California Department of Toxic Substances Control
Symposium: The Greening of Electronics in a Global Economy
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Green Electronics: Life Cycle Assessment

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- Current and former members of my research group:
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Life Cycle Assessment for Electronics

- Desktop Computer Displays
  - EPA study through characterization step
  - UC Davis study for normalization and weighting
- Lead Free Solders
  - EPA study through characterization step
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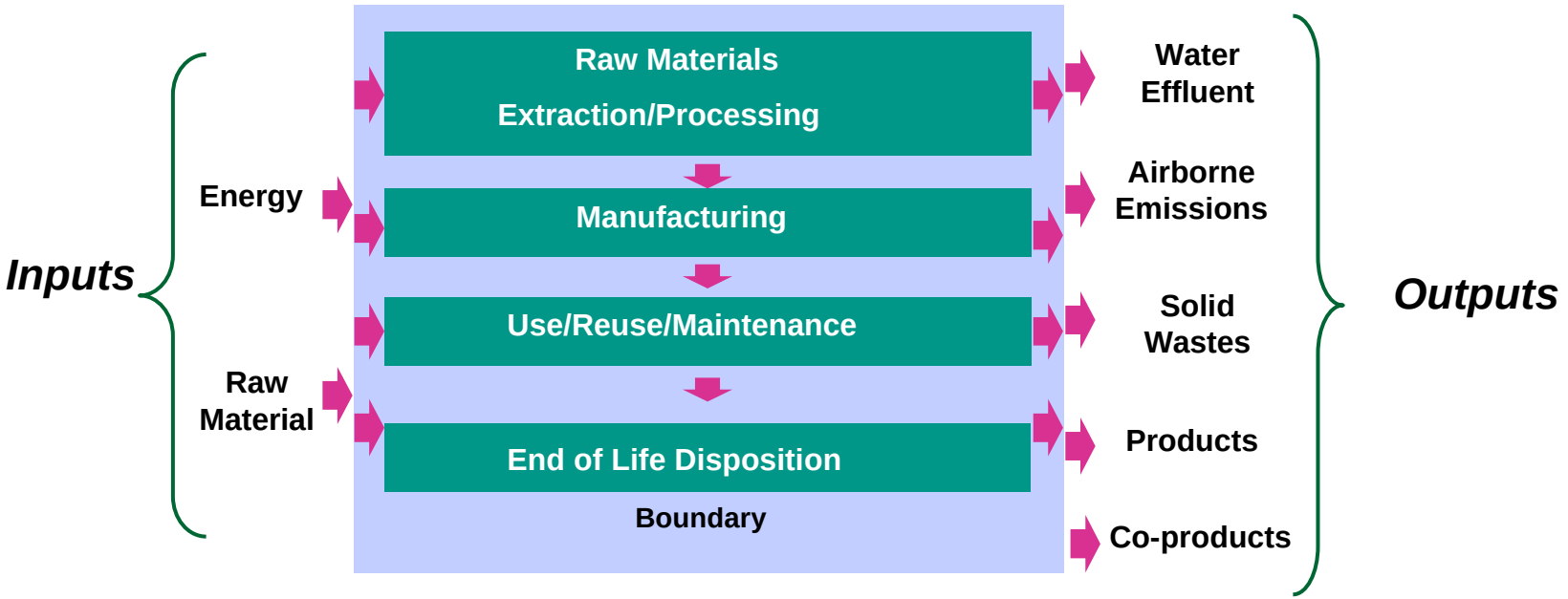
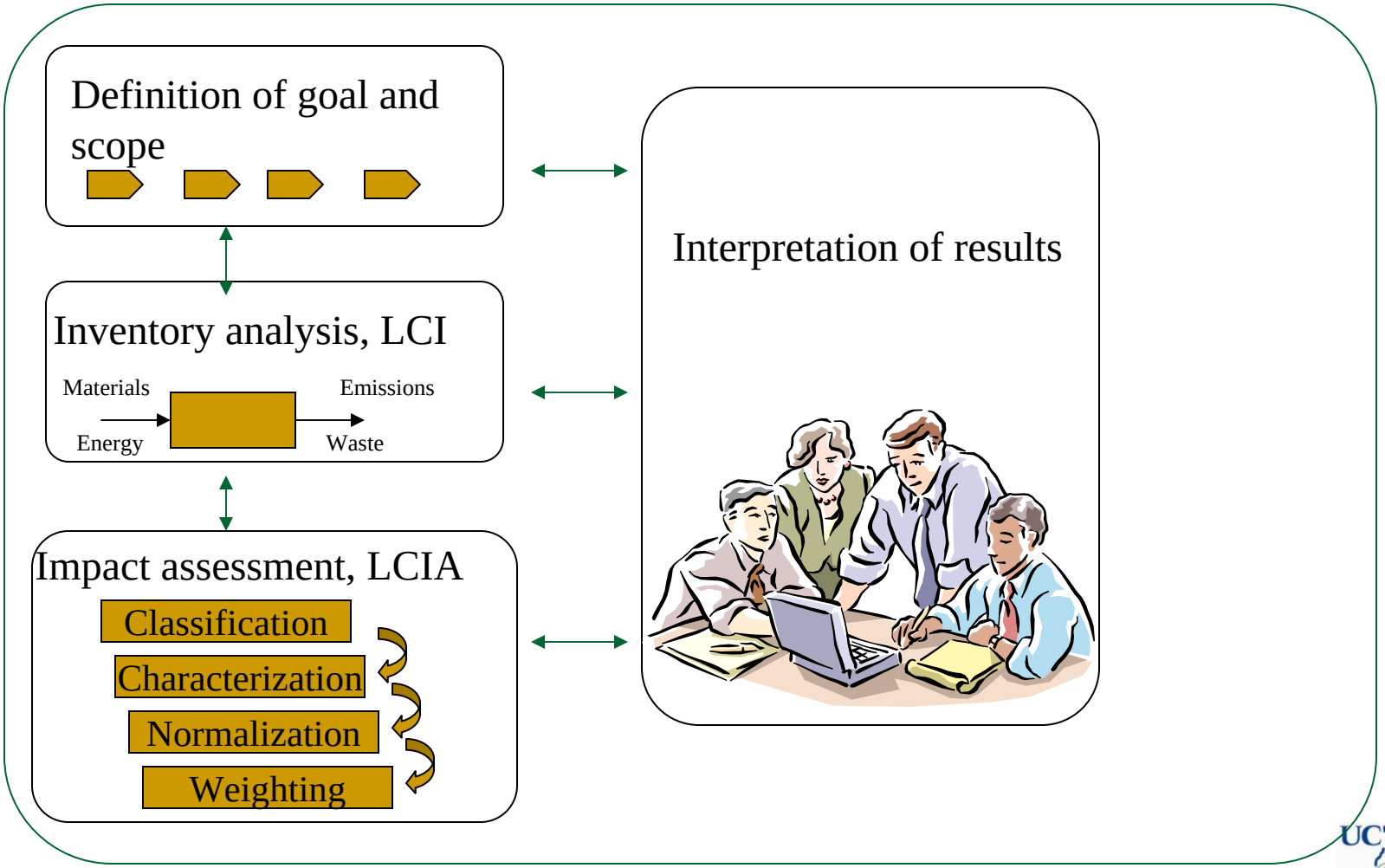
- Flat Panel Displays
  - Application of TRACI characterization factors to heavy metals
- Cellular Phones
  - Application of TRACI characterization factors to heavy metals

Life Cycle Stages



(Source: EPA, 1993)

Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Life Cycle Assessment for Electronics

- Desktop Computer Displays
  - U.S. Environmental Protection Agency, Design for Environment Program in the Economics Exposure & Technology Division of the Office of Pollution Prevention and Toxics
  - University of Tennessee, Knoxville, Center for Clean Products and Clean Technologies
  - December 2001
  - EPA 744-R-01-004
  - M.L. Socolof, J.G. Overly, L.E. Kincaid and J.R. Geibig

  - Primary Findings: CRTs generate more environmental impacts than do LCDs

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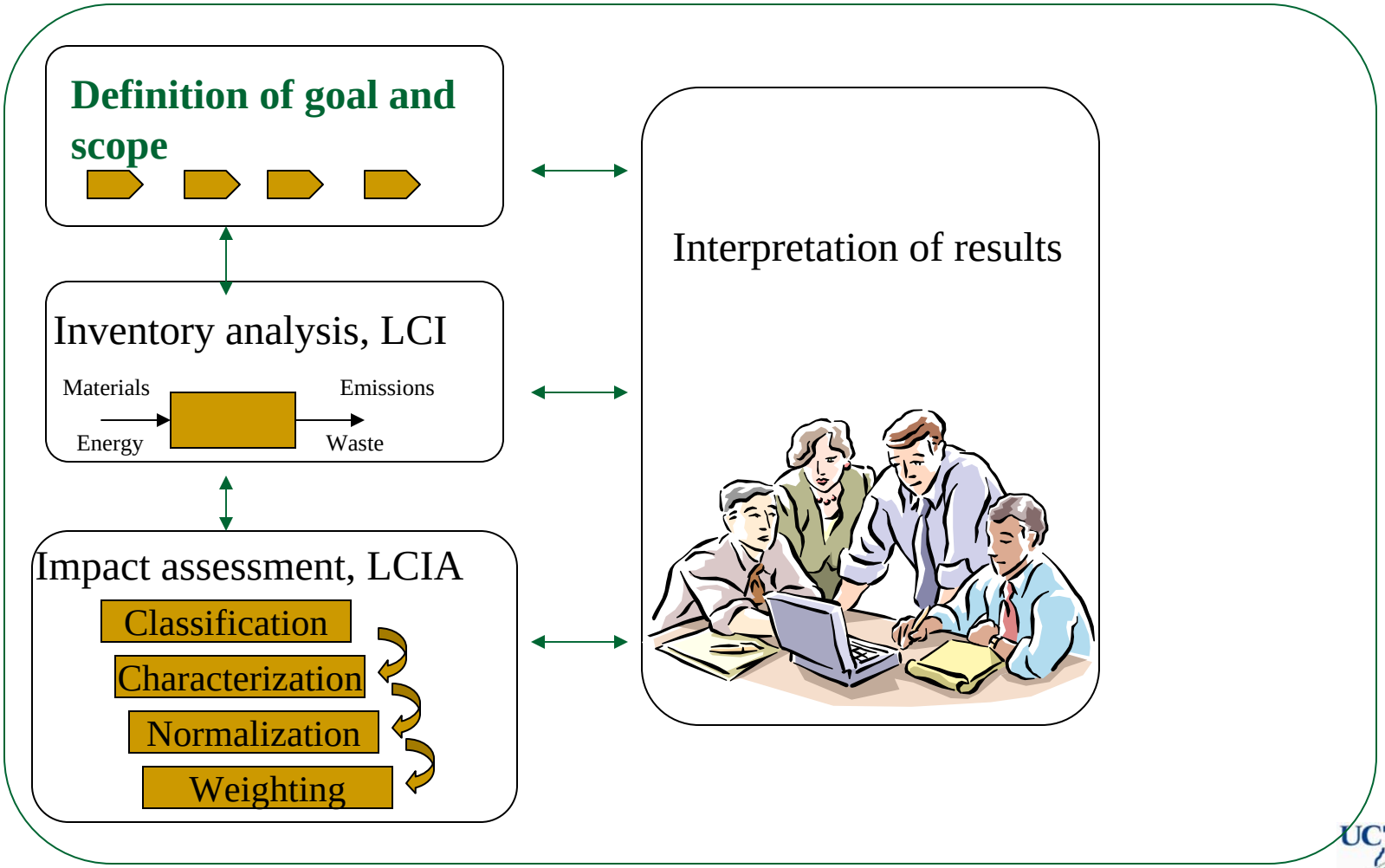
Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Desktop Computer Displays - LCA Step 1: Goal and Scope

- Purpose
  - To establish a scientific baseline that evaluates the life-cycle environmental impacts of active matrix liquid crystal display (LCD) and cathode ray tube (CRT) technologies for desktop computers
  - To develop a model that can be used with updated data for future life-cycle analyses

- Target Audience
  - Electronics Industry
  - EPA
  - Public

- Product System
  - A standard desktop computer display that functions as a graphical interface between computer processing units and users.

QuickTime™ and a TIFF (Uncompressed) decompresso are needed to see this picture.

(Source: EPA 744-R-01-004)

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Desktop Computer Displays - LCA Step 1: Goal and Scope (continued)

Table ES-1. Functional unit specifications

Specification	Measure
display size [a]	17" (CRT); 15" (LCD)
diagonal viewing area [a]	15.9" (CRT); 15" (LCD)
viewing area dimensions	12.8" x 9.5" (122 in^2) (CRT); 12" x 9" (108 in^2) (LCD)
resolution	1024 x 768 color pixels
brightness	200 cd/m^2
contrast ratio	100:1
color	262,000 colors

[a] An LCD is manufactured such that its nearest equivalent to the 17" CRT display is the 15" LCD. This is because the viewing area of a 17" CRT is about 15.9 inches and the viewing area of a 15" LCD is 15 inches. LCDs are not manufactured to be exactly equivalent to the viewing area of the CRT.

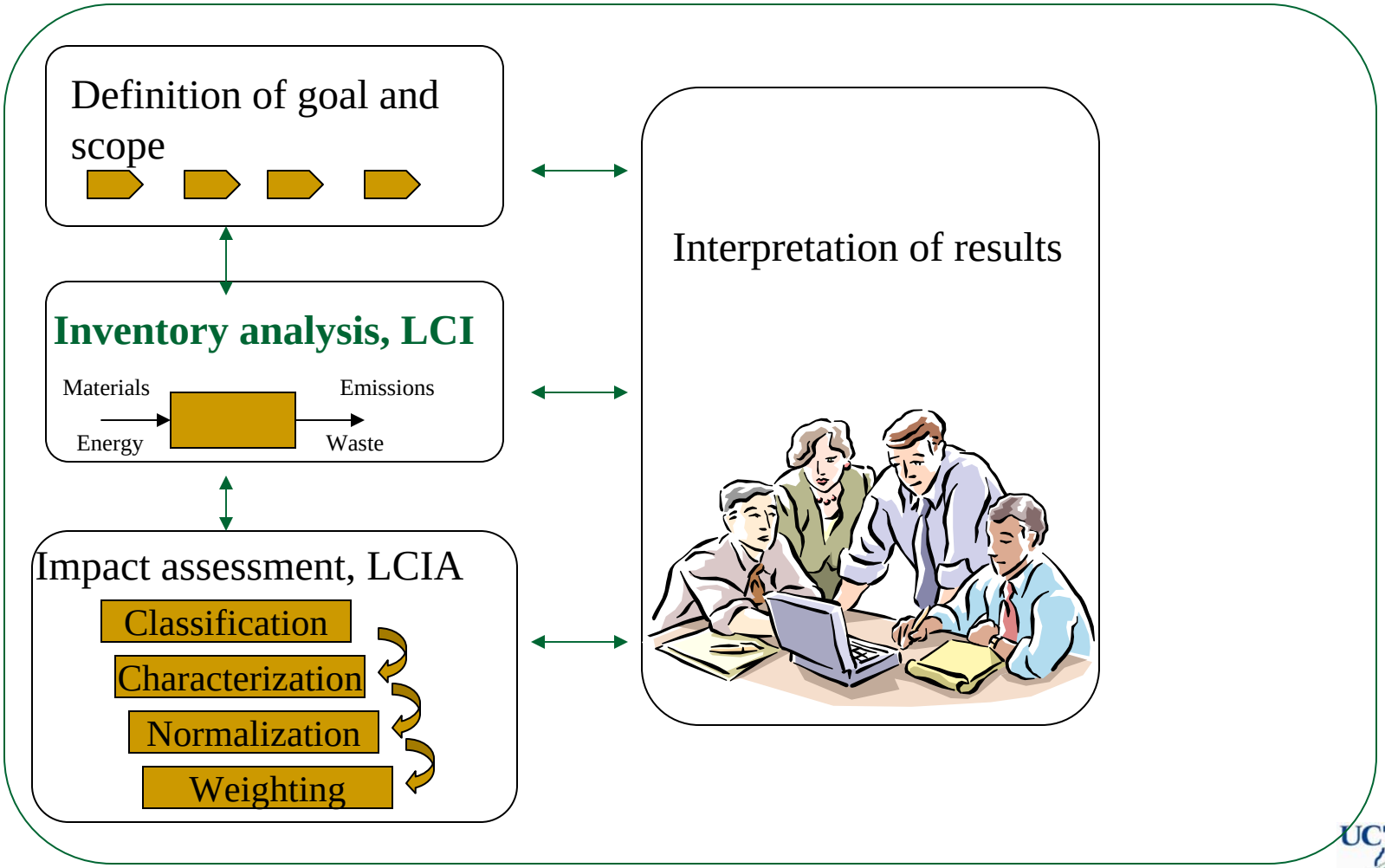
(Source: EPA 744-R-01-004)

Desktop Computer Displays - LCA Step 1: Goal and Scope (continued)

- Assessment Boundaries
  - Life Cycle Stages
    - Raw materials extraction/acquisition
    - Materials processing
    - Product manufacture,
    - Product use, maintenance and repair
    - Final disposition/end-of-life
  - Geographic Boundaries
    - United States for use and disposition stages
    - Worldwide for other stages
  - Temporal Boundaries
    - Desktop computer displays manufactured using 1997-2000 technology

(Source: EPA 744-R-01-004)

Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Desktop Computer Displays - LCA Step 2: Life Cycle Inventory (LCI)

Table ES-5. CRT inventory by life-cycle stage

Inventory type	Upstream	Mfg	Use	EOL	Total	Units [a]
Inputs						
Primary materials	1.58e+01	4.21e+02	2.19e+02	-3.32e+00	6.53e+02	kg
Ancillary materials	2.11e+00	3.54e+00	3.47e+00	1.07e+01	1.98e+01	kg
Water	5.54e+02	1.14e+04	1.14e+03	-2.73e+01	1.31e+04	kg (or L)
Fuels	8.00e+00	4.28e+02	0	-2.95e+00	4.33e+02	kg
Electricity	7.32e+01	1.29e+02	2.29e+03	2.29e-01	2.49e+03	MJ [b]
Total energy	3.66e+02	1.83e+04	2.29e+03	-1.28e+02	2.08e+04	MJ [b]
Outputs						
Air pollutants	3.00e+01	1.83e+02	4.49e+02	2.47e+00	6.64e+02	kg
Wastewater	1.70e+01	1.51e+03	0	-3.65e+00	1.52e+03	kg (or L)
Water pollutants	8.12e-01	2.01e+01	7.02e-02	-6.18e-02	2.09e+01	kg
Hazardous waste	4.89e+02	1.13e+02	0	8.28e+00	9.46e+00	kg
Solid waste	9.55e+00	8.12e+01	8.33e+01	-1.66e+00	1.72e+02	kg
Radioactive waste	4.39e-04	1.80e-04	2.28e-03	2.29e-07	2.90e-03	kg
Radioactivity	3.80e+07	3.78e+06	4.80e+07	4.80e+03	8.98e+07	Bq

[a] Per functional unit (i.e., one CRT monitor over its effective life).

[b] 3.6 MJ = 1 kWh

(Source: EPA 744-R-01-004)

Desktop Computer Displays - LCA Step 2: Life Cycle Inventory (LCI) - continued

Table ES-6. LCD inventory by life-cycle stage

Inventory type	Upstream	Mfg	Use	EOL	Total	Units [a]
Inputs						
Primary materials	2.35e+02	4.92e+01	8.01e+01	-2.19e+00	3.62e+02	kg
Ancillary materials	1.06e+00	2.04e+02	1.29e+00	2.11e+00	2.08e+02	kg
Water	2.63e+02	2.15e+03	4.25e+02	-1.80e+01	2.82e+03	kg
Fuels	1.47e+01	2.58e+01	0	-1.95e+00	3.86e+01	kg (or L)
Electricity	3.46e+01	3.16e+02	8.53e+02	1.62e-01	1.20e+03	MJ [b]
Total energy	6.33e+02	1.44e+03	8.53e+02	-8.44e+01	2.84e+03	MJ [b]
Outputs						
Air pollutants	1.12e+02	6.48e+01	1.68e+02	1.30e+00	3.46e+02	kg
Wastewater	8.57e+00	3.12e+03	0	-2.41e+00	3.13e+03	kg
Water pollutants	4.60e-01	1.23e+00	2.62e-02	-4.09e-02	1.68e+00	kg (or L)
Hazardous waste	6.72e-03	4.64e+00	0	1.64e+00	6.29e+00	kg
Solid waste	1.31e+01	1.26e+01	3.11e+01	-4.42e+00	5.23e+01	kg
Radioactive waste	2.21e+01	3.14e+03	3.11e+01	-5.23e+00	3.19e+03	kg
Radioactivity	1.20e+07	1.02e+07	1.79e+07	3.40e+03	4.01e+07	Bq

[a] Per functional unit (i.e., one LCD monitor over its effective life).

[b] 3.6 MJ = 1 kWh

(Source: EPA 744-R-01-004)

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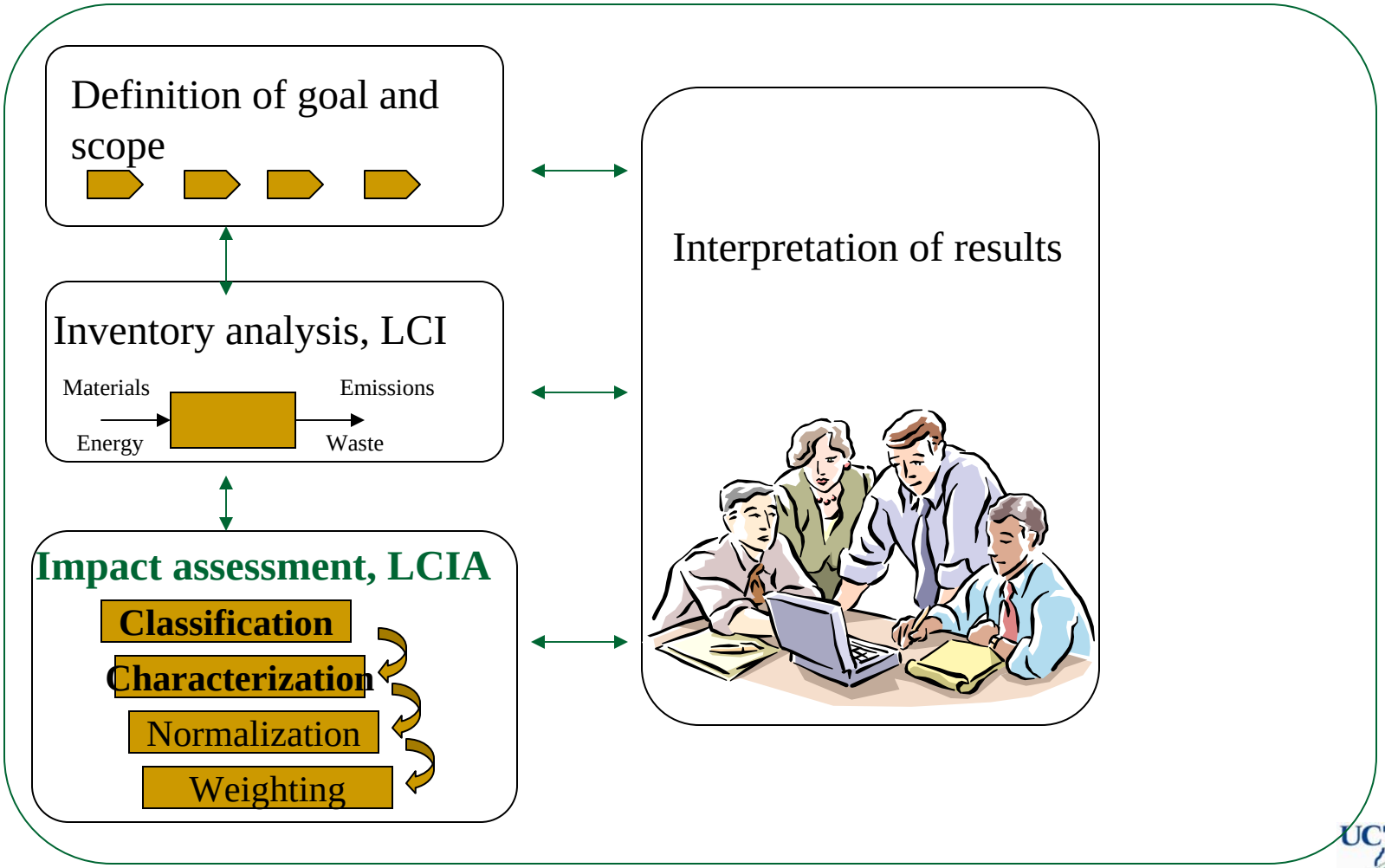
Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Desktop Computer Displays - LCA Step 3: Life Cycle Impact Assessment (LCIA)

Table ES-8. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Renewable resource use	kg	**1.31E+04**	2.80E+03
Nonrenewable resource use	kg	**6.68E+02**	3.64E+02
Energy use	MJ	**2.08E+04**	2.84E+03
Solid waste landfill use	m^3	**1.67E-01**	5.43E-02
Hazardous waste landfill use	m^3	**1.68E-02**	3.61E-03
Radioactive waste landfill use	m^3	**1.81E-04**	9.22E-05
Global warming	kg-CO_2 equivalents	**6.95E+02**	5.93E+02
Ozone depletion	kg-CFC-11 equivalents	2.05E-05[b,c]	1.37E-05[b]
Photochemical smog	kg-ethene equivalents	**1.71E-01**	1.41E-01
Acidification	kg-SO_2 equivalents	**5.25E+00**	2.96E+00
Air particulates	kg	**3.01E-01**	1.15E-01
Water eutrophication	kg-phosphate equivalents	4.82E-02	**4.96E-02**
Water quality, BOD	kg	**1.95E-01**	2.83E-02
Water quality, TSS	kg	**8.74E-01**	6.15E-02
Radioactivity	Bq	**3.85E+07**[d]	1.22E+07[d]

(Source: EPA 744-R-01-004)

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Desktop Computer Displays - LCA Step 3: Life Cycle Impact Assessment (LCIA)

Table ES-8. Baseline life-cycle impact category indicators[a]

Impact category	Units per monitor	CRT	LCD
Chronic health effects, occupational	tox-kg	**9.34E+02**	6.96E+02
Chronic health effects, public	tox-kg	**1.98E+03**	9.02E+02
Aesthetics (odor)	m^3	**7.58E+06**	5.04E+06
Aquatic toxicity	tox-kg	2.25E-01	**5.19E+00**
Terrestrial toxicity	tox-kg	**1.97E+03**	8.94E+02

[a] Bold indicates the larger value within an impact category when comparing the CRT and LCD.

[b] Several of the substances included in this category were phased out of production by January 1, 1996. Excluding phased out substances decreases the CRT ozone depletion indicator to 1.09E-05 kg CFC-11 equivalents per monitor and the LCD ozone depletion indicator to 1.18E-05 kg CFC-11 equivalents per monitor. These ozone depletion indicators are probably more representative of the CDP temporal boundaries and current operating practices. See section 3.3.6 for details.

[c] Although the CRT indicator appears larger than the LCD indicator, uncertainties in the inventory make it difficult to determine which monitor has the greater value. Therefore, this value is not shown in bold.

[d] Radioactivity impacts are being driven by radioactive releases from nuclear fuel reprocessing in France, which are included in the electricity data in some of the upstream, materials processing data sets. See section 3.3.12 for details.

QuickTime™ and a TIFF (Uncompressed) decompresso are needed to see this picture.

(Source: EPA 744-R-01-004)

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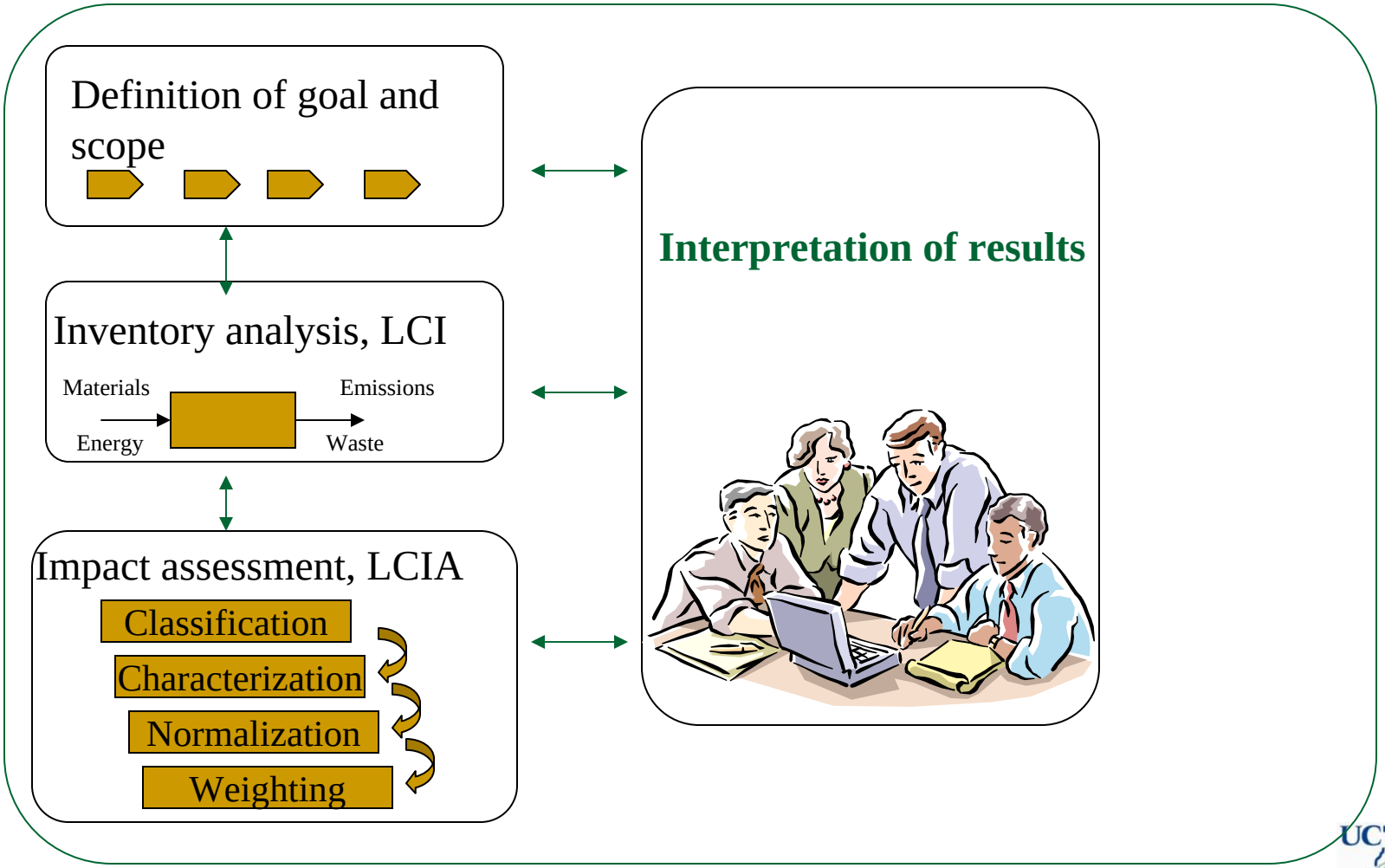
Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Desktop Computer Displays - LCA Step 4: Interpretation - Data Quality

Table ES-7. Relative data quality and major limitations

Life-cycle stage	Relative data quality	Major limitations
Upstream	Moderate	Used only secondary data, which has undetermined quality and not originally collected for the purpose of the CDP.
Manufacturing	Moderate to high	A few data points remain in question.
Use	Moderate to high	Assumptions regarding use patterns were made.
EOL	Low to moderate	Used only secondary data for incineration and landfilling processes; no data available for remanufacturing process.
Electricity generation	High	Used secondary data, however it was collected and modeled for the CDP, resulting in a higher quality rating despite use of secondary data.

(Source: EPA 744-R-01-004)

Desktop Computer Displays - LCA Step 4: Interpretation - Sensitivity Analysis

Table ES-11. List of sensitivity analysis scenarios

Monitor type	Sensitivity analysis scenario
Baseline analyses (for reference)	
CRT	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used)
LCD	Effective life scenario with average glass energy inputs (all glass manufacturing energy data used) and outliers in the LCD module manufacturing energy data removed
Sensitivity analyses	
CRT	Manufactured life scenario same as baseline except lifespan is based on manufactured life instead of effective life, which results in some revised functional equivalency calculations
LCD	Manufactured life scenario same as baseline except lifespan is based on manufactured life, which results in some revised functional equivalency calculations
CRT	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified glass energy scenario same as baseline except comparatively high glass manufacturing energy inputs are removed
LCD	Modified LCD module energy scenario same as baseline except LCD monitor/ module manufacturing energy outliers are included in the average
LCD	Modified LCD EOL scenario same as baseline except LCD EOL dispositions are modified

(Source: EPA 744-R-01-004)

Desktop Computer Displays - LCA Step 4: Interpretation - Sensitivity Analysis

Table ES-12. Summary of CRT and LCD LCIA results

Impact category	Monitor type with greatest impacts by scenario				
	Baseline	Manu-factured life	Modified glass energy	Modified LCD module energy	Modified LCD EOL distribution[a]
Renewable resource use	CRT	CRT	CRT	CRT	CRT
Nonrenewable resource use	CRT	CRT	LCD	CRT	CRT
Energy use	CRT	CRT	CRT	CRT	CRT
Solid waste landfill use	CRT	CRT	CRT	CRT	CRT
Hazardous waste landfill use	CRT	CRT	CRT	CRT	CRT
Radioactive waste landfill use	CRT	CRT	CRT	CRT	CRT
Global warming	CRT	CRT	LCD	CRT	CRT
Ozone depletion	b	b	b	b	b
Photochemical smog	CRT	CRT	LCD	CRT	CRT
Acidification	CRT	CRT	CRT	CRT	CRT
Air particulates	CRT	CRT	CRT	CRT	CRT
Water eutrophication	LCD	CRT	LCD	LCD	LCD
Water quality, BOD	CRT	CRT	LCD	CRT	CRT
Water quality, TSS	CRT	CRT	LCD	CRT	CRT
Radioactivity	CRT	CRT	CRT	CRT	CRT
Chronic health effects, occupational	CRT	CRT	LCD	CRT	CRT
Chronic health effects, public	CRT	CRT	CRT	CRT	CRT
Aesthetics (odor)	CRT	CRT	LCD	CRT	CRT
Aquatic toxicity	LCD	LCD	LCD	LCD	LCD
Terrestrial toxicity	CRT	CRT	CRT	CRT	CRT

[a] Based on a qualitative evaluation, not quantitative results.

[b] CRT impacts are greater than LCD impacts in this category when all data are included in the inventories, including data for substances that have been phased out. However, LCD impacts are greater than CRT impacts when phased out substances are removed from the inventories (see Section 3.3.6).

(Source: EPA 744-R-01-004)

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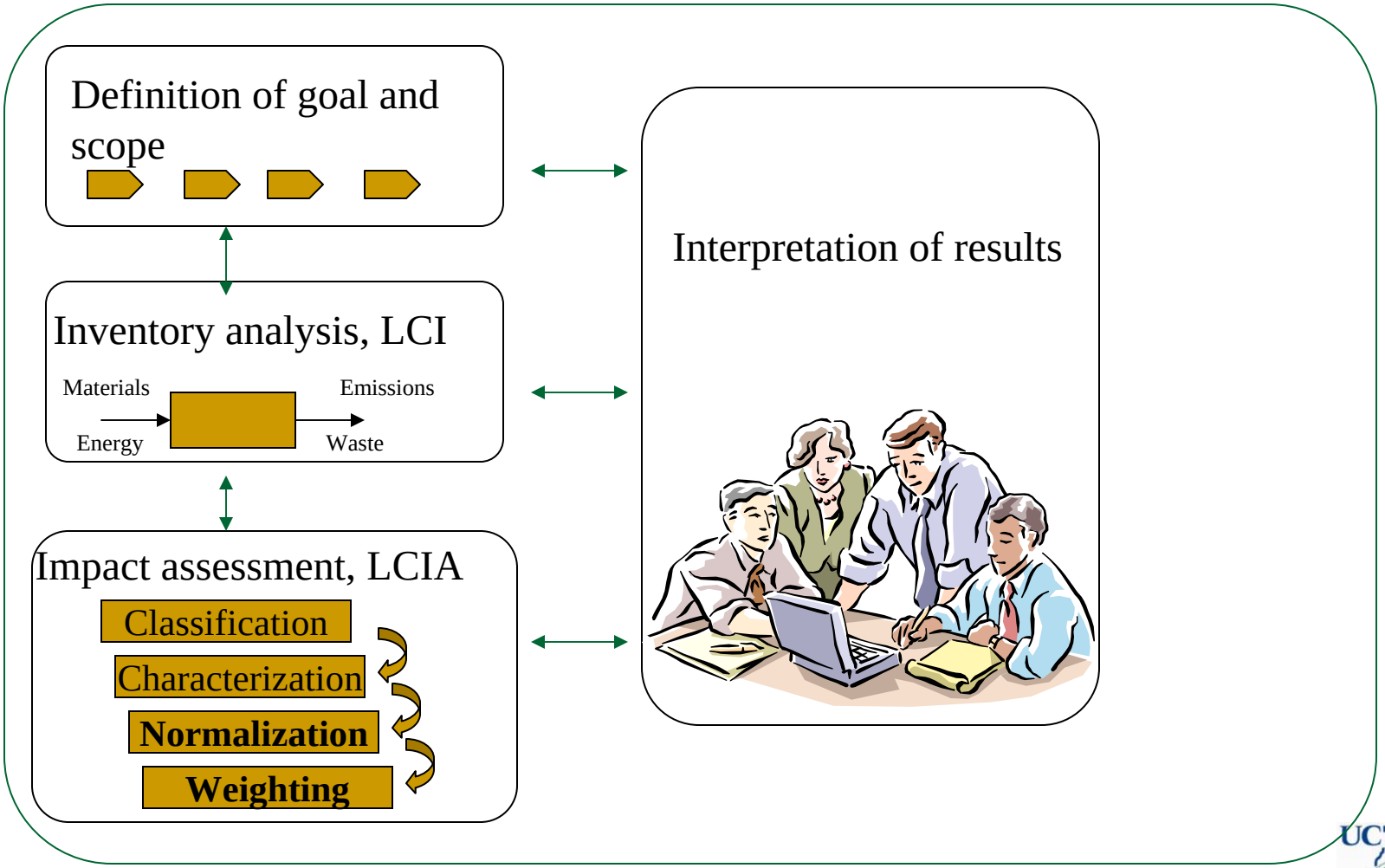
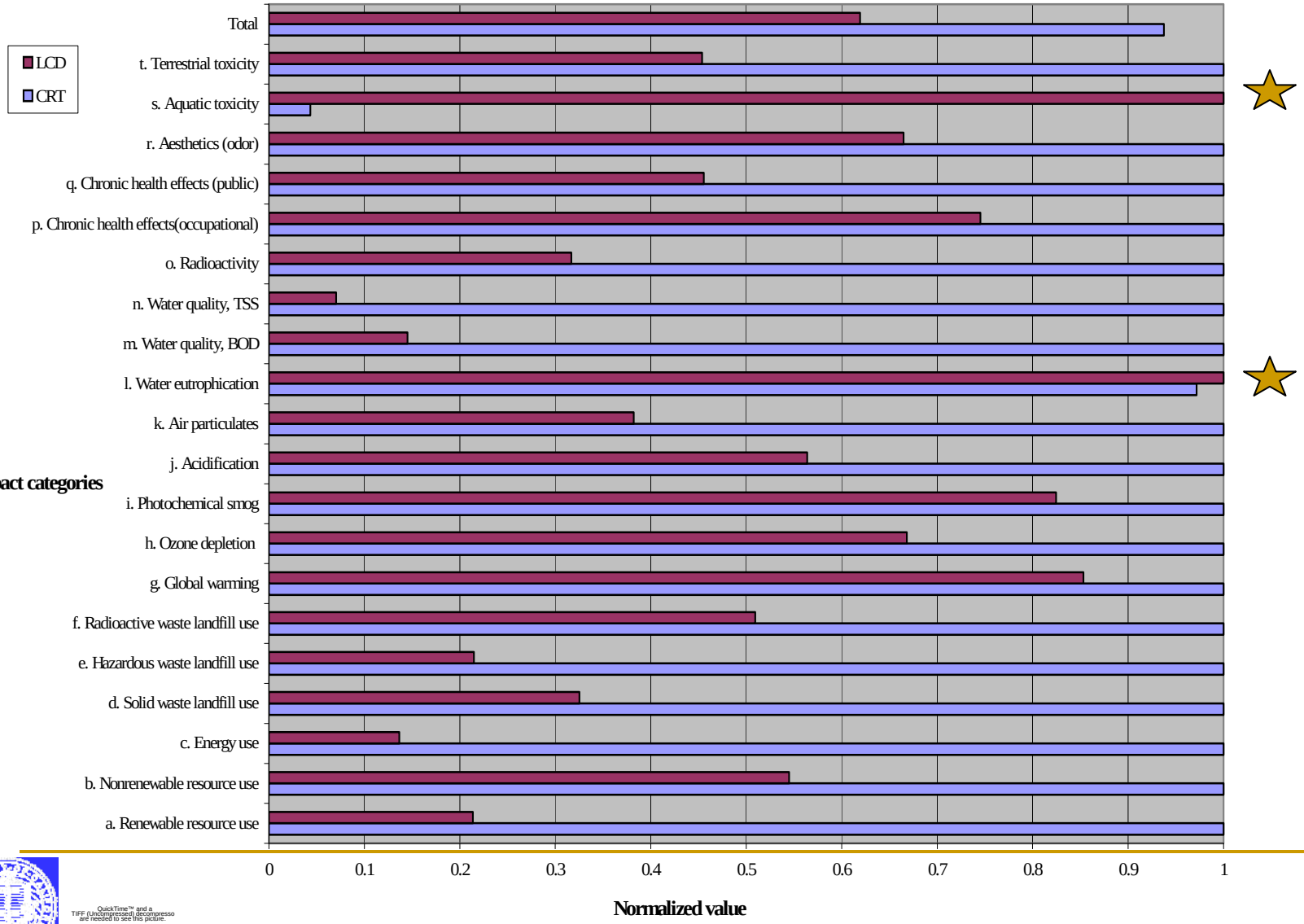
Phases in Life Cycle Assessment (LCA)



(Source: ISO14040: 2000)

Desktop Computer Displays - LCA Step 3: Normalizing

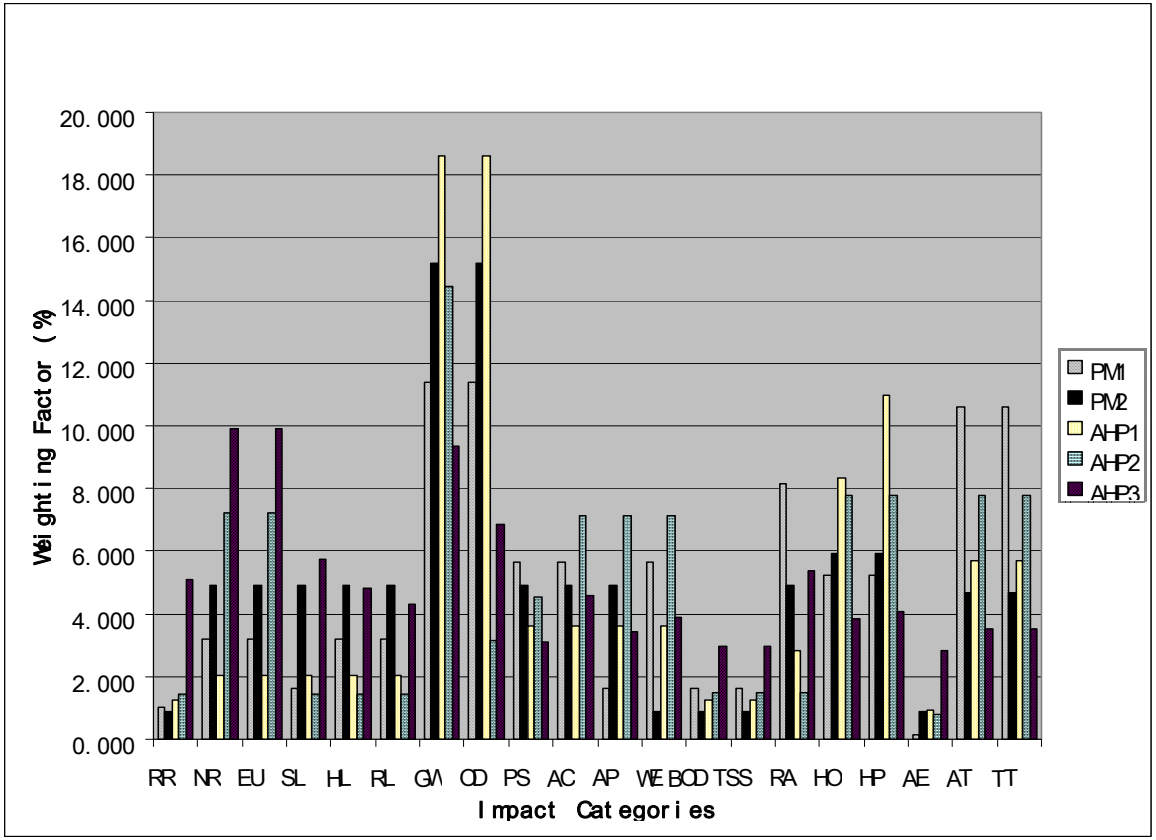


(Source: Zhou and Schoenung, 2007; derived from EPA 744-R-01-004)

Weighting - value based step

- Goal
  - Aggregate multiple attributes
  - Singular valuation
  - Trade-off analysis
- Generic weighting schemes
  - Panels
  - Monetization
  - Distance to target

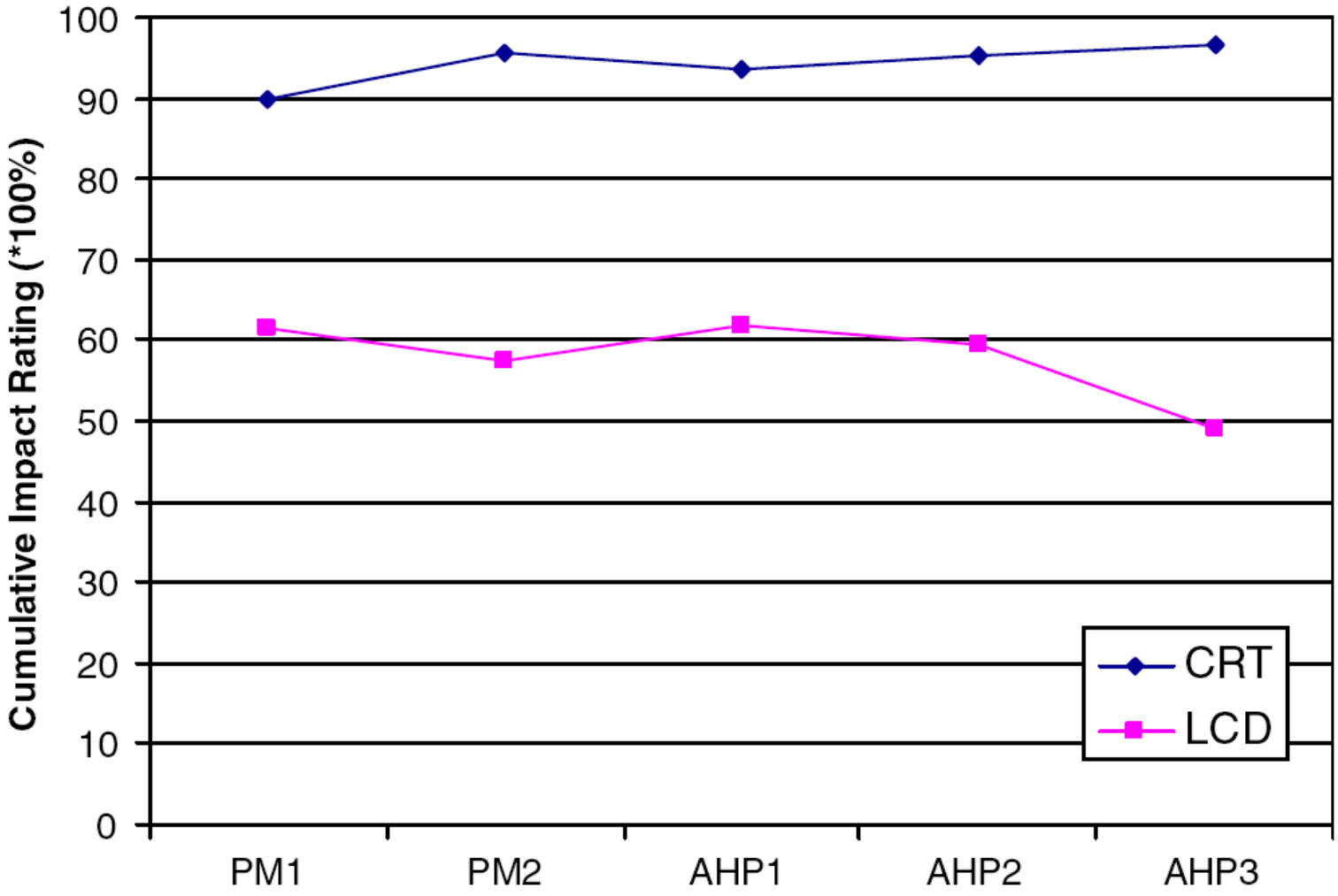
Desktop Computer Displays - LCA Step 3: Weighting



PM 1: Weighting scheme via Prioritization Matrix (consistency check: does not pass);
PM 2: Weighting scheme via Prioritization Matrix (consistency check: pass; refer to *endpoint-oriented impact assessment*);
AHP1: Weighting scheme via Analytic Hierarchy Process (consistency check: pass; refer to *distance-to-target method*);
AHP2: Weighting scheme via Analytic Hierarchy Process (consistency check: pass; refer to *monetary valuation method*);
AHP3: Weighting scheme via Analytic Hierarchy Process (consistency check: pass; multiplicative AHP model);
PM: Prioritization Matrix; AHP: Analytical Hierarchical Process

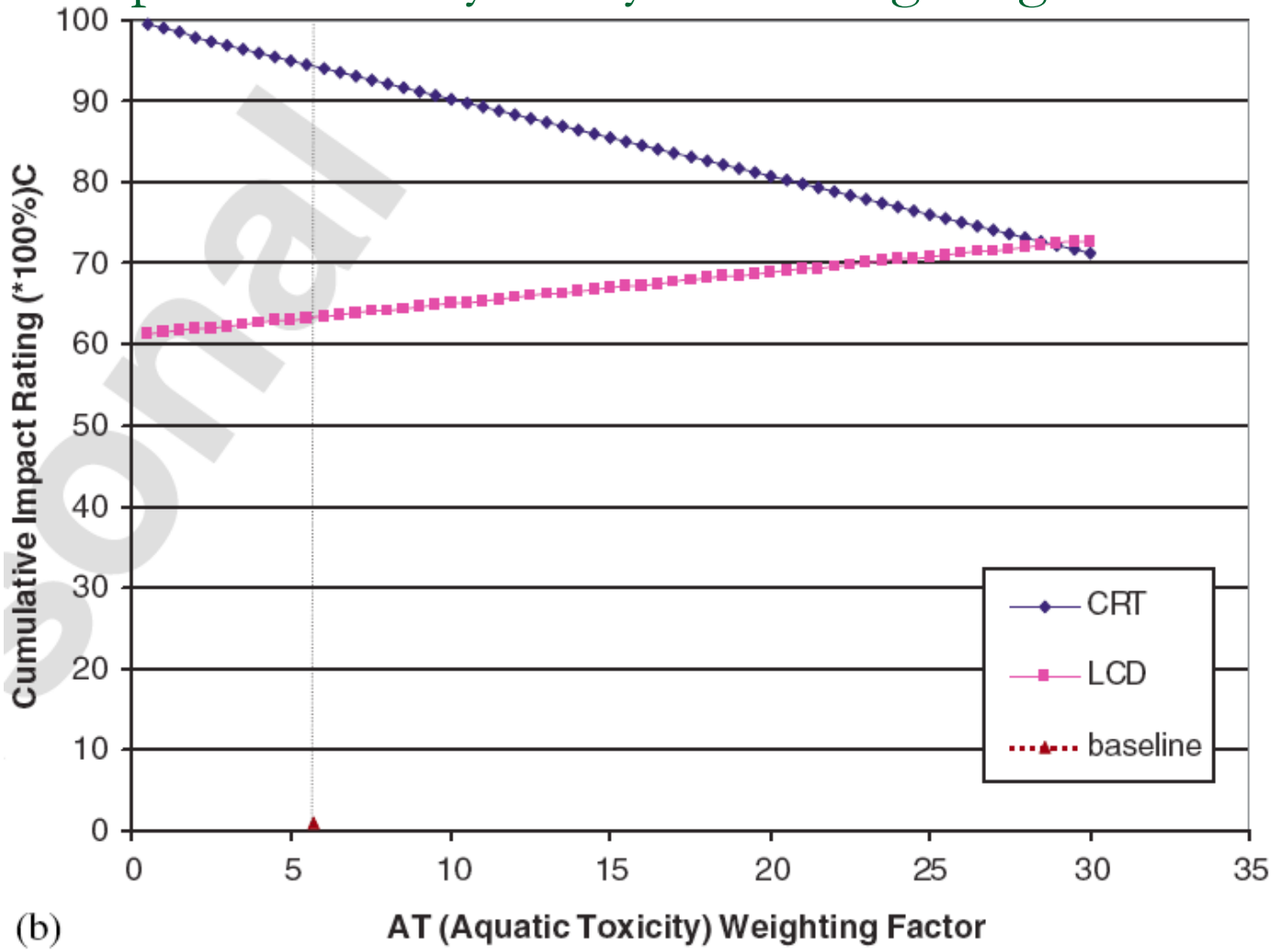
(Source: Zhou and Schoenung, 2007)

Desktop Computer Displays - LCA Step 3: Aggregate Score with Normalization and Weighting



(Source: Zhou and Schoenung, 2007)

Desktop Computer Displays - LCA Step 3: Sensitivity Analysis to Weighting Factor



(Source: Zhou and Schoenung, 2007)

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    - **EPA-744-S-05-001**
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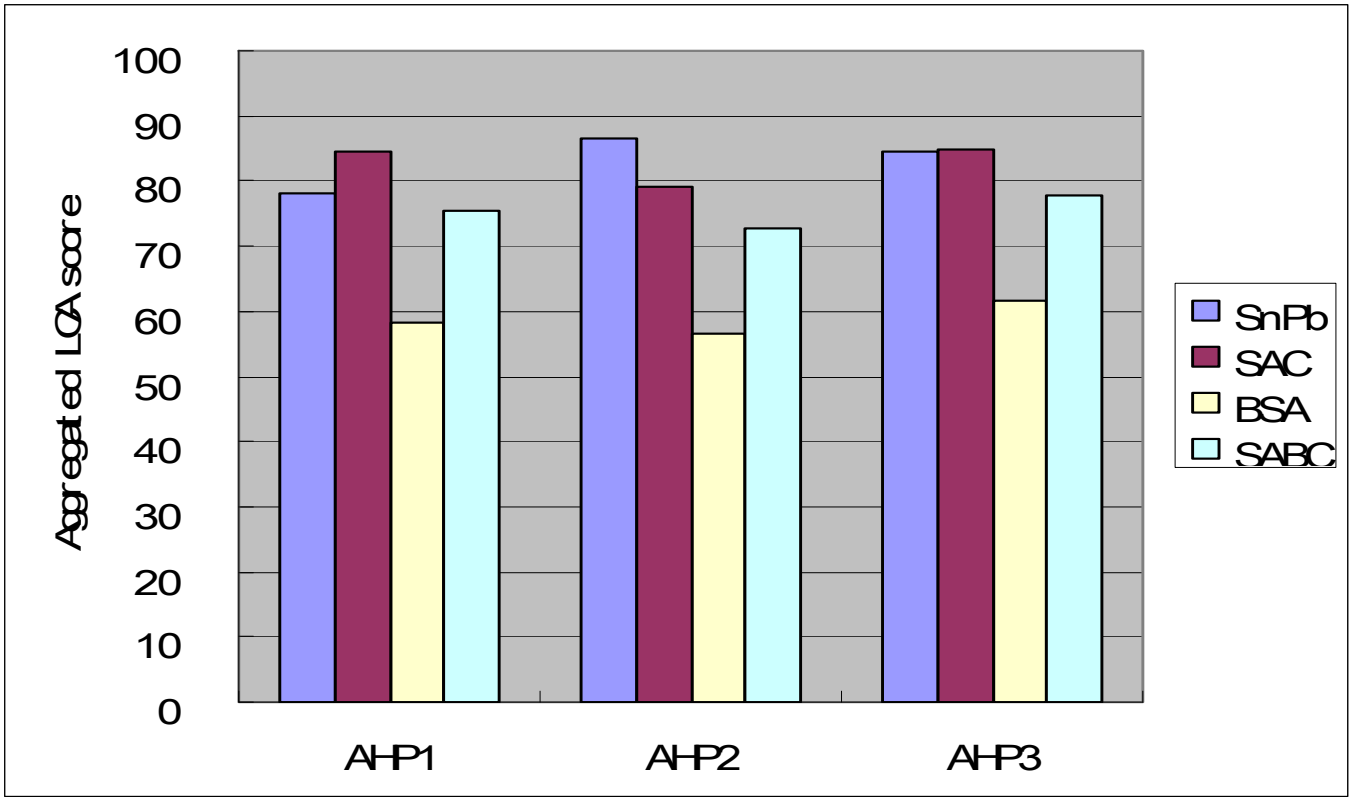
Lead-free Solders -
LCA Step 3: LCIA Characterization Scores

Normalized Life Cycle Assessment (LCA) impact score for paste Pb-free solders
(Higher value indicates higher environmental impact); SAC: SnAgCu; BSA: BiSnAg, SABC: SnAgBiCu

(Derived from: EPA-744-S-05-001)

Lead-free Solders -
LCA Step 3: Aggregate Score with Normalization and Weighting

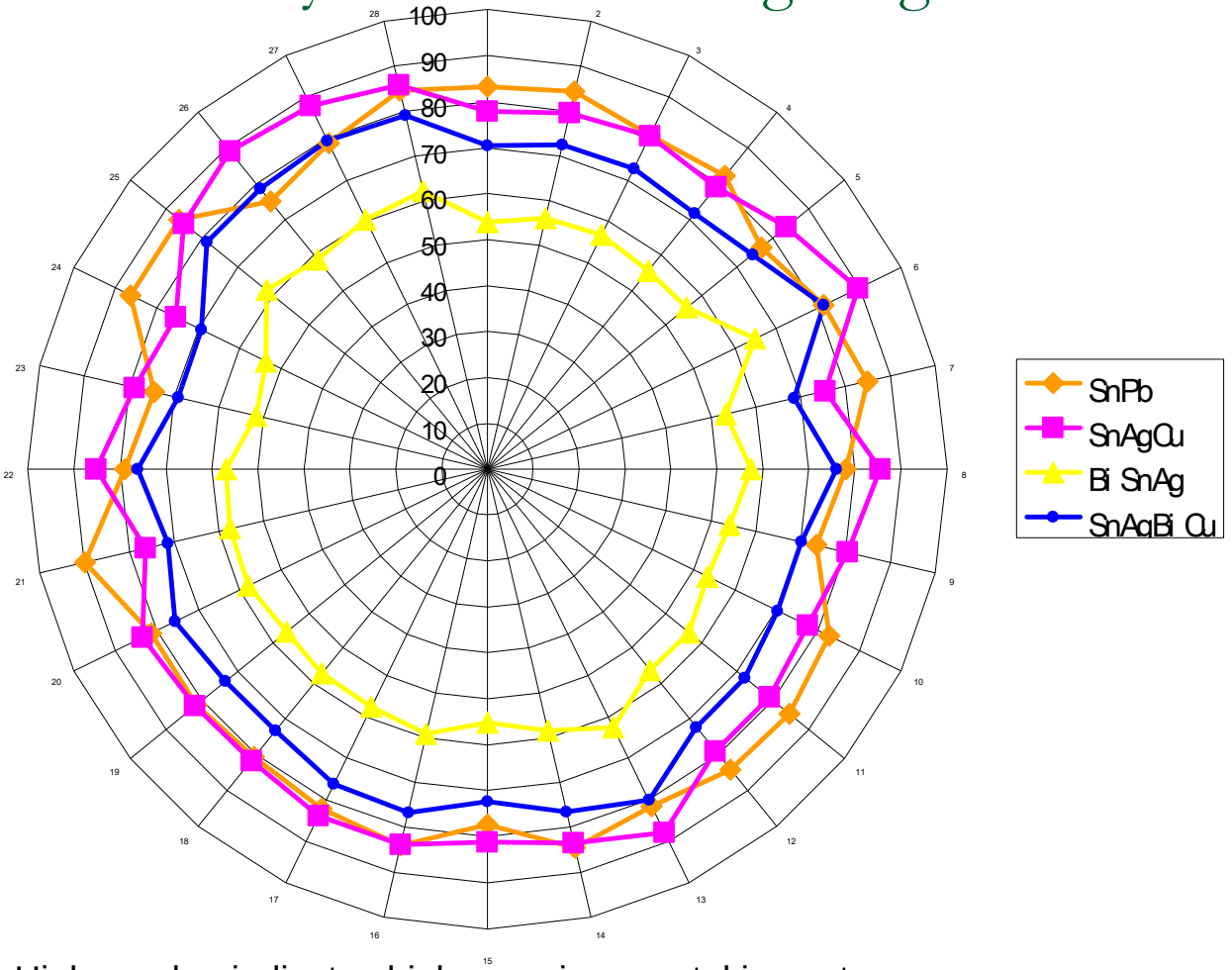


Higher value indicates higher environmental impact)
SAC: SnAgCu; BSA: BiSnAg, SABC: SnAgBiCu

AHP: Analytical Hierarchical Process

(Source: Zhou and Schoenung, 2008)

Lead-free Solders -
LCA Step 3: Sensitivity of Score to Weighting Factor Distribution



Higher value indicates higher environmental impact
SAC: SnAgCu; BSA: BiSnAg, SABC: SnAgBiCu

(Source: Zhou and Schoenung, 2008)

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TRACI: Tool for the Reduction and Assessment of Chemicals and Other Releases [U.S. EPA]

- 960 Substances
- 12 Impact Categories
  - Ozone Depletion, Global Warming, Acidification, Eutrophication, Photochemical Smog, Ecotoxicity, Human Health (HH): Criteria Air Pollutants, HH: Cancer, HH: Non-cancer, Fossil Fuel, Land Use, Water Use
- 22 Characterization Factors
  - Characterization Factors convert Life Cycle Inventory (LCI) input/output data (into air, water, soil) into Life Cycle Assessment Impact Assessment (LCIA) values for the impact categories listed above

QuickTime™ and a TIFF (Uncompressed) decompresso are needed to see this picture.

(J.C. Bare, et. al., JIE 2003)

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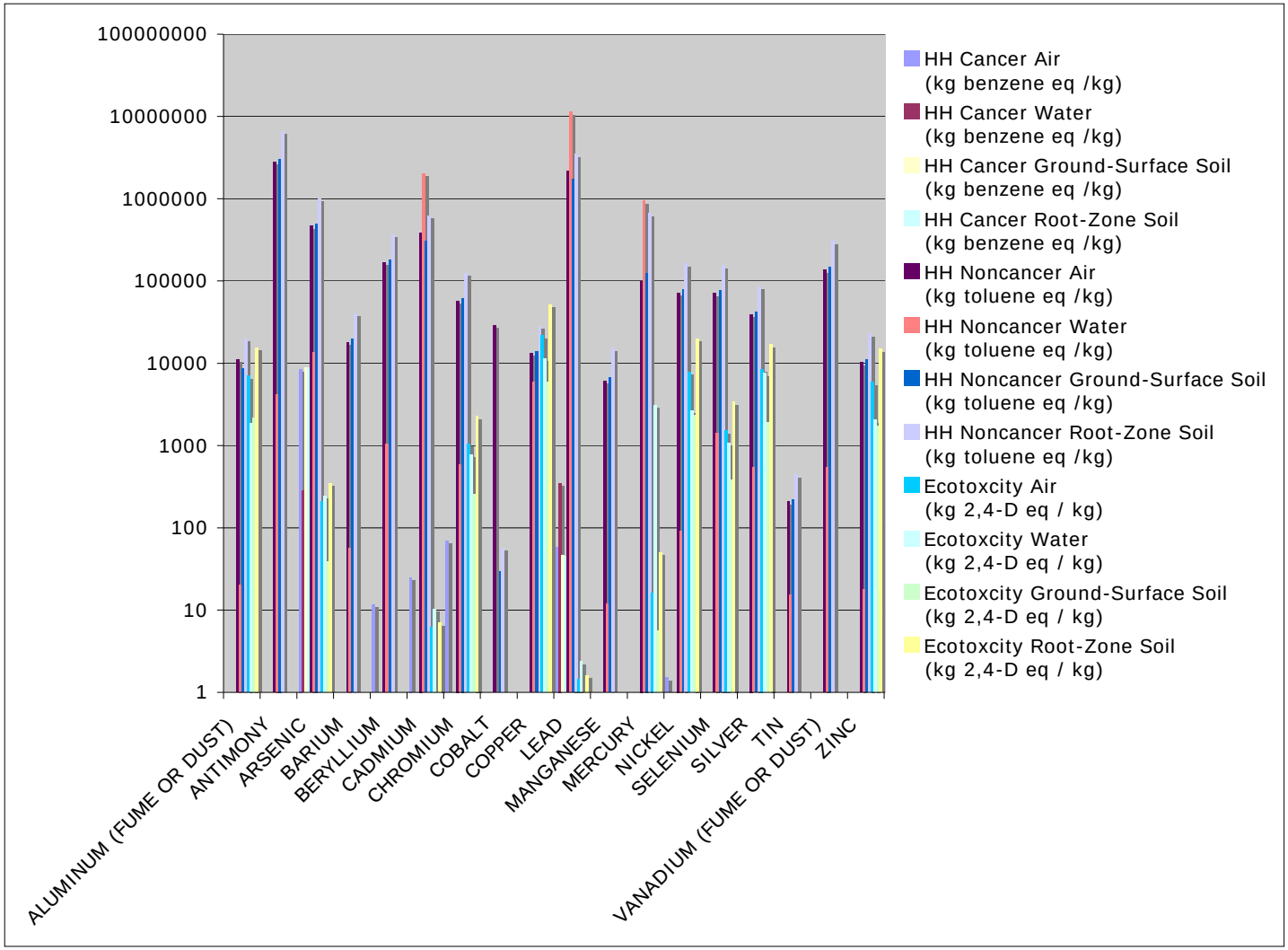
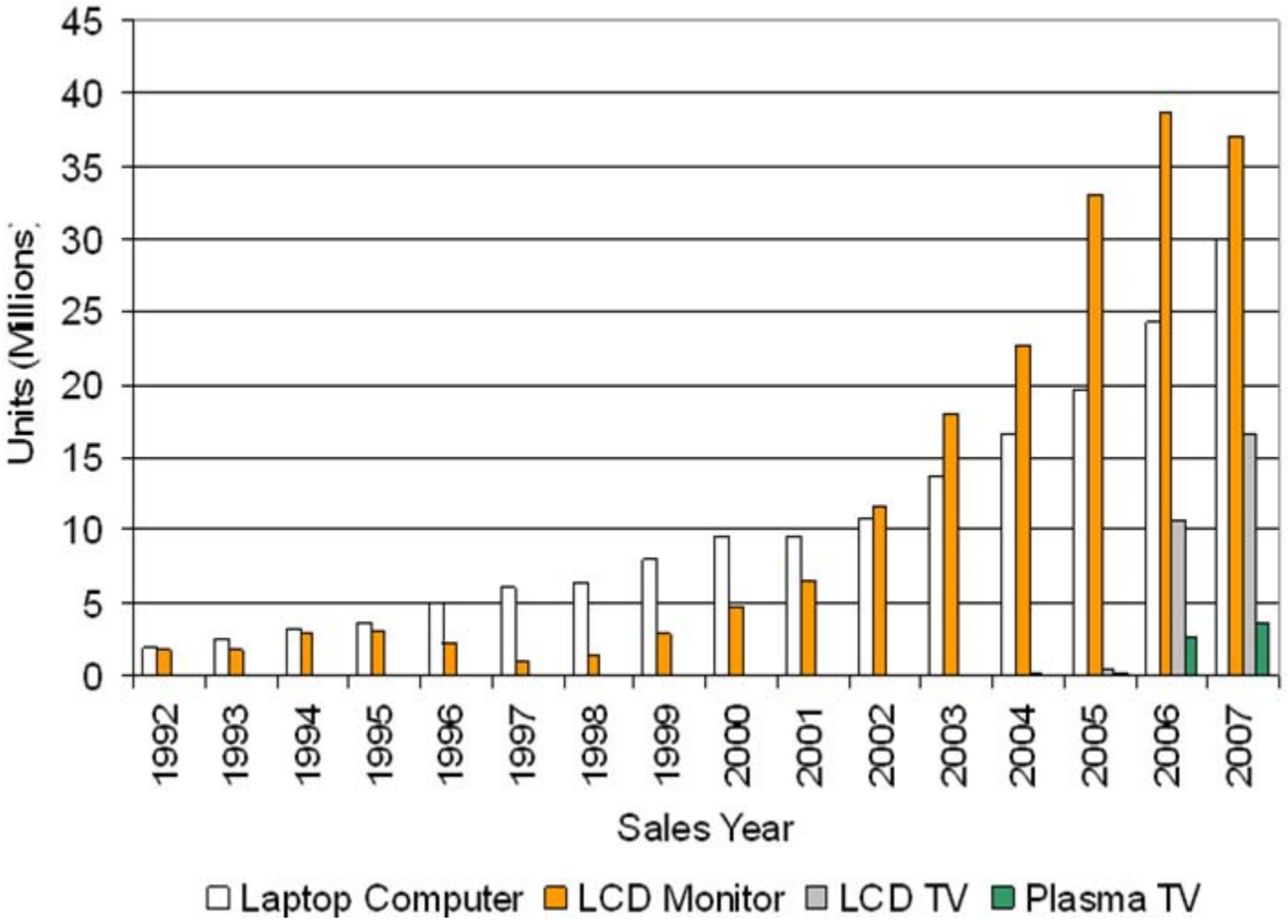
TRACI Characterization Factors for Heavy Metals



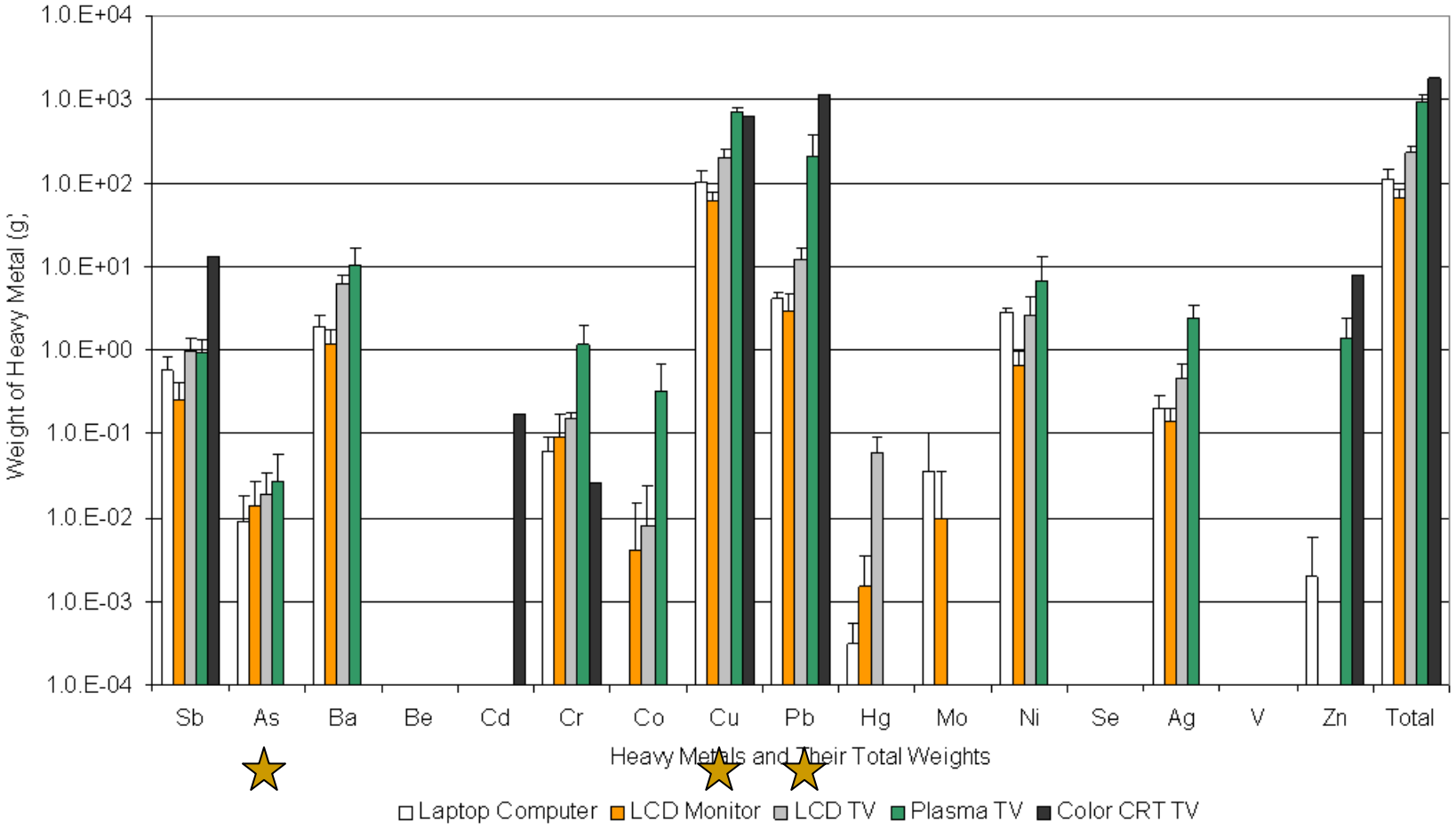
(Derived from: TRACI, US EPA)

Flat Panel Displays



(S-R. Lim and J.M. Schoenung, 2009, in review)

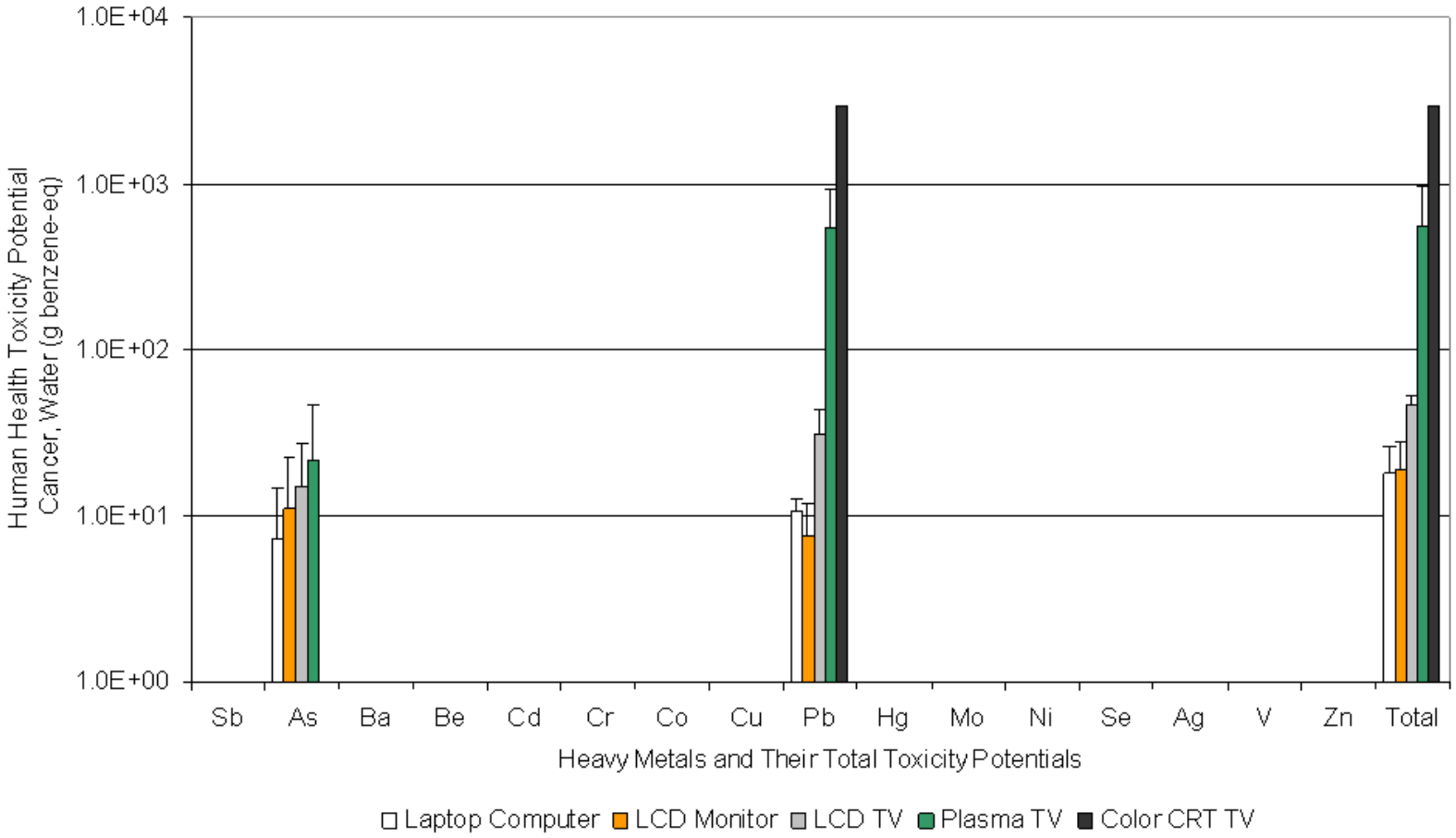
Heavy Metal Content in Flat Panel Display Devices



(S-R. Lim and J.M. Schoenung, 2009, in review)

Human Health Toxicity Potential: Cancer, Water

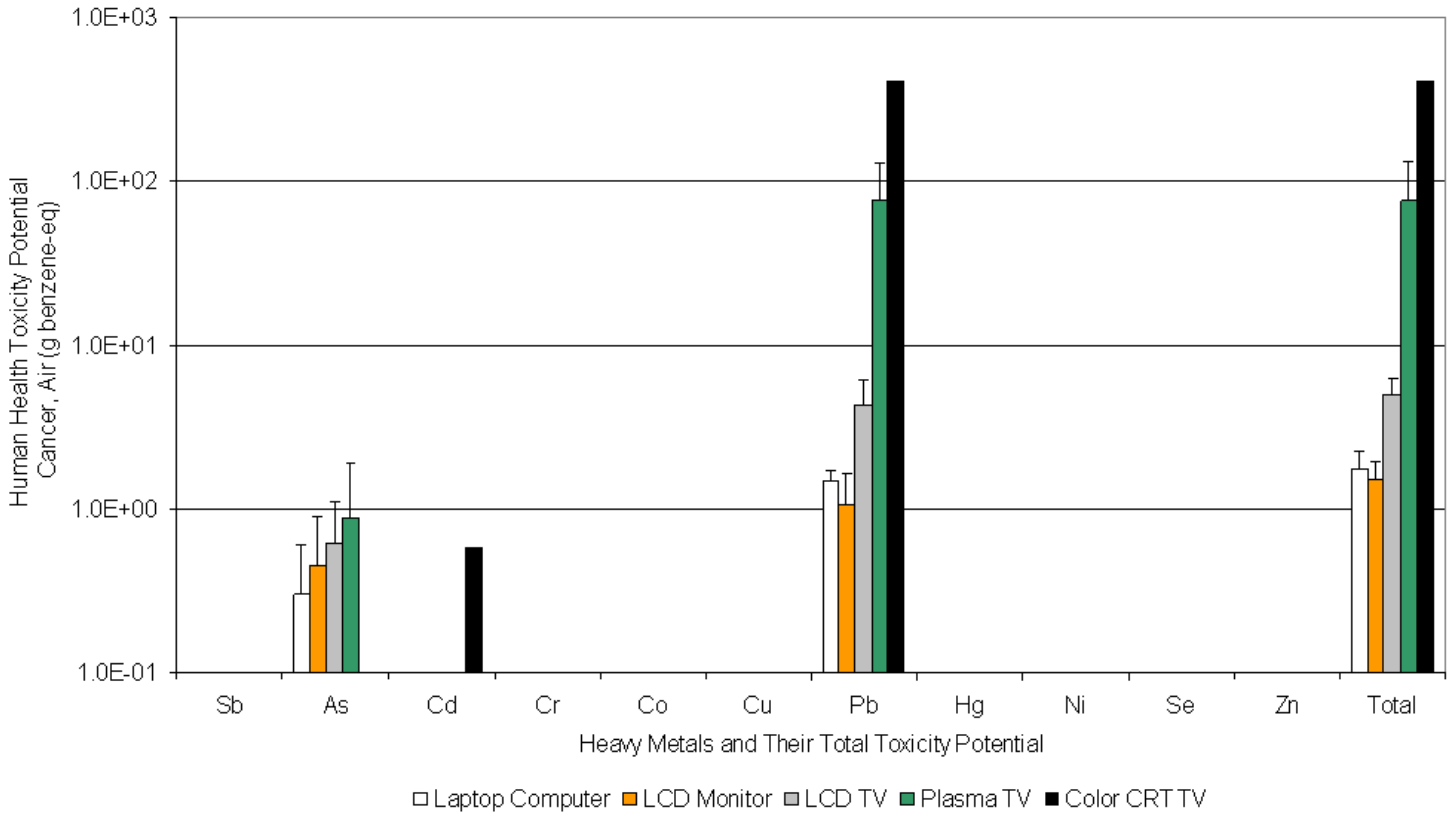
Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Human Health Toxicity Potential: Cancer, Air

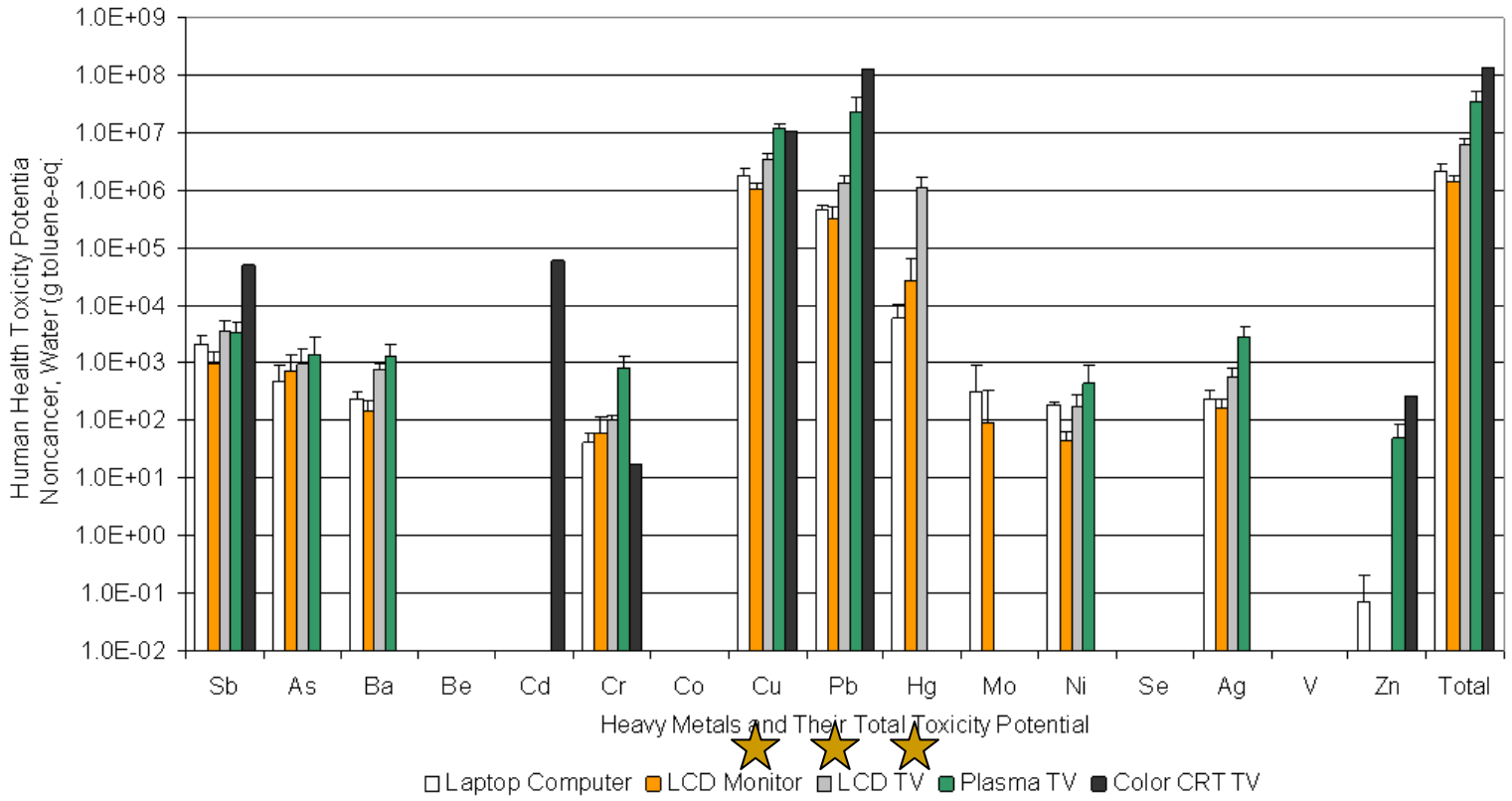
Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Human Health Toxicity Potential: Non-Cancer, Water

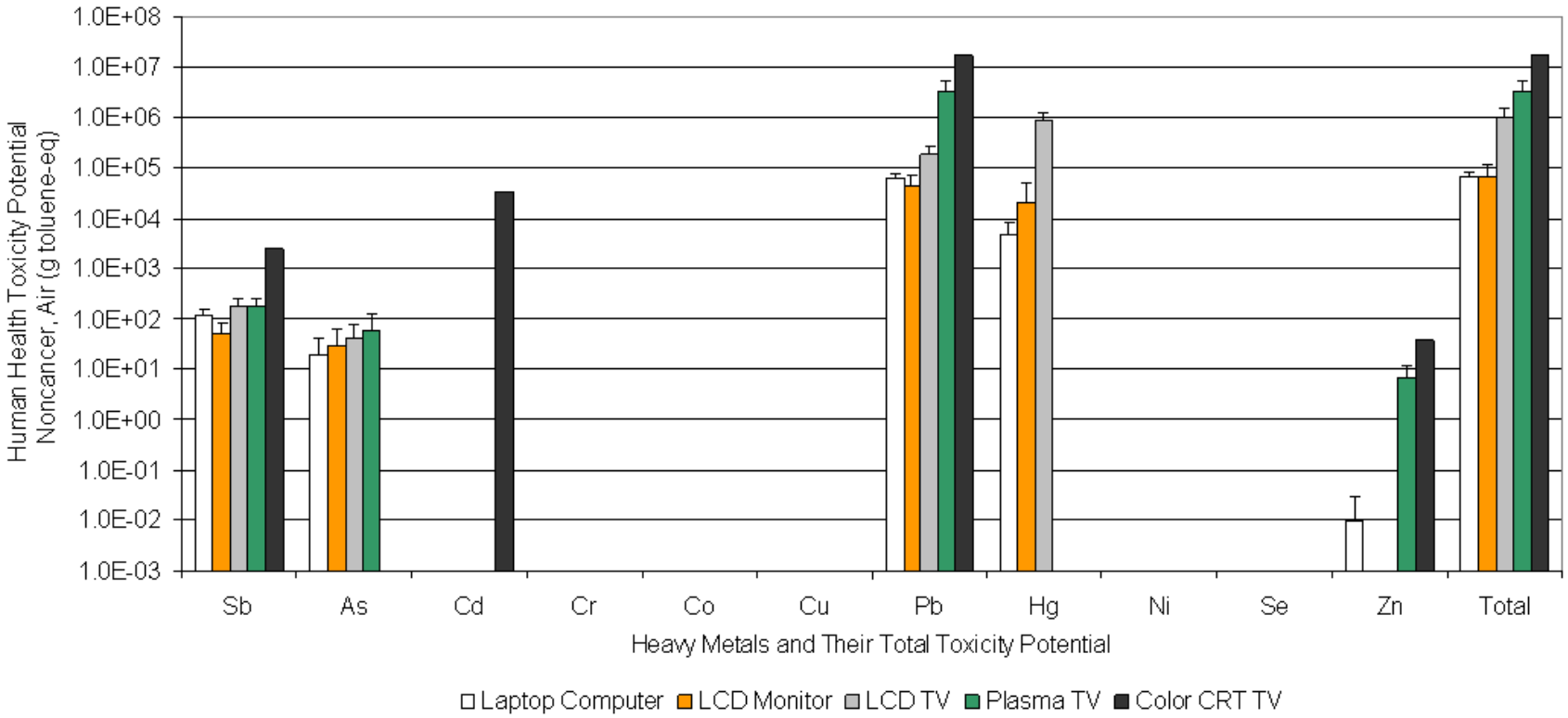
Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Human Health Toxicity Potential: Non-Cancer, Air

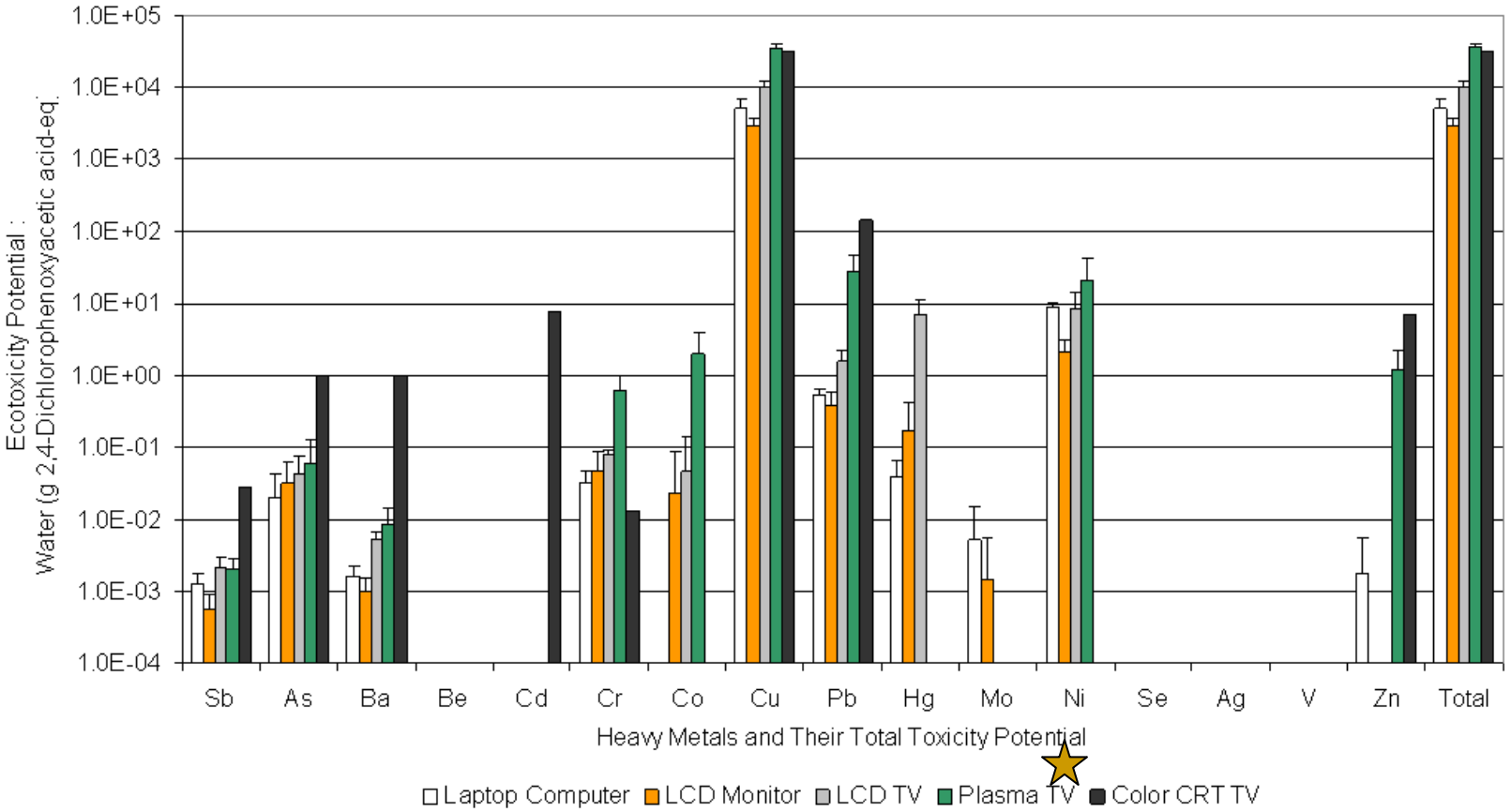
Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Ecotoxicity Potential: Water

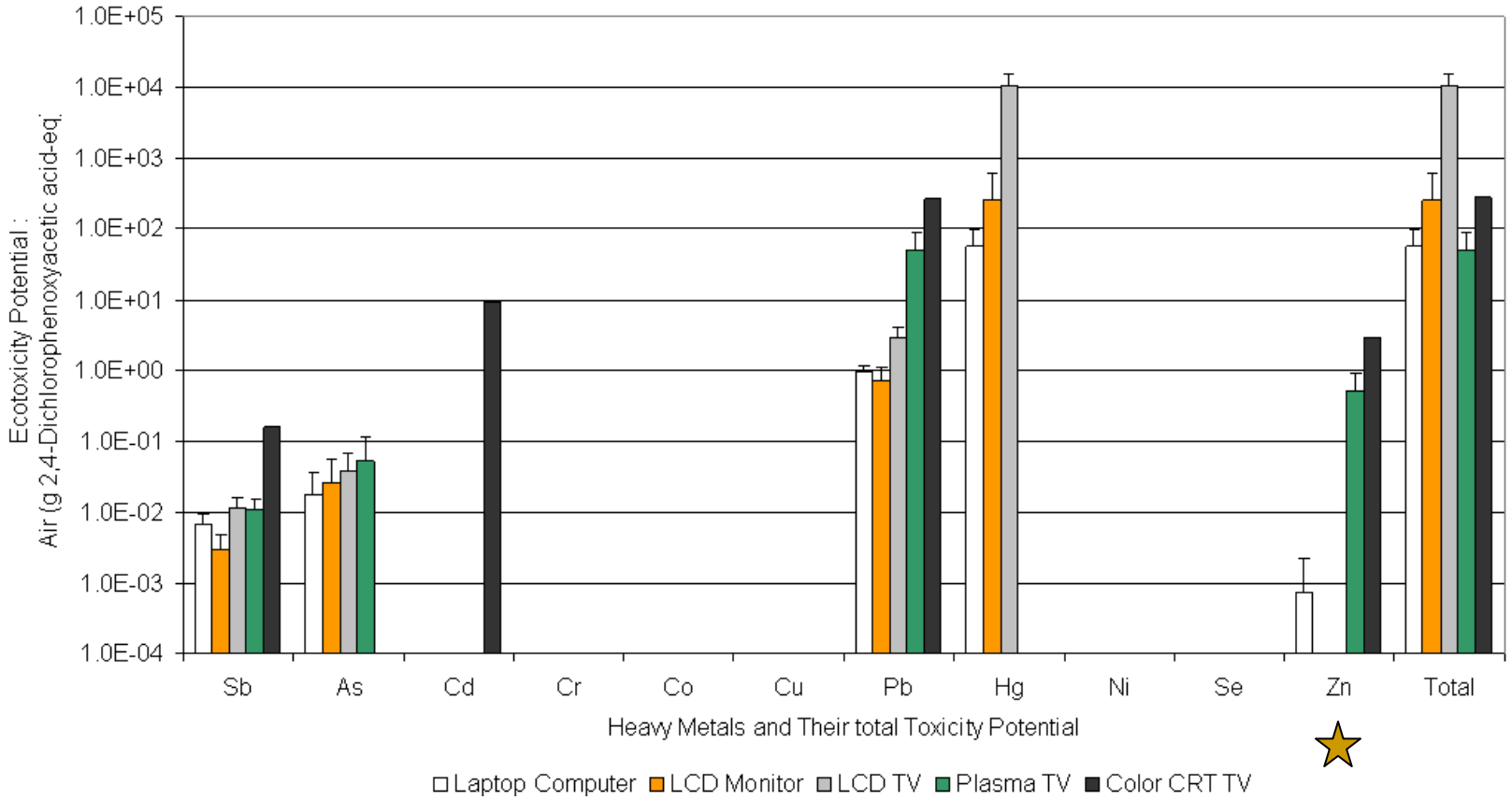
Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Ecotoxicity Potential: Air

Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Life Cycle Assessment for Electronics

- Desktop Computer Displays
  - EPA study through characterization step
  - UC Davis study for normalization and weighting
- Lead Free Solders
  - EPA study through characterization step
  - UC Davis study for normalization and weighting
- Flat Panel Displays
  - Application of TRACI characterization factors to heavy metals
- **Cellular Phones**
  - **Application of TRACI characterization factors to heavy metals**

QuickTime™ and a
TIFF (Uncompressed) decompresso
are needed to see this picture.

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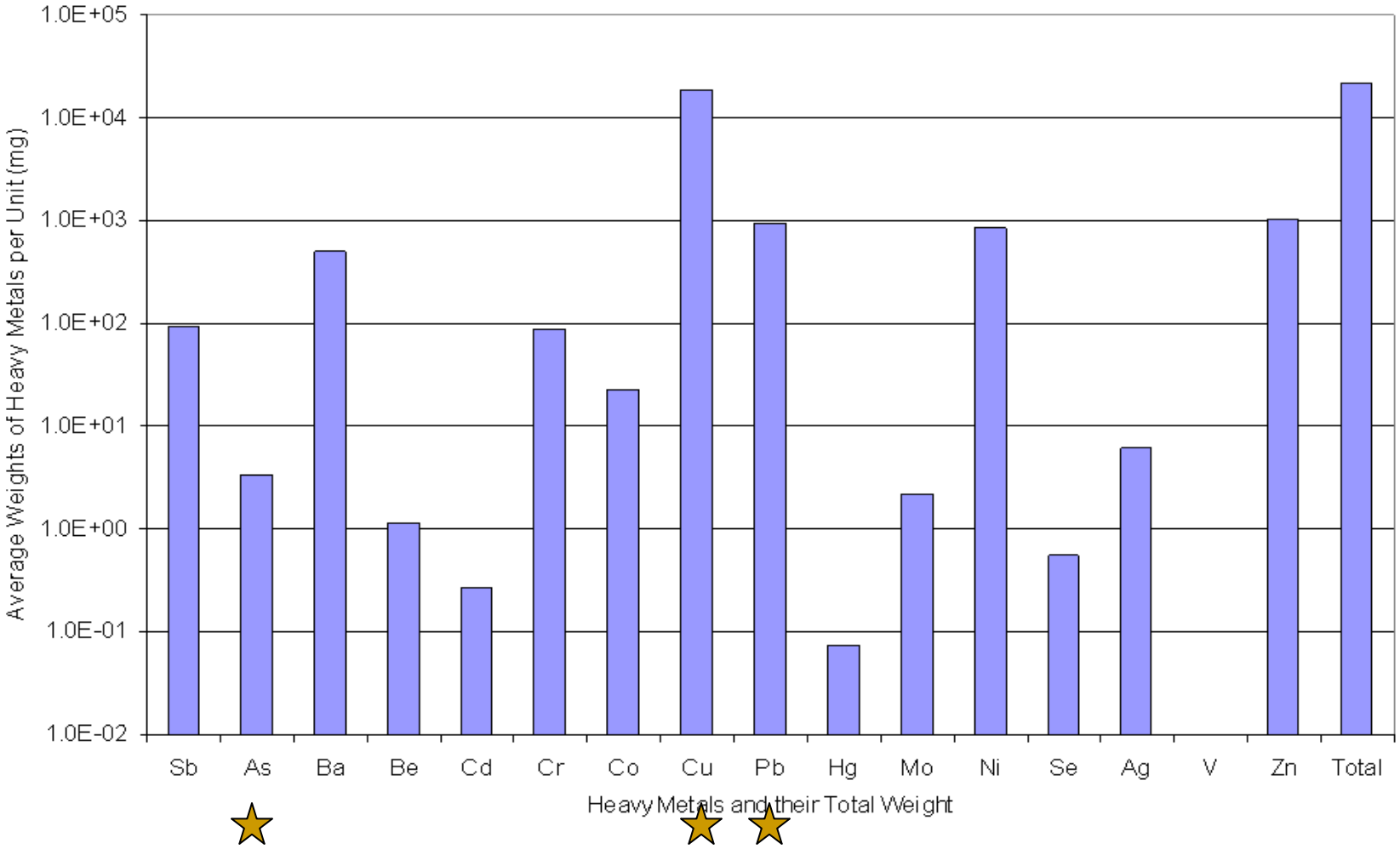
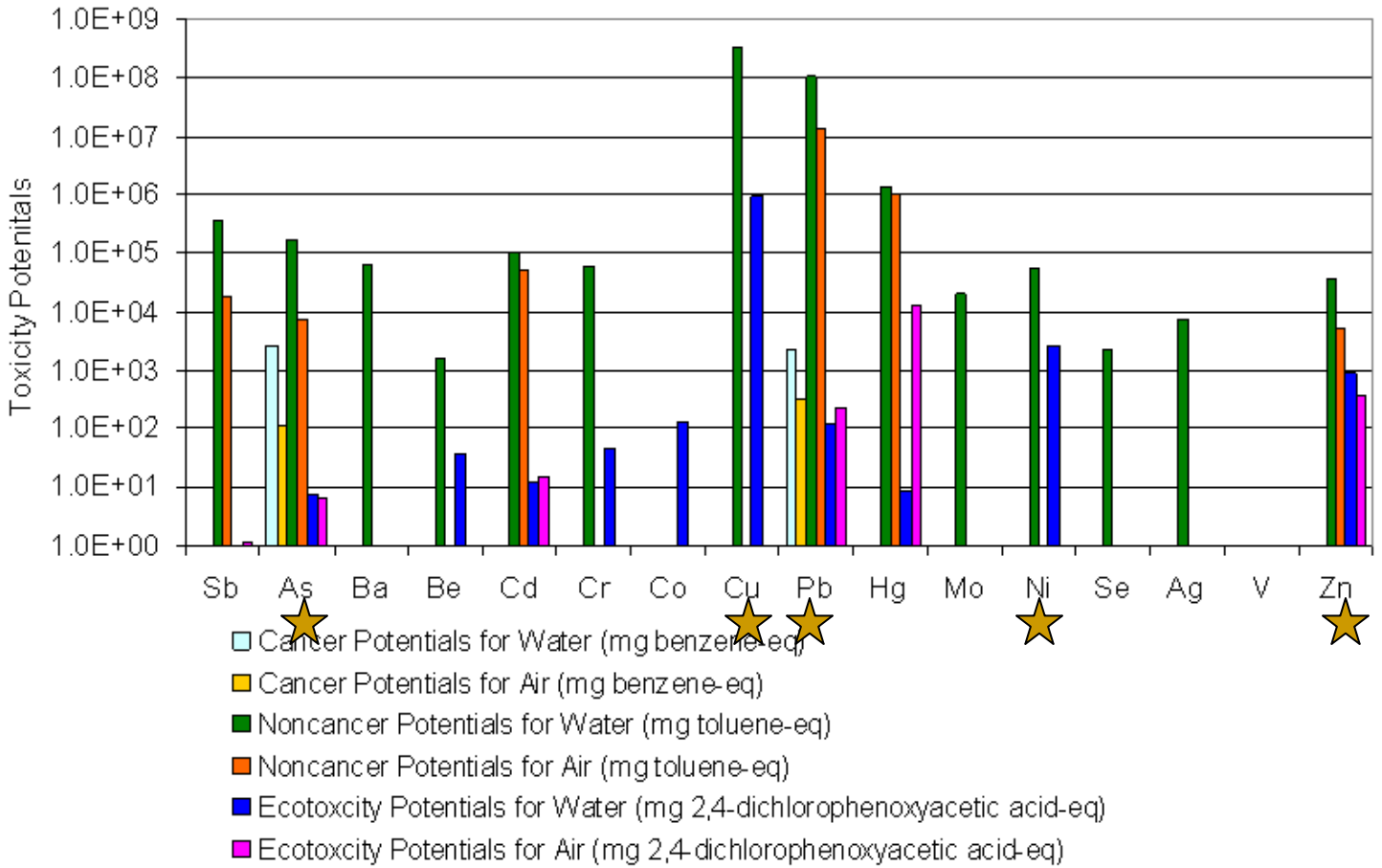
Heavy Metal Content in Cellular Phones



(S-R. Lim and J.M. Schoenung, 2009, in review)

Toxicity Potentials for Cellular Phones

Derived with TRACI Characterization Factors



(S-R. Lim and J.M. Schoenung, 2009, in review)

Concluding Remarks

- Life cycle assessment (LCA) is an important tool that can be used to identify ‘greener’ electronics.
- Case studies have been developed for a variety of electronic products, including:
  - Desktop computer displays
  - Lead-free solders
  - Flat panel displays
  - Cellular phones
- When LCA results are used for decision making, extensive sensitivity analysis should be employed.
- Targeted impact studies (such as those that focus on toxic substances or energy consumption) can often provide more guidance for Design for Environment.

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are needed to see this picture.

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