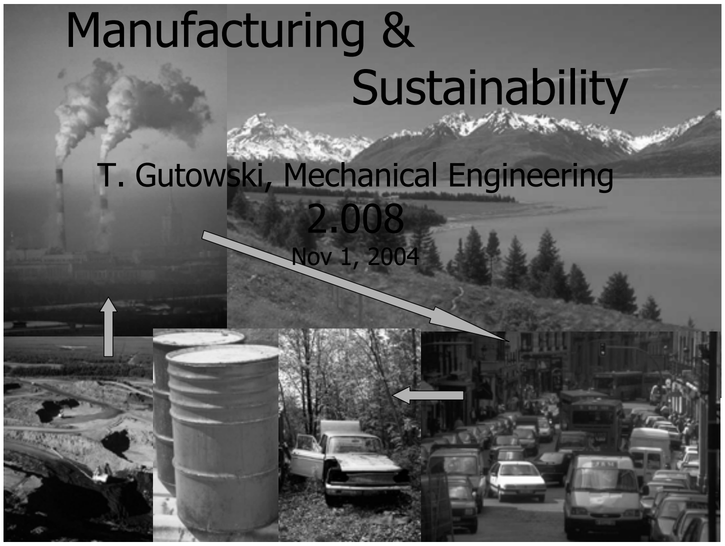
Manufacturing & Sustainability

T. Gutowski, Mechanical Engineering

2.008

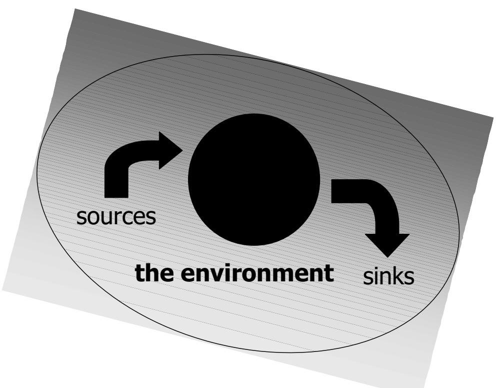
Nov 1, 2004



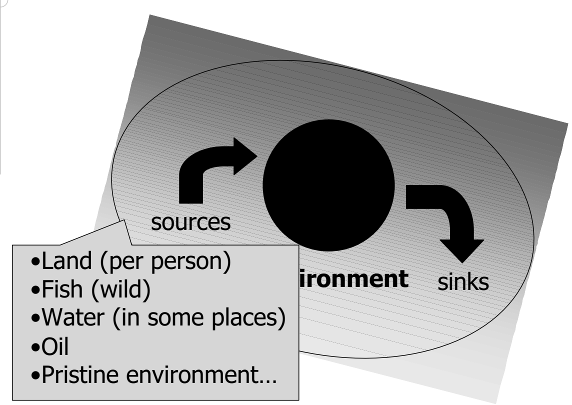
Outline

1. Sustainability as a limited resource issue
2. Corrective Actions
3. Design for Recycling

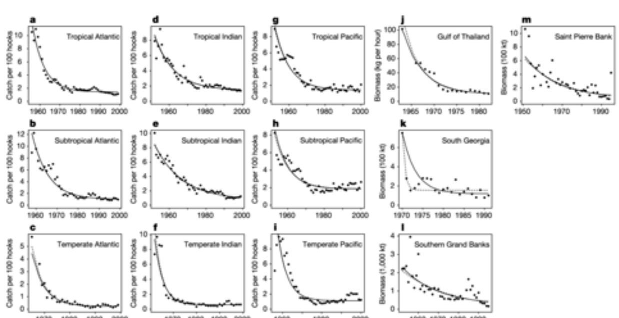
1. Sustainability as a limited resource issue



What are we running out of?

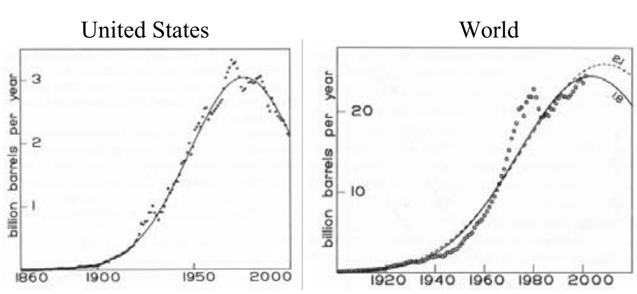


Historical Trend in Fish Stocks

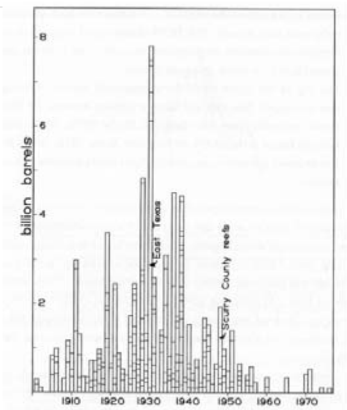


From Myers and Worm, 2003

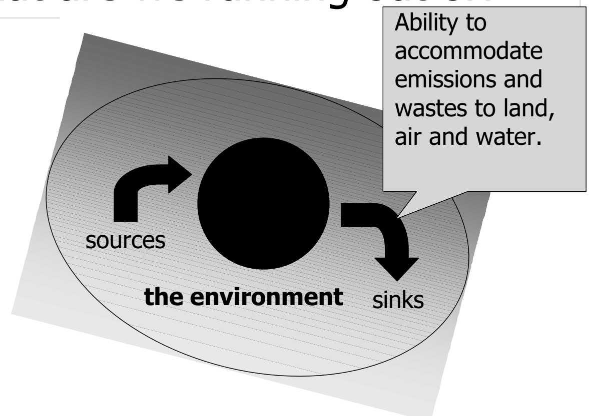
Annual Oil Production



Discovery of US Oil Fields



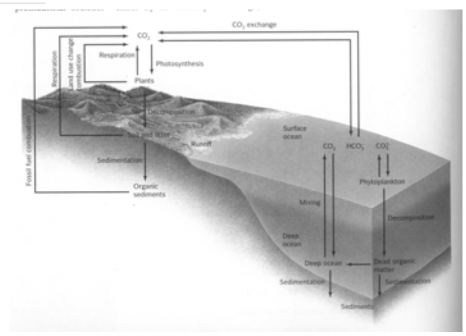
What are we running out of?



Some emissions and wastes that load the environment

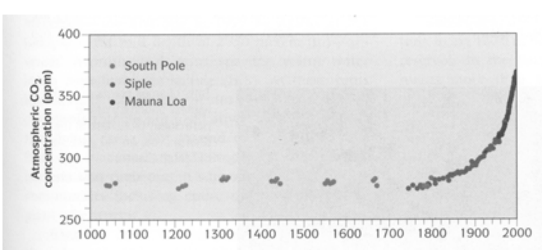
- PCB
- dioxin
- DDT
- Benzene
- PAH
- VOC
- SO_2
- NO_x
- Pb
- Cr (hexavalent)
- Hg
- As
- Ni
- Cl
- Asbestos
- etc.

Global Carbon Cycle



Ref; Smil 2001

Atmospheric CO_2 since the year 1000



CO_2 measurements from air (Mauna Loa) since 1958 and from ice cores taken in Antarctica (Siple Station and South Pole) Ref. Smil 2001

Global S & N

from Vaclav Smil
"Energy at the Crossroads"
MIT Press, 2003

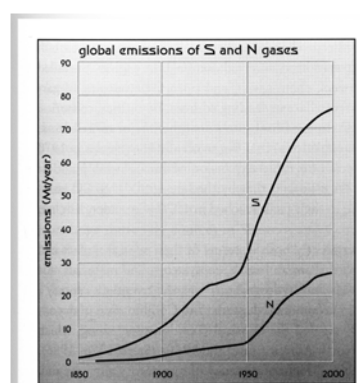
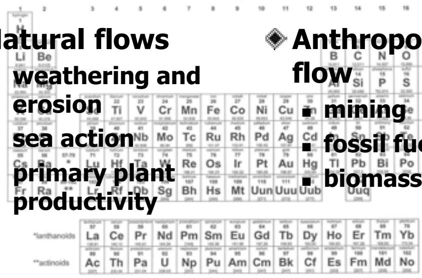


Figure 2.15

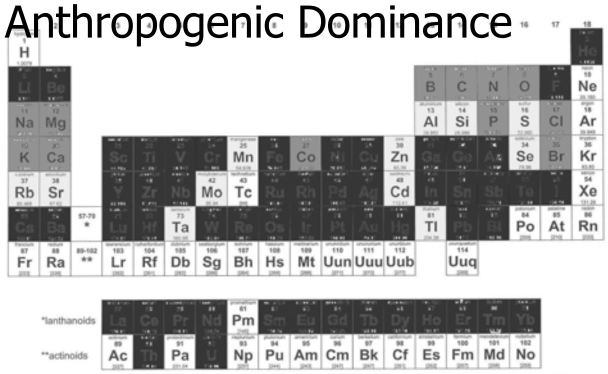
Preliminary estimates of global flows for 92 elements



- **Natural flows**
  - **weathering and erosion**
  - **sea action**
  - **primary plant productivity**
- **Anthropogenic flow**
  - **mining**
  - **fossil fuels**
  - **biomass burning**

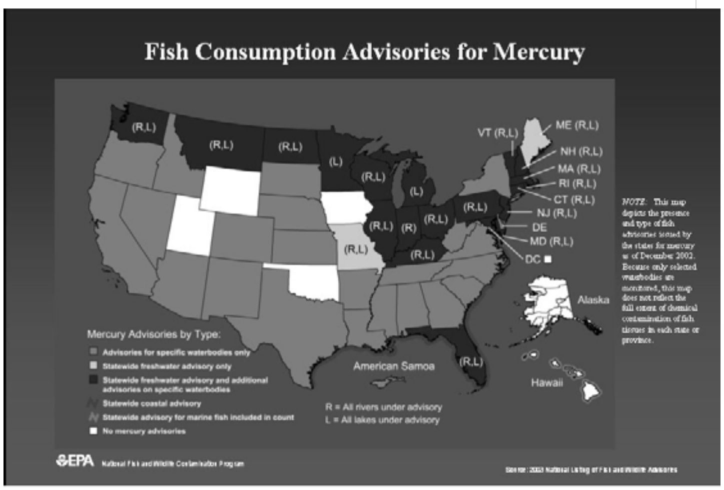
ref Klee & Graedel, ISIE

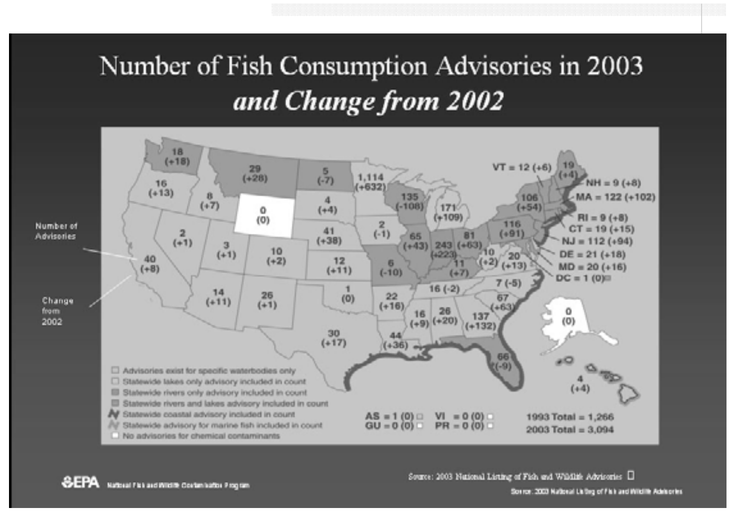
Anthropogenic Dominance



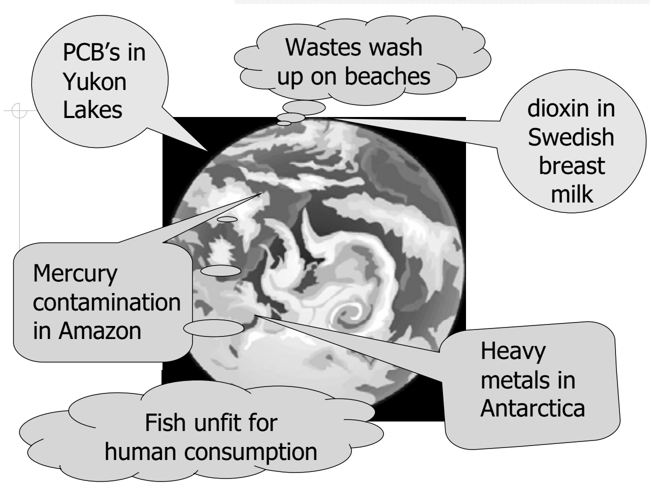
Dominated (>50% of mobilization)
Perturbed (15-50% of mobilization)
Unperturbed (<15% of mobilization)
Undetermined

From Klee and Graedel, 2003





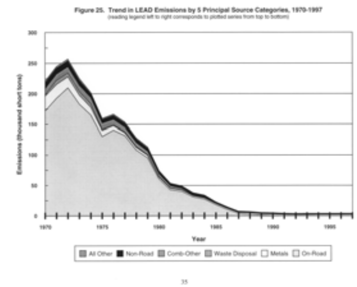
Consider the planet as a human artifact.



2. Corrective Actions

1. Substitution (type)
2. Reduction (scale)
   1. eco-efficiency
   2. “end of pipe”
   3. recirculation

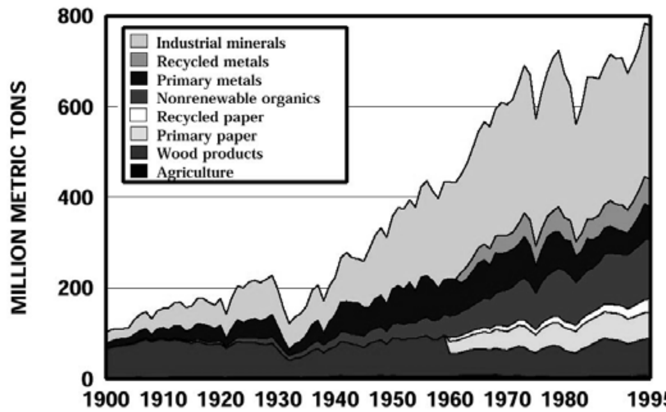
substitution can work



Substitution

- Chlorine dioxide for elemental chlorine for pulp bleaching
- Hydrogen peroxide for chlorine dioxide
- MTBE for Tetraethyl Lead
- …for MTBE
- R-134a for R-12 (CFC)
- Zn for Cd plating
- sub-bituminous for high sulfur coal
- Organo-phosphates for DDT
- water cleaning for organic solvents

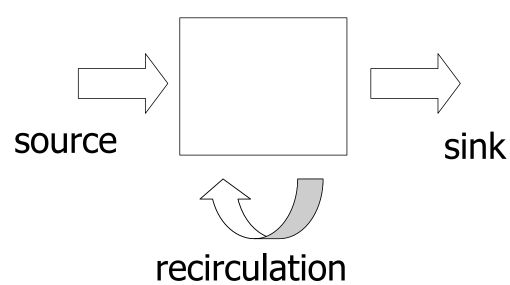
Material Consumption in the US



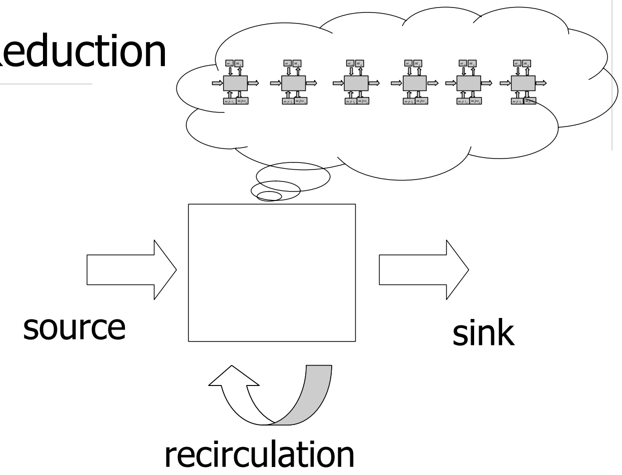
3. Corrective Actions

1. Substitution (type)
2. Reduction (scale)
   1. eco-efficiency
   2. “end of pipe”
   3. recirculation

Reduction: Mass Flow

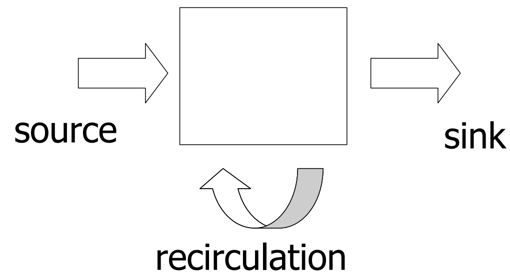


Reduction

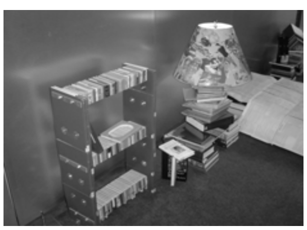


Reduction

1. eco-efficiency
2. "end of pipe"
3. recycle



DESIGN FOR RECYCLING



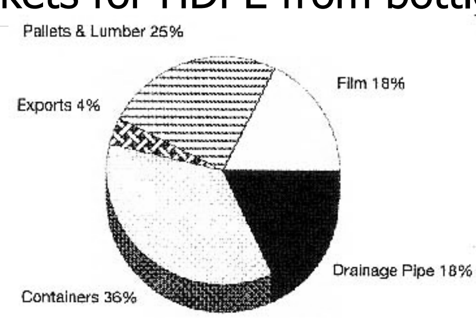

Outline

1. What gets recycled and why
2. Recycling tours
3. Separation technologies
4. Cost and energy accounting
5. Design for recycling

1. What gets recycled?

- Metals
- Paper
- Tires
- Auto Batteries
- beverage containers
- PET
- HDPE

Markets for HDPE from bottles



Plastic bottle recycling rates

TABLE 2.2 Plastic bottle recycling rates, 1998

Plastic Bottle type	Resin sales 1998	Pounds recycled 1998	1998 Recycle rate	1997 Recycle rate
PET soft drink	1628	580.3	35.6	35.8
PET customer	1278	129.7	10.1	10.2
Total PET	2906	710	24.4	25.4
Nat. HDPE	1415	433.7	30.7	30.6
HDPE Pig.	1497	300.2	20.1	19.3
Total HDPE	2912	733.9	25.2	24.7
HDPE base cups	6	1.5	25	30
PVC	152	0.2	0.1	0.1
LDPE/LLDPE	51	0.1	0.2	0.3
PP	145	5.3	3.7	4.1
PS	10	<0.1	<0.1	<0.1
Total bottles	6182	1451	23.5	23.7

Source: R. W. Beck for American Plastics Council 1999.

Why?

- Economics
- Mandates
- Landfill Bans
- Extended Producer Responsibility
- Liability Avoidance

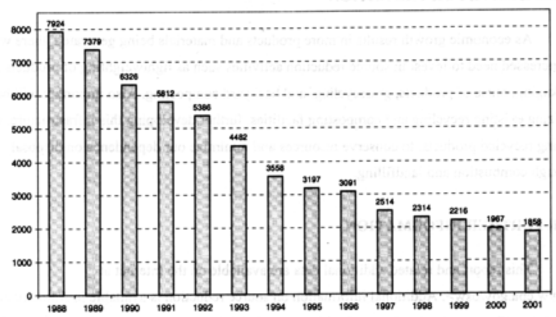
Landfill Bans

TABLE 2.3 Landfill bans—sample laws

State	Lead-acid batteries	Tires	Yard waste	Used oil	White goods	All house-hold-waste	House-hold batteries	Packaging	Scrap metal	Other	Local bans
California	X	X		X	X	NE	X		X	Merc, AF	Yes
Connecticut	X		X				X				Merc
Florida	X	X	X	X	X		X			C&D	Yes
Iowa	X	X	X	X				DEP		Liquid	No
Minnesota	X	X	X	X	X	X		X		PH, Merc, FT, AF OF	Few
Missouri	X	X	X	X	X	X					No
Nebraska	X	X	X	X	X	X					No
North Carolina	X	X	X	X	X			X (cans)		AF	Yes
South Dakota	X		X	X	X			X		All Pkg (1997) PP	No†
Vermont	X	X		X	X		X (ni–cd)			Paint (oil/latex), merc	Yes
Wisconsin	X	X	X	X	X			X*		ONP	Yes

Acronyms: AF = antifreeze; C&D = construction and demolition debris; DEP = deposit; FT = flourescent tubes; merc = mercury, mercury products; OF = oil filters; PH = phone books; pkg = packaging; ONP = old newsprint; PP = paper products.
*Wisconsin passed a bill in 1996 allowing an exemption from the rigid plastics landfill bans.
†Counties can be exempted.

Figure ES-5: Number of Landfills in the U.S.



Purchasing preference laws

TABLE 2.4 Purchasing preference laws—samples

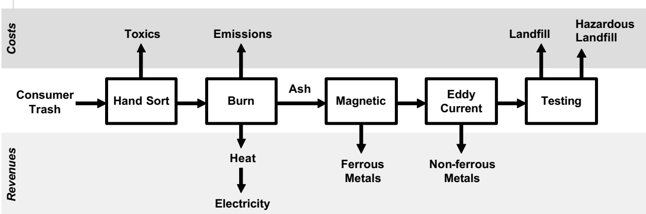
State	Year	Product	% Content*	Price preference	Set-asides
Arizona	1990	Paper	10% PC	5%	No
California	1977, 1986, 1989, 1993, 1994, 1998	All Engine coolant or antifreeze	Paper: 50% Sec., 10% PC; All PC must increase to 30% by 1/99 Grants variance from specs if chloride content less than 150 ppm	10%	Yes
Colorado	1989, 1990, 1993	Plastics and paper	Plastics: min. 10% RC Paper: 50% Sec., 50% PC min. 10% PC		Yes
Maryland	1988, 1990, 1993	All	EPA	5%	40%
Massachusetts	1989	All		10%	No
Oregon	1991, 1998	All	50% Sec. or 25% PC paper; 25% by 1997; 40% by 1999	5% = 12% on printing paper	Yes
Washington	1991, 1996	Paper, compost All		10%	Yes

*Sec = secondary; RC = recycled content; PC = postconsumer.

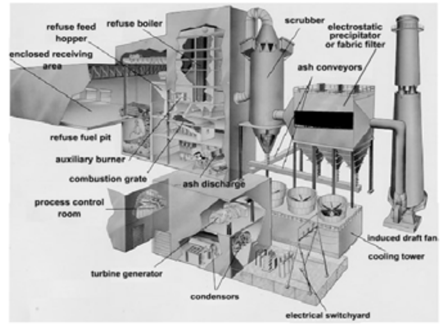
2. Recycling Tours

- Wheelabrator
- CFR
- Autos
- Metech
- HP/Noranda
- DEER2

Wheelabrator – Trash to Ash Worcester, MA



Wheelabrator – Trash to Ash

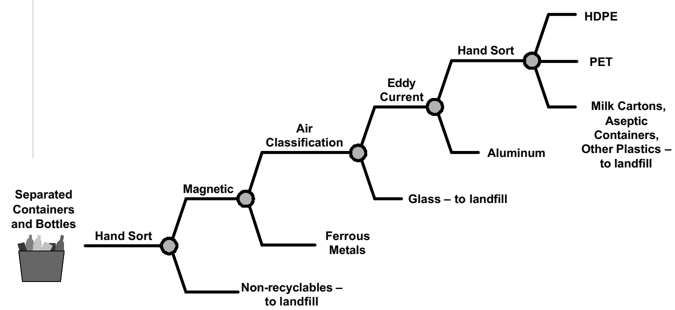


Wheelabrator

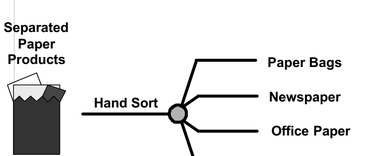
- 70% reduction in weight to landfill
- 500,000 tons processed per year
- 45 MW (produced) – 5 MW (used)

  = 40 MW to grid
- 2.8 MJ/kg (coal ~29 MJ/kg)
- Emissions and Dioxin issues

Curbside Recycling (FCR Charlestown, MA)



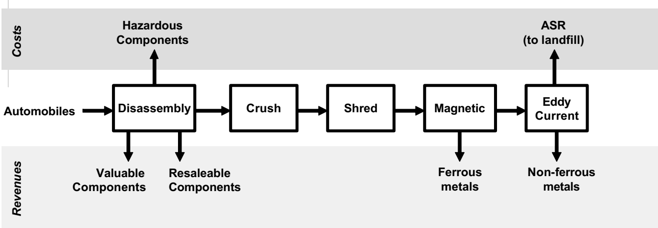
FCR Recycling – Paper



FCR Recycling

- Recycle ferrous, non-ferrous, paper, HDPE, and PET
- Landfill glass, all other plastics, aseptic containers, and material contaminated by food products
- Hand and automatic sorting

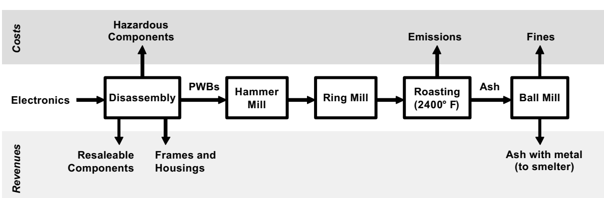
Automobile Recycling



Automobile Recycling

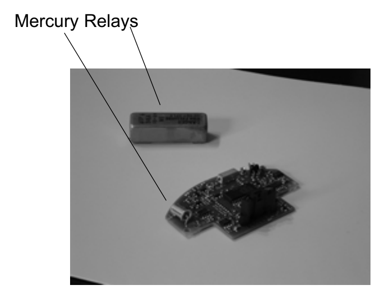
- Over 94% of cars are recycled
- Over 75% of each car is recycled
- European Union automobile take-back legislation
  - by 2006,
    - 80% reuse/recycling by weight
    - 85% reuse/recovery by weight
  - By 2012,
    - 85% reuse/recycling by weight
    - 95% reuse/recovery by weight

Metech Computer Recycling

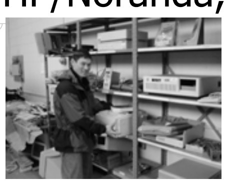


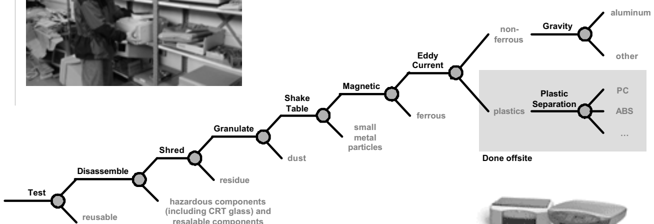
Metech

- Customers pay to dispose of computers
  - 20¢/ lb without CRT
  - 35¢/ lb with CRT
- Certificate of destruction



HP/Noranda, Roseville, CA

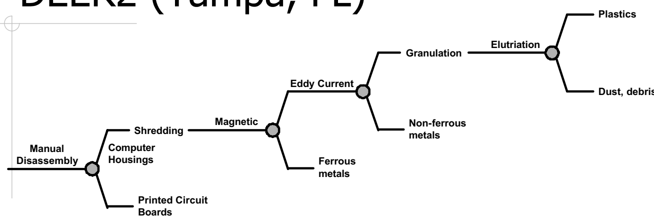




HP/Noranda

- Customers pay to return HP products
  - Monitor $29
  - PC (without monitor) $21
  - Ink printer $17
- 1.6 million lbs processed per month
- 400 hp shredder motor
- $4-5 million capital investment in plant
- No water used in process

DEER2 (Tampa, FL)

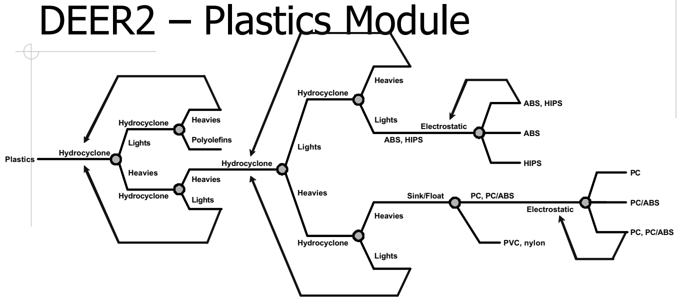


Manual Disassembly

Shredding

Granulation

DEER2 – Plastics Module



Hydrocyclone

Sink/Float

Electrostatic

DEER2

- Funded by the DOD
- Technology demonstration
- $1.2 million for plastic separation module
- Max throughput = 1000 lb/hr
- Wash/Rinse most expensive step
- Metal contaminants cause problems in electrostatic separation
- Shape factors cause problems in hydrocyclone and electrostatic separation
- 15-17¢ / lb for plastics shred and separate

RRT Design and Construction

CRT recycling

Envirocycle (largest CRT tube recycler in US)

Techniglass (one of few US CRT manufacturing, produces high quality tubes for military, hospitals)

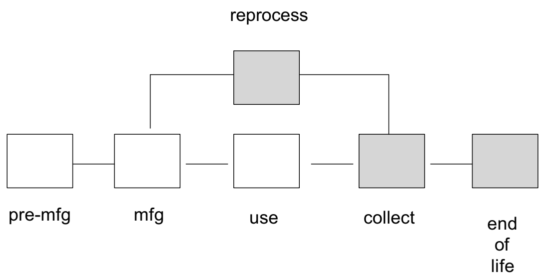
Doe-Run (primary Pb smelter in US, uses Pb-glass as flux)

RRT has designed and built systems to crush 300 tubes/hr at capital cost of $250,000 for automated system. Compare to manual 500 monitors/day by 4 people

3. Separation Technologies

- Magnetic
- Eddy Current
- Sink-Float
- Hydro-cyclone
- Electrostatic

4. Cost and energy Accounting

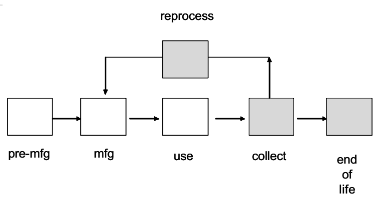


Cost Questions

1. Can you reduce disposal costs?

2. Can the recycler make a profit?

Cost Calculation



Recycling Revenues = Revenues – (Collection + Reprocessing + Disposal)

Recycling Revenues

Revenues
- fees
- resale value

Costs
- collect inefficiency
- reprocessing
- transportation
- disposal

HAZARDOUS WASTE 9.11

TABLE 9.6 Categorization of Priority Pollutants (28)

Volatile organics
acrolein
acrylonitrile
benzene
bis(chloromethyl)ether
bromoform
carbon tetrachloride
chlorobenzene
chlorodibromomethane
pentachlorophenol
2-chloroethyl vinyl ether
chloroform
dichlorobromomethane
1,2-dichloroethane
1,1-dichloroethane
1,1-dichloroethylene
1,2-dichloropropane
1,2-dichloropropylene
ethylbenzene
methyl bromide
methyl chloride
methylene chloride
1,1,2,3-tetrachloroethane
tetrachloroethylene
toluene
1,2-trans-dichloroethylene
1,1,1-trichloroethane
1,1,2-trichloroethane
trichloroethylene
vinyl chloride

Acid-extractable organics
2-chlorophenol
2,4-dichlorophenol
2,4-dimethylphenol
4,6-dinitro-o-cresol
2-nitrophenol
4-nitrophenol
parachlorometacresol
1,2,4-trichlorobenzene phenol
2,4,6-trichlorophenol

Base and neutral organics
acenaphthene
acenaphtylene
anthracene
benzidine
benzo(a)anthracene
benzo(a)pyrene
benzo(ghi)perylene
benzo(k)fluoranthene
3,4-benzo-fluoranthene
bis(2-chloroethoxy) methane
bis(2-chloroethyl)ether
bis(2-chloroisopropyl)-ether
bis(2-ethylhexyl)phthalate
4-bromophenyl phenyl ether
butyl benzyl phthalate
2-chloro-naphthalene
4-chlorophenyl phenyl ether
chrysene
di-n-butyl phthalate
di-n-octyl phthalate
dibenzo(a,h)anthracene
1,2-dichlorobenzene
1,2-dichlorobenzene
4,4'-DDT
1,4-dichlorobenzene
diethyl phthalate
dimethyl phthalate
2,4-dinitrotoluene
2,6-dinitrotoluene
1,2-diphenylhyrazine
fluoranthene
fluorene
hexachlorobenzene
hexachlorobutadiene
hexachlorocyclo-pentadiene
hexachloroethane
indeno(1,2,3-cd)-pyrene
isophorone
naphthalene
nitrobenzene
N-nitrosodi-n-propylamine
N-nitrosodi-methylamine
N-nitroso-diphenylamine
phenathrene
pyrene
2,3,7,8-tetrachloro-dibenso-p-dioxin

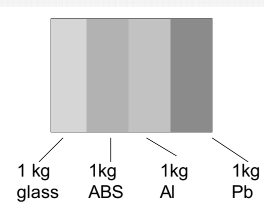
Pesticides and PCBs
aldrin
alpha-BHC
beta-BHC
gamma-BHC
delta-BHC
chlordane
4,4'-DDD
4,4'-DD chloroethane
dieldrin
alpha-endosulfan
beta-endosulfan
endosulfan sulfate
endrin
endrin aldehyde
heptachlor
heptachlor epoxide
PCB-1016
PCB-1221
PCB-1232
PCB-1242
PCB-1248
PCB-1254
PCB-1260
toxaphene

Metals
antimony
arsenic
beryllium
cadmium
chromium
copper
lead
mercury
nickel
selenium
silver
thallium
zinc

Cyanides

Asbestos

Cost Example



Case #1

disposal of 4 kg as hazardous waste (shipped to Niagra Falls)

cost 4 kg X $2.2/kg = $8.8

Case # 2 Disassemble Pb. Recycle, the rest to landfill

Costs	1. disassemble (1 min. unskill)	$ 0.20
	2. transport (1920 km)	$ 1.92
	3. Landfill (3kg)	$0.38
	Total Cost	$2.50
Revenues	1. Pb	$0.70

net cost = $2.50 - $0.70 = $1.80

Case # 3 Disassemble Pb, recycle, the rest to the shredder & recycle

Costs	1. disassemble (1 min. unskilled)	$0.20
	2. transport (1920 km)	$1.92
	3. shred and separate (3 kg)	$0.60
	4. Transport (200 Km, 3 kg)	$0.60
	Total Cost	$3.32
Revenues	1. Pb	$0.70
	2. A1	$0.80
	3. ABS	$0.50
		$2.00

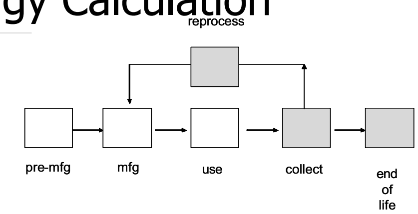
net cost = $3.32 - $2.00 = $ 1.32

Case # 4 Lead free; shredder & recycle

Costs	1. shred and separate (3 kg)	$0.60
	4. Transport (200 Km, 3 kg)	$0.60
	Total Cost	$1.20
Revenues	1. A1	$0.80
	2. ABS	$0.50
		$1.30

net revenue = $1.30 - $1.20 = $ 0.10

Energy Calculation



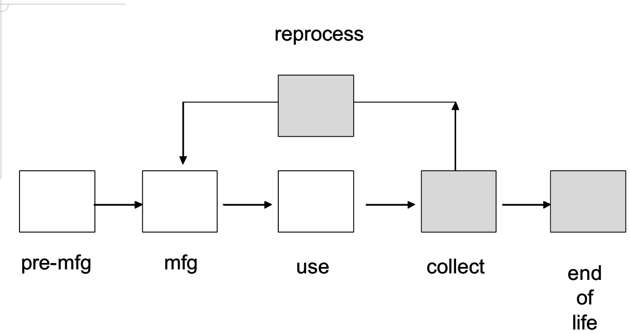
Energy Credit = avoided Pre-mfg + avoided end of life
- reprocessing
- additional travel
- collection inefficiency

Energy Account for Case # 3

Energy credits	254 MJ
	30 MJ
	1 MJ
	50 MJ
	335 MJ
Energy Costs (transportation)	
4kJ/km.kg x 1kg x 1920km =	8 MJ
4kJ/km.kg x 3kg x 200km =	2 MJ
	10 MJ

Net Credit = 335 - 10 = 325 MJ

Life Cycle Analysis



5. Design for recycle

- Recycling is like mining.
- How would you design an ore?

5. Design for recycle

- Recycling is like mining.
- How would you design an ore?
- high value
- lots available
- easy to get at

Price and dilution for metal ores

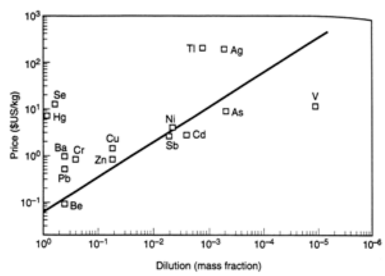
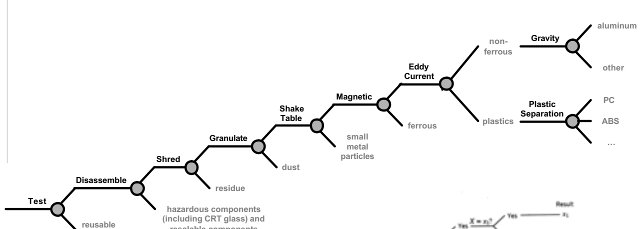


Figure 8.4 The relationship between dilution and price. The solid line shows the relationship between the price of virgin materials and their dilution in the matrices from which they are extracted. The individual points are for metal residues undergoing recycling. Additional discussion is contained in the text. (Reproduced with permission from D. T. Allen and N. Behmanesh, in *The Greening of Industrial Ecosystems*, B. R. Allenby and D. J. Richards, eds., pp. 69–89. Copyright 1994 by National Academy of Sciences.)

how about mixtures of materials?

- develop a measure of mixtures
- develop tree diagram representations of recycling systems
- show that the measure of mixtures represents the most compact tree diagram for a given mixture
- ref. Material "Entropy" and Product Recycling, Timothy G. Gutowski and Jeffrey B. Dahmus, 1st Global Conference on Sustainable Product Development and Life Cycle Engineering, Berlin, Germany, September29 -October 1, 2004.

Analogy with information systems



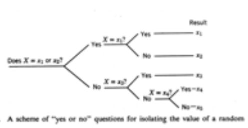
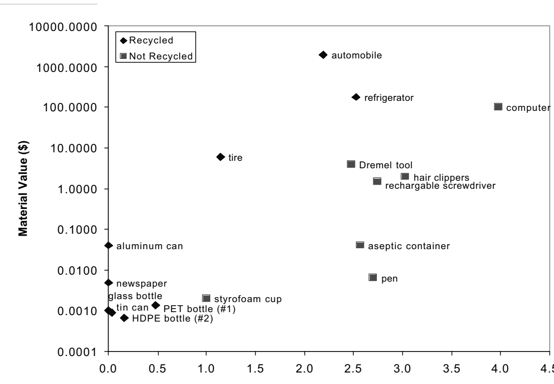


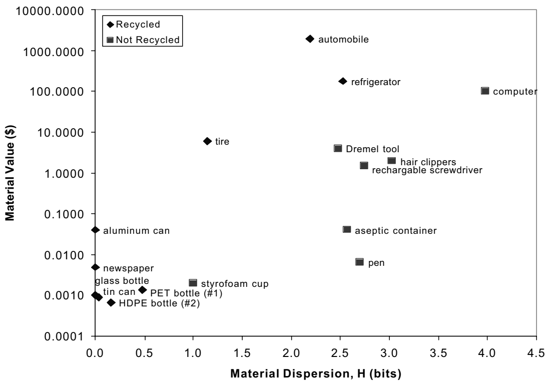
Fig. 1.3.1. A scheme of "yes or no" questions for isolating the value of a random variable.

Ash 1965

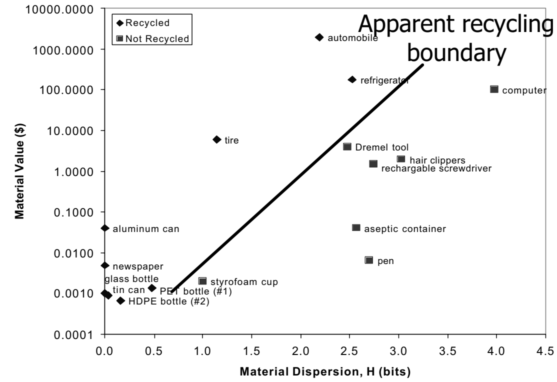
Material Value, Material Mixing and Recycling for Products in U.S.



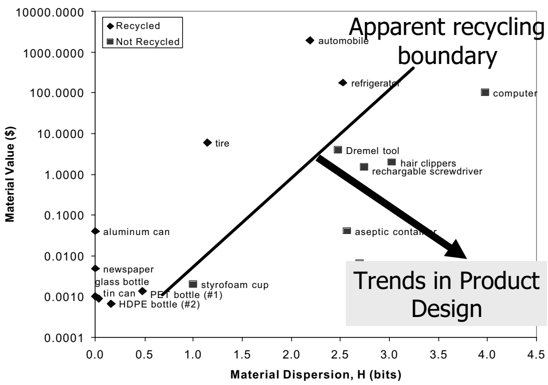
Material Value, Material Mixing and Recycling for Products in U.S.



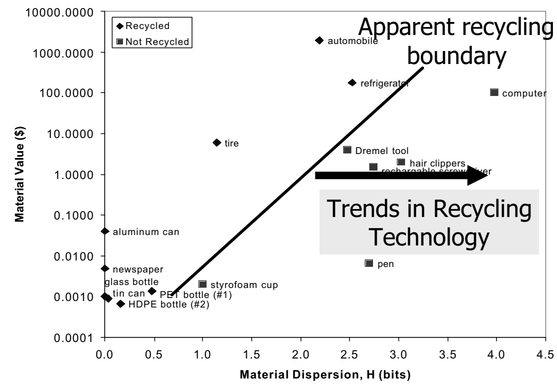
Material Value, Material Mixing and Recycling in U.S.



Material Value, Material Mixing and Recycling in U.S.



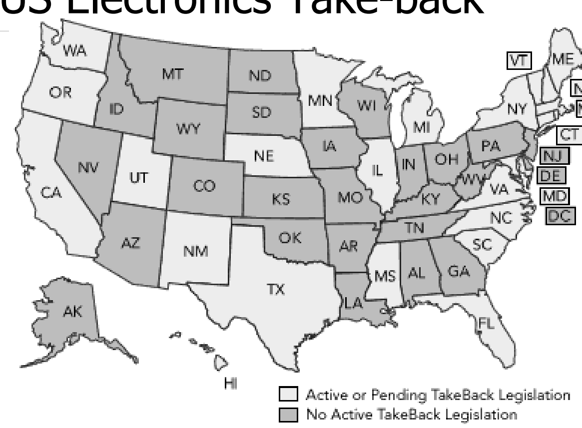
Material Value, Material Mixing and Recycling in U.S.

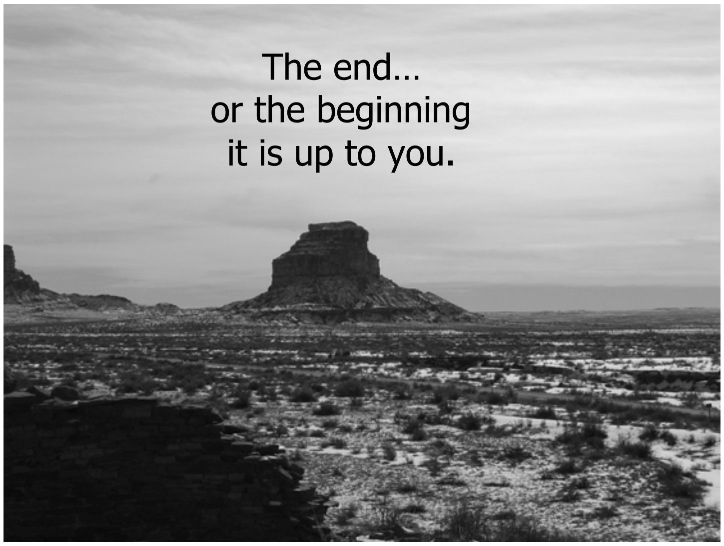


DfE Summary

- mandates with some flexibility are needed
- taxes on materials would do the trick too
- as would landfill bans etc.
- design must be for the <u>system</u>

US Electronics Take-back




The end…
or the beginning
it is up to you.