Green Chemistry Education Webinar Series

Introduction to Green Engineering

July 29, 2014

GREEN CHEMISTRY & COMMERCE COUNCIL
Business Mainstreaming Green Chemistry

Today's Speakers

Julie Zimmerman

Yale University

Associate Professor of Chemical & Environmental Engineering, Forestry & Environmental Studies

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Northeastern University

Assistant Professor of Civil and Environmental Engineering

Julie Schoenung

University of California Davis

Professor and Vice Chair of Chemical Engineering and Materials Science

Green Chemistry and Engineering: The How of Sustainability

Julie Beth Zimmerman, PhD
School of Engineering and Applied Science
School of Forestry and Environmental Studies
Yale University

Doing the right things wrong

- Can we appropriately and successfully address sustainability challenges if our designs are not in themselves sustainable?

Doing the right things wrong

Purifying water with acutely lethal substances

Doing the right things wrong

Precious, rare, toxic metals in photovoltaics

Doing the right things wrong

Agricultural crop
efficiency from
persistent pesticides

Doing the right things wrong

Energy saving compact fluorescent light bulbs reliant on toxic metals

How did we get there?

- Urgent and necessary challenges
- Noble goals
- Exciting science and technology
- Best of intentions


energy
climate
toxics
biodiversity
water

New Approach

- Innovation based
- Solutions oriented
- Advancing competitiveness
- Intrinsic versus circumstantial
- Systematic sustainability

Sustainability

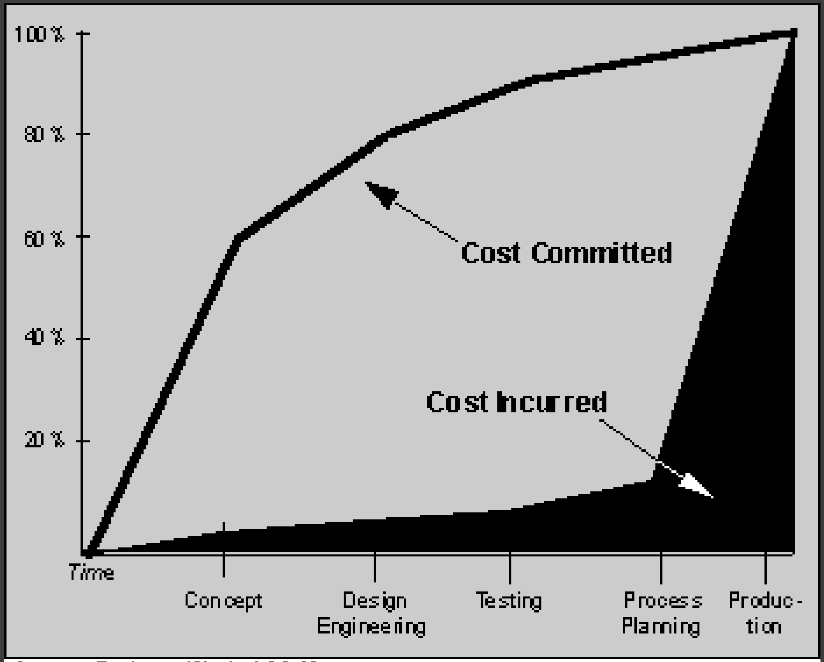
"the design of human and industrial systems to ensure that mankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment"

J.R. Mihelcic, J.C. Crittenden, M.J. Small, D.R. Shonnard, D.R. Hokanson, Q. Zhang, H. Chen, S.A. Sorby, V.U. James, J.W. Sutherland,
J.L. Schnoor, Env. Sci. Tech. 2003, 37, 5314-5324.

The necessary transformational change of engineering design

Impacts of Design Decisions

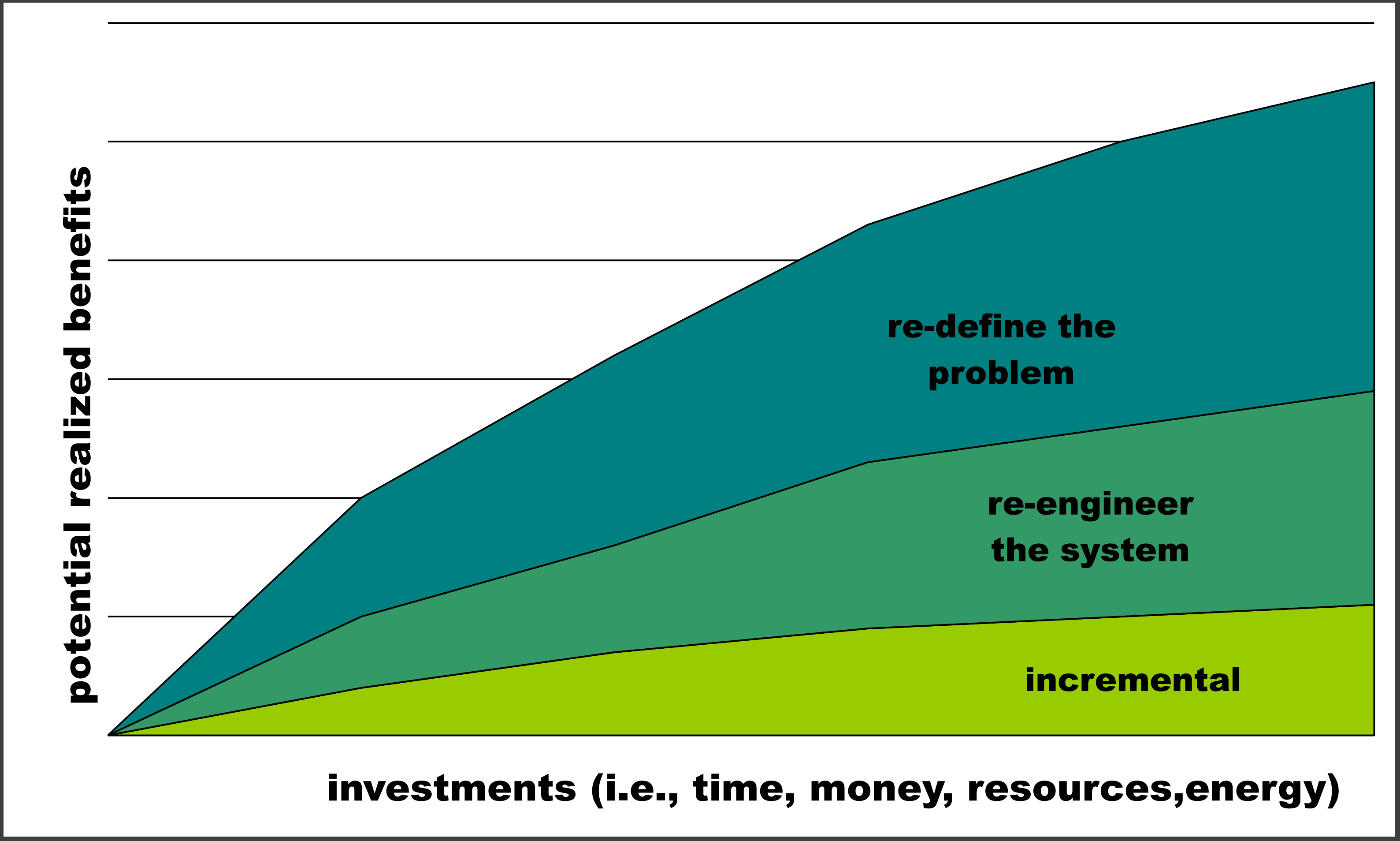
- For a typical product, 70% of the cost of development, manufacture and use is determined in its design phase.
- Analogous for environmental impacts



Source: Business Week 4-30-90

Not just how you design but <u>what</u> you design

Schematic of potential benefits vs. investments



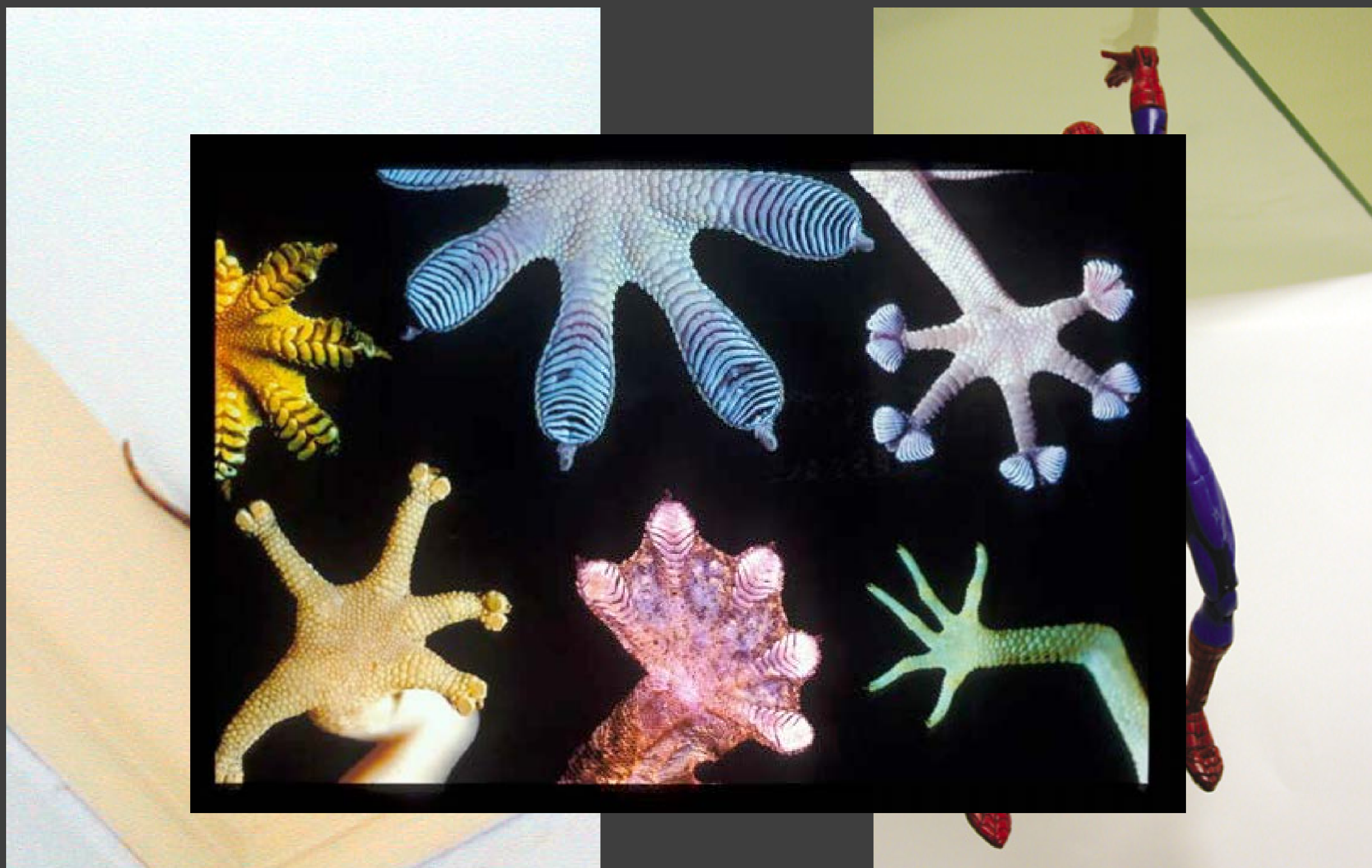

Leap frog or disruptive innovation

Sustainability

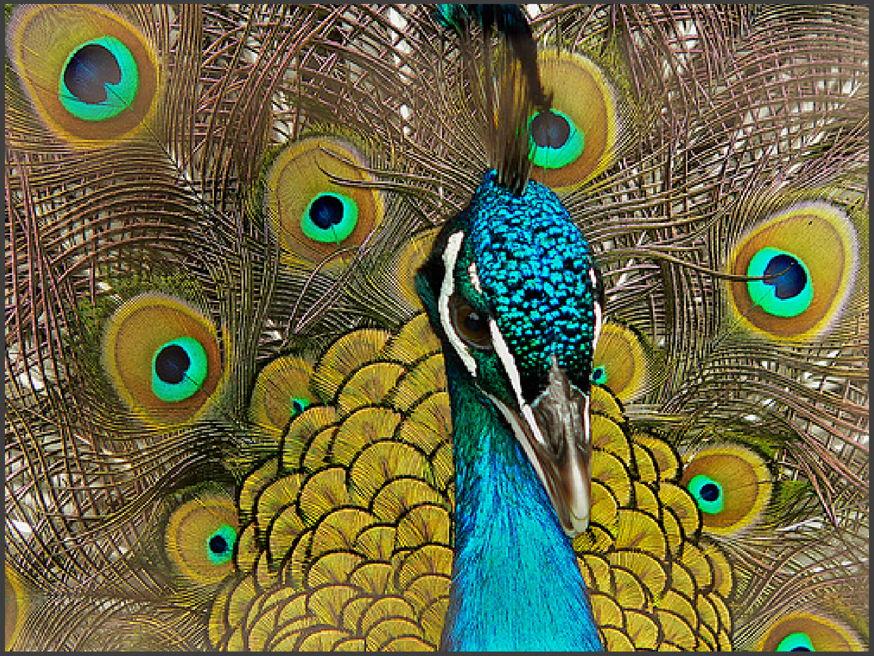
"Sustainability" without innovation is….unsustainable.

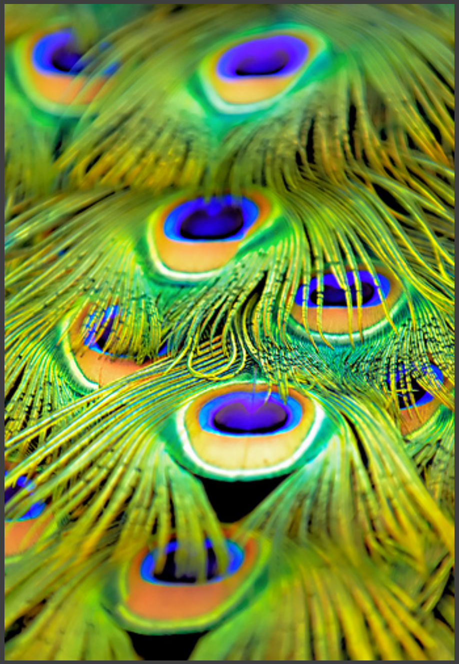
"Innovation" without sustainability is….unsustainable.

Biomimicry



Peacock





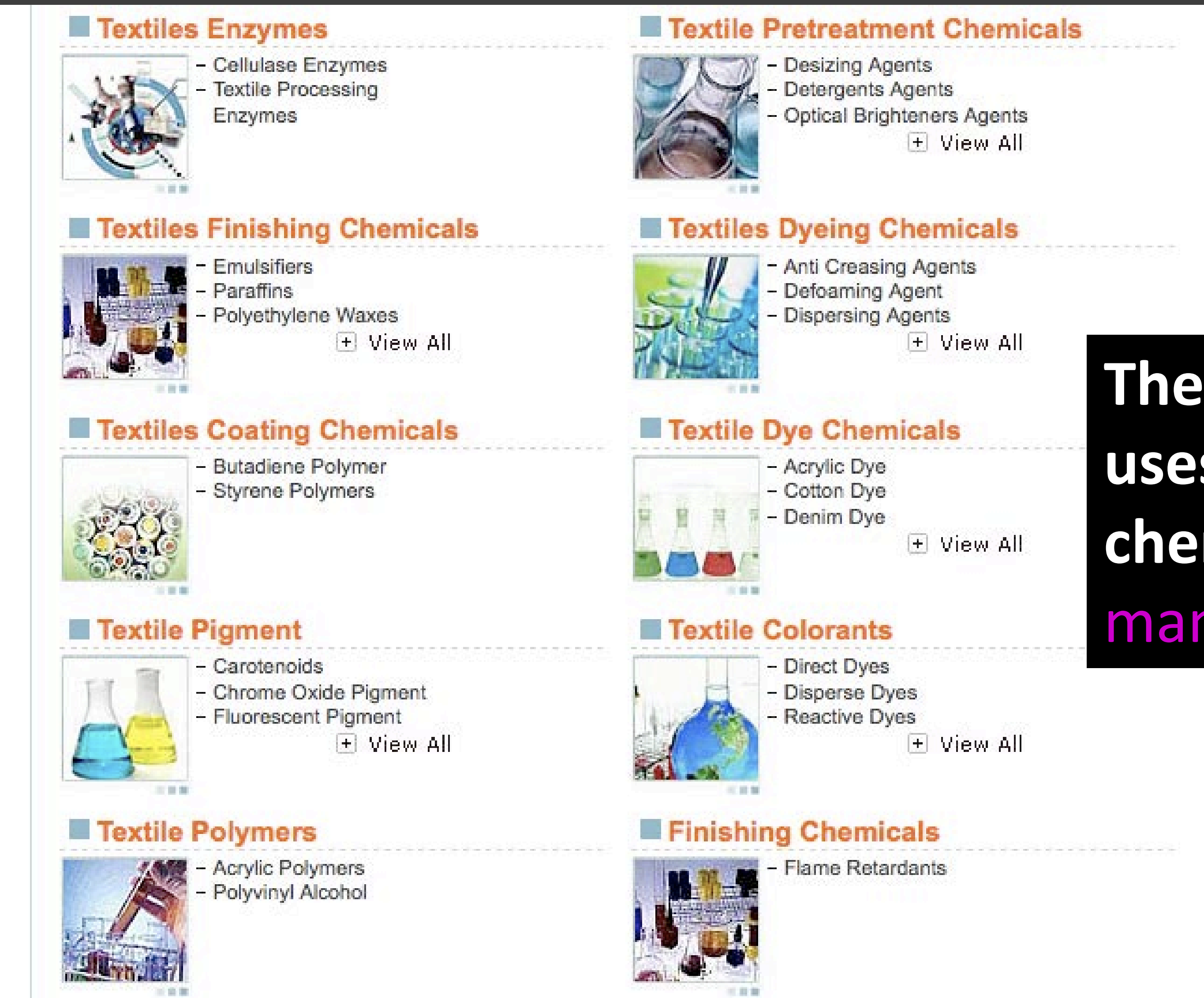
How many chemical pigments are needed to produce this assortment of colors?

None! Color is produced through optical interference arising from the surface structure of the feathers

Textiles…

How many pigments used here?

Textiles...



The textiles sector uses thousands of chemicals

many of them toxic

Abalone Shell

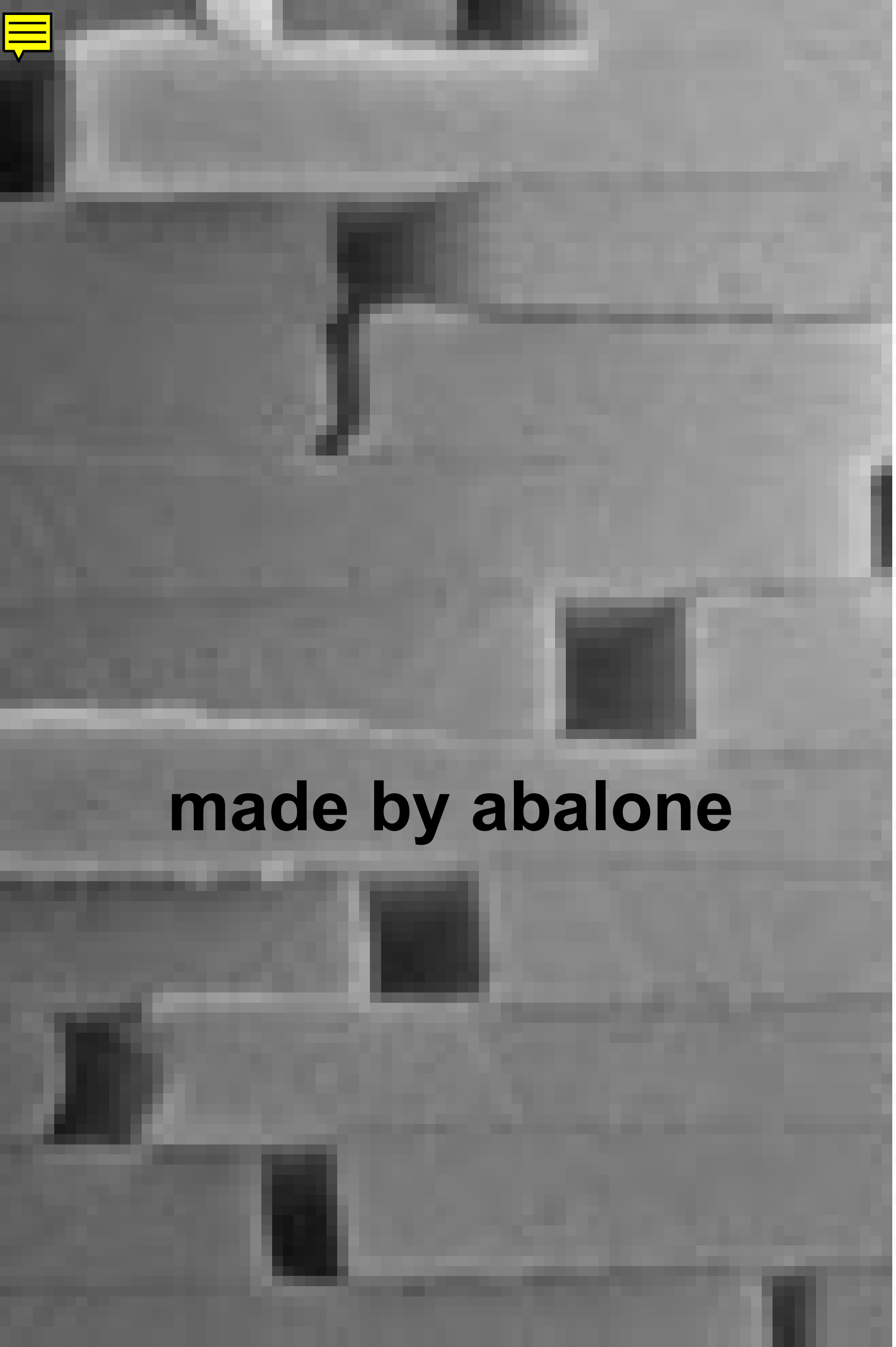
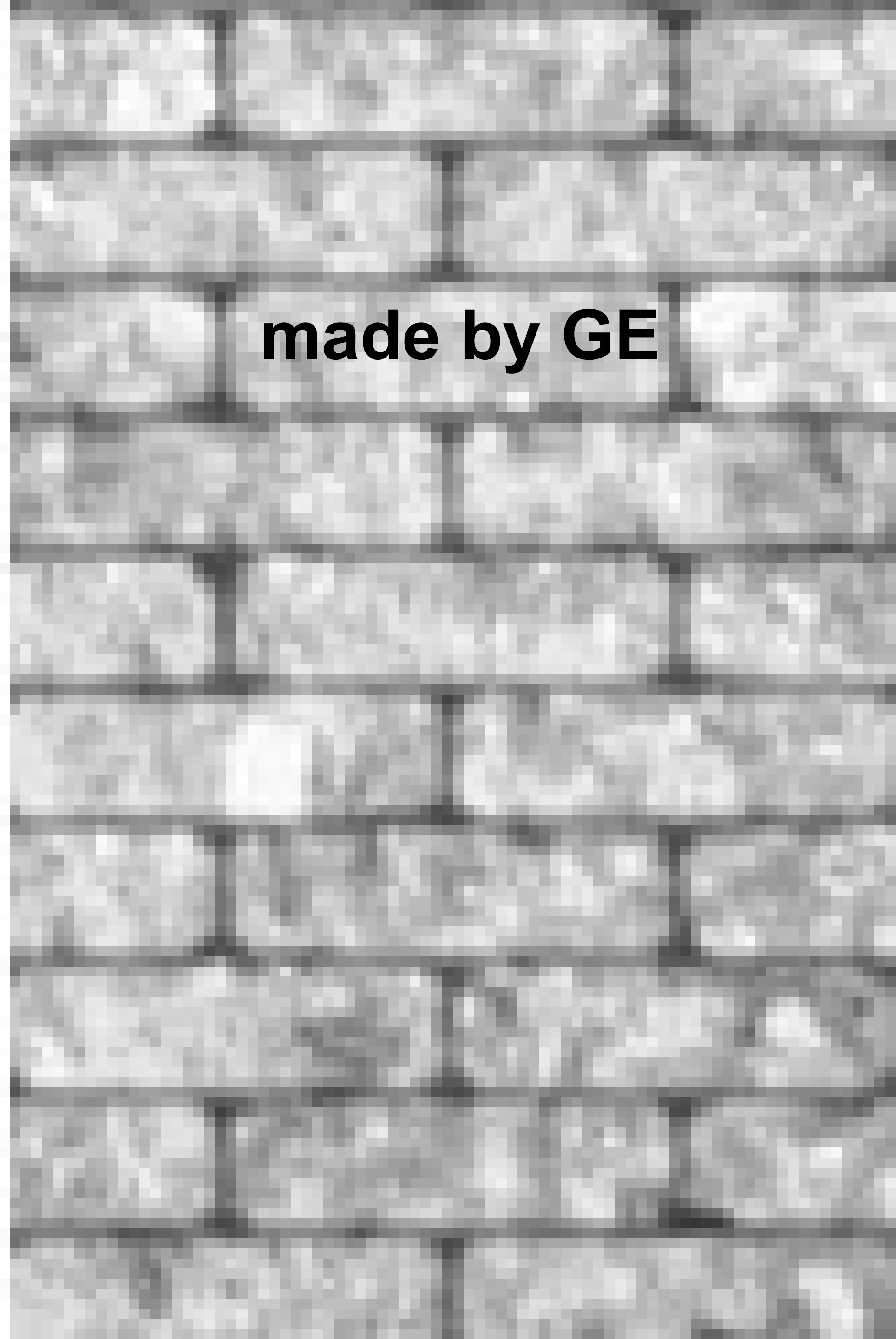
- Twice as hard as high-tech ceramics.
- Behaves like metal under stress.

How Industry Makes Ceramics

- **BEAT…** **clay to proper consistency.**
- **BAKE…** **at high temperatures (2000 - 3000 ^{o}f).**

  for prolonged periods (15 – 50 Hours).

(Ceramics Industry Major Contributor To Global Warming)


made by abalone

made by GE


Abalone
Ceramics Factory
Glenn Allen

How do we make things?

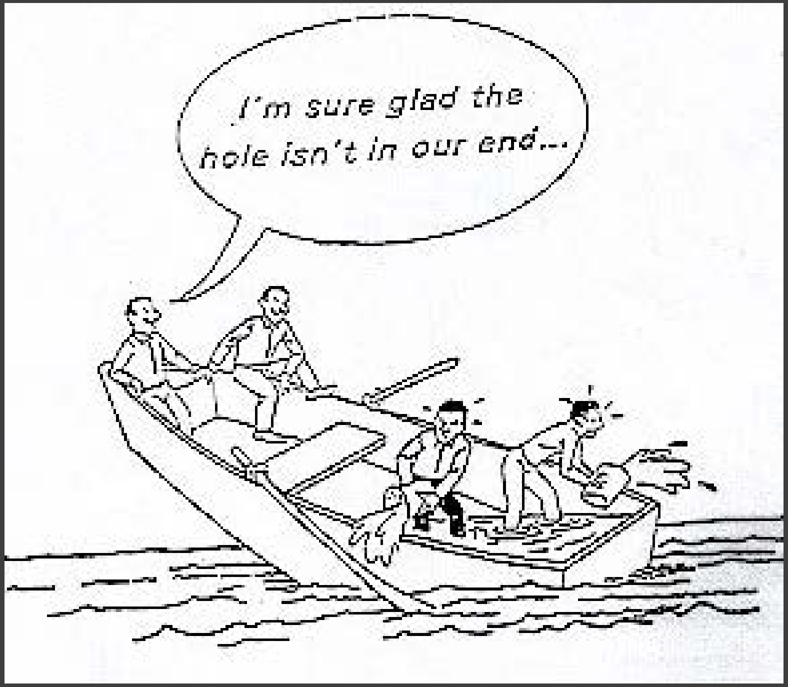
“Heat, beat, and treat”

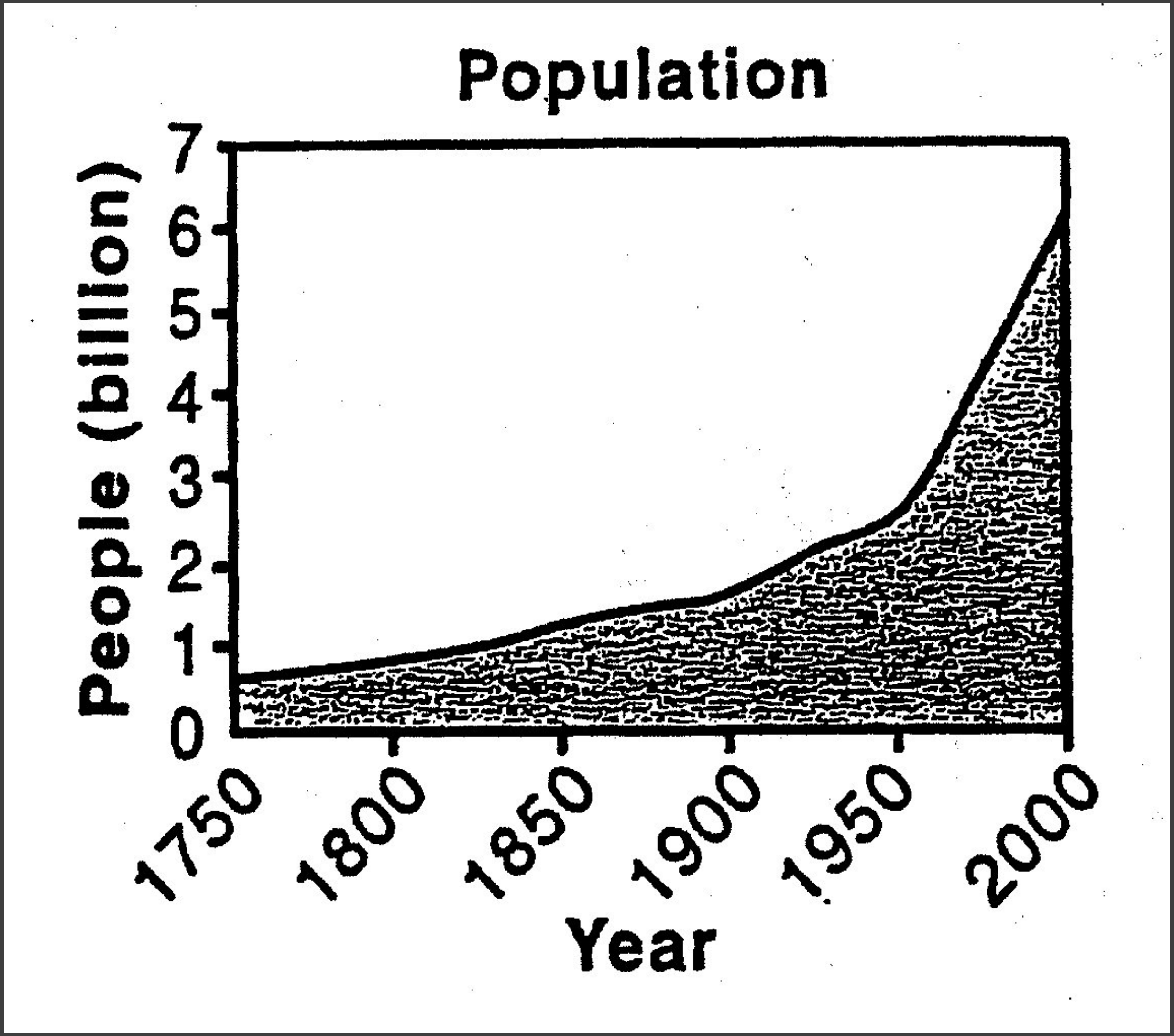
How nature makes things…

* Nature runs on sunlight
* Nature uses only the energy it needs
* Nature fits form to function
* Nature recycles everything
* Nature rewards cooperation
* Nature banks on diversity
* Nature demands local expertise
* Nature curbs excesses from within
* Nature taps the power of limits

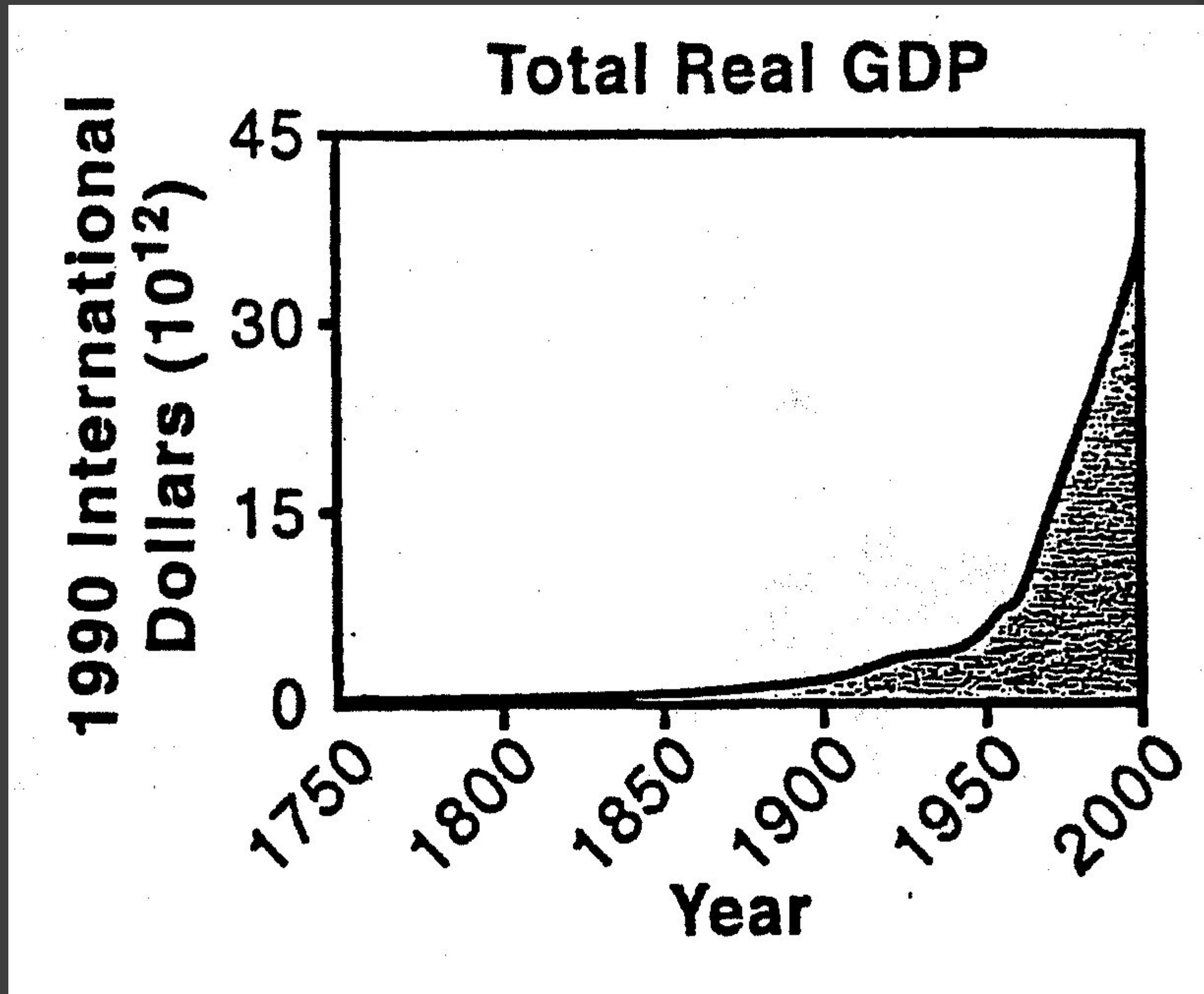
- Janine Benyus, *Biomimicry*

Systems thinking





Crutzen, P. J. The Anthropocene: The Current Human-Dominated Geological Era—Human Impacts on Climate and the Environment. In *Climate Change and Its Effect*



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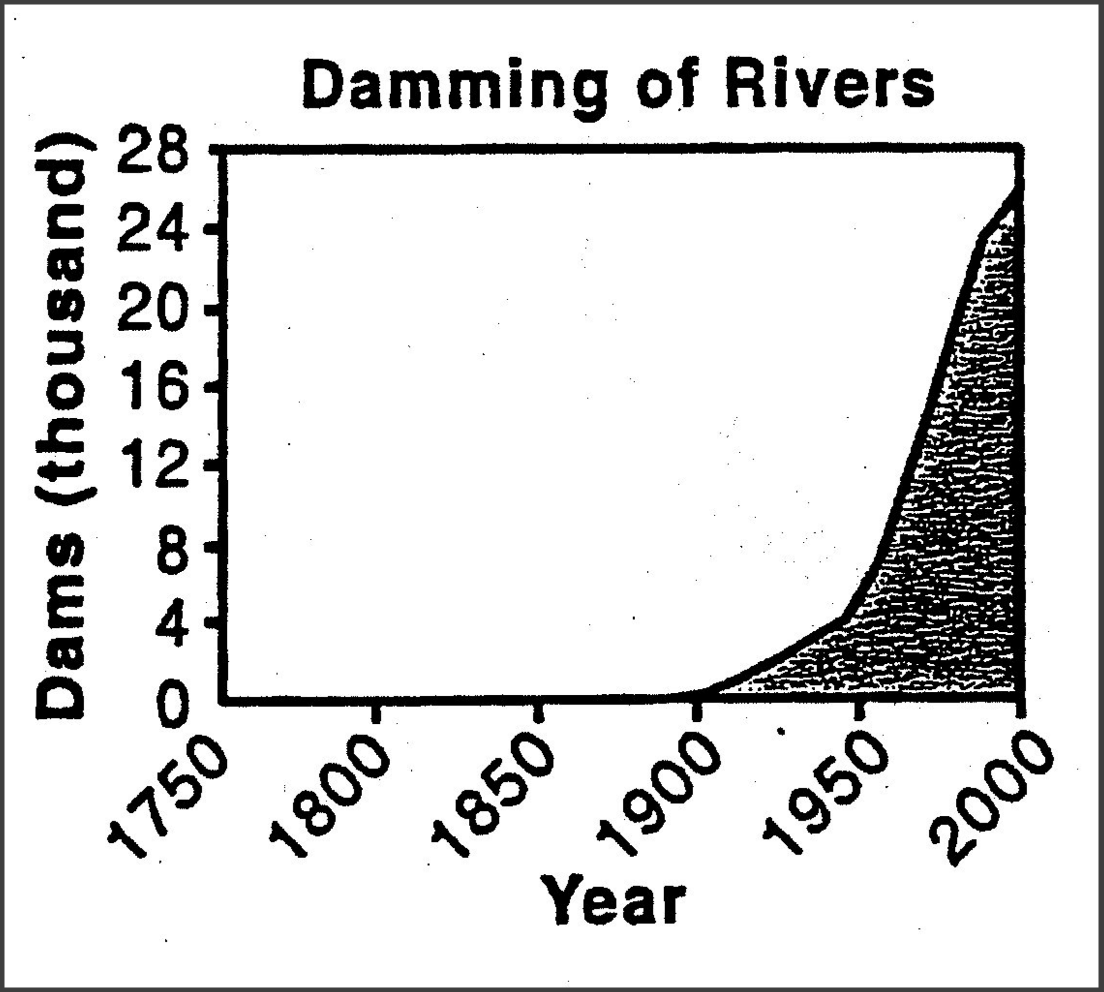

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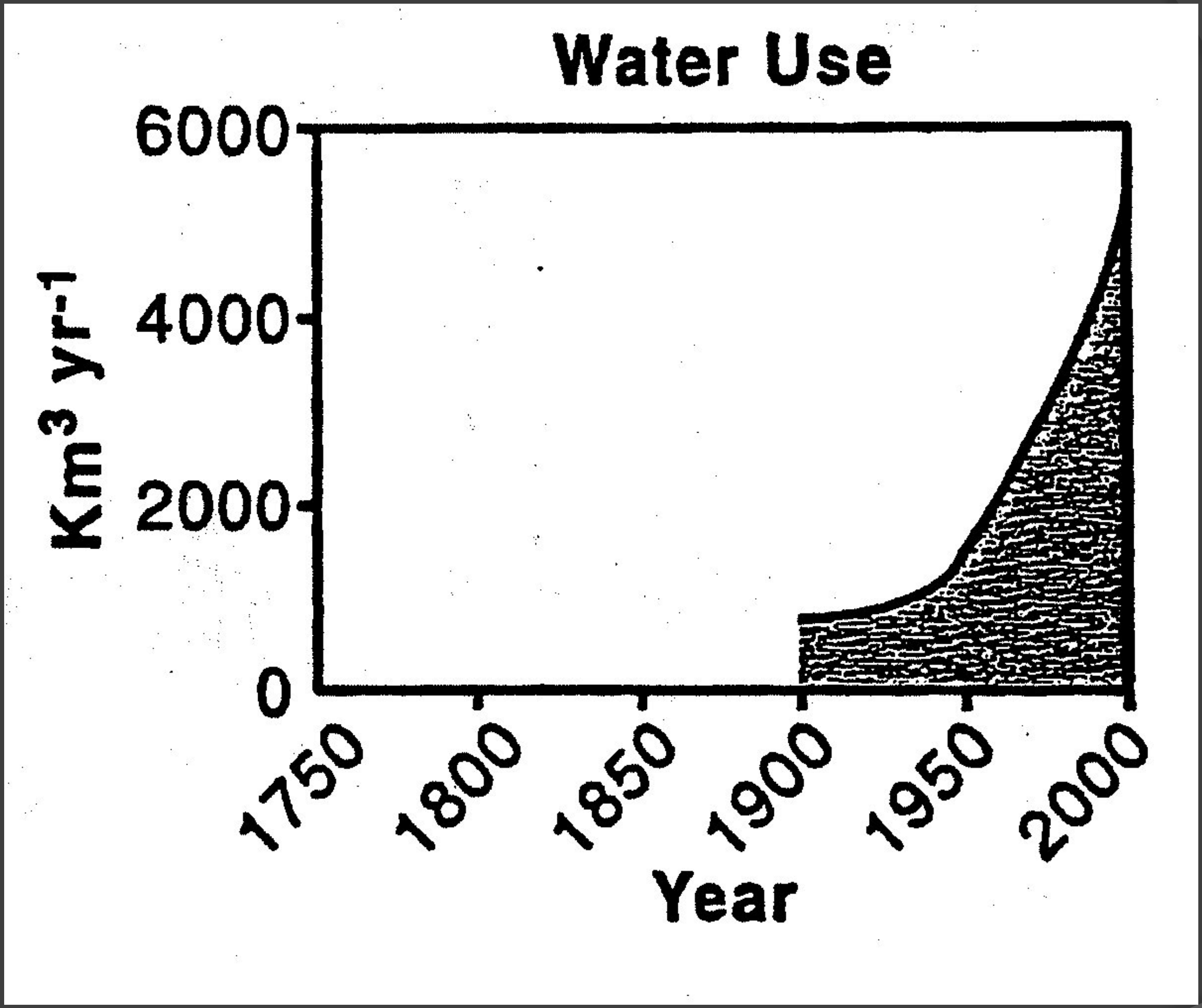

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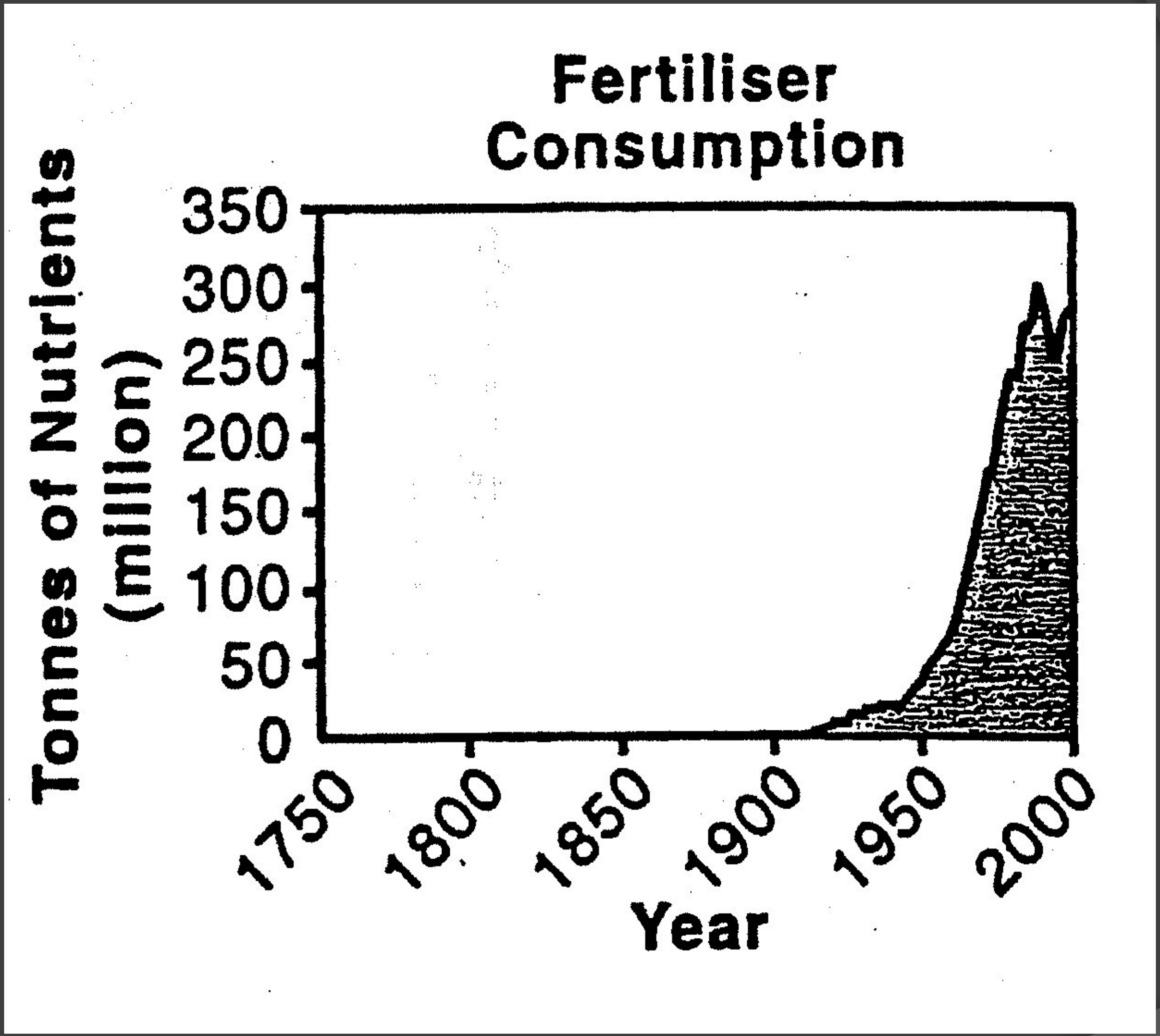

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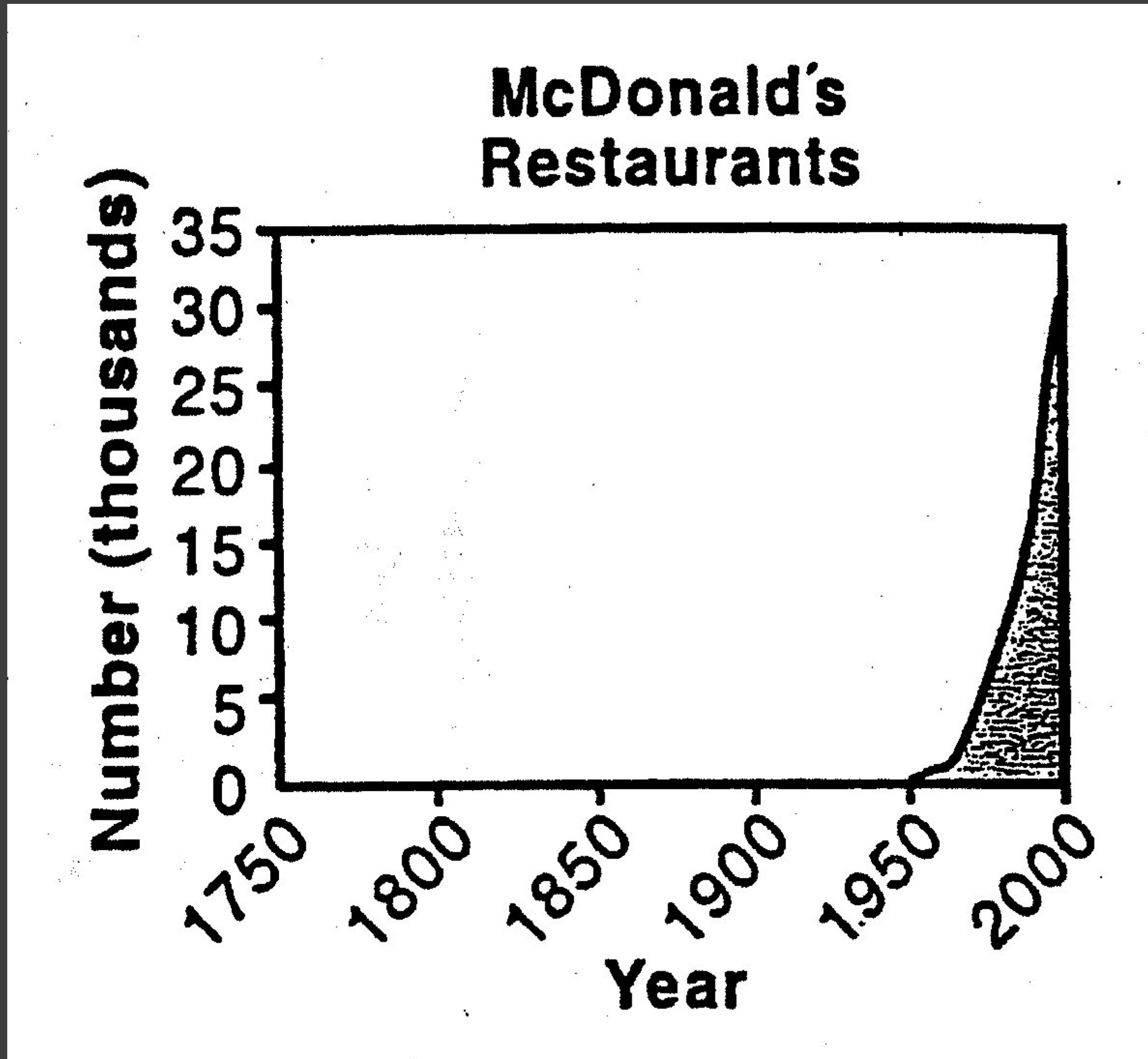

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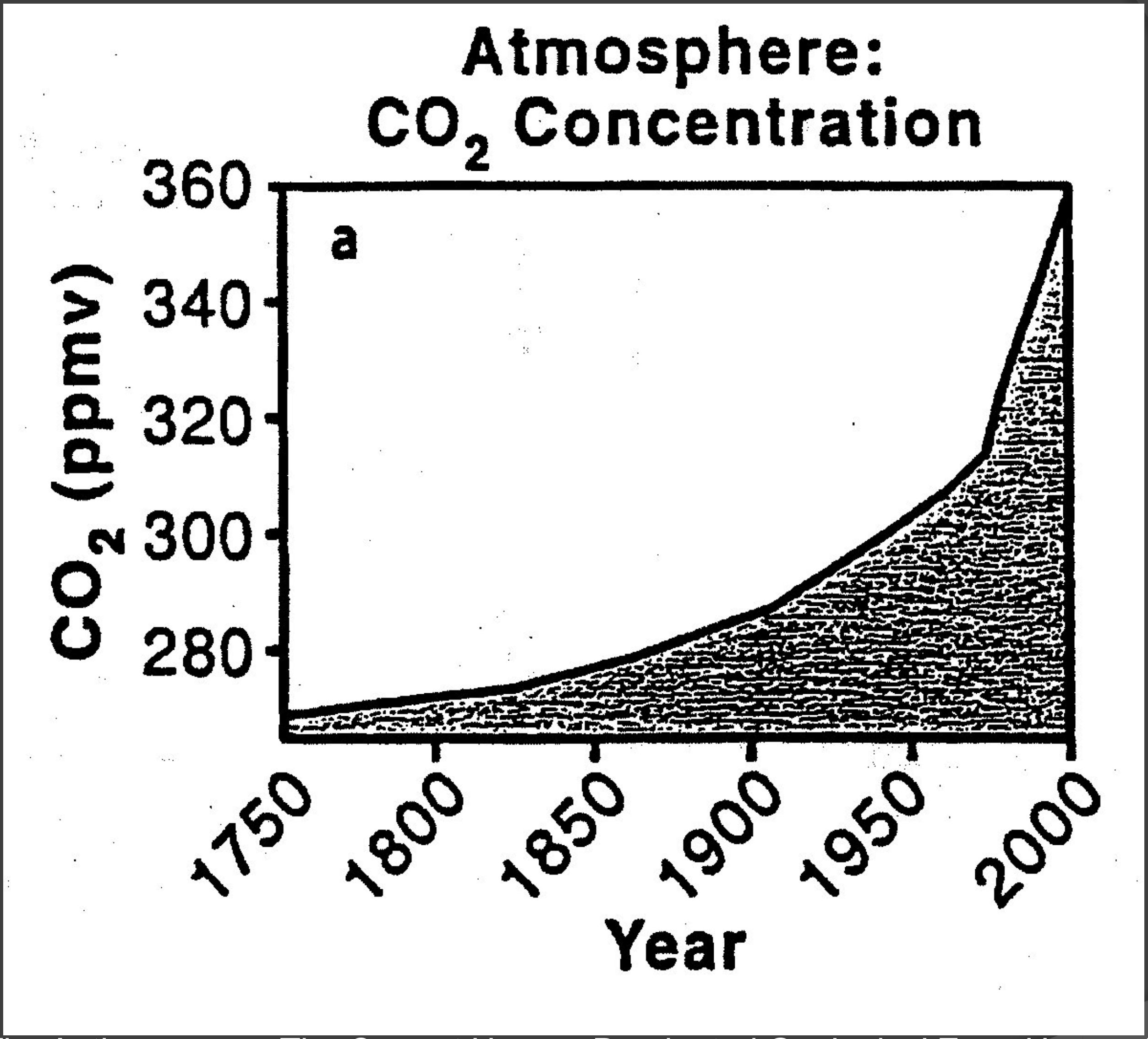

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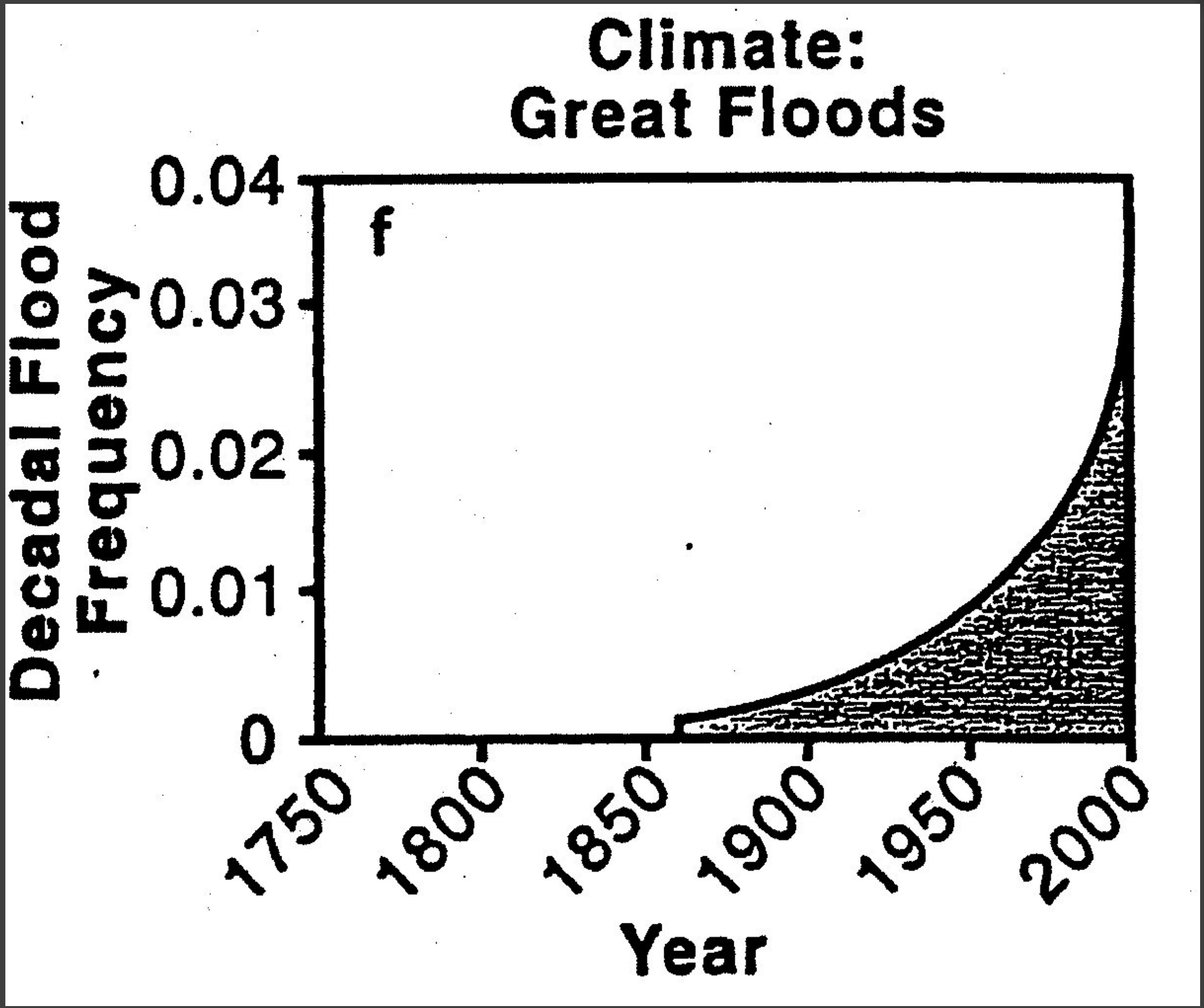

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Principles of Green Engineering

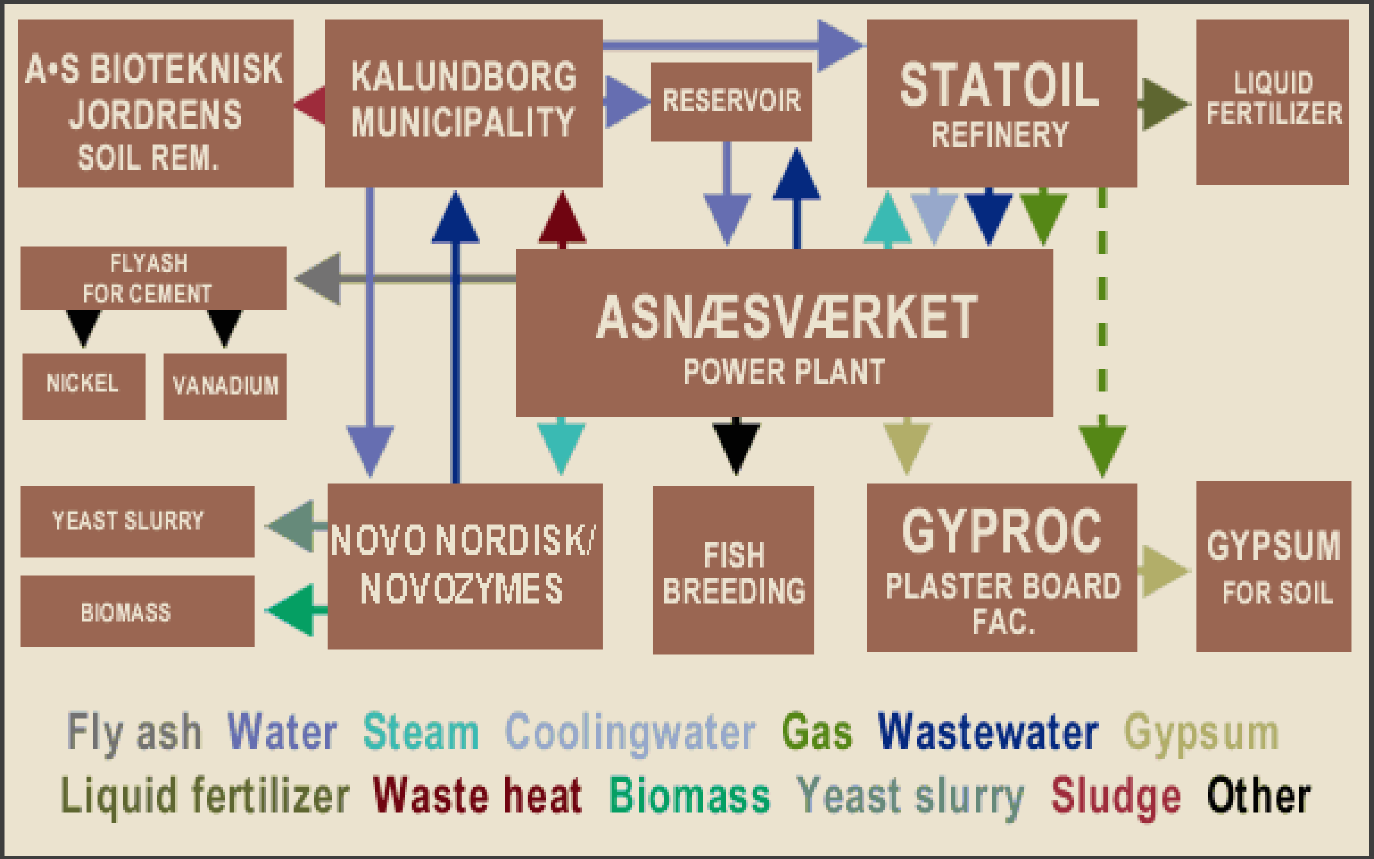
1. Green Chemistry
2. Prevention rather than treatment.
3. Design for separation.
4. Maximize mass, energy, space, and time efficiency.
5. “Out-pulled” rather than “input-pushed”.
6. View complexity as an investment.
7. Durability rather than immortality.
8. Need rather than excess.
9. Minimize material diversity.
10. Integrate local material and energy flows.
11. Design for commercial “afterlife”.
12. Renewable and readily available.

Anastas and Zimmerman, Environmental Science and Technology, March 1, 2003

View complexity as an investment

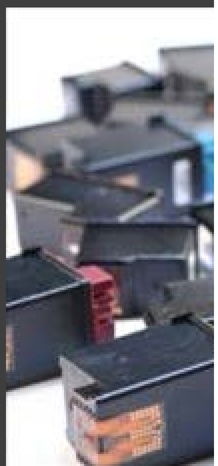
- Case for modular, standardized, platform-based, upgradable design

Integrate material and energy flows

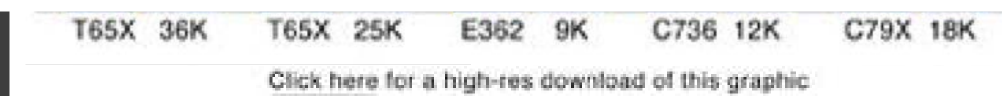


Durability rather than immortality

Design for commercial “afterlife”



"When we reuse our products — much less recycle them — we keep our costs down significantly," says Rob Fischmann, head of worldwide recycling at Lexmark. "The second-time cost for these cartridges is essentially zero."



Renewable and readily available

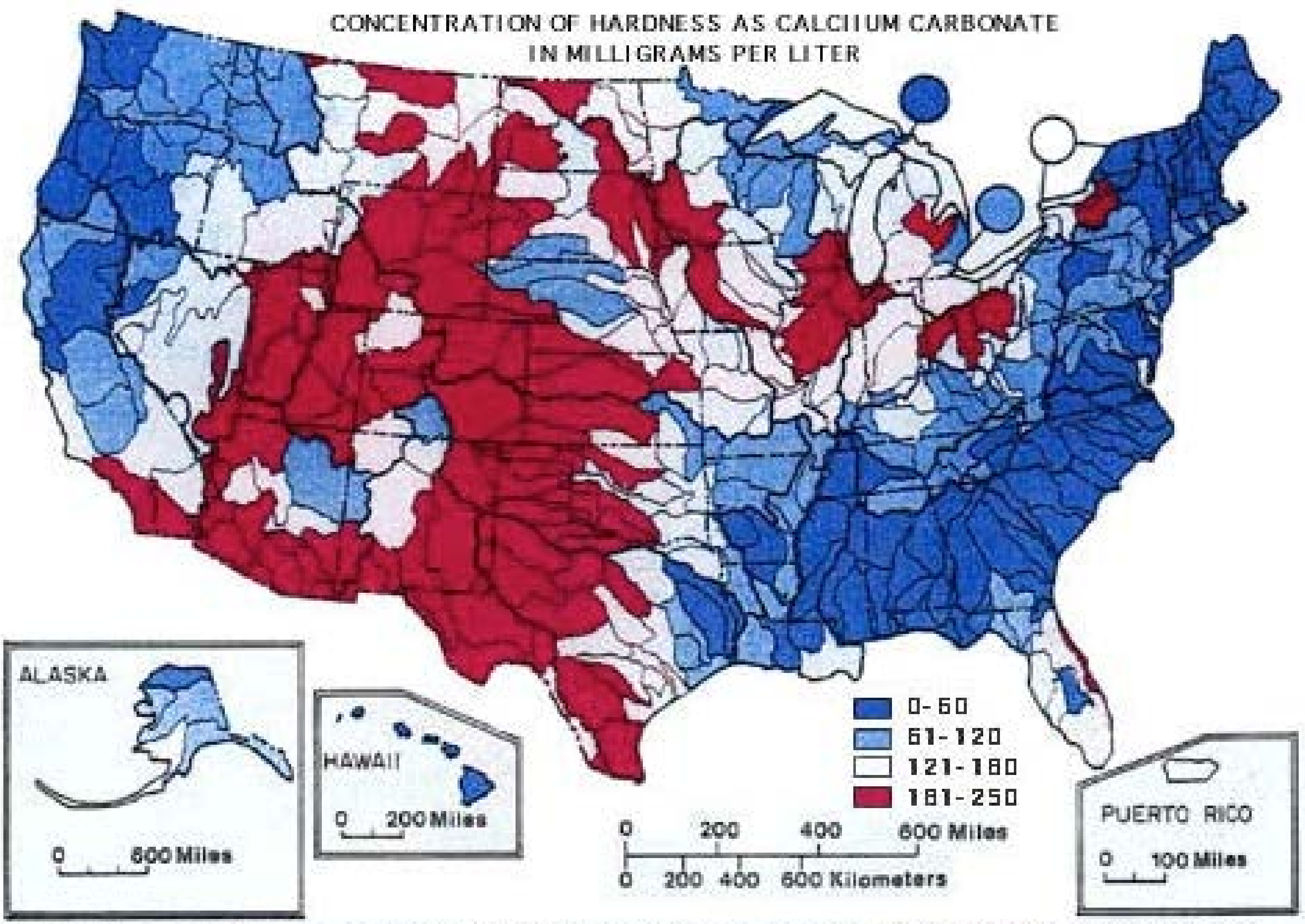


Figure 5.–Mean hardness as calcium carbonate at NASQAN stations during 1975 water year. Map at bottom is colored to show station data representing flow from the accounting unit.

Need rather than excess

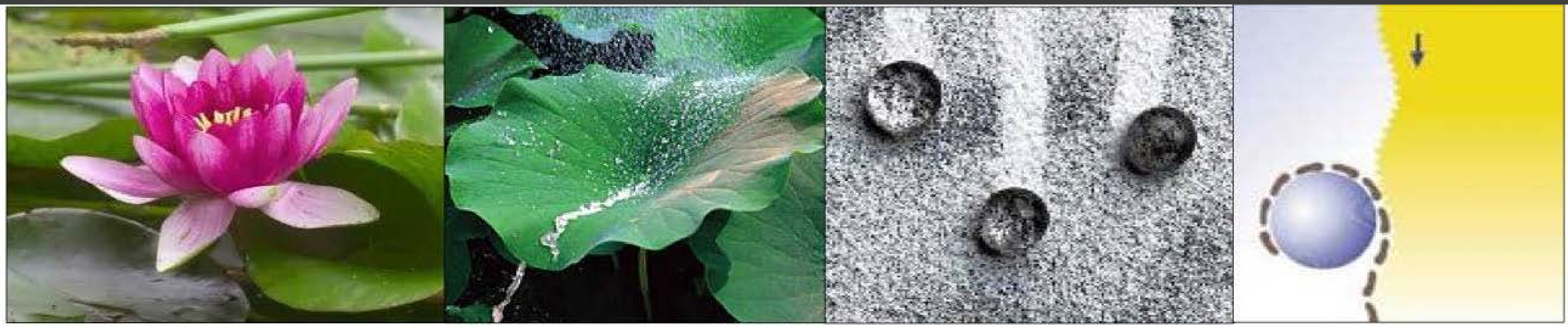
Key concepts and relation to sustainable design

Fundamental concept: Technologies tend to evolve in similar ways towards “ideality”, where all of the benefits of a product can be achieved while the product itself ceases to exist physically.

What?

How we typically waterproof surfaces

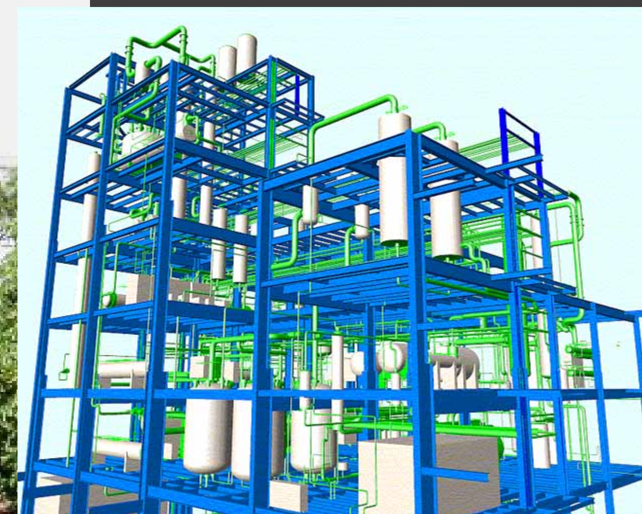
Lotus flower



Ideality, sustainability, & product design

Coffee decaffeination using methylene chloride

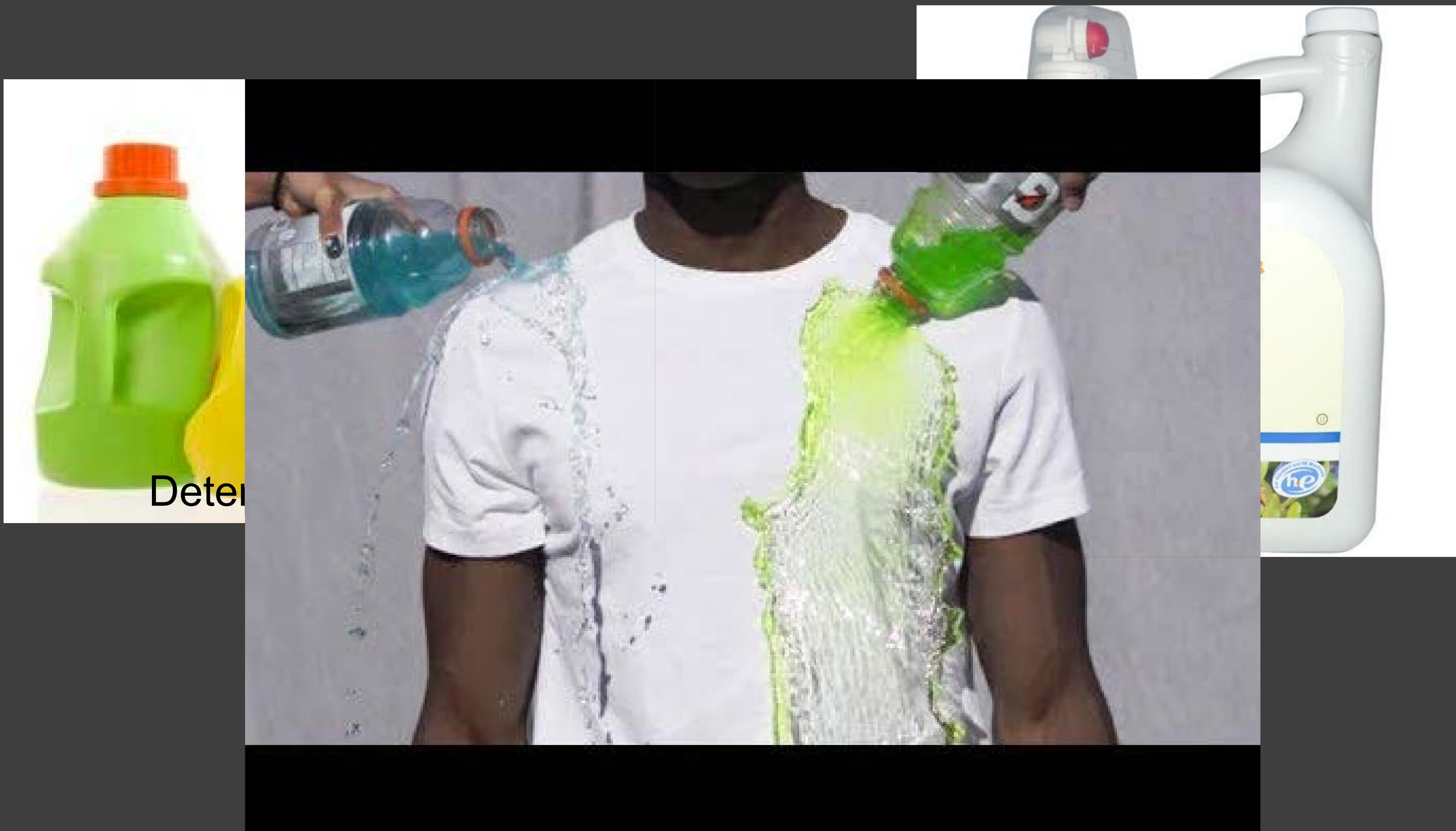
Coffee beans without caffeine



Coffee decaffeination using CO_2 (not a “solvent” by FDA)

Ideality, sustainability, & product design

The task is the cleaning of clothes; current product is detergent.



Ideation and Sustainability

The “ideal” solutions do represent leap-frog innovations

But…..

Corporate structural problems with ideality

- Leap-frog may not fit within portfolio – can a detergent company develop self-cleaning clothes?
- The will may be present, but the expertise may be lacking.

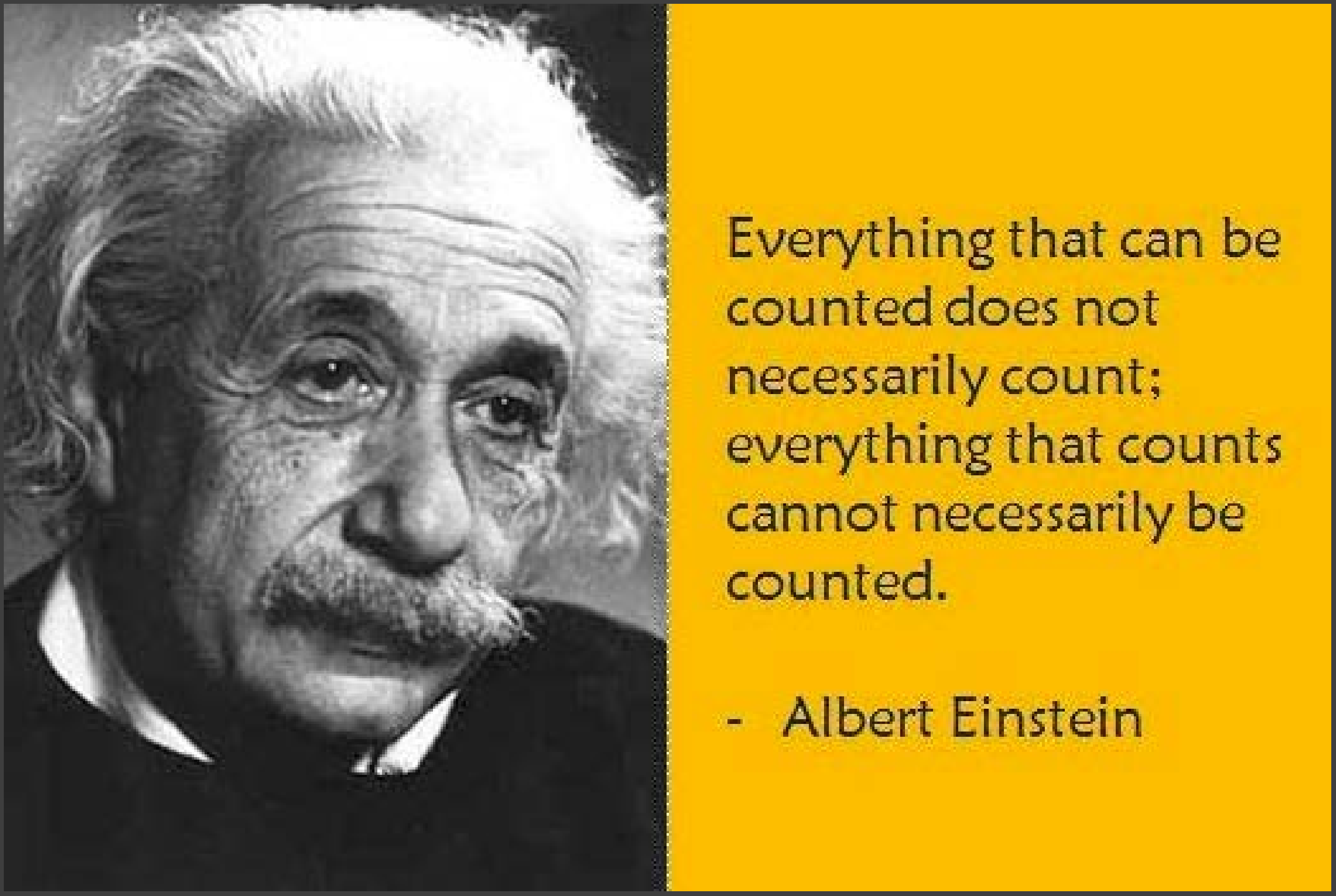
Leap-frog ideas can create structural problems

A necessary caveat: How do we know our frog is jumping in the right direction?

Some frogs are poisonous ..

Sustainability is a process of continuous improvement, we can’t forget to check to make sure we’re actually improving.

Measurement Innovation



GC3 Webinar on Green Engineering

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July 29, 2014

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Anastas, PT and Zimmerman, JB (2003)
Environ. Sci. Tech., 37(5) 94A-101A.

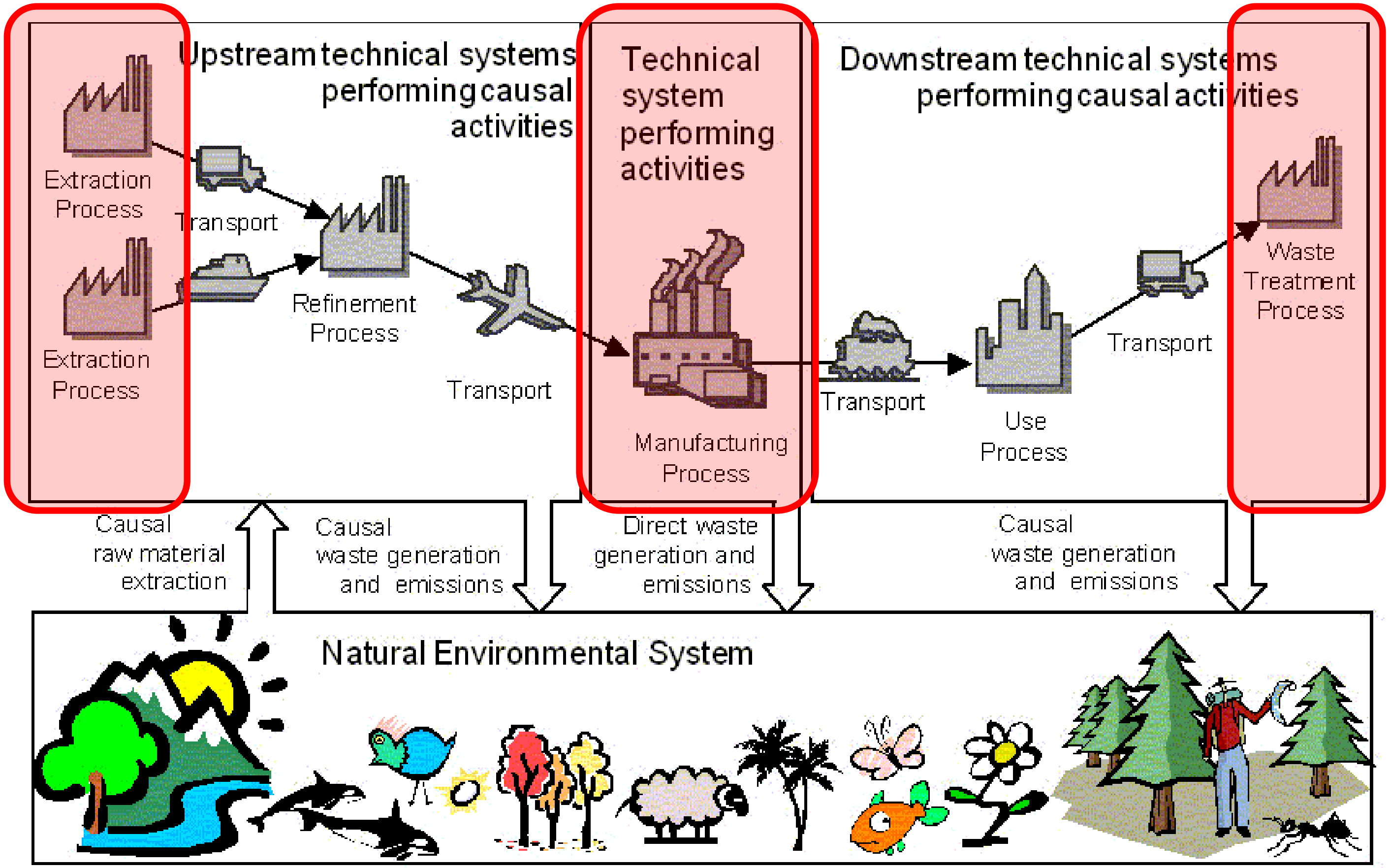
Do Principles get us to the Destination?

- ***Design*** principles
- Should produce superior products and projects
- Need to follow up with comprehensive assessment to ensure performance and guard against unintended effects

the road to somewhere, but where?

Life Cycle Assessment (LCA)

Focus Areas of Design Principles

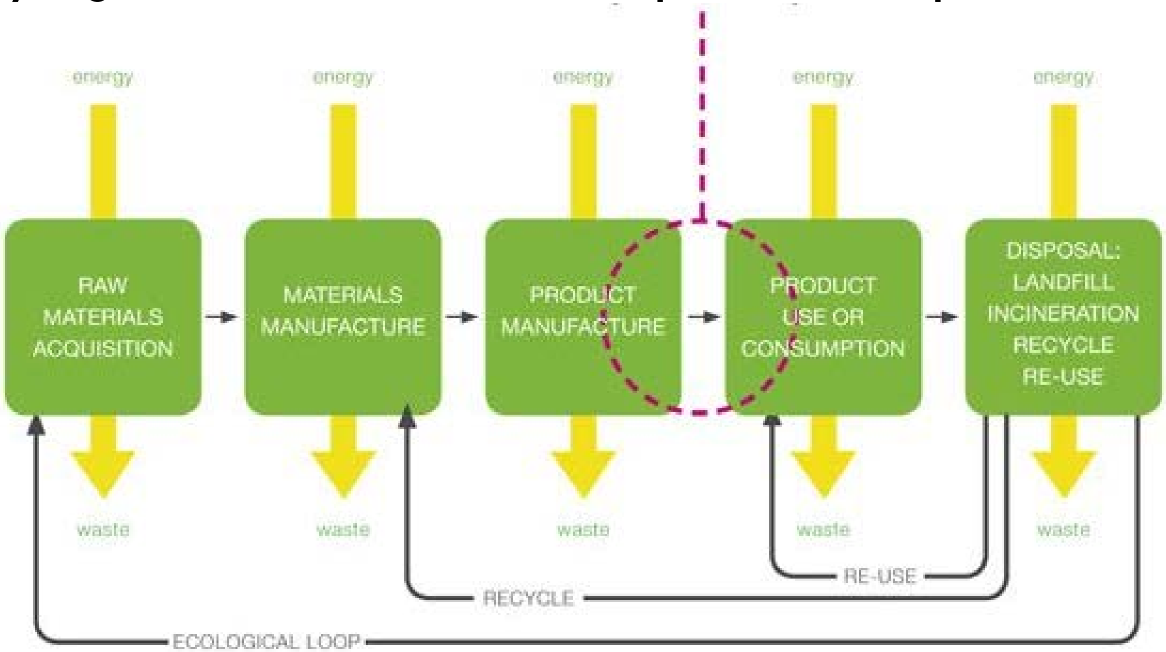


Overview

- Brief Description of LCA Methods
- Case Studies
  - Life cycle mercury emissions from CFLs
  - Use of nanomaterials in electronics
- Efforts to Integrate LCA and Green Chem/Engineering

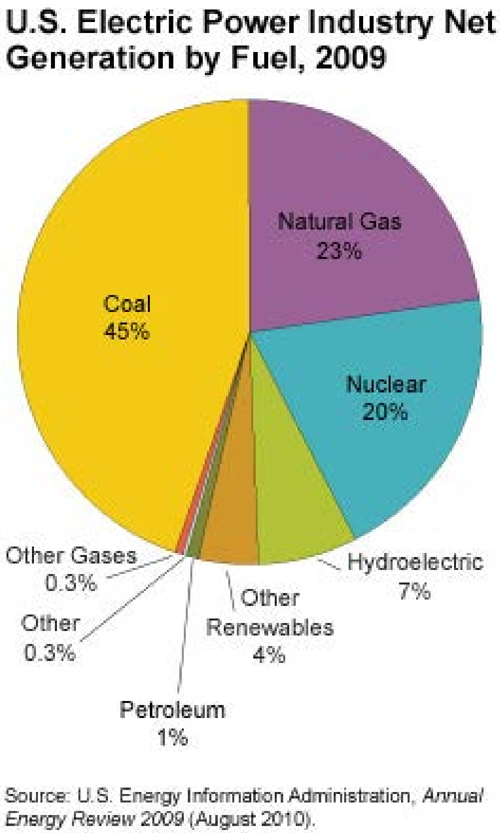
Life Cycle Assessment (LCA) in Brief

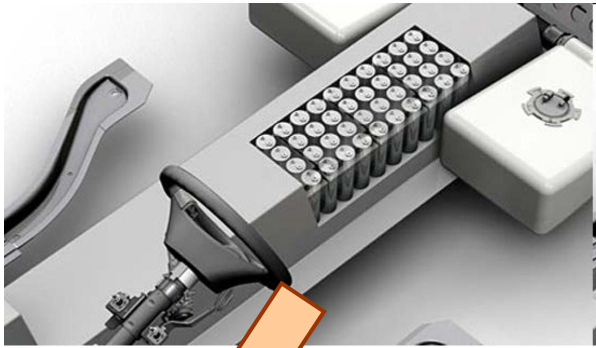
A ***systems modeling tool*** for characterizing, locating and quantifying the environmental impacts of a product or service



- Environmental impacts can occur at each life cycle stage and be non-intuitive
- Need to consider all stages in order to inform design or policy decisions
- Need to consider multiple environmental impacts, to ensure that we are not simply shifting burdens from one impact to another

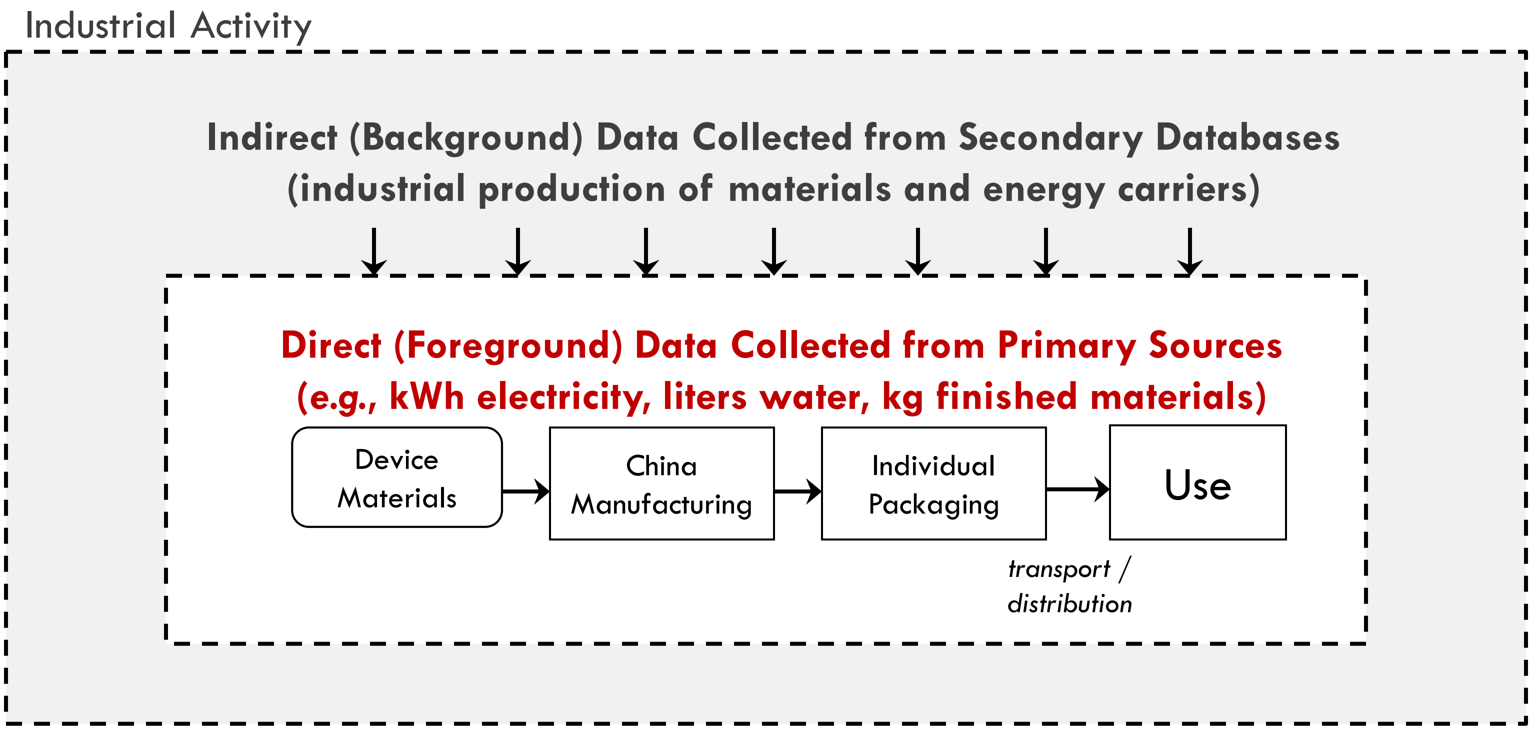
Life Cycle Management: Electric Cars





"Its advanced powertrain will deliver significant energy efficiency advantages and zero CO2 emissions without compromising driving enjoyment."
- Ford, 1/8/11

Life Cycle Assessment Steps



Assemble into a Life Cycle Inventory (LCI)

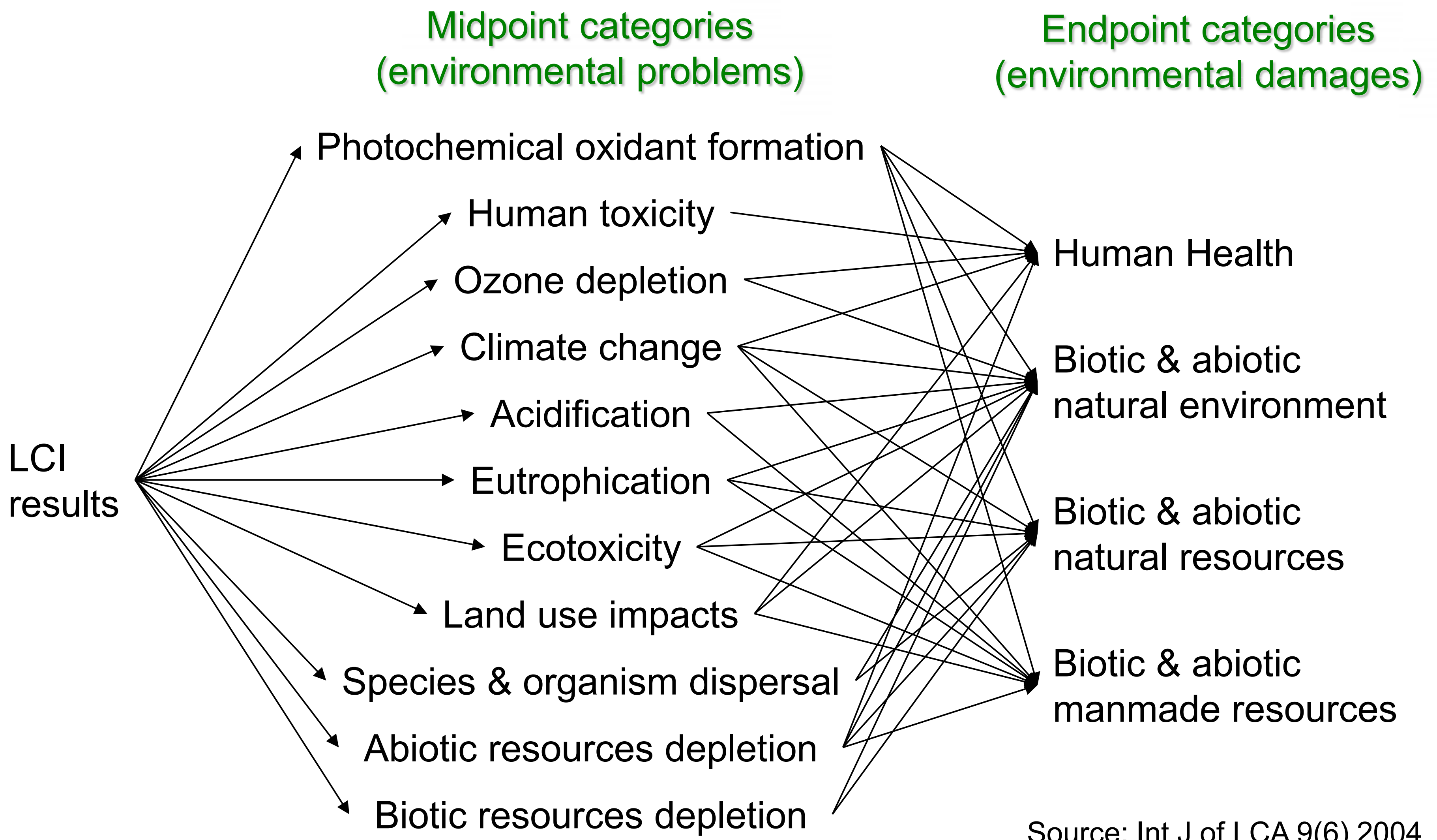
system-wide bill of resource use and **emissions**

↓

Link to Life Cycle Impact Assessment (LCIA)

emission-fate-exposure-effect modeling of impacts

Linking Environmental Impacts to Damages

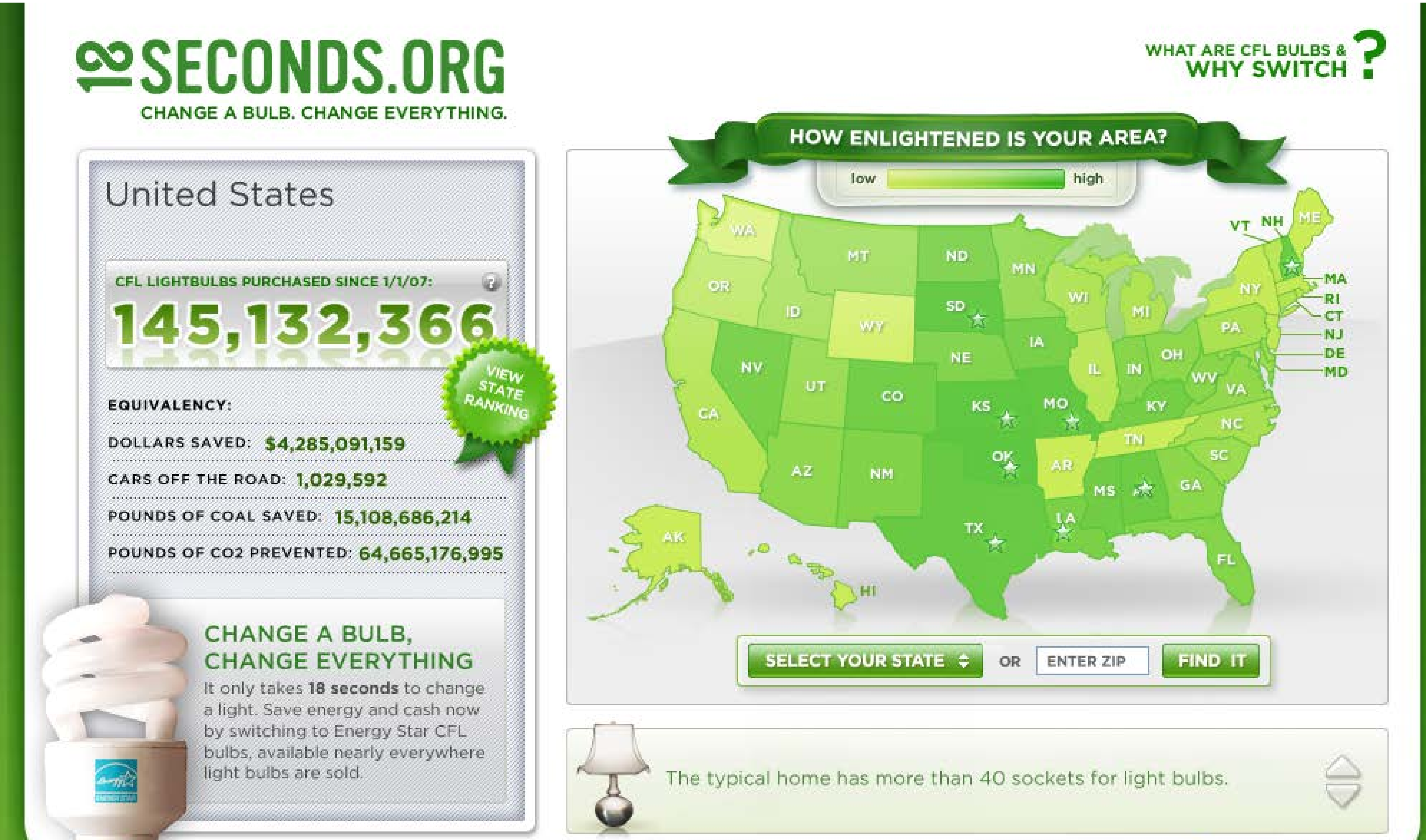


Source: Int J of LCA 9(6) 2004

Ex1 - Mercury Trade-Offs for CFLs

PHILIPS
sense and simplicity

WAL★MART
Save money. Live better.



Mercury Sources in US

The major sources of atmospheric mercury in the United States are:

Utility boilers	32.8%
MSW combustors	18.7%
Commercial/Ind boilers	17.9%
Medical waste incinerators	10.1%
Chlor-alkali	4.5%
…	…
Fluorescent lamps	1.0%

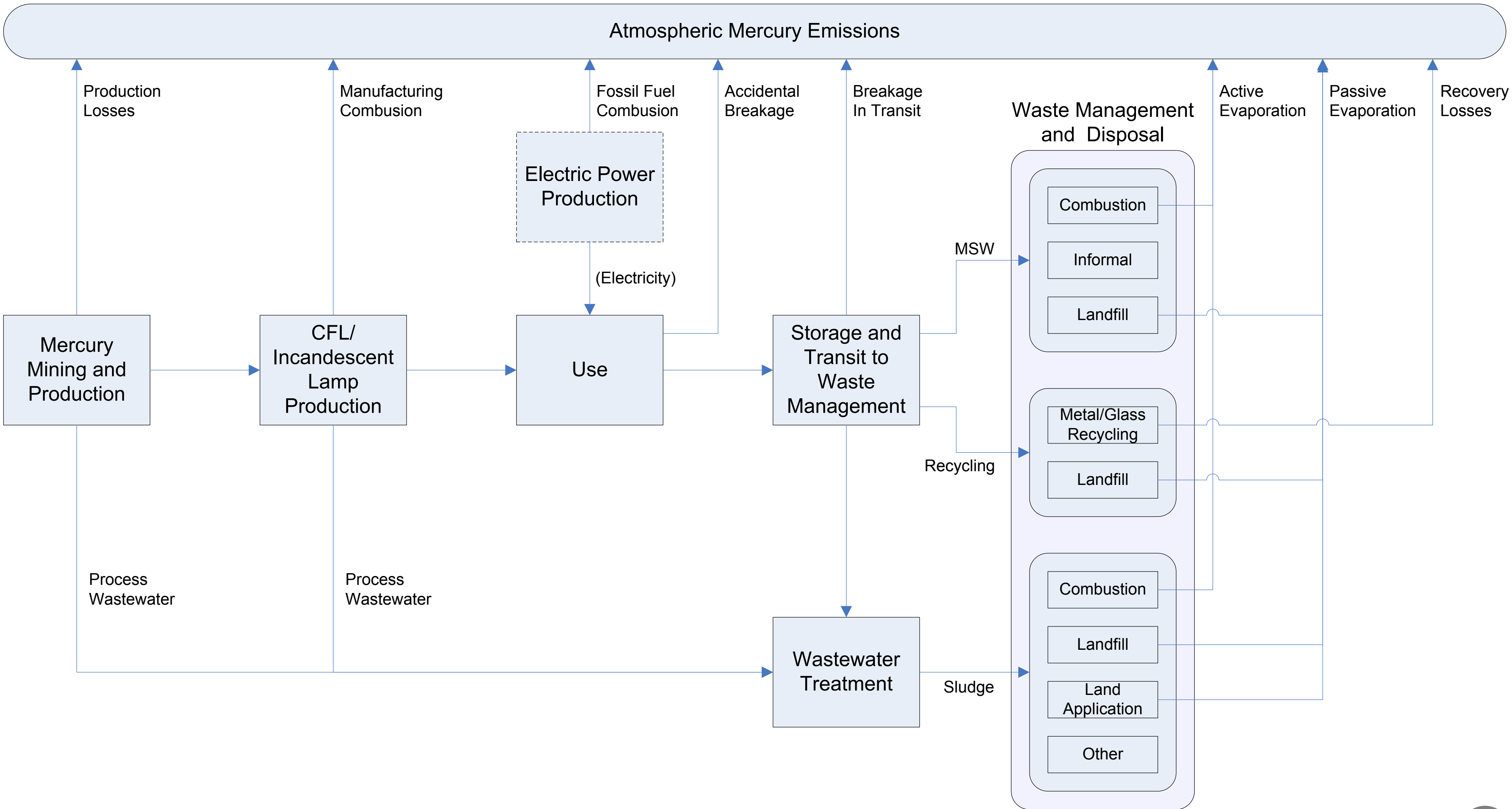
Total Emissions:

144 Mg/yr

Mercury Study Report to Congress

Volume II:
An Inventory of Anthropogenic Mercury Emissions in the United States

Material Flow of Mercury

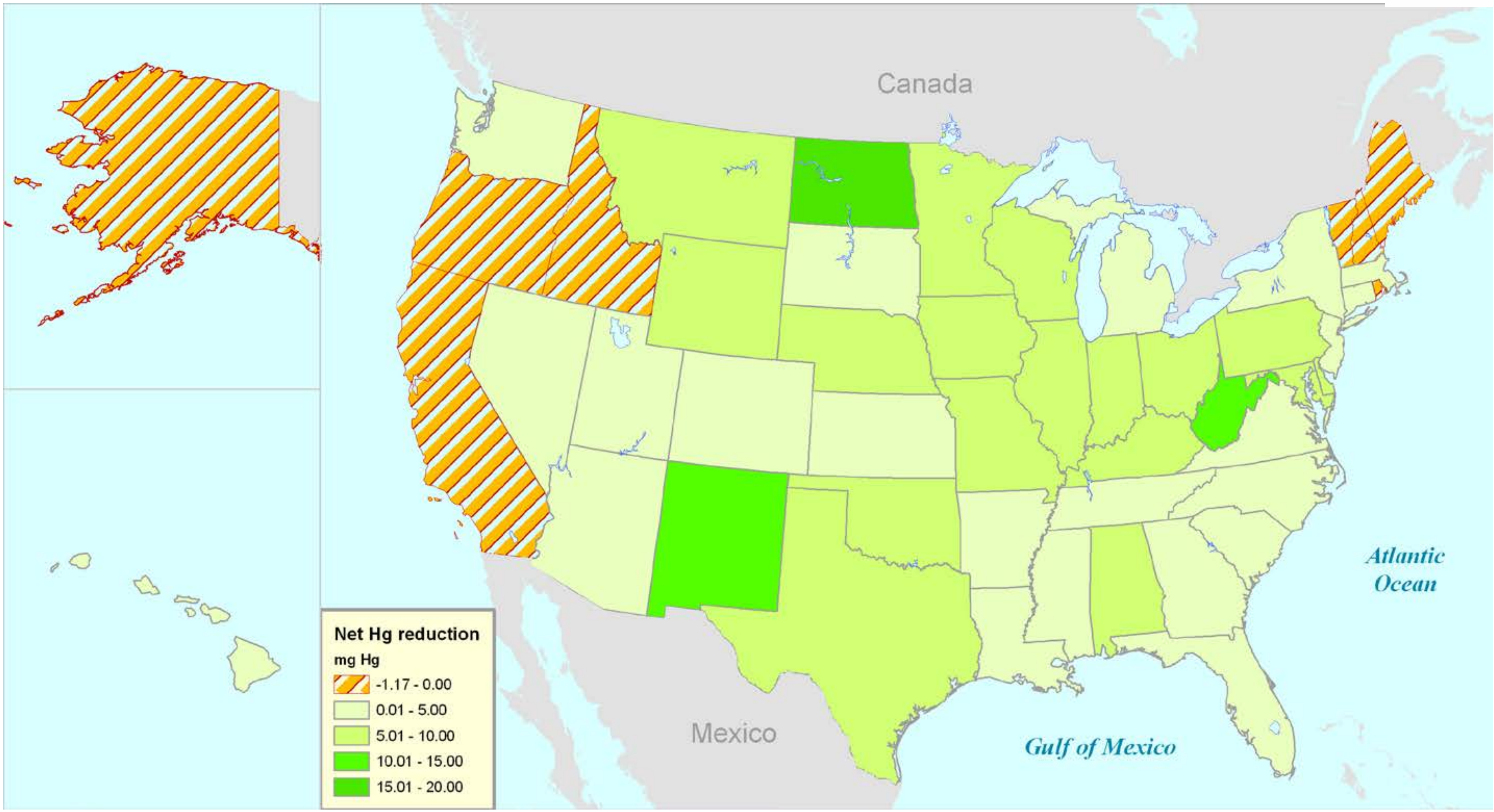


Indirect Mercury Emissions

Coal coming in ← *Electric Power Production* ← *Electricity coming out*

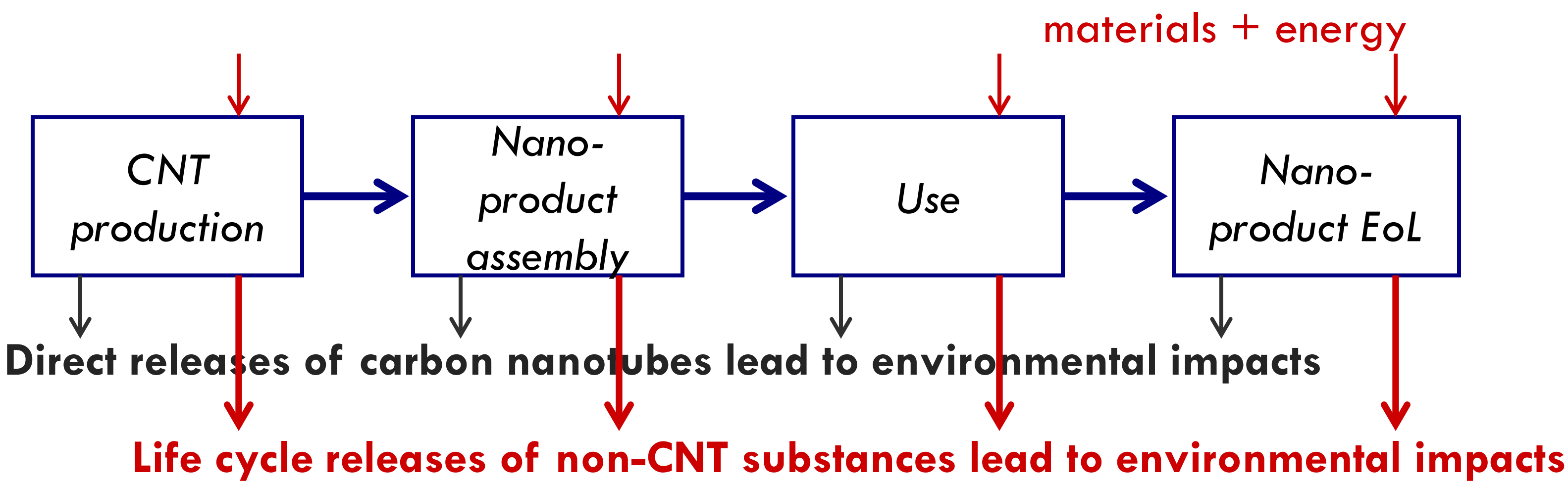
Coal heat content	Conversion efficiency	Electricity mix
Coal washing	Pollution control	Trans & dist losses
Coal Hg content	Volatilization fraction	Grid transfers
		Reduced demand from lighting efficiency

US Results

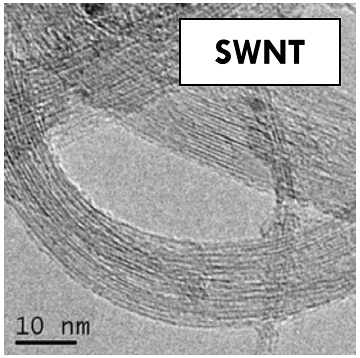


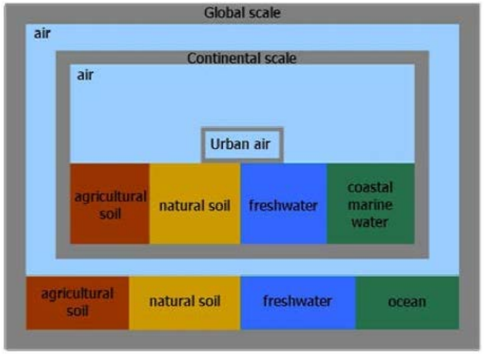
Eckelman, *et al*. (2008). *Environ. Sci. Technol.* 42, 8564-8570

Ex2- Carbon Nanotube Life Cycle



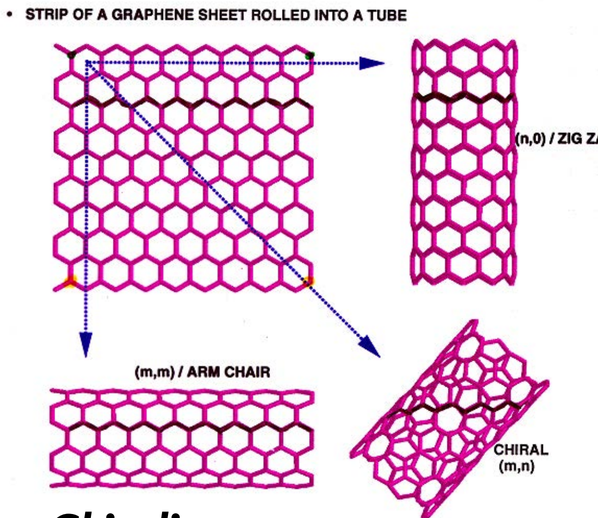
- Adapt consensus USEtox impact assessment model for SWNTs to include colloidal processes
- Only consider freshwater ecotoxicity



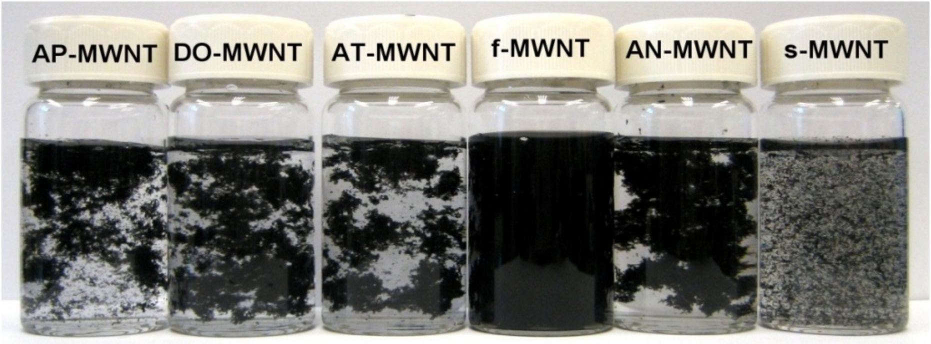


Differential CNT Toxicity

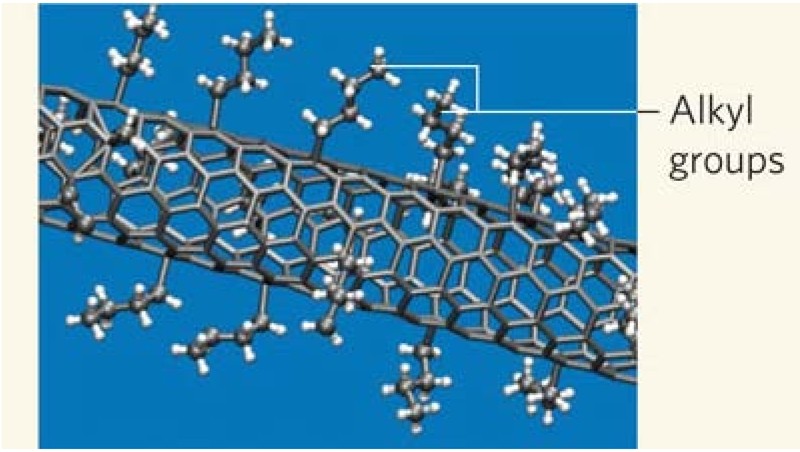
- Metallic or semiconducting depending on chirality and number – this also helps determine toxicity
- Large variation among CNT types in parameters that affect fate, transport, and toxicity



Chirality

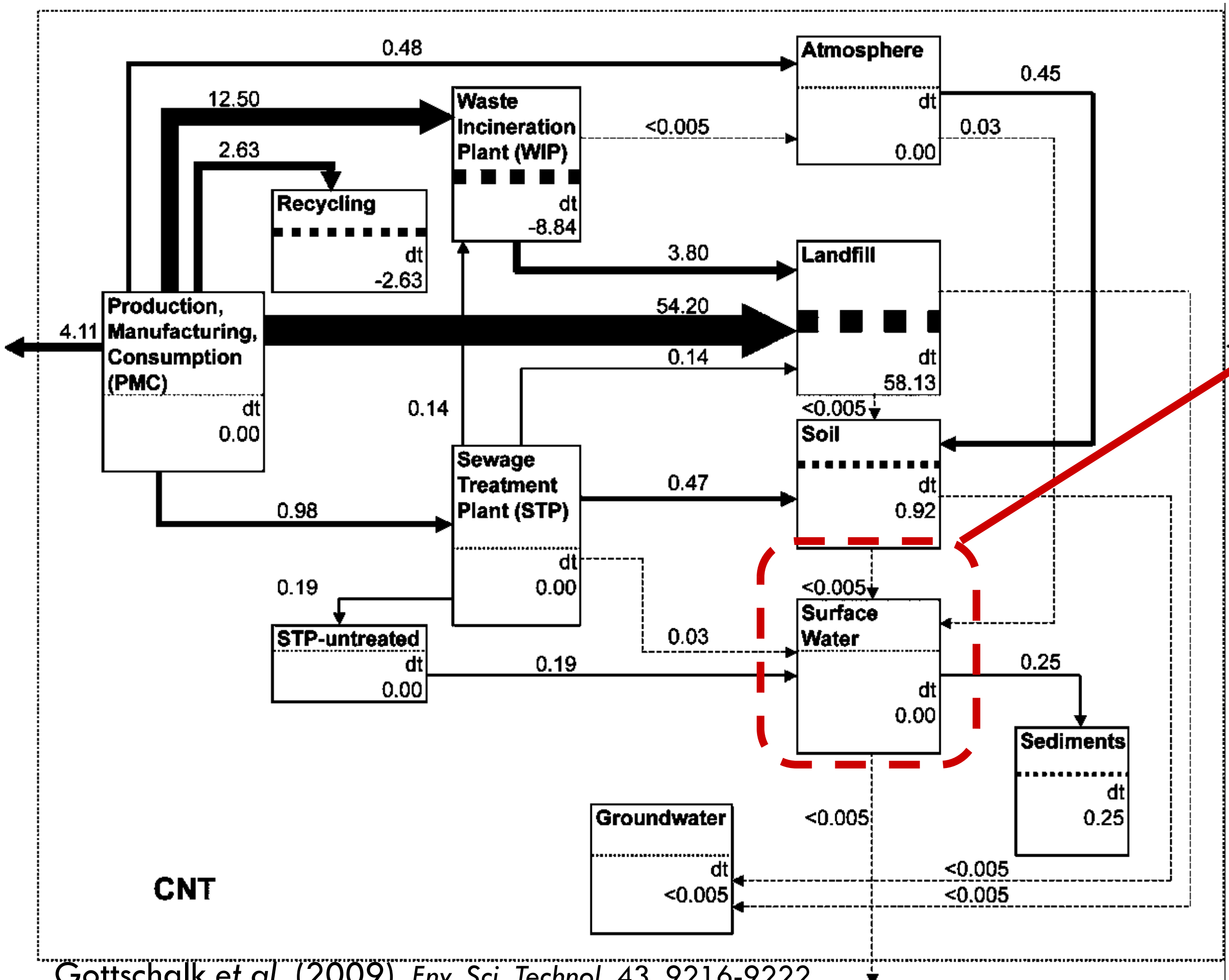


Purification and treatment
Aspect ratio
Residual metal content



Functionalization

CNT Releases

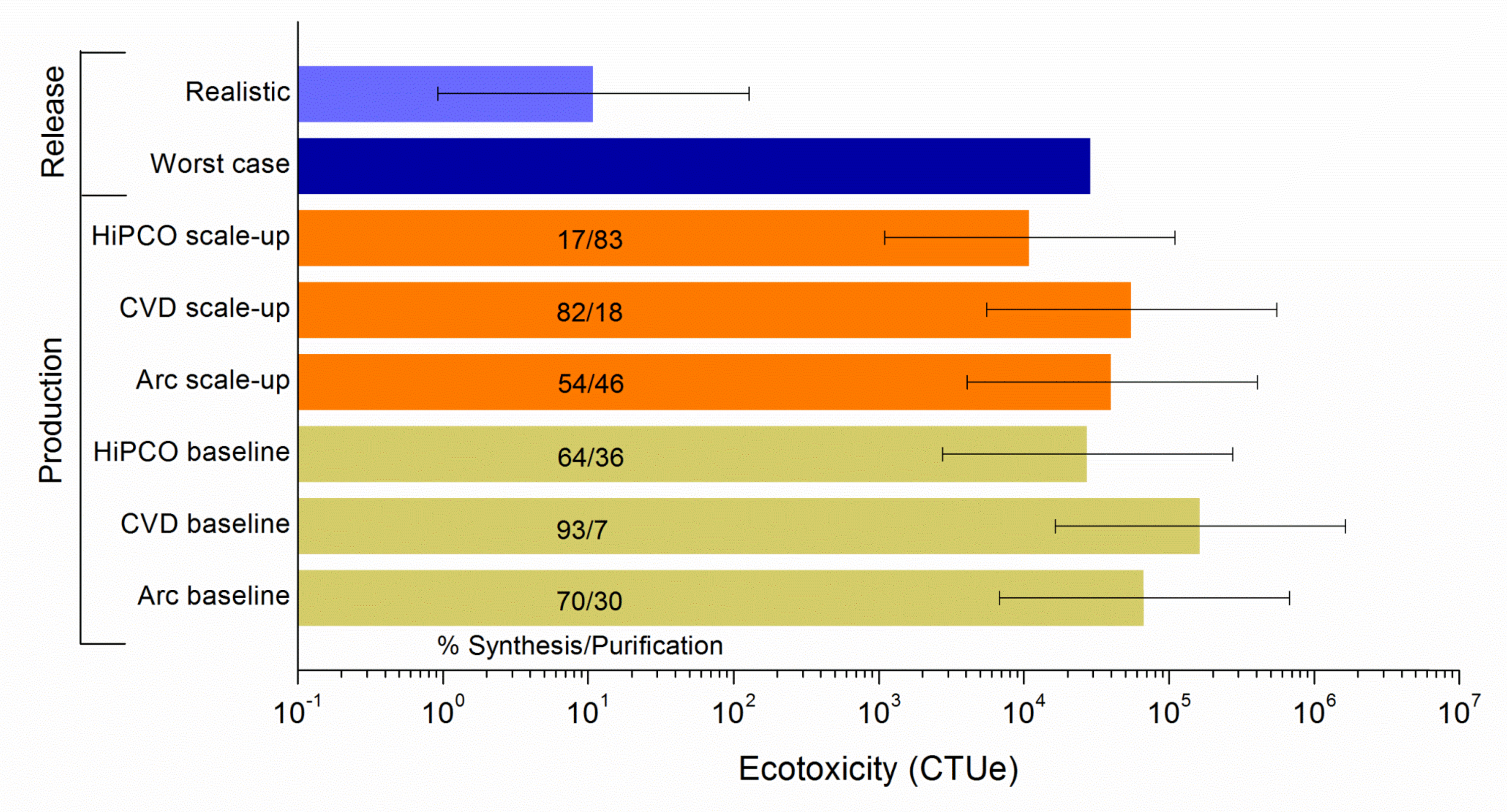


Gottschalk *et al.* (2009). *Env. Sci. Technol.* 43, 9216-9222

Worst Case Scenario
100% release;
All CNTs stable in water column

Realistic Scenario
Modeled concentrations based on fate and transport parameter estimates

CNT Ecotoxicity Production vs Releases



Eckelman, *et al.* (2012). *Environ. Sci. Technol.* 46, 2902-2910

Bits

OCTOBER 28, 2012, 2:00 PM | 34 Comments

I.B.M. Reports Nanotube Chip Breakthrough

By JOHN MARKOFF

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TWITTER
GOOGLE+
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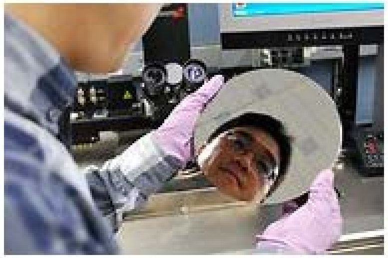
SAN FRANCISCO — I.B.M. scientists are reporting progress in a chip-making technology that is likely to ensure that the basic digital switch at the heart of modern microchips will continue to shrink for more than a decade.



I.B.M. Research

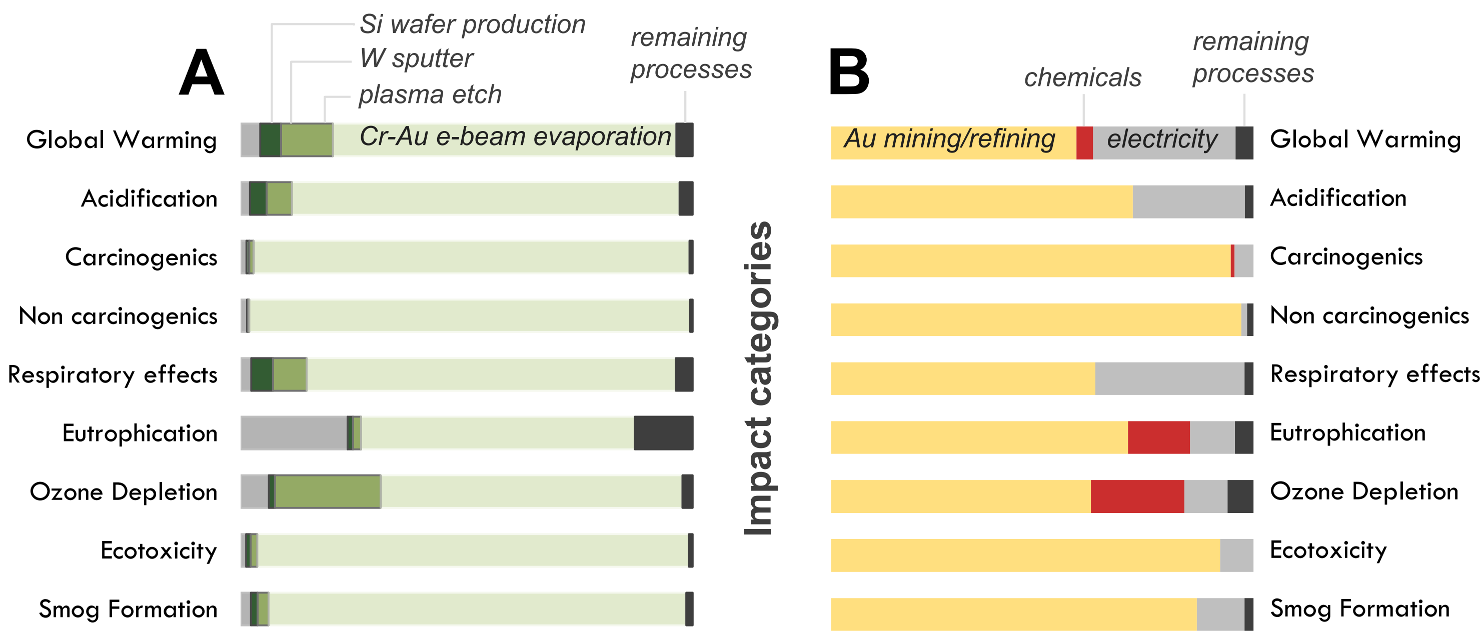
The face of an I.B.M. research scientist, Hongsik Park, is reflected in a wafer used to make microprocessors.

The advance, first described in the journal Nature Nanotechnology on Sunday, is based on carbon nanotubes — exotic molecules that have long held out promise as an alternative to silicon from which to create the tiny logic gates now used by the billions to create microprocessors and memory chips.

The I.B.M. scientists at the T.J. Watson Research Center in Yorktown Heights, N.Y., have been able to pattern an array of carbon nanotubes on the surface of a silicon wafer and use them to build hybrid chips with more than 10,000 working transistors.

Life Cycle of Nano-enabled Products

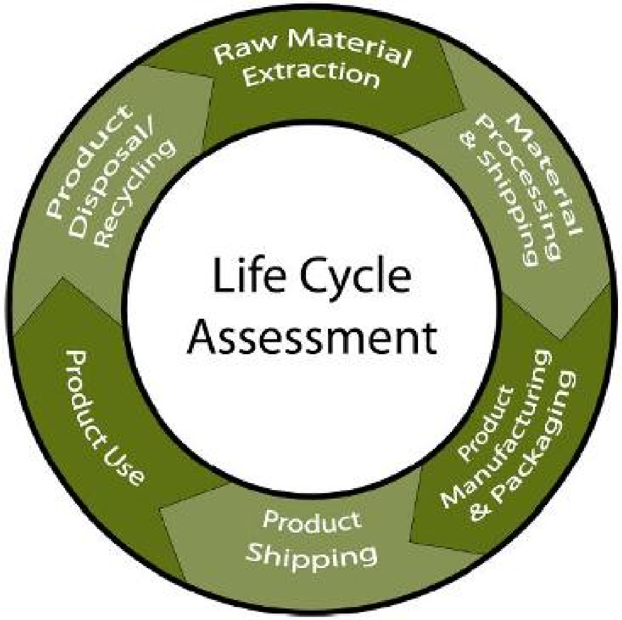
Should a new GE principle be no nano?



CNT synthesis is insignificant: <0.000000000001% of impacts

Dahlben, Eckelman, *et al.* (2013). *Environ. Sci. Technol. 47*, 8471-8478

Integration of Green Chem/Eng + LCA



We're getting closer…

Green Chemistry Limitations

- GC Principles guard against use of toxic inputs, but the field does not have a consensus quantitative method for evaluating upstream inherent risk

- *iSustain* metrics for green chemistry principles

$$I = \frac{\sum_i (MatImpact_i)(wt\%\ RawMat_i)(100 - Rec\%_i)}{\sum_i (wt\%\ RawMat_i)(100 - Rec\%_i)}$$

scaled 1-100 on safety, health effects, environment, regulatory status

- Only considers 'first tier' inputs, doesn't consider multiple intermediate steps and complexities

Green Chemistry and LCA

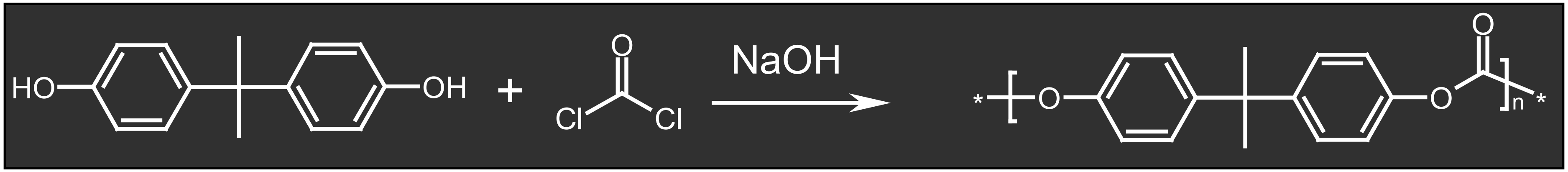
- *Life cycle assessment and green chemistry: the yin and yang of industrial ecology*
  - Anastas and Lankey
- *Life-Cycle Approaches for Assessing Green Chemistry Technologies*
  - Lankey and Anastas
- LCA identifies hotspots and GC used to inform design…

Life Cycle Assessment Limitations

characterization factors have units of
impact/kg emitted…

zero emissions means zero impacts

Ex: Polycarbonate via Phosgene Process



- Polycarbonate is contaminated with Cl
- Requires stoichiometric quantities of phosgene
- Phosgene is highly toxic and corrosive

Alter Computational Structure of LCA

To calculate the LCI of a product system generating a given reference flow, we first calculate the **activity vector**, which represents all outputs of the product system, including all **intermediate flows**

$$\vec{q} = \mathbf{A} \times \vec{\gamma} \Rightarrow \vec{\gamma} = \mathbf{A}^{-1} \times \vec{q}$$

and multiply the vector of activity levels with the matrix of elementary flows

$$\vec{e} = \mathbf{B} \times \vec{\gamma}$$

Impacts are calculated with the inventory vector and characterization factors:

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \end{pmatrix} \begin{pmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{pmatrix} = \begin{pmatrix} i_1 = \sum_{m=1}^{4} c_{1m} \cdot e_m \\ i_2 = \sum_{m=1}^{4} c_{2m} \cdot e_m \\ i_3 = \sum_{m=1}^{4} c_{3m} \cdot e_m \end{pmatrix}$$

New LCA Metrics Using GC Concepts

Now calculate impacts based on *use* of all intermediate flows, rather than emissions

$$i^* = \sum_k c_k \cdot \gamma_k$$

This represents **life cycle inherent hazard** or toxicity
NOT based on projected emissions

Conclusions

- Life cycle modeling is a useful complement to Green Engineering design principles

- Indirect impacts or benefits may outweigh direct effects, so be careful for unintended trade-offs

- New tools and metrics are being introduced regularly to support Green Engineering practices

GC3 Webinar on Green Engineering

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Thanks!

GC3 Webinar on Green Engineering

Julie M. Schoenung, Ph.D.
Professor and Vice Chair
Department of Chemical Engineering & Materials Science
University of California, Davis
July 29, 2014

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Green Engineering Case Studies:

Methods and Applications

- Economic Assessment
  - Materials Recovery Facility for Computer Displays (CRTs)
  - Cell Phone Disassembly
- Toxicity Potential and Chemical Hazard Assessment
  - Utility Meter Products
  - Thin Film Photovoltaics (CIGS)
- Hazardous Waste, Resource Depletion and Toxicity Potentials
  - Light Emitting Diodes (LEDs)
  - Artificial Lighting (LEDs, CFLs, Incandescent)

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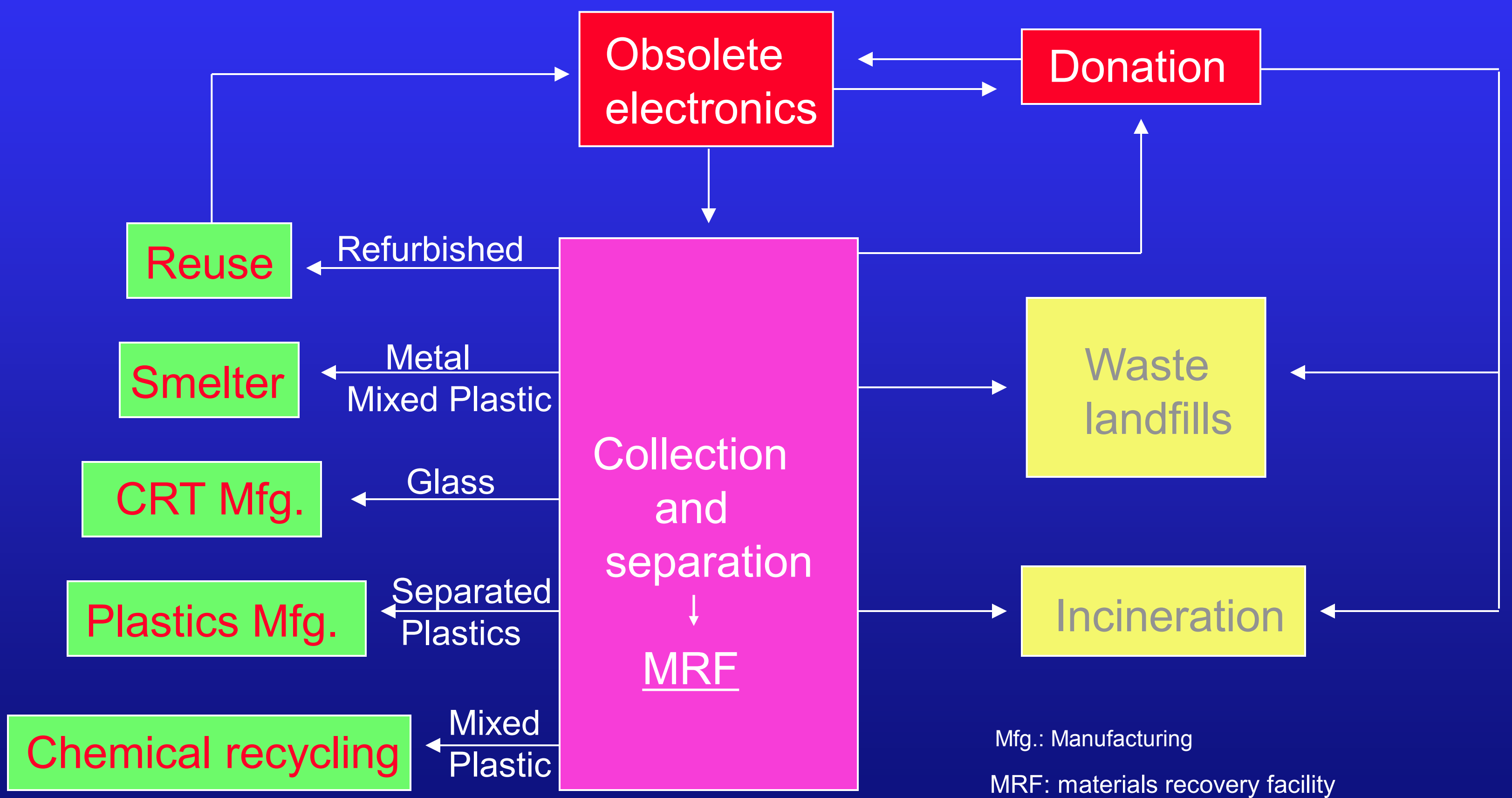
Materials flow for end-of-life electronics



Kang and Schoenung, *Environmental Science & Technology, 2006, 40, 1672-1680*

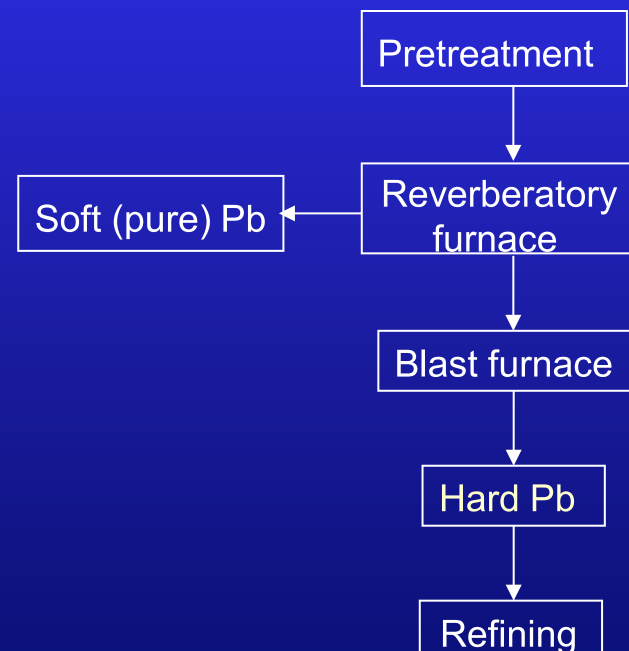
Cathode Ray Tube (CRT) recycling

Glass-to-Glass recycling

- **Closed loop recycling**
- **Conventional process**
  - Separate case and metal part
  - Depressurize the tube, grind to cullet
  - Mixed output
- **Saw cutting process**
  - Cut with saw
  - Intact panel and funnel glass
  - Separate panel and funnel glass

Glass-to-Lead (Pb) recycling

- **Open loop recycling**
- **Pb in the CRTs**
- **Crush and remove foreign materials**
- **Pb smelter**



CRTs after depressurized

Exporting harm, 2002

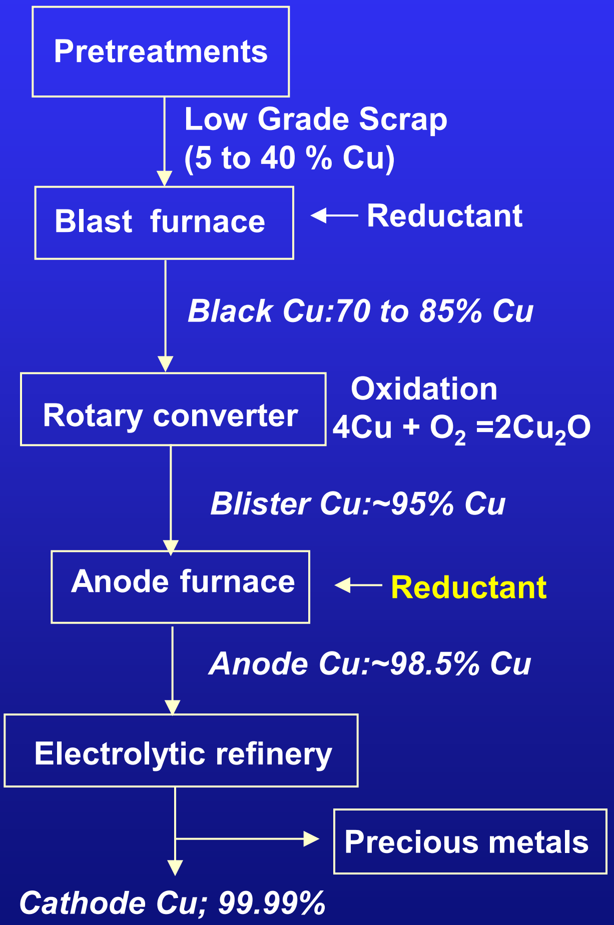
Saw cut CRT : funnel, panel.

Deer2,2003

Kang and Schoenung, *Resources, Conservation & Recycling (2005) Volume 45. Issue 4. pp. 368-400*

Secondary copper (Cu) recycling

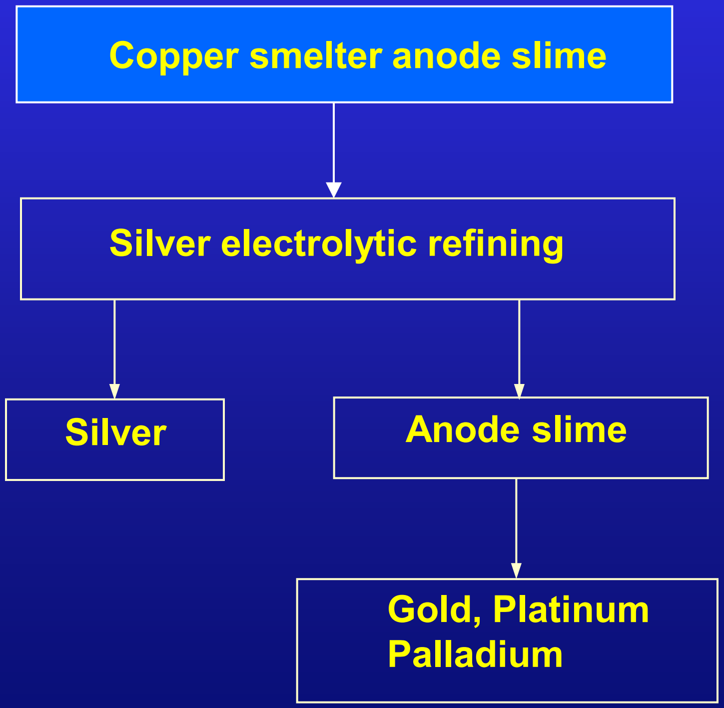
- **Blast Furnace**
  - Electronic scrap: 5 ~ 40 % Cu
  - Reduction; $Fe + Cu_2O \longrightarrow FeO + 2Cu$
  - Black Copper: 70 ~ 85%Cu
- **Converter**
  - Oxidation : $4Cu + O_2 \longrightarrow 2Cu_2O$
  - Blister Copper : ~95% Cu, oxide form.
- **Anode Furnace**
  - Reduce Cu (reductant: plastics, wood)
  - Cu cast into Anode : ~ 98.5% Cu
- **Refining Electrolysis**
  - Dissolved in H_2SO_4 electrolyte
  - Pure Cu deposited on cathode : 99.99%
  - Precious metals recovered as anode slimes



Kang and Schoenung, *Resources, Conservation & Recycling (2005) Volume 45. Issue 4. pp. 368-400*

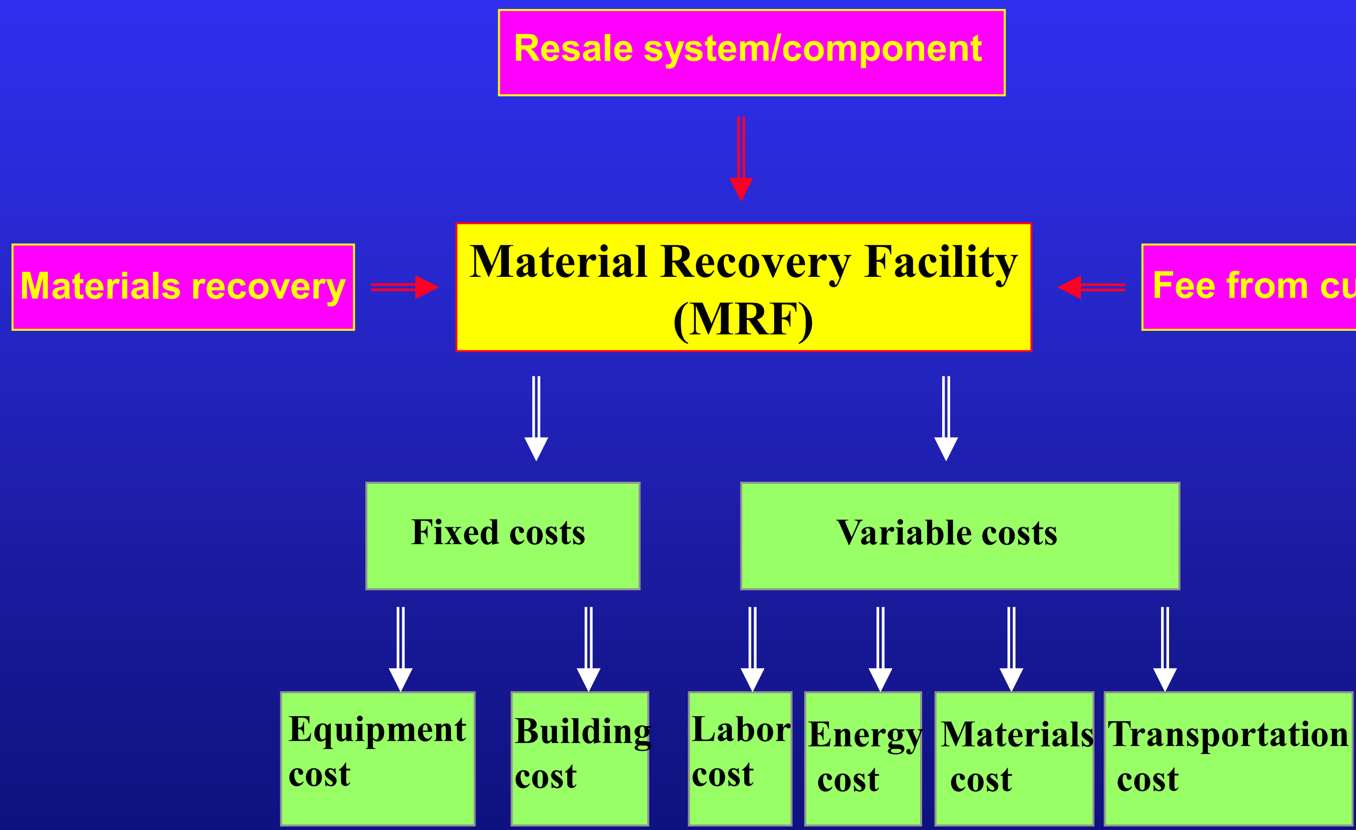
Precious metals recovery

- Silver, gold, platinum, palladium
- By-products of copper smelter
- Anode slime from copper electrolysis process.



Kang and Schoenung, *Resources, Conservation & Recycling (2005) Volume 45. Issue 4. pp. 368-400*

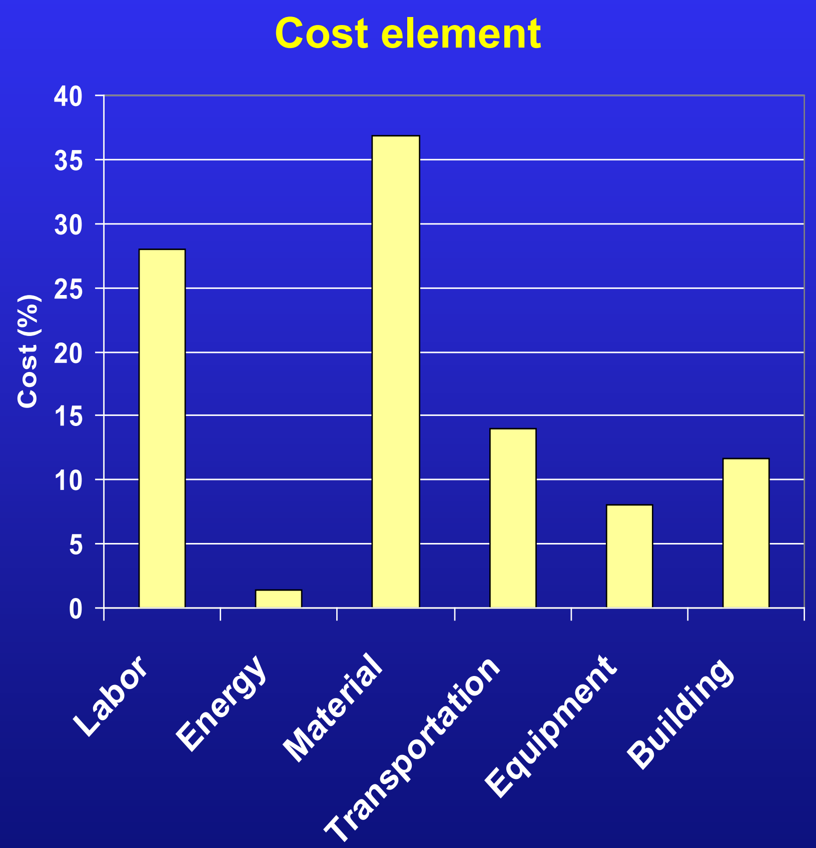
Flow of cost and revenue in a MRF

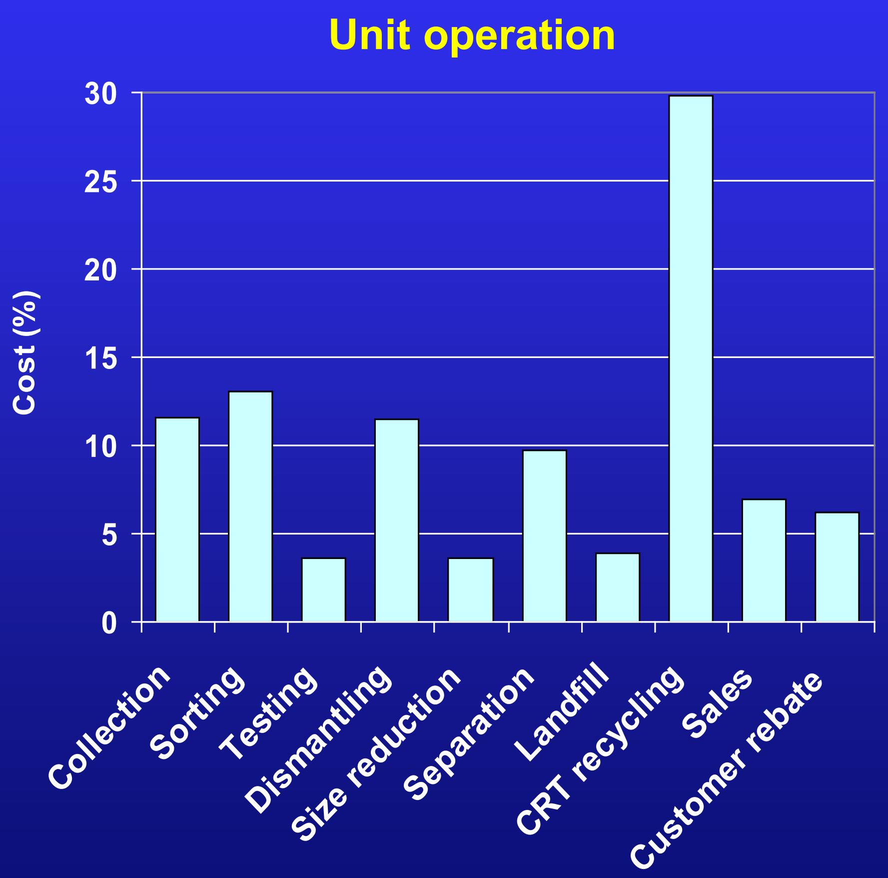


Kang and Schoenung, *Environmental Science & Technology, 2006, 40, 1672-1680*

Cost analysis (1)

Annual operating cost for an e-waste MRF.

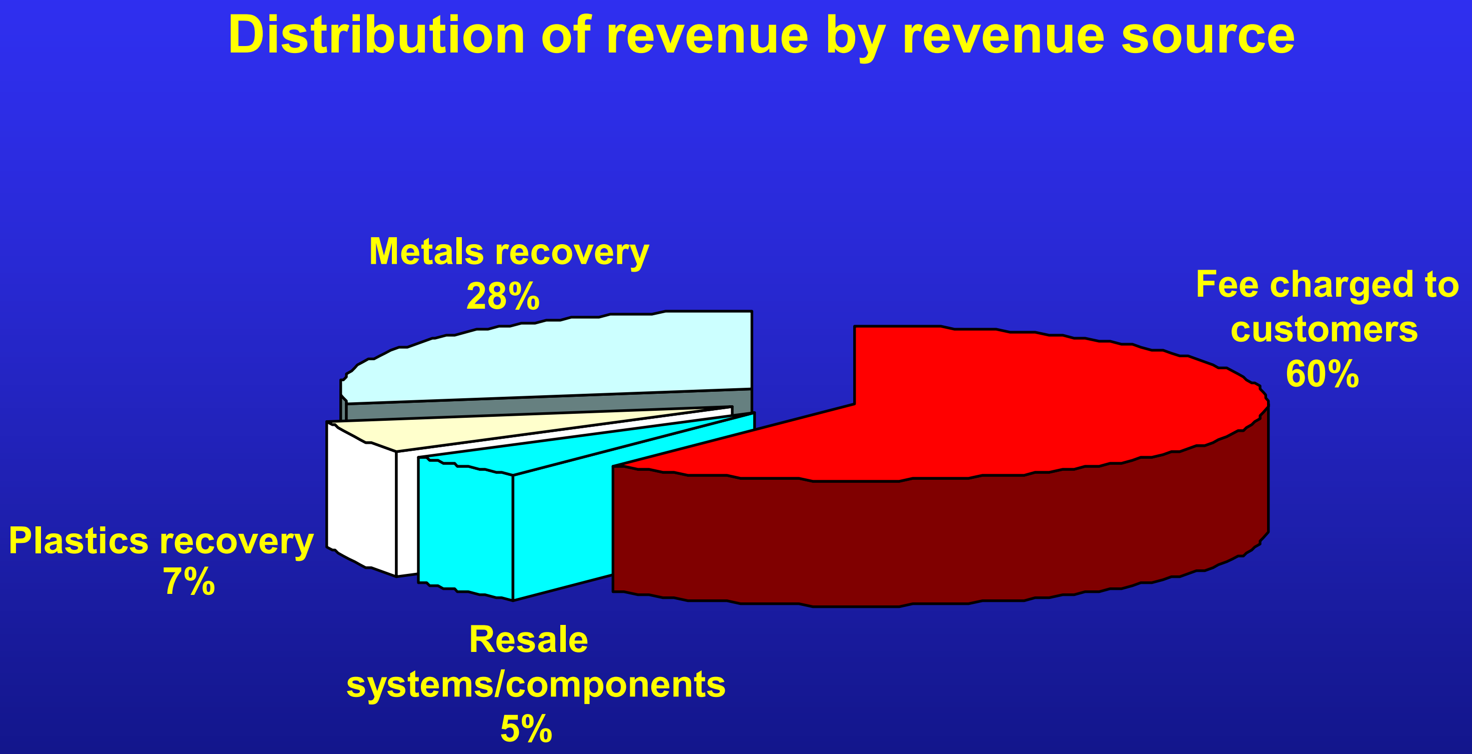




CRT: 75 wt%, CPU: 25 wt%. Treatment amount: 2,500 ton/year.

Kang and Schoenung, *Environmental Science & Technology, 2006, 40, 1672-1680*

Revenue analysis (1)



CRT: 75 wt%, CPU: 25 wt%, Total treatment: 2,500 ton/year.

Kang and Schoenung, *Environmental Science & Technology, 2006, 40, 1672-1680*

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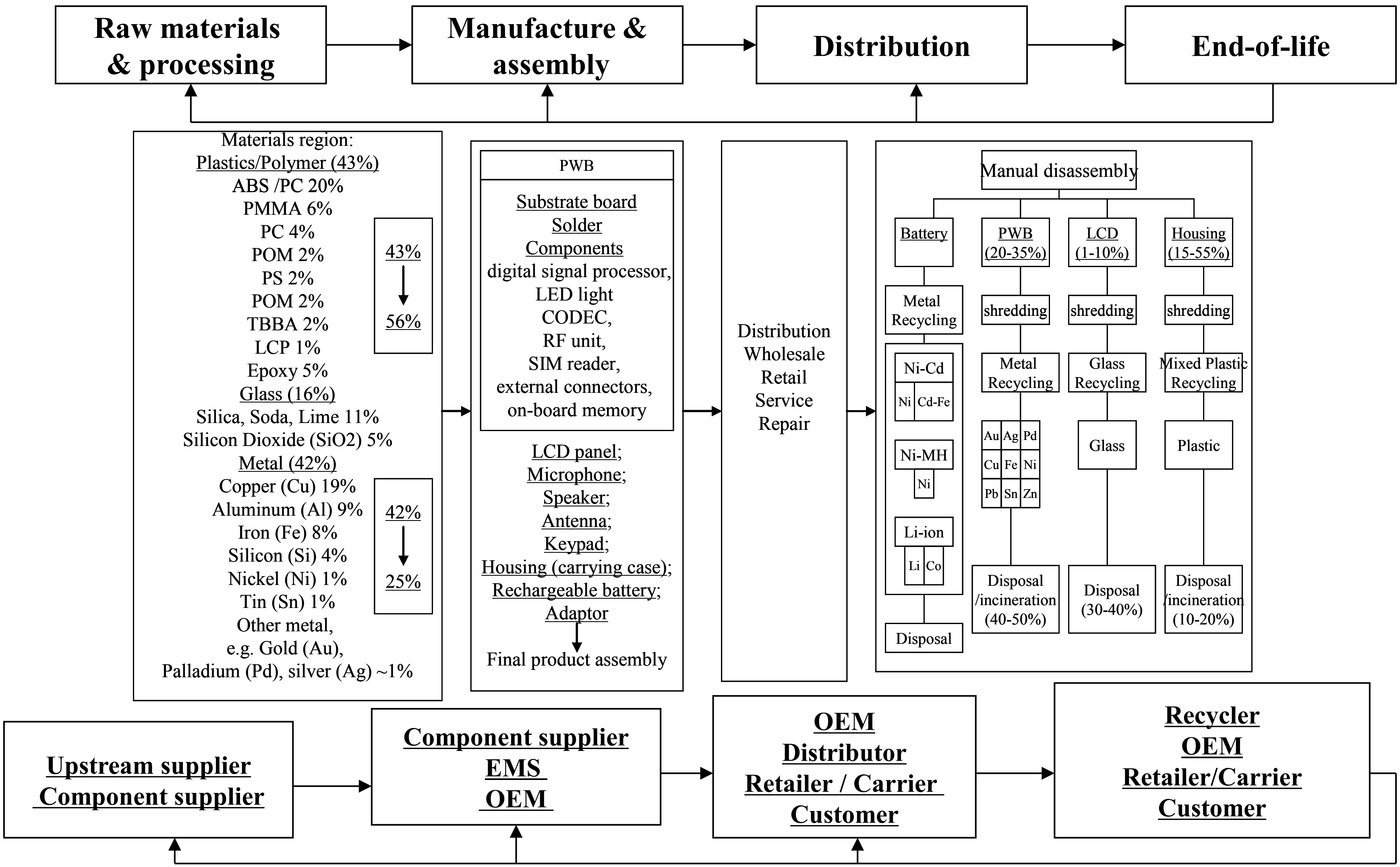
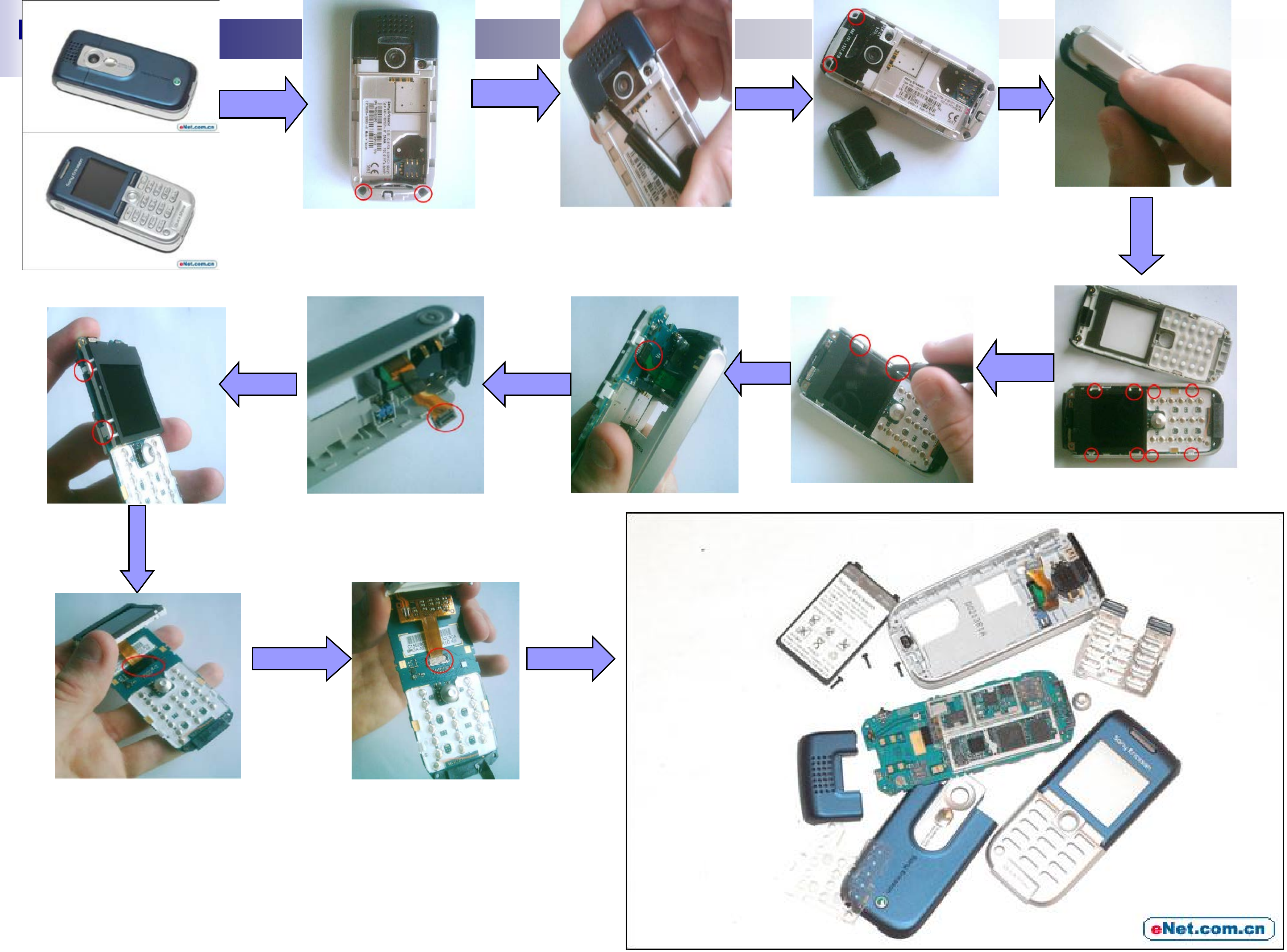
Characteristics of the product system for a cell phone

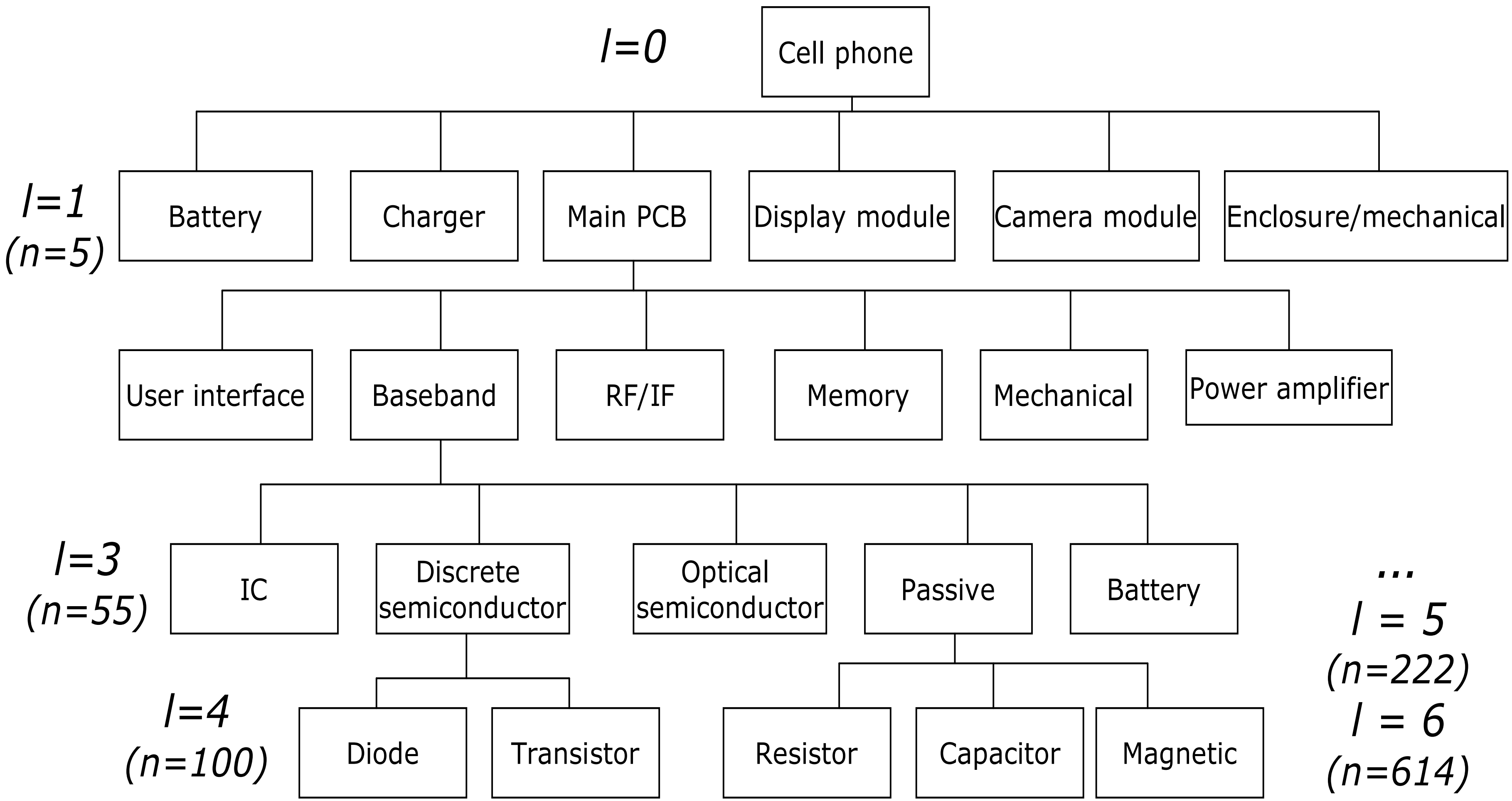


Zhou and Schoenung, *Proc. of the 2006 IEEE Intl. Symp. on Elect. & the Envt., San Francisco, pp. 173-178*



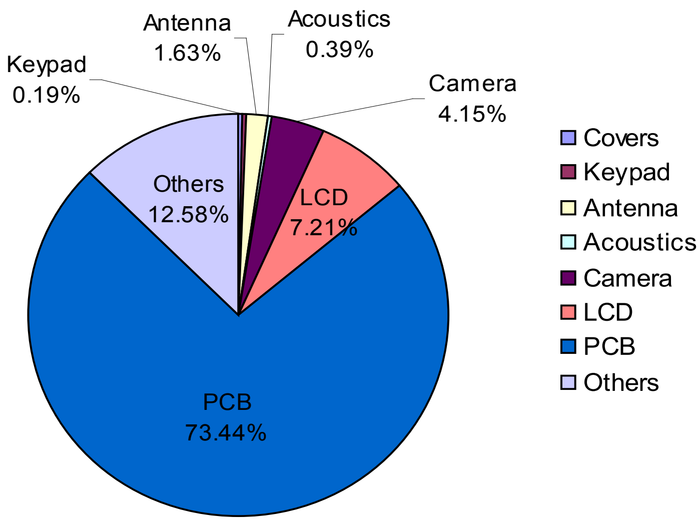
Zhou and Schoenung, *Proc. of the 2006 IEEE Intl. Symp. on Elect. & the Envt., San Francisco, pp. 173-178*

Hierarchical "bill of materials" based structure of a cellular phone

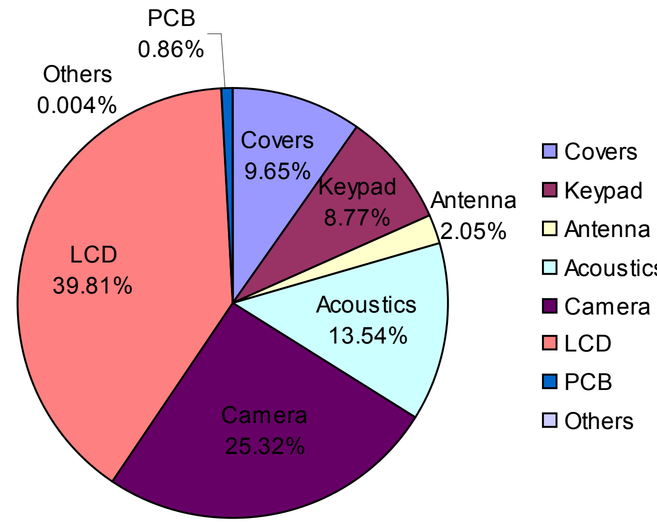


Zhou and Schoenung, *Proc. of the 2006 IEEE Intl. Symp. on Elect. & the Envt., San Francisco, pp. 173-178*

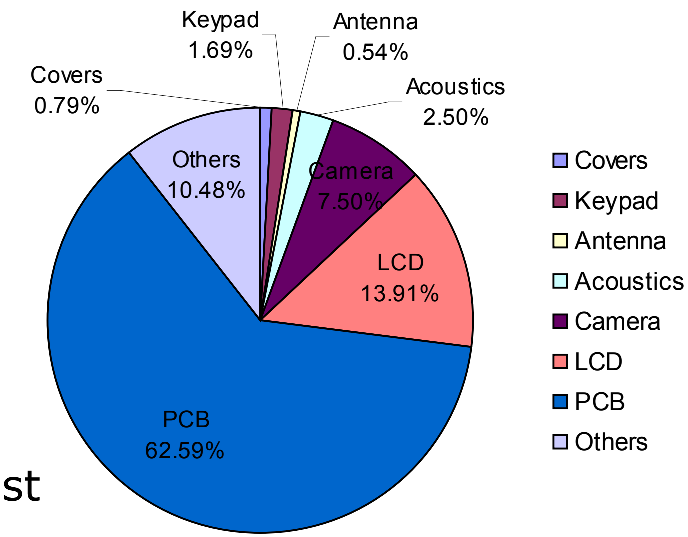
Disassembly revenue



Disassembly revenue
(quality scenario: malfunction)



Disassembly revenue
(quality scenario = good condition)



Direct materials cost

Zhou and Schoenung, *Proc. of the 2006 IEEE Intl. Symp. on Elect. & the Envt., San Francisco, pp. 173-178*

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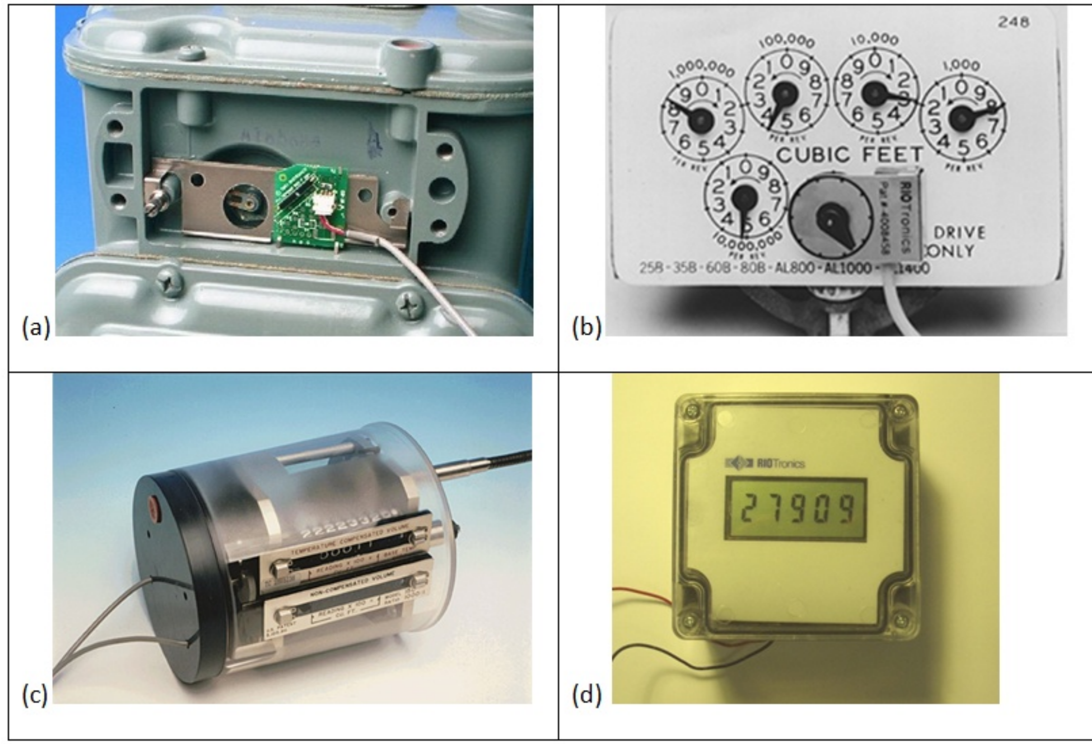
Reducing toxicity potential in RIO Tronics electronic utility meter products

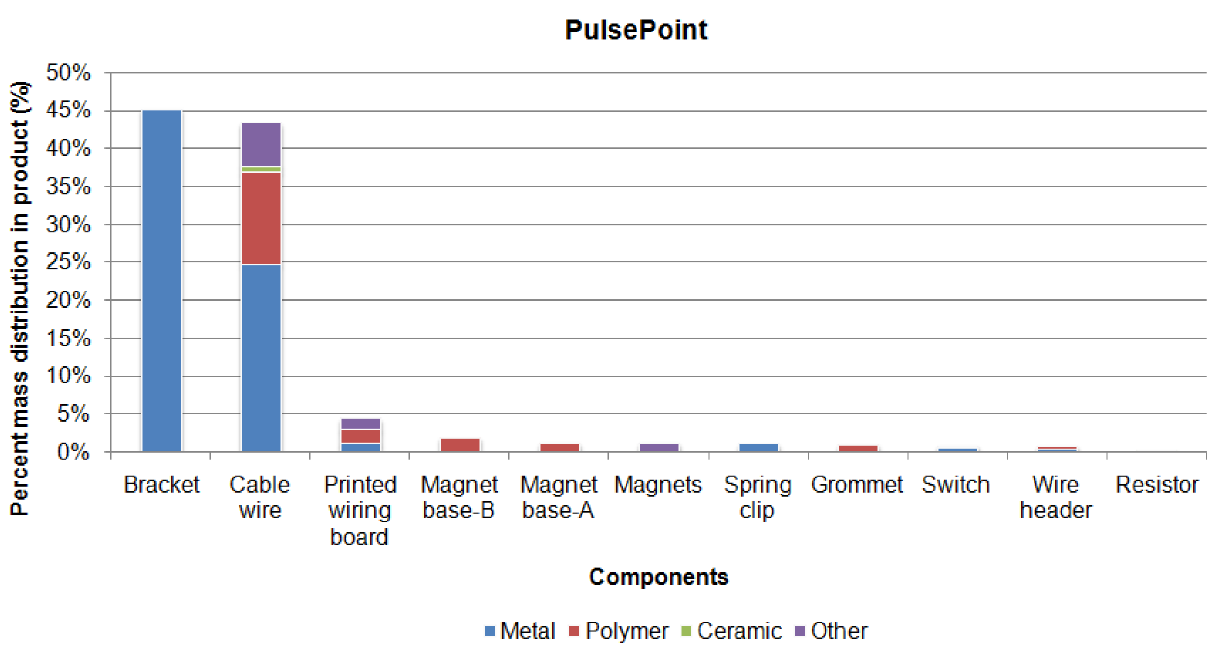
(a) PulsePoint - for domestic gas meters
(b) RegistRead – for dial indexes on both gas and electric meters
(c) RotaRead - for rotary gas meters
(d) Remote Consumption Display (RCD) – display unit connectable to other meter sensors



Lam, Lim, Ogunseitan, Shapiro, Saphores, Brock, Schoenung, *IEAM, Volume 9, Number 2, pp. 319-328*

Product bill-of-materials

- Bill of materials information provided by RIO Tronics
- Component compositions are quantified based on information provided by component manufacturers/suppliers and also estimated through dimensional specifications (e.g., printed wiring board components).
- Composition uncertainty is introduced due to reliability of data



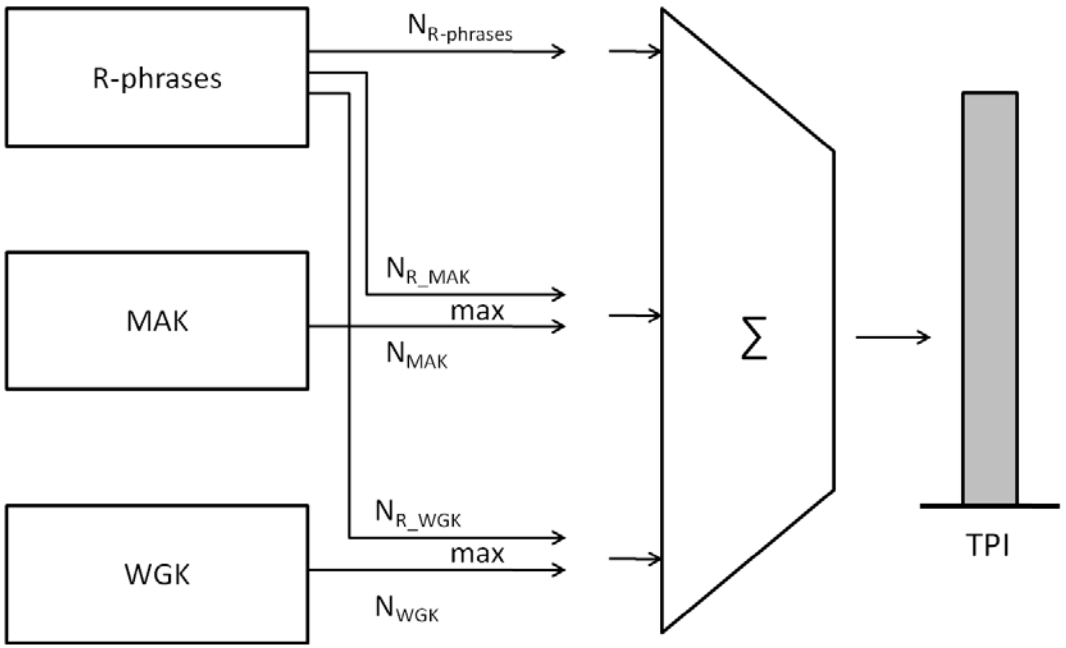
Lam, Lim, Ogunseitan, Shapiro, Saphores, Brock, Schoenung, *IEAM, Volume 9, Number 2, pp. 319-328*

Fraunhofer IZM Toxic Potential Indicator (TPI)

Takes into account three main toxicity inputs based on European Union (EU) regulations:

1) Occupational exposure limits based on maximum workplace concentration (MAK) or EU carcinogenic classification;
2) Water hazard classification (WGK); and
3) Risk phrases (R-phrases)

Outputs a TPI score for materials from zero to 100.



Nissen et al, 2000

Two component TPI scoring methods

1) Sum-weighted Component TPI method – weighs TPI scores by mass of materials in components

$$TPI\_sum_k = \sum mass_{j,k} * TPI_{j,k}$$

2) Max Component TPI method – assigns max TPI score to component based on highest impact material

$$TPI\_max_k = \max(TPI_{all\_materials,k})$$

where j represents material and k represents component.

Lam, Lim, Ogunseitan, Shapiro, Saphores, Brock, Schoenung, *IEAM, Volume 9, Number 2, pp. 319-328*

Summary Results for Both Component TPI Scoring Methods (e.g., PulsePoint)

PulsePoint Component Rank	Sum-weighted method (baseline)	Sum-weighted method (sensitivity analysis)	Max method (baseline)	Max method (sensitivity analysis)
1	Bracket	Bracket	Grommet	Grommet
2	Cable wire	Cable wire	Bracket	Bracket
3	Grommet	Magnets	Spring clip	Spring clip
4	Magnet base-B	Grommet	Printed wiring board	Printed wiring board
5	Spring clip	Magnet base-B	Resistor	Resistor

Lam, Lim, Ogunseitan, Shapiro, Saphores, Brock, Schoenung, *IEAM, Volume 9, Number 2, pp. 319-328*

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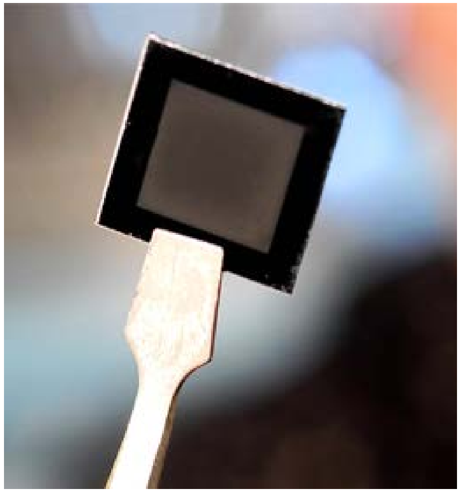
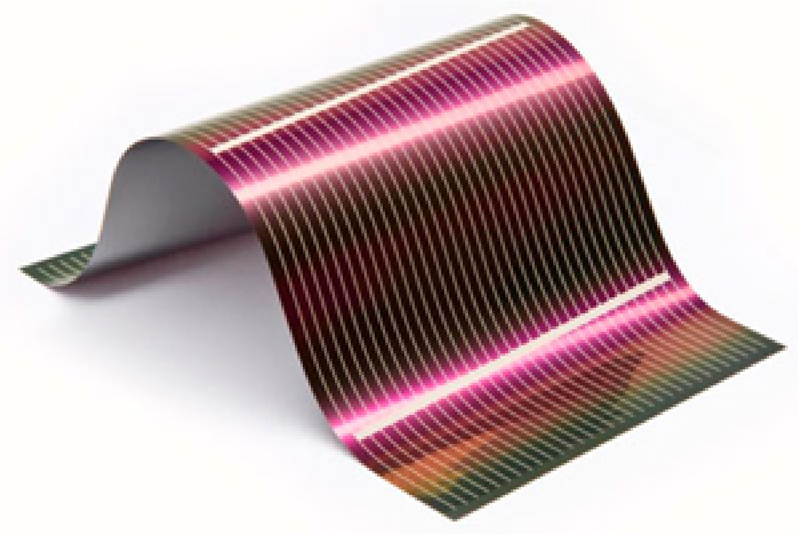
Overview of CIGS Technology

CIGS is one of the most promising thin-film PV technologies
CIGS = CuInGaS/Se

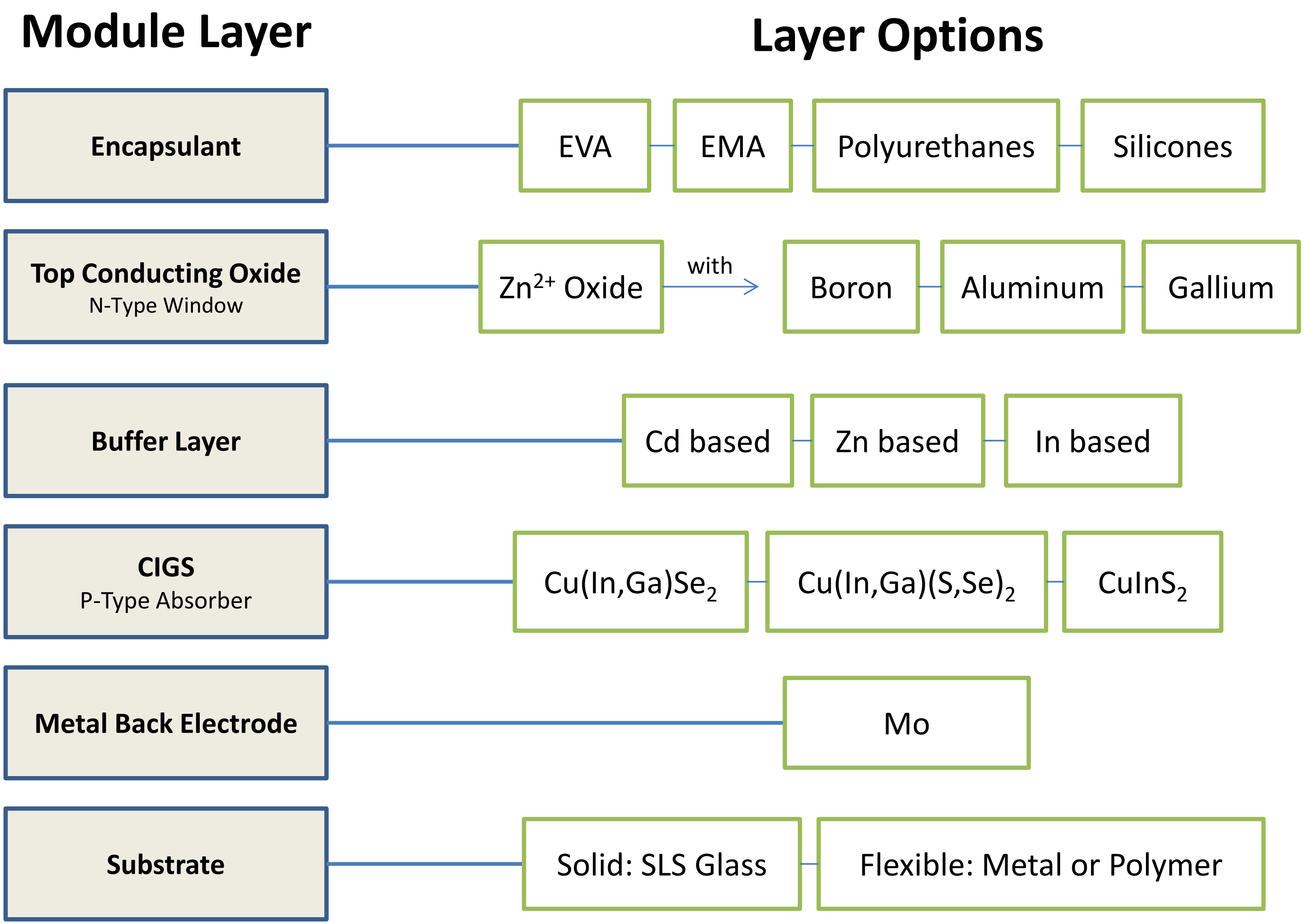


Thin Film



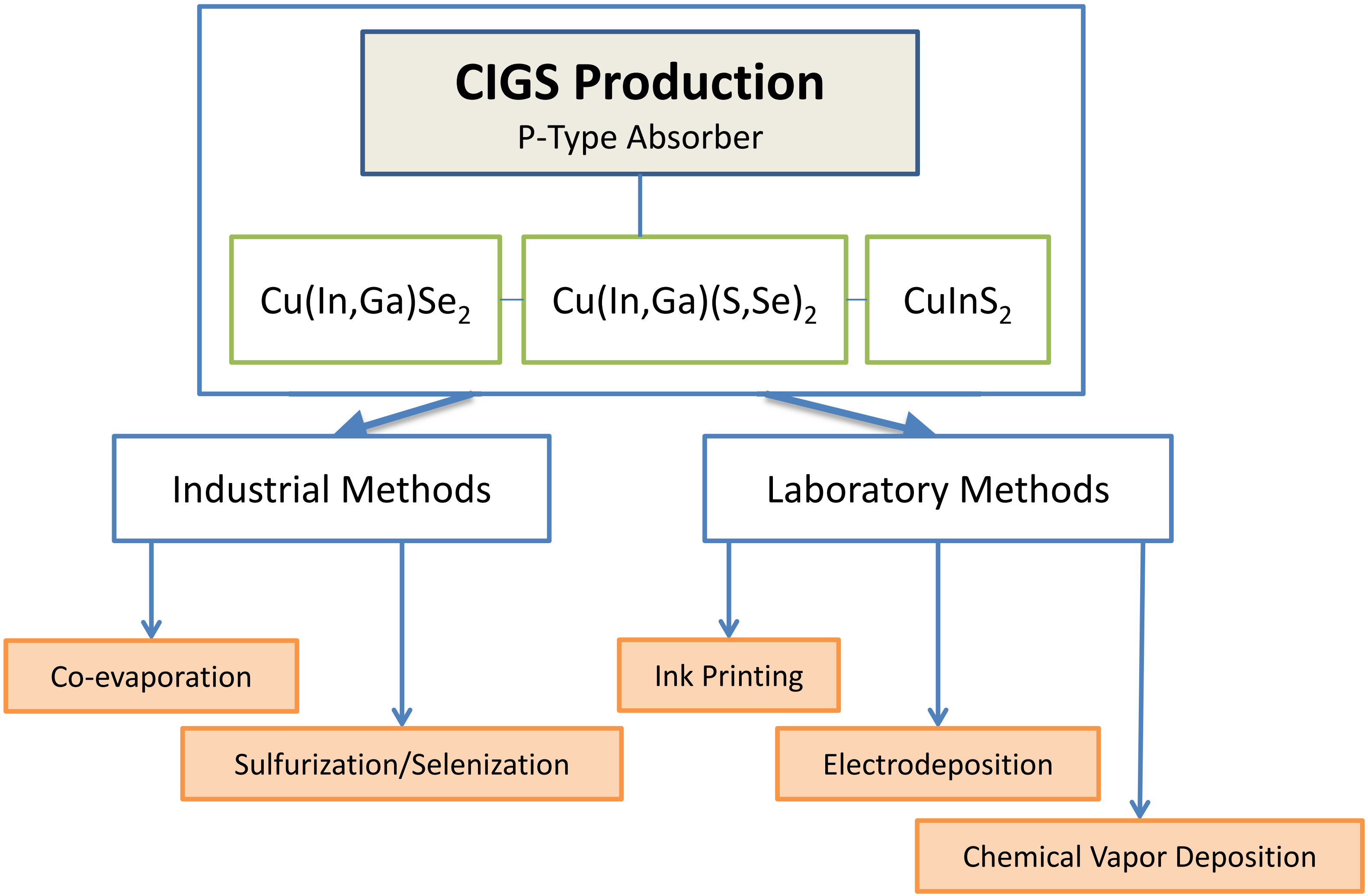
Unique Applications

http://solarcellcentral.com/solar_page.html
http://solar.calfinder.com/blog/solar-research/cigs-solar-record-efficiency/



*EVA: Ethylene Vinyl Acetate, EMA: Ethylene Methacrylic Acid *SLS: Soda Lime Glass

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*



Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

CHA Tools: TPI and Green Screen for Safer Chemicals ®

Priority Human Health Effects (PE)	Human Health Effects (HH)	Ecotoxicity (Eco)	Environmental Fate (EF)	Physical Hazards (Phy)
Carcinogenicity (C)	Acute Toxicity (AT)	Acute Aquatic Toxicity (AA)	Persistence (P)	Explosivity (E)
Mutagenicity (M)	Irritation and Corrosion (IC)	Chronic Aquatic Toxicity (CA)	Bioaccumulation (B)	Flammability (F)
Reproductive (R)	Skin/Eye Sensitization (S)			
Developmental (D)	Immune System effects (IS)			
Endocrine Disruption (ED)	Systemic Organ Toxicity (SOT)			
Neurological (N)				

Utilizes 17 hazard traits from United Nations Globally Harmonized System (GHS)

*CHA: Chemical Hazard Assessment

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

CHA Tools: Green Screen

When all hazard traits are accounted for use iterative scheme to determine final hazard benchmark

Benchmark 4: Safer Chemical

Benchmark 3: Use but Still Opportunity for Improvement

Benchmark 2: Use but Search for Safer Substitutes

Benchmark 1: Chemical of High Concern

Must pass all benchmark criteria before considered for next level

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

Substance Level CHA Example: Green Screen of CdS

	PE						HH					Eco		EF		Phy	
CAS #/Material	C	M	R	D	ED	N	AT	IC	S	IS	SOT	AA	CA	P	B	E	F
1306-23-6/ CdS																	

Use GHS and other national and international standardized hazard classification systems to determine relative hazard of each trait

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

Substance Level CHA Example: Green Screen of CdS

	PE						**HH**					**Eco**		**EF**		**Phy**	
CAS #/Material	C	M	R	D	ED	N	AT	IC	S	IS	SOT	AA	CA	P	B	E	F
1306-23-6/ CdS	**1A**	**3**	**2**	**ND**	**ND**	**1**	**4**	**2**	**2**	**ND**	**1**	**1**	**1**	**--**	**--**	**4**	**4**

Use GHS and other national and international standardized hazard classification systems to determine relative hazard of each trait

*ND: Not Detectable or No Data

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

Substance Level CHA Example: Green Screen of CdS

	PE						HH					Eco		EF		Phy	
CAS #/Material	C	M	R	D	ED	N	AT	IC	S	IS	SOT	AA	CA	P	B	E	F
1306-23-6/ CdS	**1A**	**3**	**2**	**ND**	**ND**	**1**	**4**	**2**	**2**	**ND**	**1**	**1**	**1**	**--**	**--**	**4**	**4**

High Hazard in Priority Health Effects

Medium Hazard in Priority Health Effects and High Hazard in Human Health Effects

Very High Health Toxicity → **CdS = Benchmark 1: Chemical of Concern**

*CHA: Comparative Hazard Assessment

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

Process Level CHA Example: CIGS Deposition

CIGS Deposition Process		GS-Based Benchmark frequency				TPI score frequency			
Type of Processing	Specific Deposition Method	4	3	2	1	low	mid	high	very high
Industrial Process	Coevaporation	0	1	4	0	1	1	2	1
Ink Printing	Spray Pyrolysis of $CuInS_2$	0	0	2	1	0	0	3	0
Electrodeposition	Kapmann Method	1	1	4	2	2	0	5	1
Industrial Process	Sulfurization/ Selenization	1	1	4	1	1	1	3	1
Chemical Vapor Deposition	AP-MOCVD	0	0	6	1	3	0	2	1
Electrodeposition	Kapmann Method with Ammonia	1	1	4	3	2	1	5	1

Hazard Low → High Low → High

Eisenberg, Yu, Lam, Ogunseitan, and Schoenung, *Journal of Hazardous Materials 260 (2013) 534-542*

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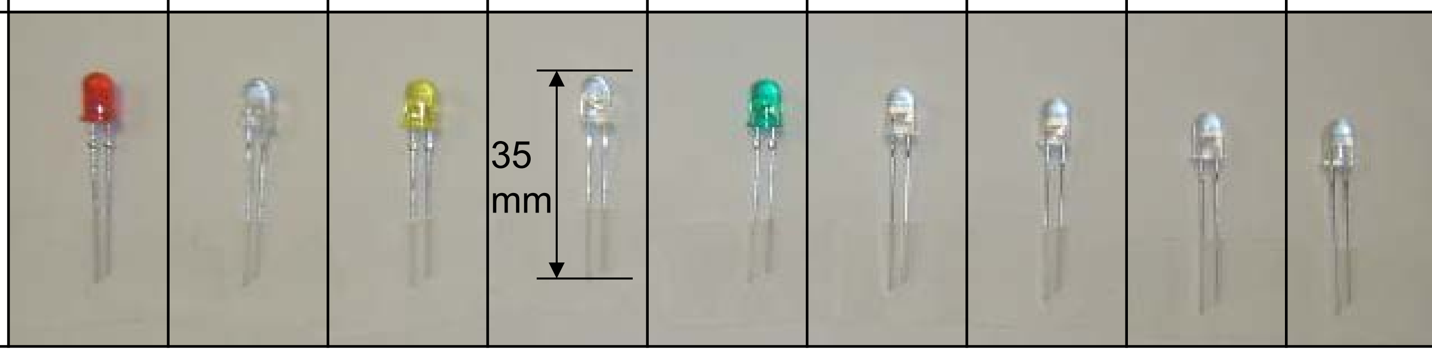
3. Materials and Methods
3.1. Materials

○ Small LEDs

Sample Name (color/intensity)	Red /Low	Red /High	Yellow /Low	Yellow /High	Green /Low	Green /High	Blue /Low	Blue /High	White
LED Color	Red	Red	Yellow	Yellow	Green	Green	Blue	Blue	White
Luminous Intensity (mcd)	150	6000	50	9750	50	5000	400	900	10000
Average Weight (g)	0.3098	0.2792	0.3130	0.2822	0.3114	0.2984	0.2982	0.3001	0.3068
Figure									

Lim, Kang, Ogunseitan and Schoenung, *Environmental Science & Technology, 45: 320-327 (2011)*

3. Materials and Methods
3.1. Materials

○ Bulbs

	Incandescent Bulb	CFL Bulb	LED Bulb
Wattage (W)	60	13	7.3
Luminous Intensity (lumens)	860	800	280
CRI (Color Rendering Index)	100	80	80
Color Temperature	3000*	2700	3000-3500
Lifetime (hours)	**1000**	**10,000**	**50,000**
Working Voltage (V)	120	120	85-265
Weight (g)	**26**	**58**	**172**

Lim, Kang, Ogunseitan and Schoenung, *Environmental Science & Technology 2013, 47, 1040-1047*

4. Results and Discussion

4.1. Leachability Test: Small LEDs

○TCLP results for U.S. EPA hazardous waste regulation

Substance	TCLP Threshold	LED (color/intensity)								
		Red /Low	Red /High	Yellow /Low	Yellow /High	Green /Low	Green /High	Blue /Low	Blue /High	White
Aluminum	N/A	-	-	-	-	-	-	-	-	-
Antimony	N/A	-	-	-	-	-	-	-	-	-
Arsenic	5.0	-	-	-	-	-	-	-	-	-
Barium	100.0	-	-	-	-	-	-	-	-	-
Cerium	N/A	-	-	-	-	-	-	-	-	-
Chromium	5.0	-	-	-	-	-	-	-	-	-
Copper	N/A	-	-	-	-	-	-	-	-	-
Gadolinium	N/A	-	-	-	-	-	-	-	-	-
Gallium	N/A	-	-	-	-	-	-	-	-	-
Gold	N/A	-	-	-	-	-	-	-	-	-
Indium	N/A	-	-	-	-	-	-	-	-	-
Iron	N/A	332.5	178.3	206.0	163.5	211.8	161.8	178.5	130.8	202.3
Lead	5.0	**186**	-	-	-	-	-	-	-	-
Mercury	0.2	-	-	-	-	-	-	-	-	-
Nickel	N/A	-	-	-	-	-	-	-	-	-
Phosphorus	N/A	-	-	-	-	-	-	-	-	-
Silver	5.0	-	-	-	-	-	-	-	-	-
Tungsten	N/A	-	-	-	-	-	-	-	-	-
Yttrium	N/A	-	-	-	-	-	-	-	-	-
Zinc	N/A	-	-	-	-	-	-	-	-	-

-"N/A" : Not Applicable, "-" : Not Detected

4. Results and Discussion

4.1. Leachability Test: Small LEDs

○ TTLC results for State of California hazardous waste regulation

Substance	TTLC Threshold	LED (color/intensity)								
		Red /Low	Red /High	Yellow /Low	Yellow /High	Green /Low	Green /High	Blue /Low	Blue /High	White
Aluminum	N/A	97.0	158.0	104.0	156.0	79.6	156.0	153.0	73.4	84.5
Antimony	500	15.4	2.0	2.8	1.9	3.6	2.5	1.3	1.5	25.9
Arsenic	500	11.8	111.0	8.0	84.6	7.8	15.2	5.7	5.4	-
Barium	10000	-	-	-	-	-	-	-	-	-
Cerium	N/A	-	-	-	-	-	-	-	-	-
Chromium	500(VI);2500(III)	138.0	28.6	32.7	27.9	84.1	49.3	50.9	30.3	65.9
Copper	2500	87.0	**3818.0**	956.0	**2948.0**	1697.0	**3702.0**	**3892.0**	2153.0	31.8
Gadolinium	N/A	-	-	-	-	-	-	-	-	-
Gallium	N/A	135.6	95.0	63.8	79.1	75.6	3.1	2.1	1.5	3.8
Gold	N/A	39.8	45.8	30.5	30.1	40.2	176.3	32.5	118.6	115.9
Indium	N/A	3.4	1.7	-	-	2.5	-	-	-	-
Iron	N/A	285558.2	363890.8	300905.6	398630.4	310720.6	395652.2	339234.5	256499.3	311303.6
Lead	1000	**8103.0**	8.9	7.7	-	5.0	-	-	-	-
Mercury	20	-	-	-	-	-	-	-	-	-
Nickel	2000	**4797.0**	**2054.0**	1541.0	**2192.0**	**2442.0**	**2930.0**	1564.0	1741.0	**4083.0**
Phosphorus	N/A	114.2	-	58.4	-	78.5	91.8	79.1	84.3	110.8
Silver	500	430.0	409.0	248.0	336.0	270.0	306.0	418.0	**721.0**	**520.0**
Tungsten	N/A	-	-	-	-	-	-	-	-	-
Yttrium	N/A	-	-	-	-	-	-	-	-	-
Zinc	5000	48.2	66.2	36.5	63.6	41.8	62.5	42.6	36.7	49.2

-"N/A" : Not Applicable, "-" : Not Detected

4. Results and Discussion
4.1. Leachability Test: Bulbs

○ TCLP results for U.S. EPA hazardous waste regulation

Substance	TCLP Threshold	Incandescent Bulb	CFL Bulb	LED Bulb	
				Ground to less than 2 mm	Less than 9.5 mm
Aluminum	N/A	13.3	39.8	59.8	8.9
Antimony	N/A	ND	ND	ND	ND
Arsenic	5	ND	ND	ND	ND
Barium	100	0.3	2.4	3.3	0.1
Cerium	N/A	47.9	7.6	19.6	0.003
Chromium	5	ND	ND	ND	ND
Copper	N/A	ND	4.3	3.1	0.027
Gadolinium	N/A	0.2	0.1	0.1	ND
Gallium	N/A	3.6	0.7	1.7	ND
Gold	N/A	ND	ND	ND	ND
Indium	N/A	ND	ND	ND	ND
Iron	N/A	59.1	967	1180	1.6
Lead	5	0.1	132	44.4	ND
Mercury	0.2	ND	ND	ND	ND
Nickel	N/A	14.1	7.3	17.0	0.2
Phosphorus	N/A	ND	ND	ND	ND
Silver	5	ND	ND	ND	ND
Tungsten	N/A	ND	ND	ND	ND
Yttrium	N/A	7.1	64.9	26.3	ND
Zinc	N/A	0.9	16.0	175	4.7

-”N/A” : Not Applicable, “-” : Not Detected

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4. Results and Discussion

4.1. Leachability Test: Bulbs

○ TTLC results for State of California hazardous waste regulation

Substance	TTLC Threshold	Incandescent Bulb	CFL Bulb	LED Bulb
Aluminum	N/A	40,100	31,700	947,000
Antimony	500	ND	117	123
Arsenic	500	ND	2.6	ND
Barium	10000	4.1	17.8	364
Cerium	N/A	9.4	9.6	7.8
Chromium	500 (VI); 2500 (III)	5.8	1.1	120
Copper	2500	942	111,000	31,600
Gadolinium	N/A	ND	0.6	0.1
Gallium	N/A	7.9	6.0	108
Gold	N/A	ND	ND	2.2
Indium	N/A	ND	ND	ND
Iron	N/A	372	12,800	12,300
Lead	1000	6.9	3860	16.7
Mercury	20	0.1	18.3	0.4
Nickel	2000	188	120	151
Phosphorus	N/A	ND	222	127
Silver	500	16.2	12.2	159
Tungsten	N/A	24.4	1.4	1.2
Yttrium	N/A	0.6	2540	1.7
Zinc	5000	320	34,500	4540

-"N/A" : Not Applicable, "ND" : Not Detected

Lim, Kang, Ogunseitan and Schoenung, *Environmental Science & Technology 2013, 47, 1040-1047*

4. Results and Discussion
4.3. Toxicity Potential: Bulbs

○ Comparison of the incandescent, CFL, and LED bulbs taking into account design lifetimes (1000, 10,000, 50,000 hr, respectively).

Environmental Impact Assessment Category and Method			Incandescent Bulb	CFL Bulb	LED Bulb
Resource Depletion Potential	CML 2001		1	3	3
	EPS 2000		1	5	2
Hazard-based Toxicity Potential	TLV-TWA		1	4	3
	PEL-TWA		1	13	3
	REL-TWA		1	8	2
	TPI		1	16	2
Life Cycle Impact (USEtox™)-based Toxicity Potential	Human-Toxicity Potential	Urban Air	1	22	2
		Rural Air	1	22	2
		Freshwater	1	25	2
		Sea Water	1	22	2
		Natural Soil	1	26	2
		Agricultural Soil	1	22	2
	Eco-toxicity Potential	Urban Air	1	22	3
		Rural Air	1	22	3
		Freshwater	1	22	3
		Sea Water	1	23	2
		Natural Soil	1	22	3
		Agricultural Soil	1	22	3

- The CFL and LED bulbs have higher resource depletion and toxicity potentials.
- The CFL bulb exhibits higher toxicity potentials than the LED bulb.
- The lower potentials of LED bulb are mainly due to the longer life of LED bulb.

Lim, Kang, Ogunseitan and Schoenung, *Environmental Science & Technology 2013, 47, 1040-1047*

Concluding Remarks

- The environmental and human health impacts of engineered products can be reduced through the application of green engineering principles.

- Various methods can be implemented to guide greener design, including economic impact assessment; life cycle assessment; hazardous waste, resource depletion and toxicity potential; and chemical hazard assessment.

- Implementation of these methods early in the design phase maximizes the potential benefit to society while also maximizing engineering functionality.

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