

- Sn/Pb
- Sn/Cu
- Sn/Ag/Cu
- Sn/Ag/Bi
- Sn/Ag/Cu/Bi

Criteria for Selection

Performance

Resource constraints

Data availability

Diversity of materials

Alloys of interest

Solders Selected for Evaluation

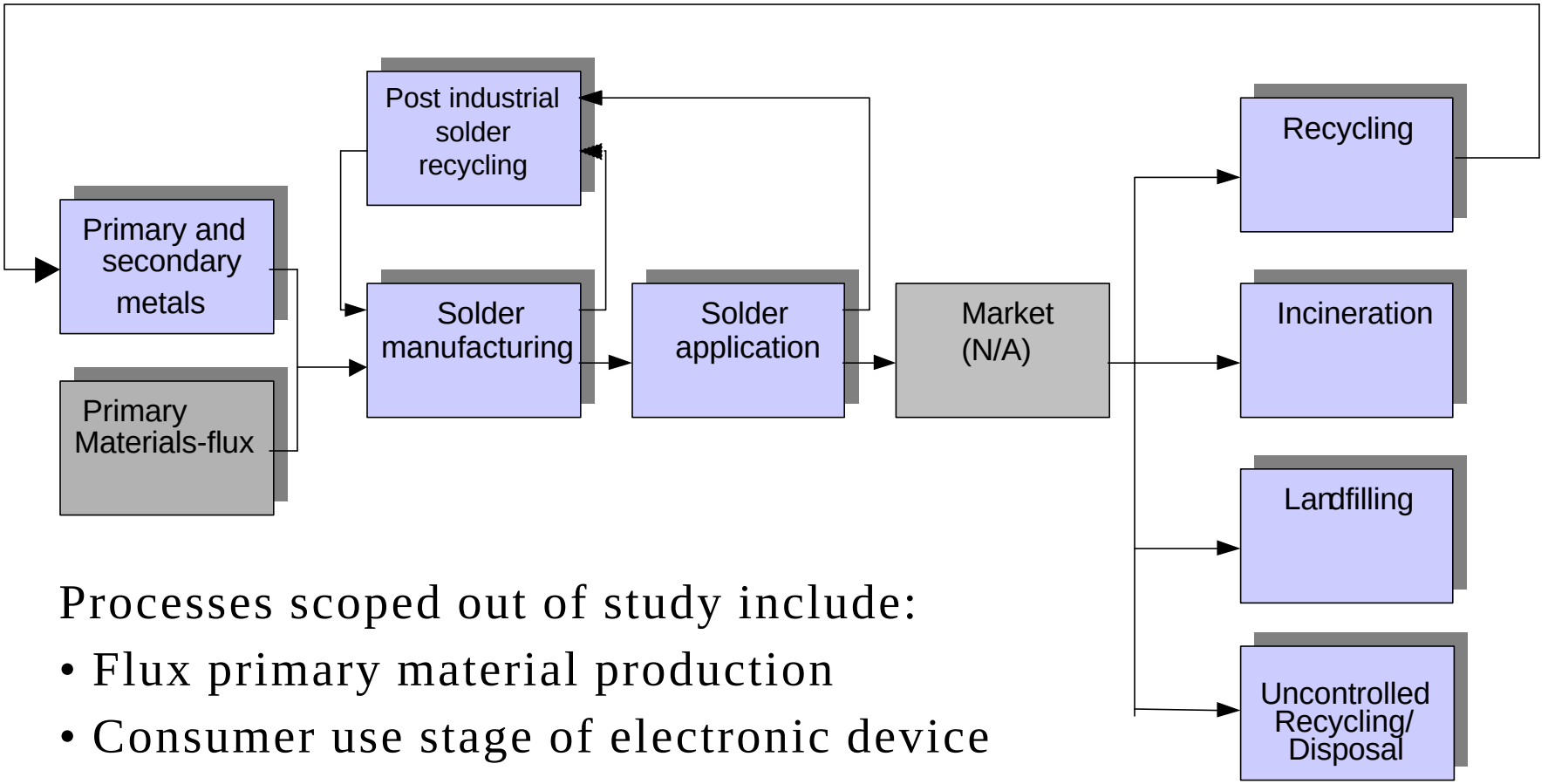
Wave Application Solders

- Sn/Pb (63 Sn/ 37 Pb)
- Sn/Cu (99.2 Sn/ 0.8 Cu)
- Sn/Ag/Cu (95.5 Sn/3.9 Ag/0.6 Cu)

Reflow Application Solders

- Sn/Pb (63 Sn/ 37 Pb)
- Sn/Ag/Cu (95.5 Sn/3.9 Ag/0.6 Cu)
- Sn/Ag/Bi (42 Sn/1.0 Ag/57 Bi)
- Sn/Ag/Cu/Bi (96 Sn/2.5 Ag/0.5 Cu/1.0 Bi)

LFSP Scoping – The Solder Product System

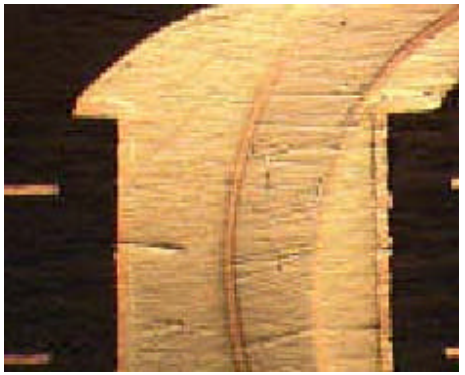


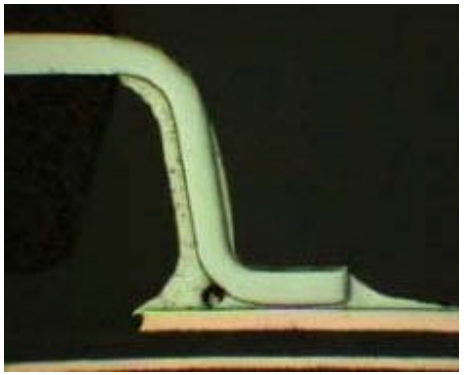
Processes scoped out of study include:

- Flux primary material production
- Consumer use stage of electronic device

LFSP Scoping - Selection of the Functional Unit

- Selected solders varied in functional use
  - Application/assembly process (wave vs reflow)
  - Solder manufacturing (bar vs paste)
- Two possible approaches considered
  - Volume of solder joint
  - PWB design-based (e.g. volume scaled to specific board design)

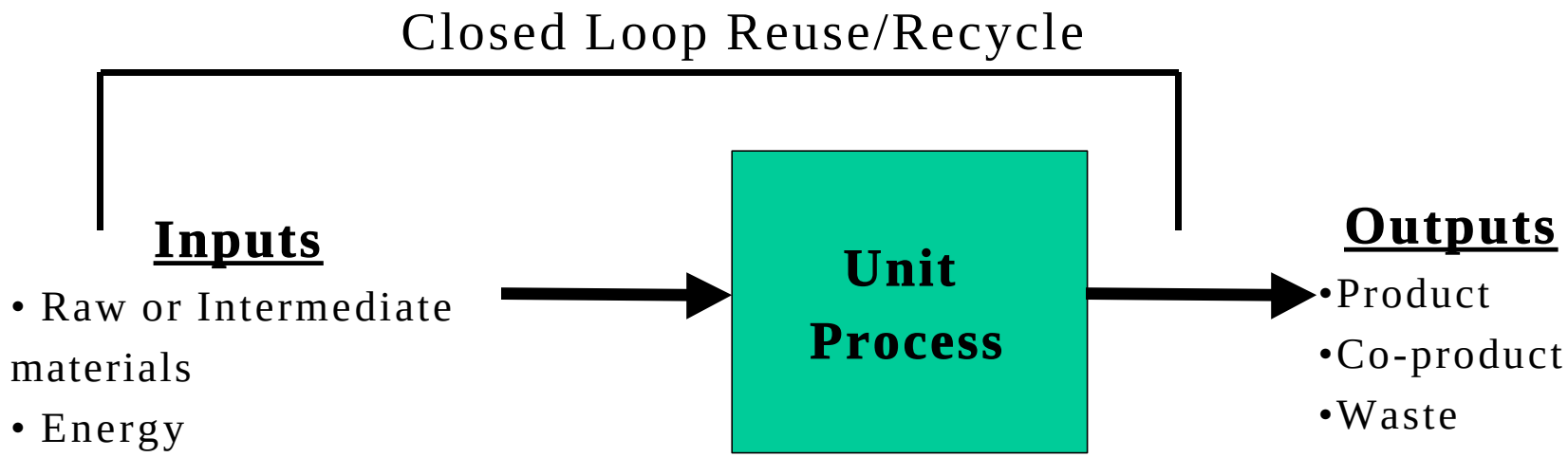




Life-Cycle Inventory

LIFE-CYCLE INVENTORY

...is the identification & quantification of material and energy inputs and emission and product outputs.



Source: Joyce Cooper, University of Washington ,2003

LFSP Data Sources/Scope of LCI

Life-cycle Stage	Data Sources	Scope
Material Extraction	Suppliers, USGS, Mining companies (Secondary Data)	Less Emphasis
Solder Manufacturing	Solder Suppliers/ Manufacturers, (Primary Data)	Greater Emphasis
Solder Application	PWB Assemblers and OEMS (Primary Data)	Greater Emphasis
Use/Reuse/ Maintenance	PWB Assemblers, OEMS, Other Studies	Scoped out of Study
EOL Disposition	PWB Recyclers, Copper Smelters, Other Sources (Primary and/or Secondary)	Greater Emphasis

LCI Inventory Summary

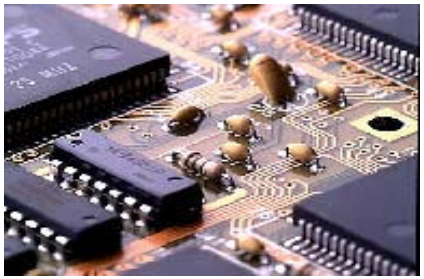
- Materials Extraction- Secondary data from 2 different sources
- Solder Manufacturing- Primary data from 5 solder manufacturers representing 80% of U.S market
- Use/Application- Primary data collected from 3 companies and compared to provided data from 2 others
- EOL- Disposition gathered from 11 states and 2 municipalities

LFSP Solder Manufacturing Stage

- Data aggregated from 5 companies
- Sn/Pb and Lead-free solders
- Bar and paste data collected separately
- Major inputs:
  - Metals: primary vs. secondary
  - Energy: mix of power/fuels
  - flux assumed same for each
    - differences appear in functional unit normalization (Pb vs Pb-free)
    - Flux composition varies by alloy type and user preference

LFSP Post-Industrial Recycling of Waste Solder

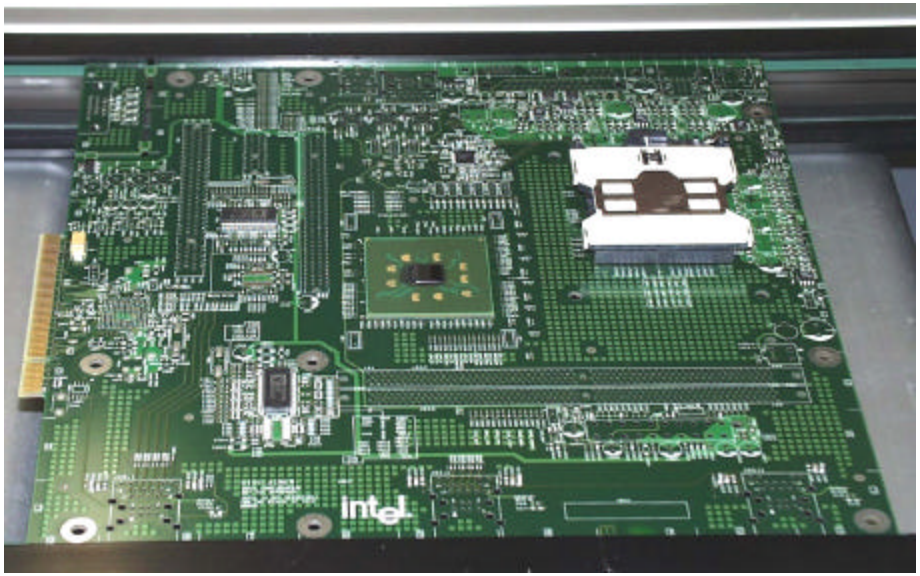
- Solder recycled through Sn or Pb smelting and refining process
  - Inputs include waste from solder manufacturing and application as well as materials from other industries
  - All metal content undergoes smelting and refining
  - Additional process steps required to separate lead-free metals (e.g. Ag, Bi)
- Lead limit of 0.1% Pb will present difficulties for solder recycling:
  - Feedstock segregation and sampling problems
  - Contamination of equipment equals high capital investment
  - Economics may be barrier depending on solder type



LFSP Application (Use) Life-Cycle Stage

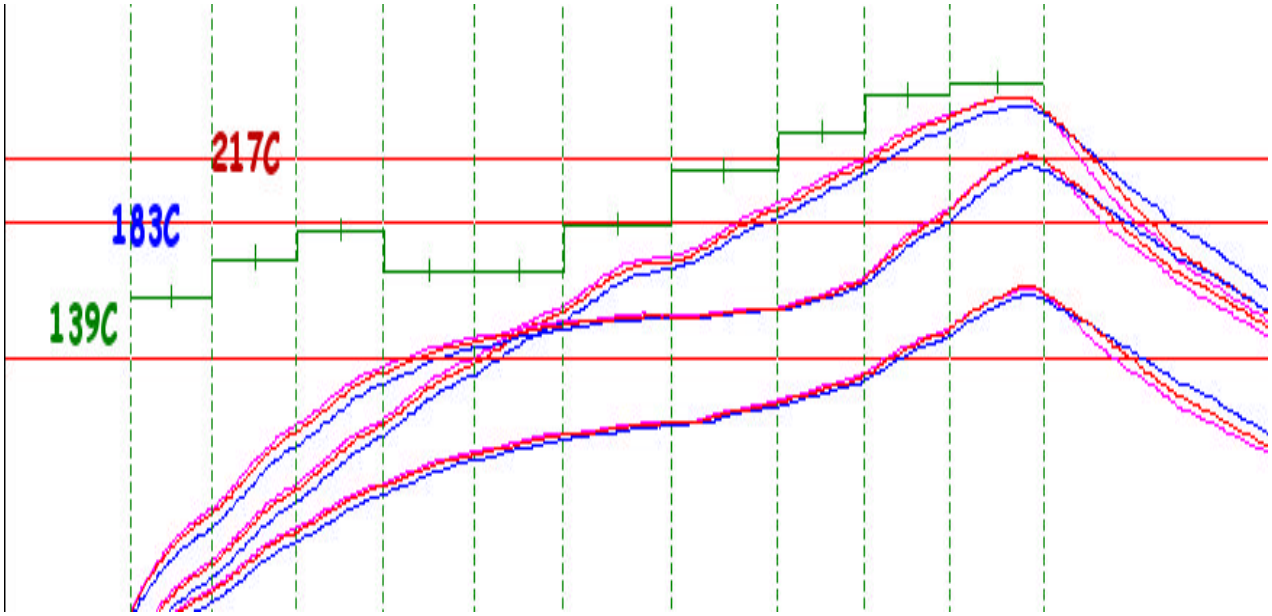
- Primary inventory items of interest
  - Energy consumption during assembly (both wave and reflow)
  - Dross formation (wave)
  - Flux (wave)
- Conducted testing to determine reflow energy consumption (kW-h/g solder)
  - Reflow process creates optimal conditions required to reflow solder
    - Temperature profile (TAL)
    - Conveyor rate
    - Mass of board
  - No direct correlation between energy consumption and mass of solder processed

PWB Specs for Reflow Testing



PWB Type	Micro ATX Motherboard
Length	9.6 inches
Width	9.6 inches
Mass of Assembly	225 grams
Mass of Solder (est.)	2.5 grams/board

Reflow Test Profile Characteristics



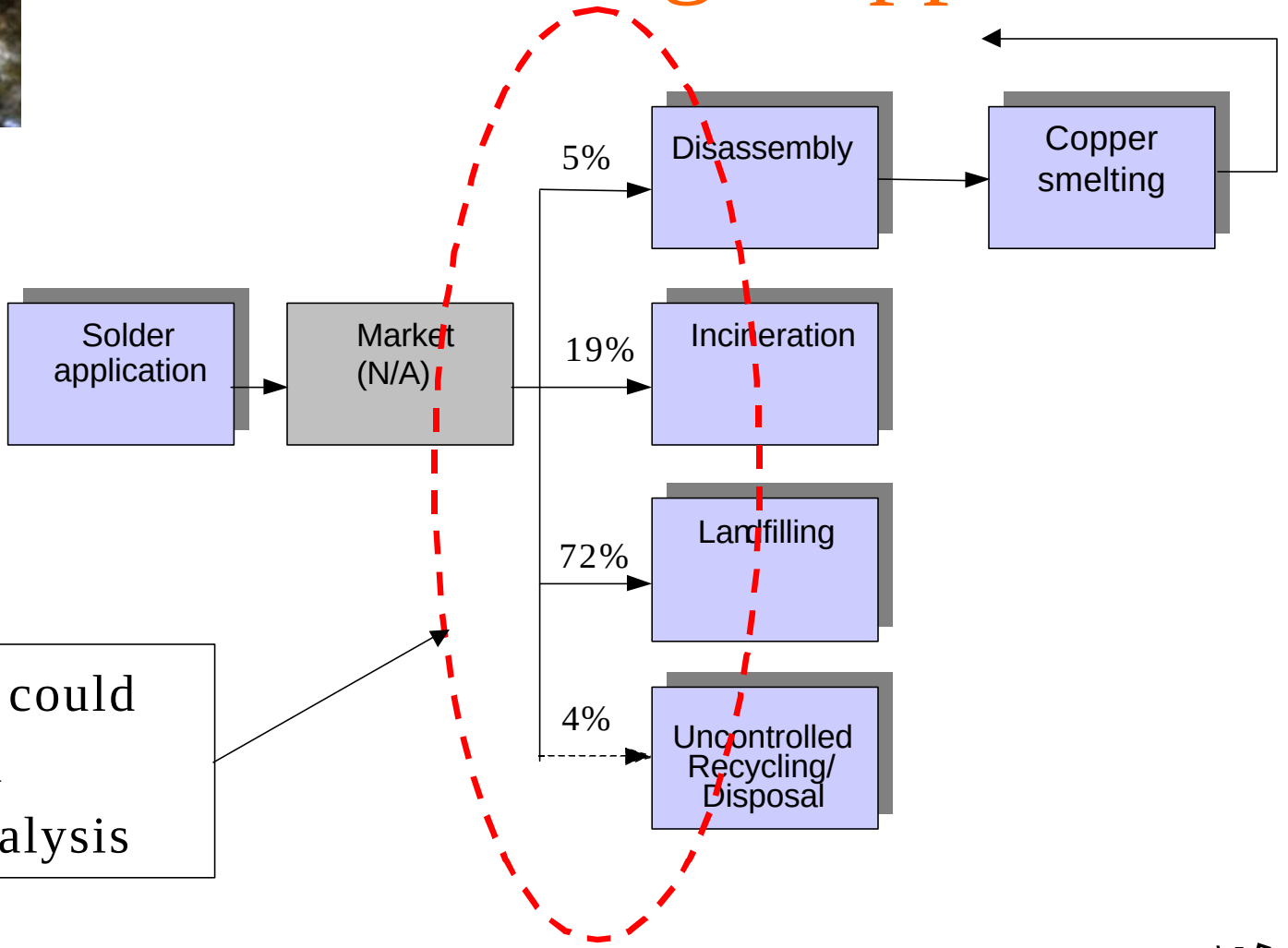
Solder	Peak Temperature (range)	TAL (average)	dTemp
Sn/Ag/Bi	160.2-170.1C	65 secs	9.9C
Sn/Pb	204.4-219.1C	51 secs	14.7C
Sn/Ag/Cu	235.2-248.8C	65 secs	13.6C

Solder Application Testing- Energy consumption

Solder	Application method	Energy inputs (MJ/kg of solder)	% change from SnPb
SnPb	Reflow	412	na
SAC	Reflow	447	8.52%
BSA	Reflow	297	-28.0%
SABC*	Reflow	447	8.52%
SnPb	Wave	58.7	na
SAC	Wave	67.8	15.6%
SnCu	Wave	68.3	16.4%
* assumed the same as SAC			
na=not applicable			

- Note, SnPb reflow based on 20.9 kW, compared to 14.8 kW in NEMI Testing for (41% increase)
- Differences in reflow energy consumption highlight importance of normalization assumptions and equipment efficiency of reflow ovens

EOL Stage Approach



Distributions could be varied in a sensitivity analysis

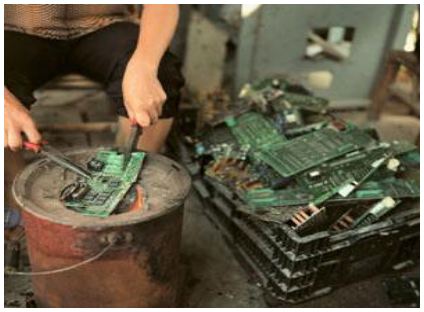
LCI Inventory Summary

- Incineration- Data gathered from EPA conducted test burn of electronics in rotary kiln and from other published data
- Recycling- Data from 2 copper smelters and 4 electronics demanufacturers.
- Landfilling- conducted thorough leachability testing of PWBS w/ alt solders. Secondary landfilling data used
- Unregulated- modeled releases based on best guess of recycling practices (low confidence)

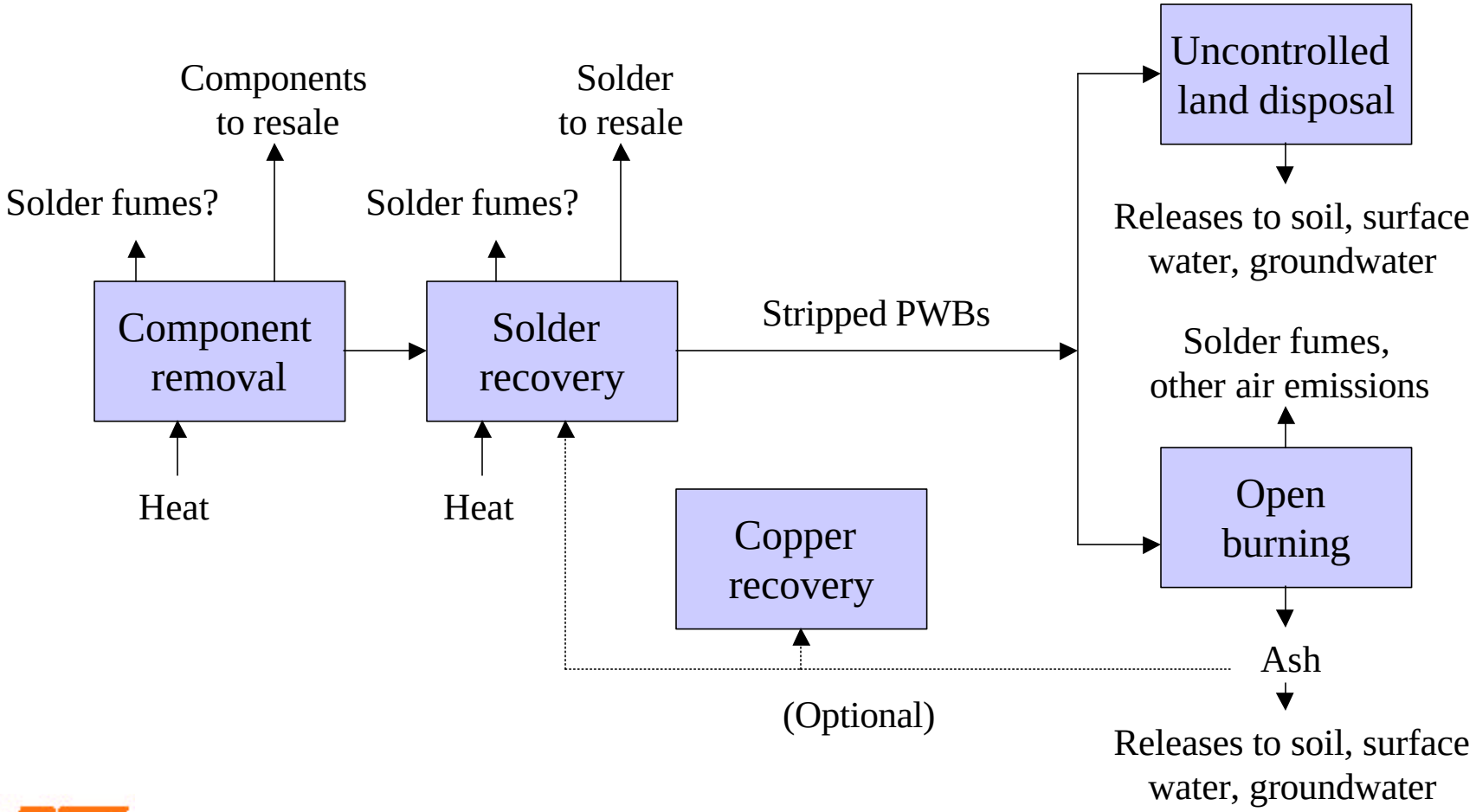
LFSP Leachability results

- Results used to estimate metal outputs to the environment from landfilling PWBs or incinerator ash from burning PWBs

Solder Alloy	Solder Type	Metal	Fraction Leached (kg metal/ kg solder)
SnPb	Paste and bar	Pb	1.88E-01
SnPb	Paste and bar	Sn	2.93E-05
SAC	Paste and bar	Ag	1.86E-05
SAC	Paste and bar	Sn	1.86E-05
SAC	Paste and bar	Cu	1.34E-05
BSA	Paste	Bi	2.39E-02
BSA	Paste	Sn	5.18E-04
BSA	Paste	Ag	2.03E-05
SABC	Paste	Bi	9.09E-04
SABC	Paste	Cu	3.59E-05
SABC	Paste	Ag	2.39E-05
SABC	Paste	Sn	2.39E-05
SnCu	Bar	Cu	2.72E-05
SnCu	Bar	Sn	2.39E-05



Unregulated recycling/disposal process flow diagram



Life-Cycle Impact Assessment

LFSP Life-Cycle Impact Categories

Natural Resources

- Non-renewable Resource consumption
- Non-renewable resource consumption)
- Energy consumption
- Landfill space use

Ecosystem - Water

- Water eutrophication
- Local water quality (BOD, TSS)

Ecosystem-Atmosphere

- Global warming
- Ozone depletion
- Photochemical smog
- Acidification
- Air particulate matter

Toxicity

- Chronic human health toxicity (occupational & public, non-cancer and cancer)
- Aquatic ecotoxicity

LCIA Impact Scores for Paste Solders

Table 3-10. Paste solder LCIA results

Impact category	Units per functional unit*	Quality rating**	SnPb	SAC	BSA	SABC
Non-renewable resource use	kg	M-H	1.61E+03	**1.82E+03**	1.76E+03	1.72E+03
Renewable resource use	kg	M-H	**3.48E+04**	3.47E+04	2.64E+04	3.41E+04
Energy use	MJ	H	1.25E+04	**1.36E+04**	9.76E+03	1.31E+04
Landfill space	m^3	M-H	2.75E-03	**1.62E-02**	6.57E-03	1.13E-02
Global warming	kg CO_2-equiv.	H	8.17E+02	**8.73E+02**	6.31E+02	8.49E+02
Ozone depletion	kg CFC-11-equiv.	L-M	9.95E-05	**1.10E-04**	7.98E-05	1.04E-04
Photochemical Smog	kg ethene-equiv.	M-H	3.13E-01	**6.18E-01**	3.61E-01	5.05E-01
Acidification	kg SO_2-equiv.	M-H	6.50E+00	**1.25E+01**	7.32E+00	1.03E+01
Particulate matter	kg	M-H	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00
Eutrophication	kg phosphate-equiv.	H	**1.22E-01**	1.18E-01	9.06E-02	1.17E-01
Water quality	kg	H	1.79E-01	**2.26E-01**	1.64E-01	2.06E-01
Occupational non-cancer	kg noncancertox-equiv.	M-H	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03
Occupational cancer	kg cancertox-equiv.	L-M	**7.62E+01**	7.20E+01	6.34E+01	7.23E+01
Public non-cancer	kg noncancertox-equiv.	M-H	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03
Public cancer	kg cancertox-equiv.	L-M	6.96E+00	**7.05E+00**	5.15E+00	6.51E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	M-H	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01

* The functional unit is 1,000 cc of solder applied to a printed wiring board.

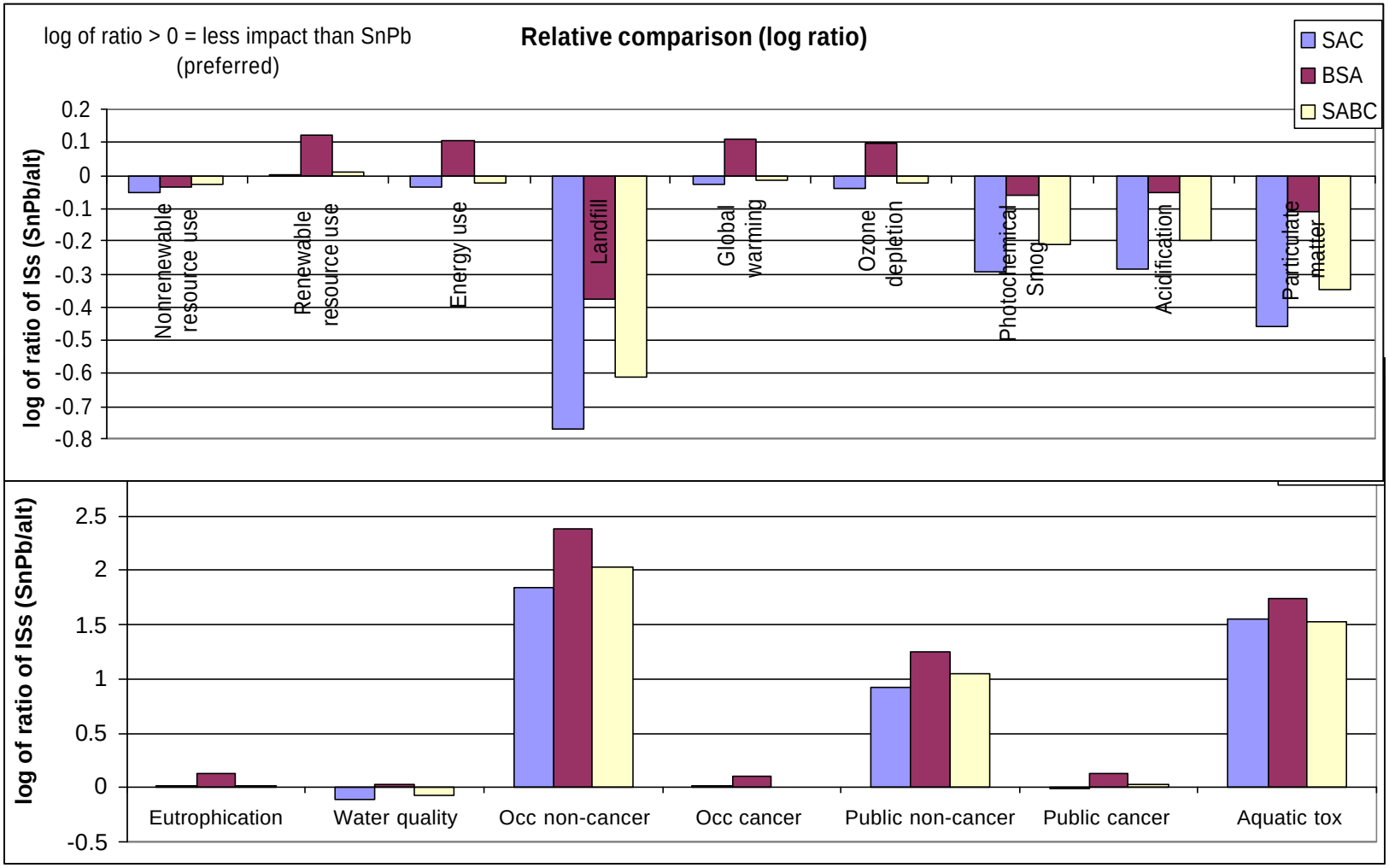
Notes: Bold impact scores indicate the alloy with the highest score for an impact category. Shaded impact scores indicate the alloy with the lowest score for an impact category.

= highest impact score

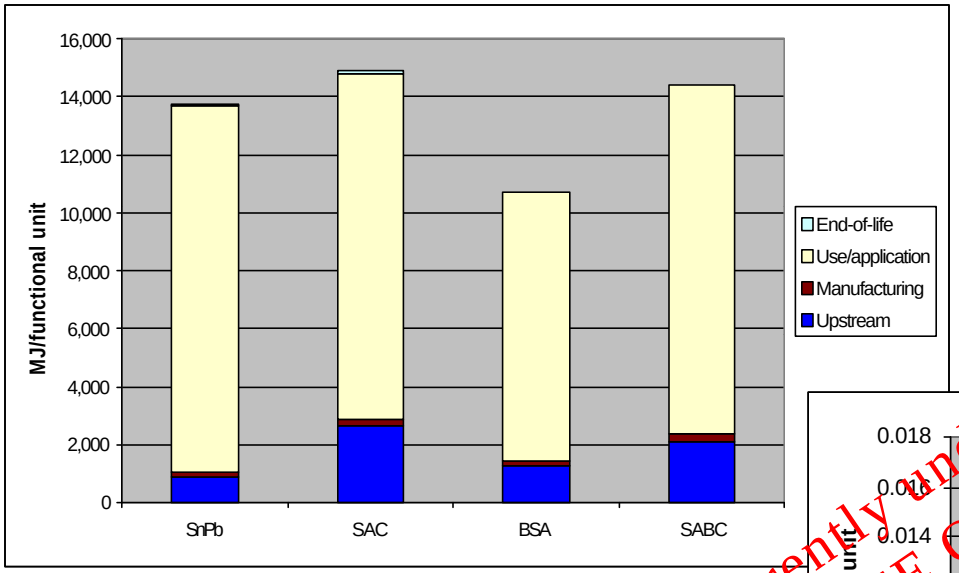
= lowest impact score

Paste Solders-Relative diff. from SnPb

(do not compare across impact categories)

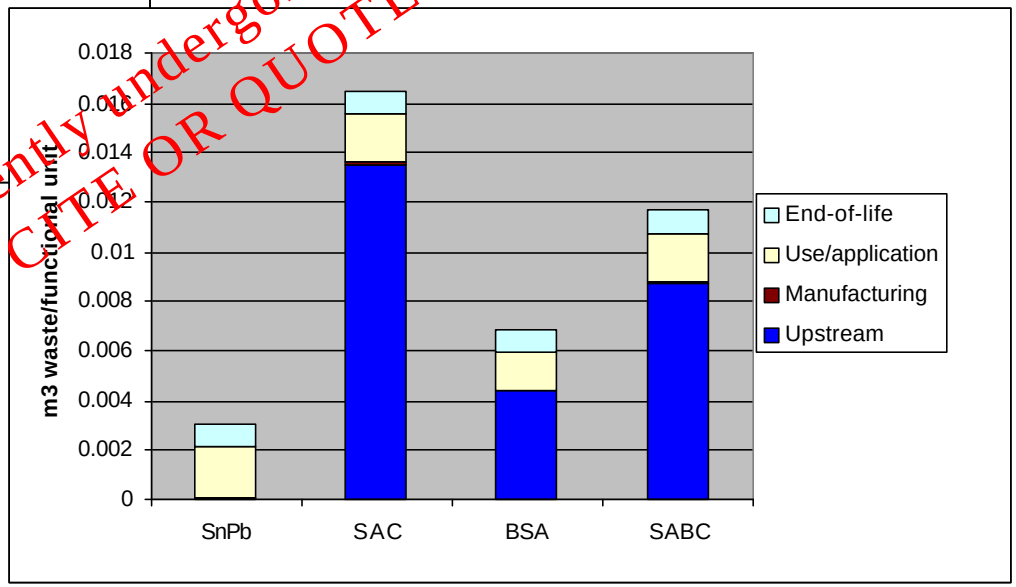


LFSP Paste Solder Results (1)



Energy Use

Landfill Space Use



Impact Category Drivers

Table 3-62. Solder paste life-cycle stages contributing a majority of impacts

Impact category	SnPb	SAC	BSA	SABC
Non-renewable resource use	Use/application	Use/application	Use/application	Use/application
Renewable resource use	Use/application	Use/application	Use/application	Use/application
Energy use	Use/application	Use/application	Use/application	Use/application
Landfill space use	Use/application	Upstream	Upstream	Upstream
Global warming	Use/application	Use/application	Use/application	Use/application
Ozone depletion	Use/application	Use/application	Use/application	Use/application
Photochemical smog	Use/application	Upstream	Use/application	Use/application
Air Acidification	Use/application	Upstream	Use/application	Use/application
Air particulates	Use/application	Upstream	Upstream	Upstream
Water eutrophication	Use/application	Use/application	Use/application	Use/application
Water quality	Use/application	Use/application	Use/application	Use/application
Occupational health - non-cancer	Manufacturing/ End-of-life	Manufacturing/ End-of-life	End-of-life— Use/application	Manufacturing/ End-of-life
Occupational health - cancer	Use/application	Use/application	Use/application	Use/application
Public human health - non-cancer	End-of-life	Upstream	Upstream	Upstream
Public human health - cancer	Use/application	Use/application	Use/application	Use/application
Aquatic ecotoxicity	End-of-life	Upstream	End-of-life	End-of-life

Paste Solder - Results Summary

LCA Results Summary for Paste

Solder Alloy	All Paste Solders		Pb-Free Only	
	High	Low	High	Low
SnPb	6	5	--	--
SAC	10	0	14	0
BSA	0	11	0	15
SABC	0	0	2	1

LCIA Impact Scores for Bar Solders

Table 3-11. Bar solder LCIA results

Impact category	Units per functional unit*	Quality rating**	SnPb	SAC	SnCu
Non-renewable resource use	kg	M-H	3.15E+02	**7.68E+02**	3.12E+02
Renewable resource use	kg	M-H	6.03E+03	**8.76E+03**	5.83E+03
Energy use	MJ	H	2.91E+03	**5.77E+03**	3.40E+03
Landfill space	m^3	M-H	1.34E-03	**2.14E-02**	1.33E-03
Global warming	kg CO_2-equiv.	H	1.87E+02	**3.57E+02**	2.16E+02
Ozone depletion	kg CFC-11-equiv.	L-M	1.87E-05	**4.13E-05**	1.78E-05
Photochemical smog	kg ethene-equiv.	M-H	6.98E-02	**5.51E-01**	7.06E-02
Acidification	kg SO_2-equiv.	M-H	1.43E+00	**1.10E+01**	1.53E+00
Particulate matter	kg	M-H	1.49E-01	**1.47E+00**	1.99E-01
Eutrophication	kg phosphate-equiv.	H	2.14E-02	**2.57E-02**	2.06E-02
Water quality	kg	H	3.98E-02	**1.20E-01**	3.64E-02
Occupational non-cancer	kg noncancertox-equiv.	M-H	**7.15E+05**	1.09E+04	6.53E+01
Occupational cancer	kg cancertox-equiv.	L-M	**5.94E+01**	5.75E+01	5.49E+01
Public non-cancer	kg noncancertox-equiv.	M-H	**1.33E+05**	1.22E+04	7.26E+02
Public cancer	kg cancertox-equiv.	L-M	4.13E+00	**5.04E+00**	2.58E+00
Aquatic ecotoxicity	kg aquatictox-equiv.	M-H	**1.55E+03**	1.98E+02	8.70E+00

* The functional unit is 1,000 cc of solder applied to a printed wiring board.

** Quality summarizes the overall relative data quality associated with each impact category: high (H), medium (M), or low (L). Further explanation is provided in section 3.2.1.3.

Notes: Bold impact scores indicate the alloy with the highest score for an impact category.

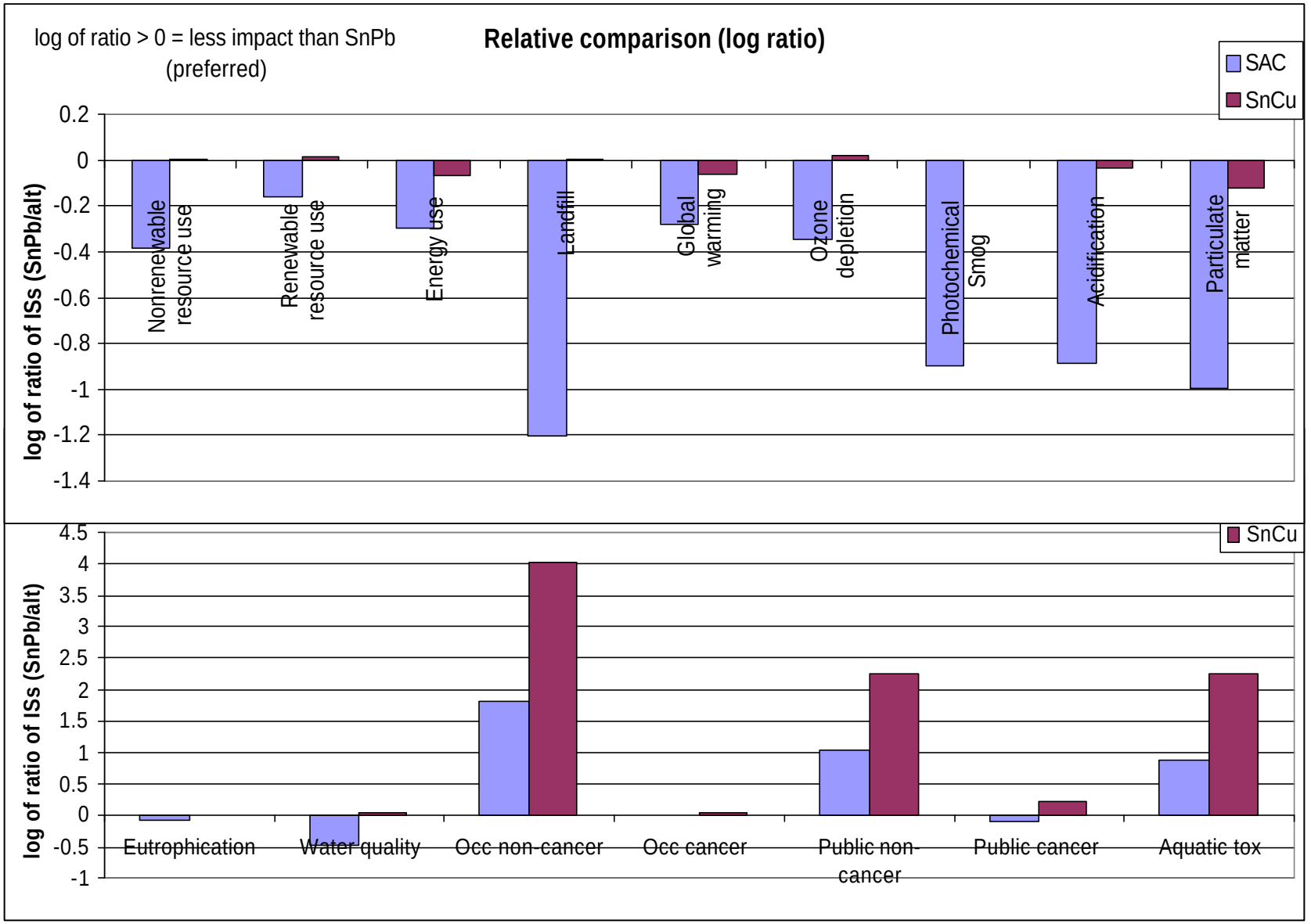
Shaded impact scores indicate the alloy with the lowest score for an impact category.

= highest impact score

= lowest impact score

Bar Solders-Relative differences from SnPb

(do not compare across impact categories)



Bar Solder Results Summary

LCA Results Summary for Bar Solders

Solder Alloy	All Bar Solders		Pb-Free Only	
	High	Low	High	Low
SnPb	4	6	--	--
SAC	12	0	16	0
SnCu	0	10	0	16

Interpretation

Sensitivity/alternate analyses

- Use/application stage energy
  - Use high and low energy estimates for reflow soldering
  - Magnitude of results change; however, comparative results of alloys same (see following graph)
  - Even with low energy estimate, use/application stage still dominates impacts as they did in the baseline
- Silver production alternate process
  - Changes several total impact category results
- EOL dispositions- analysis shows results sensitive to values
- Leachibility - TCLP vs SPLP testing results in little diff.

Sensitivity Analysis of Use/Application Energy

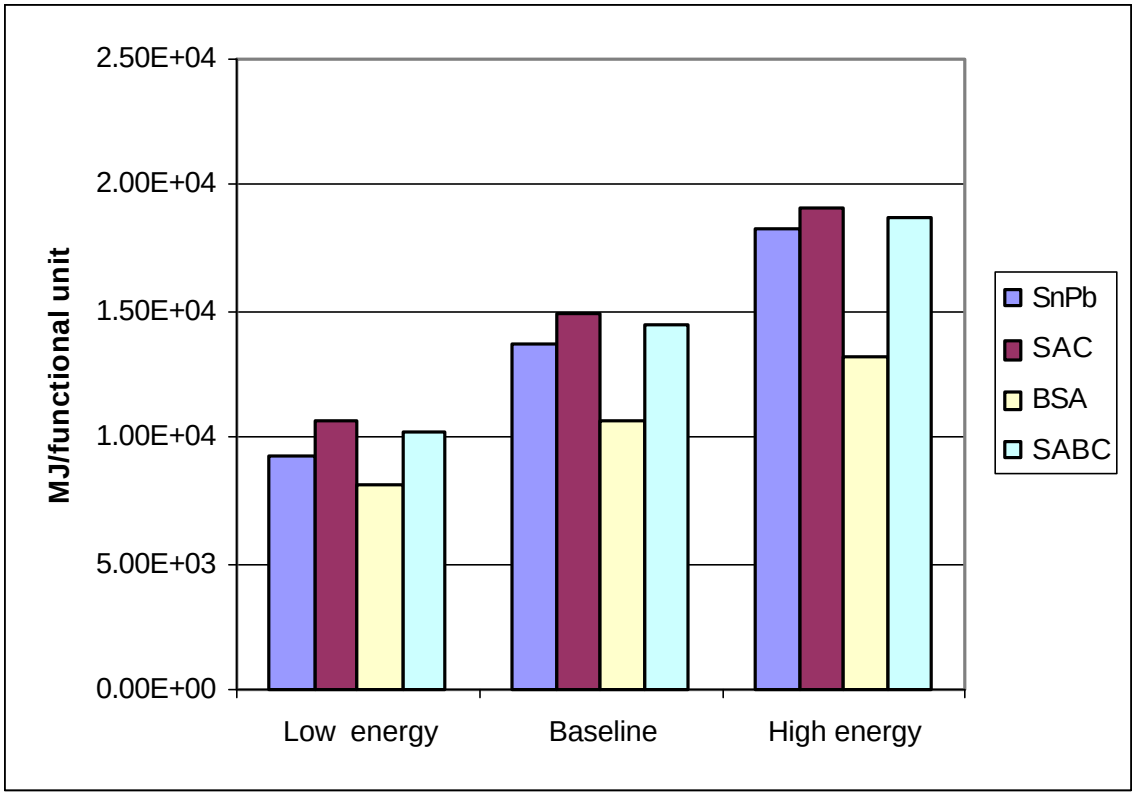


Table 3-54. Percent Contribution of Use/Application Stage

Energy estimate	SnPb	SAC	BSA	SABC
Low energy	88.2%	73.2%	83.1%	76.8%
Baseline	92.0%	80.8%	87.0%	83.6%
High energy	94.0%	85.1%	89.5%	87.4%

Alternative Silver Data- Paste Solders

	unit	Baseline				Alternate silver process			
Impact Category	**per functional unit***	**SnPb**	**SAC**	**BSA**	**SABC**	**SnPb**	**SAC**	**BSA**	**SABC**
NRR use	kg	1.61E+03	**1.82E+03**	1.76E+03	1.72E+03	1.61E+03	1.52E+03	**1.67E+03**	1.53E+03
RR use	kg	**3.48E+04**	3.47E+04	2.64E+04	3.41E+04	**3.48E+04**	3.26E+04	2.58E+04	3.28E+04
Energy use	MJ	1.25E+04	**1.36E+04**	9.76E+03	1.31E+04	**1.25E+04**	1.24E+04	9.40E+03	1.24E+04
Landfill	m^3	2.75E-03	**1.62E-02**	6.57E-03	1.13E-02	**2.75E-03**	2.62E-03	2.53E-03	2.63E-03
Global warming	kg CO_2-Equiv.	8.17E+02	**8.73E+02**	6.31E+02	8.49E+02	**8.17E+02**	8.15E+02	6.14E+02	8.11E+02
Ozone depletion	kg CFC-11-equiv.	9.95E-05	**1.10E-04**	7.98E-05	1.04E-04	**9.95E-05**	9.35E-05	7.49E-05	9.39E-05
Photochemical smog	kg ethene-equiv.	3.13E-01	**6.18E-01**	3.61E-01	5.05E-01	**3.13E-01**	3.00E-01	2.66E-01	3.01E-01
Acidification	kg SO_2-equiv.	6.50E+00	**1.25E+01**	7.32E+00	1.03E+01	**6.50E+00**	6.30E+00	5.48E+00	6.30E+00
Particulate matter	kg	4.52E-01	**1.30E+00**	5.85E-01	1.01E+00	4.52E-01	**4.95E-01**	3.44E-01	4.88E-01
Eutrophication	kg phosphate-equiv.	**1.22E-01**	1.18E-01	9.06E-02	1.17E-01	**1.22E-01**	1.14E-01	8.95E-02	1.15E-01
Water quality	kg	1.79E-01	**2.26E-01**	1.64E-01	2.06E-01	**1.79E-01**	1.68E-01	1.47E-01	1.69E-01
Occ non-cancer	kg noncancertox-equiv.	**5.60E+05**	8.12E+03	2.34E+03	5.25E+03	**5.60E+05**	1.02E+04	2.95E+03	6.57E+03
Occ cancer	kg cancertox-equiv.	**7.74E+01**	7.41E+01	6.11E+01	7.58E+01	**7.74E+01**	7.30E+01	6.71E+01	7.30E+01
Public non-cancer	kg noncancertox-equiv.	**8.80E+04**	1.05E+04	5.01E+03	7.84E+03	**8.80E+04**	2.99E+03	2.76E+03	2.99E+03
Public cancer	kg cancertox-equiv.	6.96E+00	**7.05E+00**	5.15E+00	6.51E+00	**6.96E+00**	5.44E+00	4.67E+00	5.45E+00
Aquatic toxicity	kg aquatictox-equiv.	**1.27E+03**	3.64E+01	2.34E+01	3.85E+01	**1.27E+03**	1.79E+01	1.79E+01	2.66E+01

*The functional unit is 1,000 cc of solder applied to a printed wiring board.

Bold = highest score within an impact category

Shaded = lowest score within an impact category

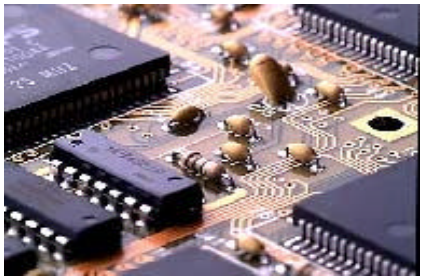
Alternative Silver - Results Summary

Table 3-113. Comparison of Baseline and Alternate LCA Analyses (paste solders)

Solder Alloy	Baseline		Alternate	
	High	Low	High	Low
SnPb	6	5	14	0
SAC	10	0	1	1
BSA	0	11	1	15
SABC	0	0	0	0

Table 3-115. Comparison of Baseline and Alternate LCA Analyses (Bar solders)

Solder Alloy	Baseline		Alternate	
	High	Low	High	Low
SnPb	4	6	9	6
SAC	12	0	7	5
SnCu	0	10	0	5



Overall Conclusions- Paste Solders

- SnPb solder presents greatest potential human health impacts due to higher toxicity (highest in 6 cats)
- SAC solder results in greater impacts to the environment in virtually every other impact category (highest in 10 cats)
- BSA is best overall performing solder due to low melting point, but is only being considered for niche applications
- SABC is middle of the pack, not highest or lowest in any impact category

Overall Conclusions- Bar Solders

- SnPb presents greatest potential human health impacts due to higher toxicity (highest in 4 categories- all toxicity related)
  - Lead toxicity is driver
- SAC solder is worse in all non-toxicity related impact categories (highest in 12 categories)
  - Highest energy use due to high melting point
  - Silver mining process drives many impacts
- SnCu presents the lowest potential impacts in 11 categories
  - No silver content

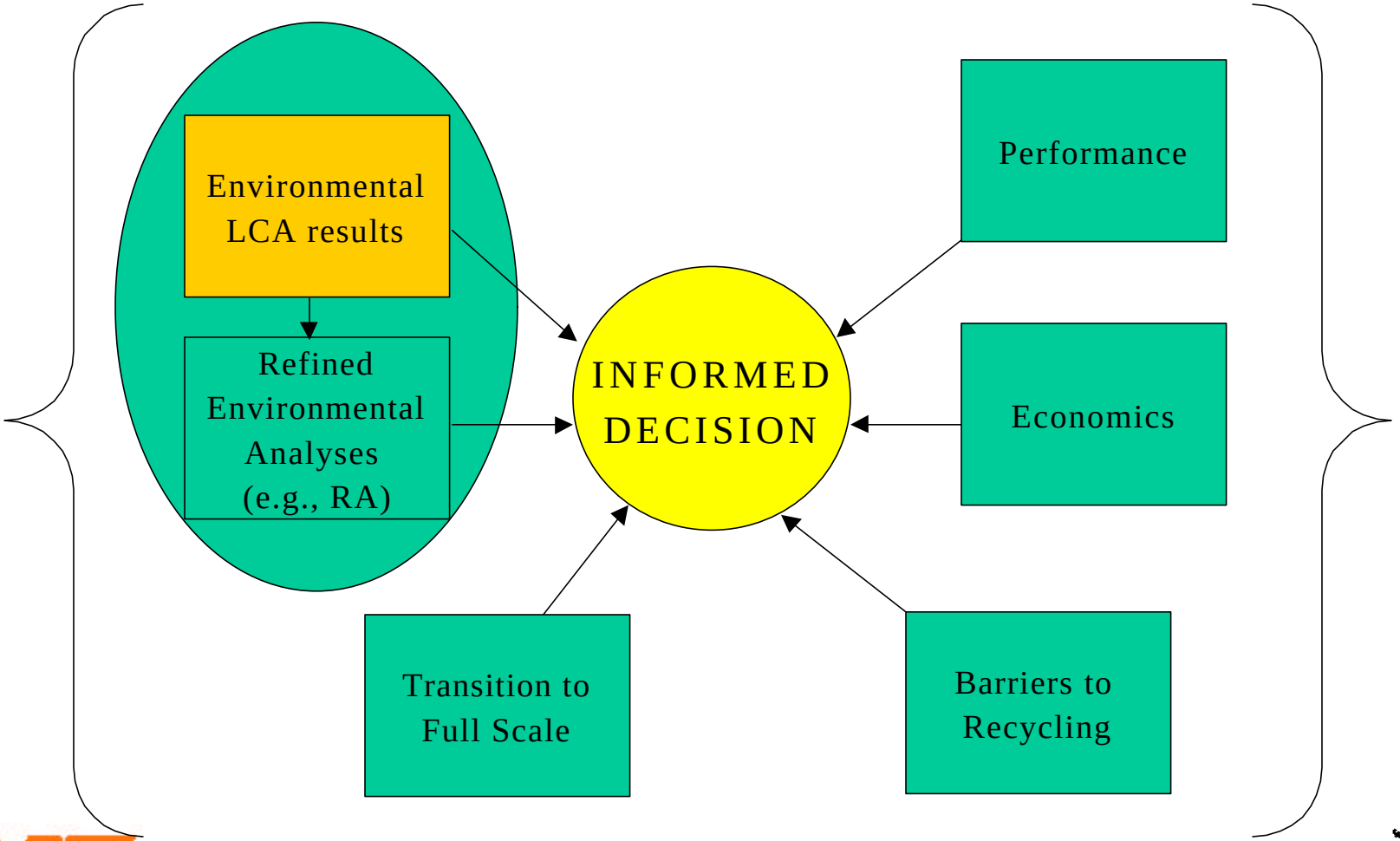
Overall Conclusions - Study

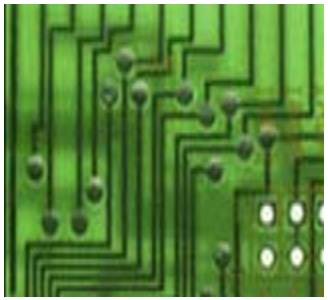
- Results extremely sensitive to silver process data
  - Alternate data set changes results in most categories significantly
  - Need clarification on data quality
- Energy production impacts drive most categories by a significant margin
  - Paste solders- use/application stage contributes significantly (> 30% of total impacts) in:
    - 14 of 16 categories for SnPb
    - from 9-13 categories for Pb-free solders
  - Bar Solders- similar to paste results

Overall Conclusions - Study

- Significant opportunities for life-cycle improvement exist;
  - Reduction of energy consumption during solder reflow process (testing showed potential 65% reduction possible)
  - Increased use of recycled secondary metals in solder manufacturing, esp. those from post-industrial recycling
    - Recycled content in SAC ranged from 0-80 percent
    - for example, a 25% reduction in primary metal in SAC leads to a 22% reduction in impacts to acidification and photochemical smog
- These types of comparative analyses critical in selecting alternatives and understanding tradeoffs
- EOL priority of pending policy efforts seem misplaced

Factors in Making an Informed Solder Selection





Project Contributors

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