Green Opportunities and Progress: Green Engineering as a Path to Sustainability

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What is Green Engineering?

Design, commercialization and use of processes and products that are feasible and economic while minimizing:

– Risk to human health and environment

– Generation of pollution at the source

Transforms existing practices to promote sustainable development.

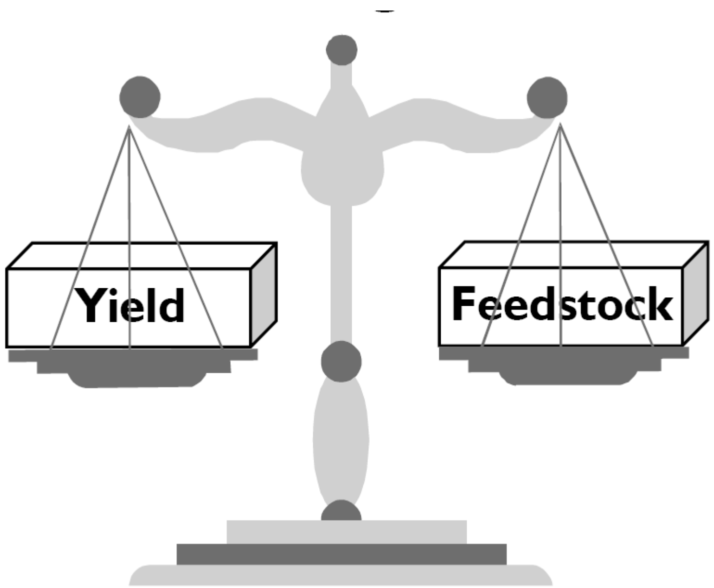
The Sandestin Declaration

Green Engineering transforms existing engineering disciplines and practices to those that lead to sustainability.

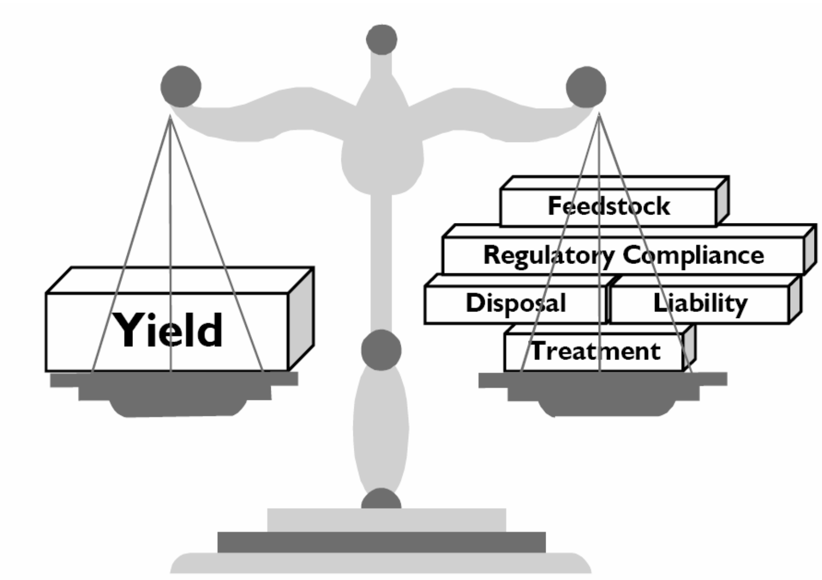
Green Engineering incorporates development and implementation of products, processes, and systems that meet technical and cost objectives while protecting human health and welfare and elevates the protection of the biosphere as a criterion in engineering solutions.

Green Engineering: Defining the Principles, Engineering Conferences International, Sandestin, FL, USA, May 17-22, 2003.

Finding a Balance in Design



Past



Present

The Sandestin GE Principles

1. Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.
2. Conserve and improve natural ecosystems while protecting human health and well-being
3. Use life-cycle thinking in all engineering activities
4. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible
5. Minimize depletion of natural resources
6. Strive to prevent waste
7. Develop and apply engineering solutions, while being cognizant of local geography, aspirations, and cultures
8. Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability
9. Actively engage communities and stakeholders in development of engineering solutions

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12 Principles of Green Engineering

1. Inherent rather than circumstantial
2. Prevention rather than treatment
3. Design for separation
4. Maximize mass, energy, space, and time efficiency
5. Output-pulled versus input-pushed
6. Conserve complexity
7. Durability rather than immortality
8. Meet need, minimize excess
9. Minimize material diversity
10. Integrate local material and energy flows
11. Design for commercial afterlife
12. Renewable rather than depleting

From Paul Anastas

Applying the Principles

- Application of innovative technology to established industrial processes
- Development of more environmentally-benign routes to desired products
- Design of new green chemicals and materials
- Use of sustainable resources
- Use of biotechnology alternatives
- Methodologies and tools for assessing environmental impact

Principle 1

- Inherent rather than circumstantial "*designers should evaluate the inherent nature of the selected material and energy inputs to ensure that they are as benign as possible as a first step toward a sustainable product, process, or system*"

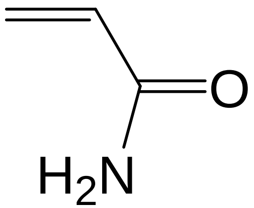
A Case Study: Two Polymers

Polyacrylamide vs. Poly (N-vinyl) Formamide

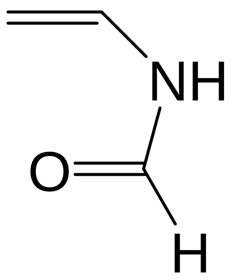
Used in papermaking, oil recovery, personal care products, water treatment

Monomers:

Acrylamide



(N-vinyl) formamide



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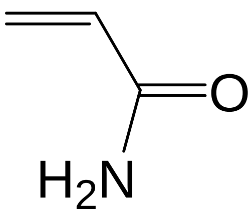

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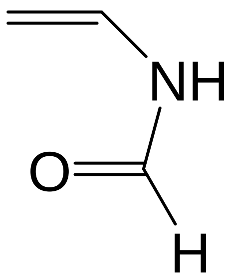

Highly toxic, causes CNS paralysis

Low toxicity, not a neurotoxin

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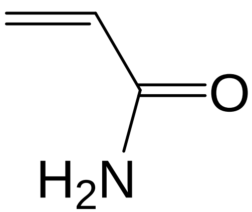

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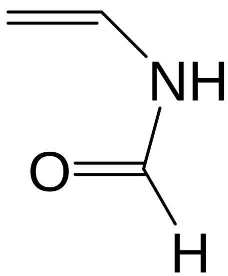

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Green enzymatic synthesis

Low toxicity, not a neurotoxin

Synthesis uses hydrogen cyanide

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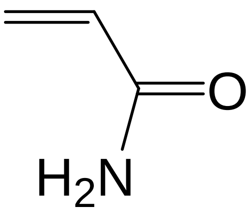

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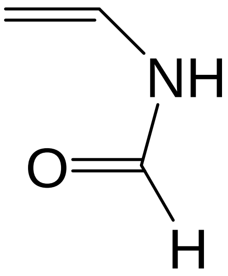


Highly toxic, causes CNS paralysis

Green enzymatic synthesis

~ $1/kg

Low toxicity, not a neurotoxin

Synthesis uses hydrogen cyanide

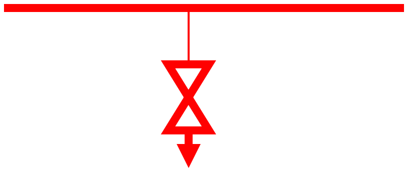
~ $4.50/kg

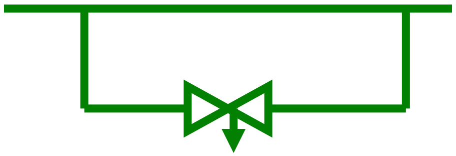
Principle 2

- Prevention rather than treatment
  "it is better to prevent waste than to treat or clean up waste after it is formed"
- Tremendous $$ spent on waste treatment, disposal and remediation; in the past not always considered in cost of plant - full cost accounting (life cycle analysis)
- Usually requires extra unit operations
- Industrial mindset is changing

How to prevent pollution?

- Implementation of new technology
  - solvent substitution
  - eliminate toxic intermediates
  - new reaction paths/new chemistry
- Optimize existing technology
  - Choice of raw materials
  - Reactor efficiency
- Simple (no/low cost) solutions
  - sloping piping downwards to cut wash solvent use
  - short, fat pipes reduces drag, lower energy use
  - paint storage tanks white
  - no dead-end sample points





A&R, 1997

Principle 3

- Design for Separation;

  "many traditional methods for separation require large amounts of hazardous solvents, whereas others consume large quantities of energy as heat or pressure. Appropriate upfront designs permit the self-separation of products using intrinsic physical/chemical properties…."

Design for Separation, the Serendipitous Result…

Polypropylene Cap (sometimes present…)

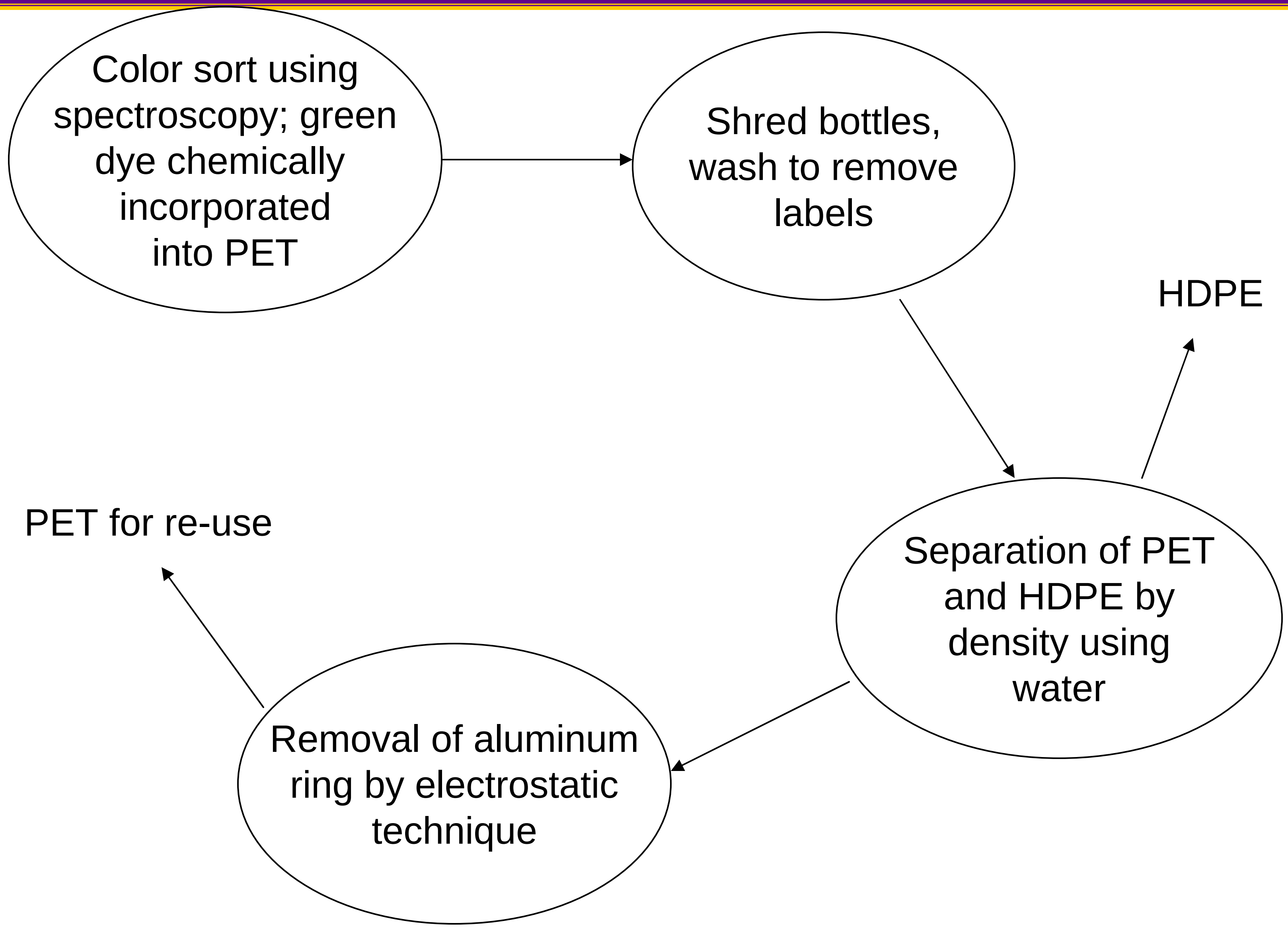
Aluminum Ring

Polyethylene Terephthalate Bottle

Paper/adhesive Label

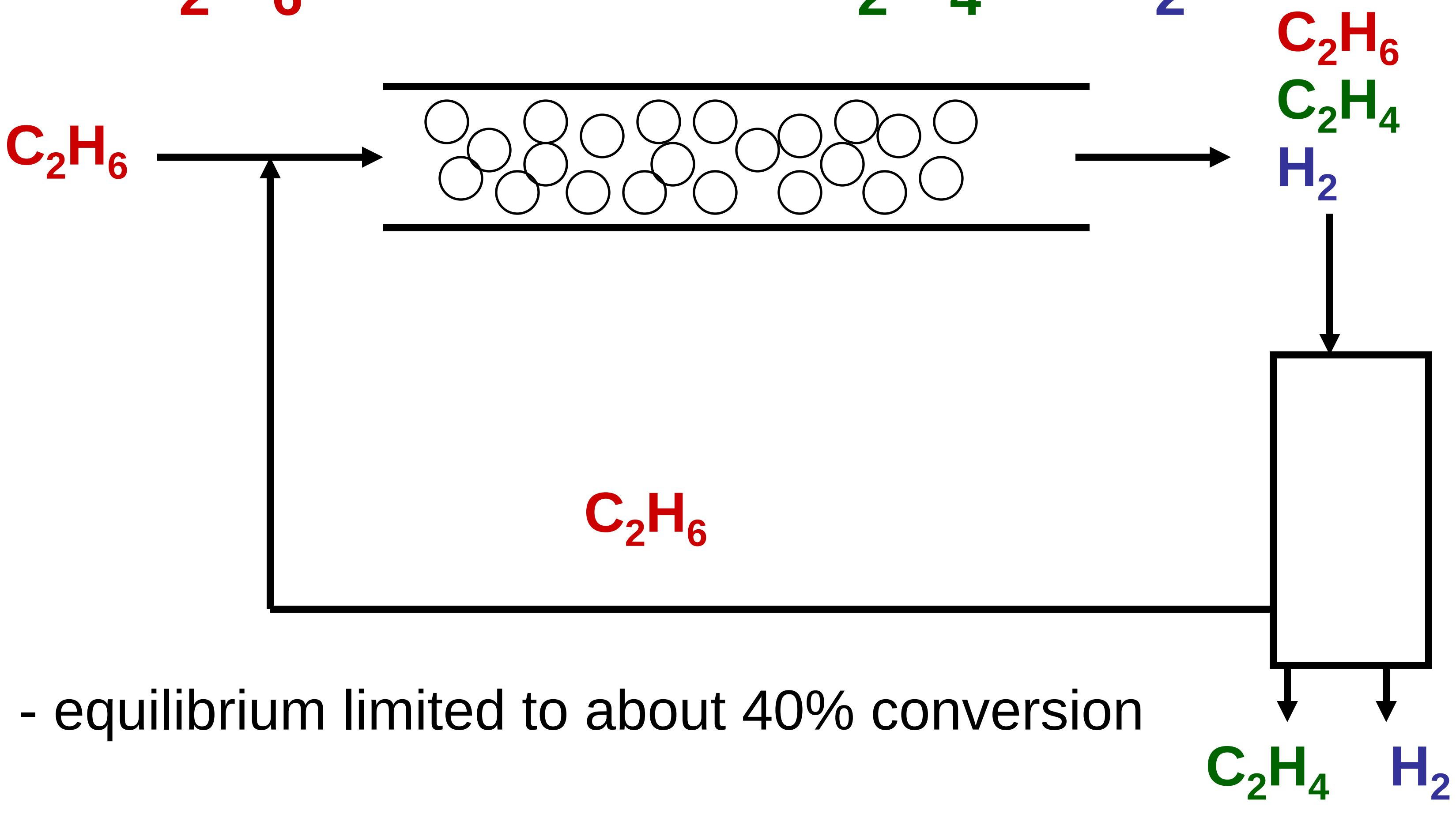
Polyethylene Base Cup

Recycling of PET bottles



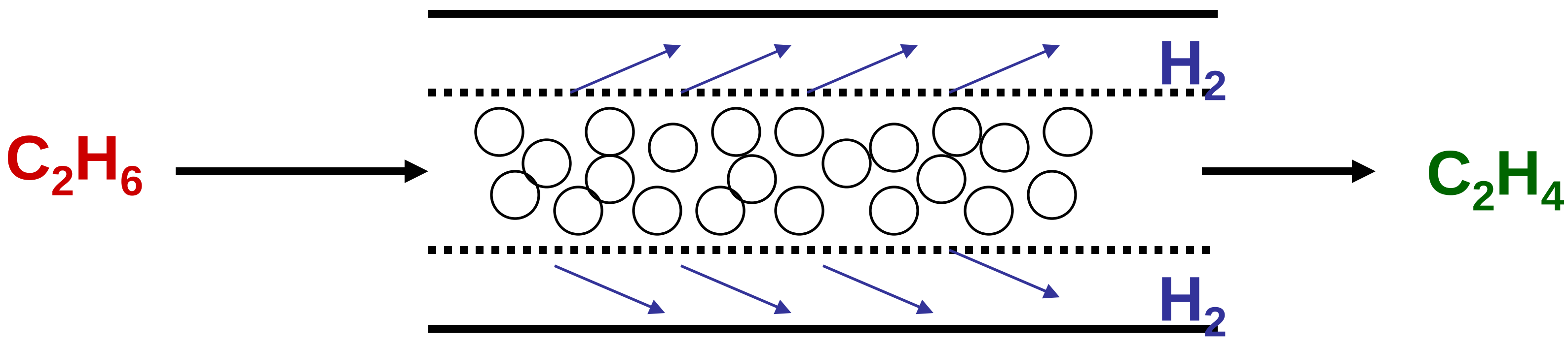
Combined reaction & separation

$C_2H_6 \longleftrightarrow C_2H_4 + H_2$



- equilibrium limited to about 40% conversion

Combined reaction & separation



- microporous membrane
- allows H_2 to pass but not C_2H_4 or C_2H_6
- allows close to 100% conversion
- eliminates need for energy-intensive separation process

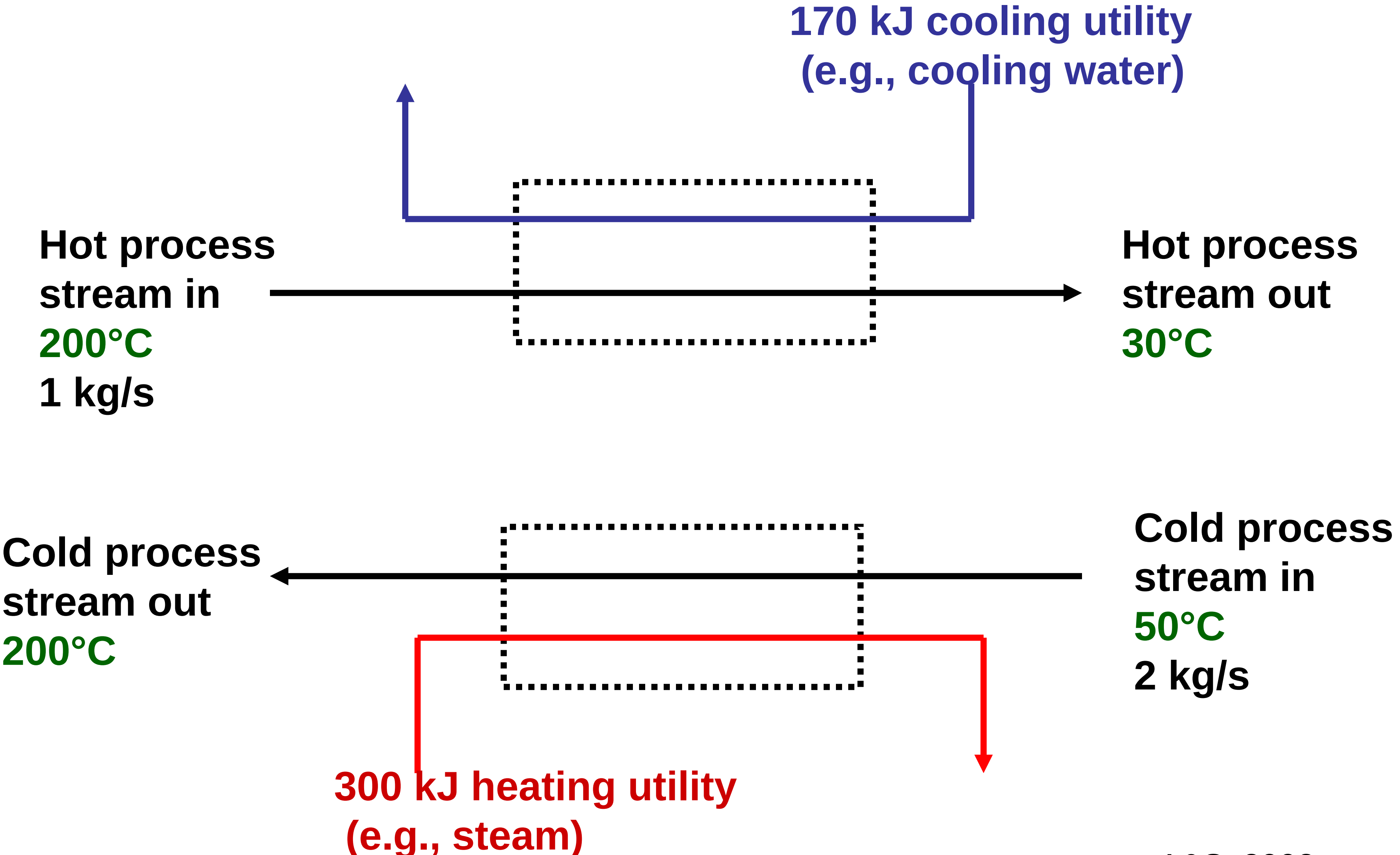
Principle 4

•Maximize efficiency

“products, processes, and systems should be designed to maximize mass, energy, space and time efficiency”

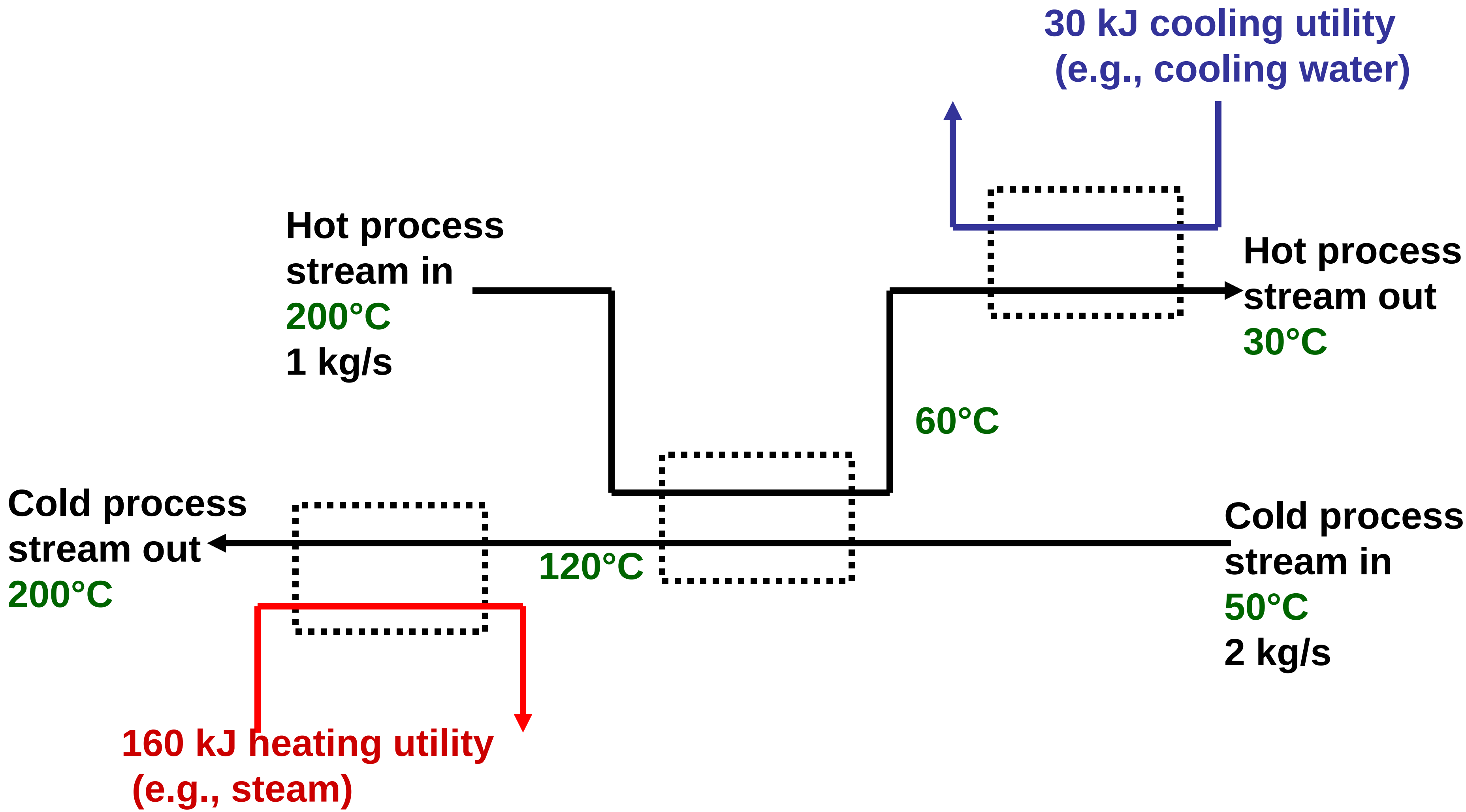
- Mass and energy efficiency is standard Chemical Engineering optimization
- Related to 8 (no overcapacity)
- Related to 10 (mass & energy integration)

Heat Integration



A&S, 2002

Heat Integration



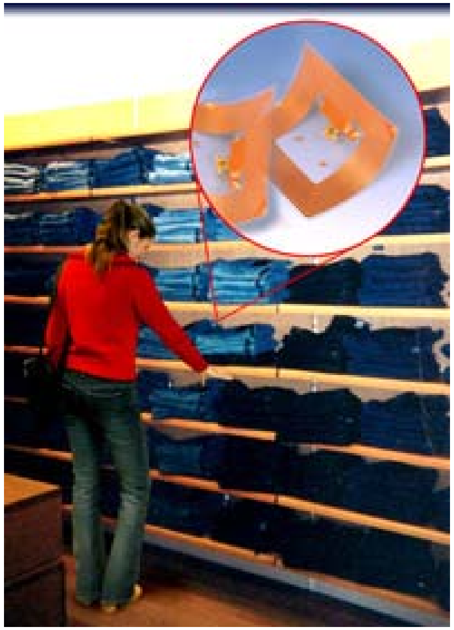
A&S, 2002

Principle 5

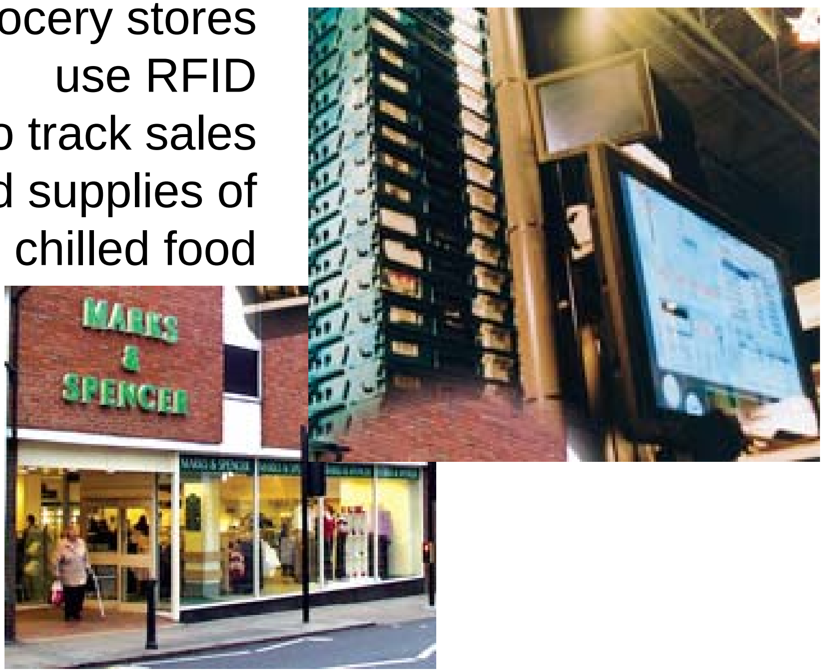
- Ouput-pulled rather than input-pushed
  “approaching design through Le Chatelier’s Principle, therefore, minimizes the amount of resources consumed to transform inputs into desired outputs”

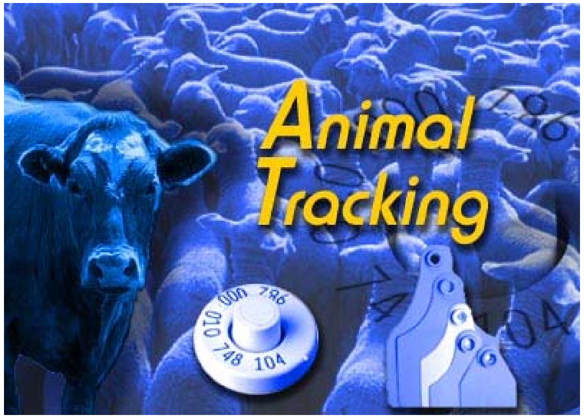
Output driven

Gap uses RFID tags to keep track of amounts on shelves versus amounts in inventory



Grocery stores use RFID to track sales and supplies of chilled food





Principle 6

•Conserve complexity

"embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition"

- More focused on products than processes
- Less complicated products can more easily be recycled
- If a product is complex then it should be designed to be reused

Unnecessary complexity

- IBM PC's used to be made with 15 different types of screws
- Replaced with 1 type of screw
- Easier to disassemble & recycle
- Why not reuse computers?
  - make modular
  - replace processors, memory…
  - economics...

Diana Bendz, IBM
Presentation at ND, 2000

Principle 7

- Durability rather than immortality;

  "It is therefore necessary to design products with a targeted lifetime to avoid immortality of undesirable materials in the environment. However, this strategy must be balanced with the design of products that are durable enough to withstand anticipated operating conditions.."

Example: CFC's

- $C_xH_yF_zCl_q$
- Non-flammable
- Non-toxic
- Inexpensive
- Effective
- Stable

Example: CFC's

- $C_xH_yF_zCl_q$
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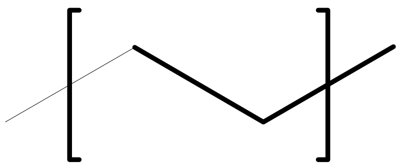
- Long-lived, migrate to upper atmosphere
- UV-induced fragmentation in upper atmosphere leads to ozone depletion

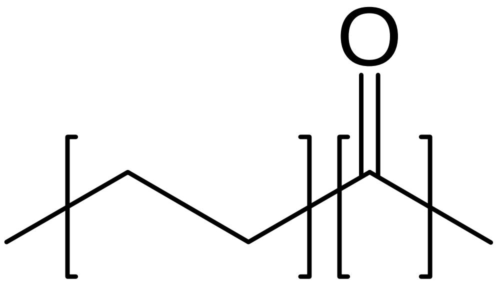
Example: Packing materials

Differences in cost, density, and energy intensity



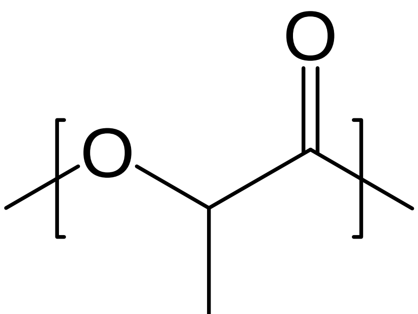
Polyethylene, packaging

Vs.



Photodegradable analog

Vs.



Biodegradable analog

Principle 8

- Meet Need, Not Excess

“design for unnecessary capacity or capability (e.g., “one size fits all”) solutions should be considered a design flaw”

- Don’t over design things; keep contingency factors low
- Extra size means wasted material and energy

Industry Overcapacity

- Global auto industry has 80 million vehicles/yr capacity for market of <60 million/yr

(“Where Optimism Meets Overcapacity”, NYTimes, Oct. 1, 1997)

- U.S. 2002 plant utilization ~ 75% (Industry Week)

Principle 9

- Minimize material diversity

  "options for final disposition are increased through upfront designs that minimize material diversity yet accomplish the needed functions"

Potential Examples…

- Automobile design: use single materials rather than alloys (metal and polymeric)
- Additives; create multi-functional additives rather than packages, incorporate additive functionality into polymeric backbone (dyes, flame retardants)
- Pigments; can pigments be switched “on” and “off”; can changes in pigment physical properties allow for variety of colors?

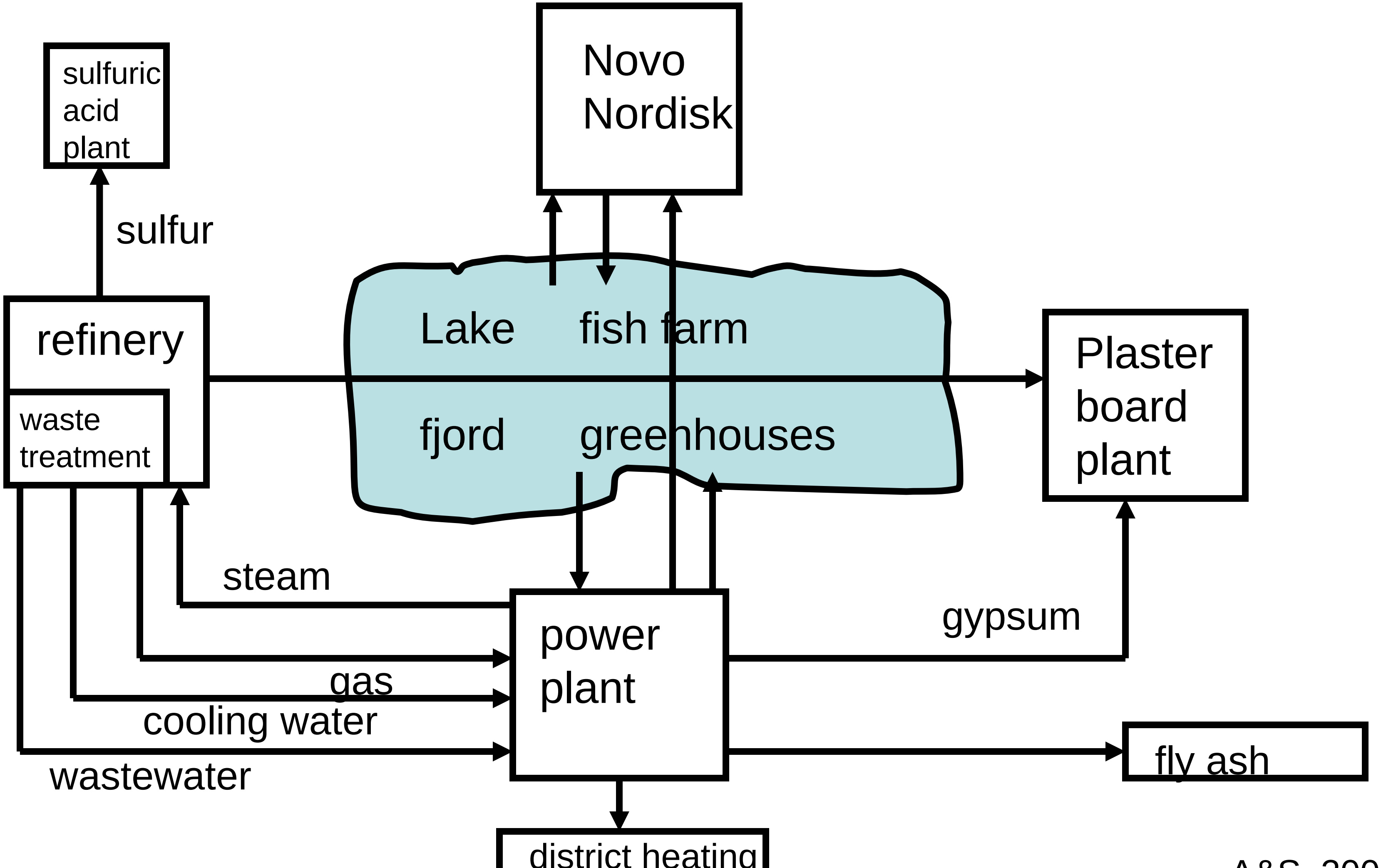
Principle 10

- Integrate Material and Energy Flows

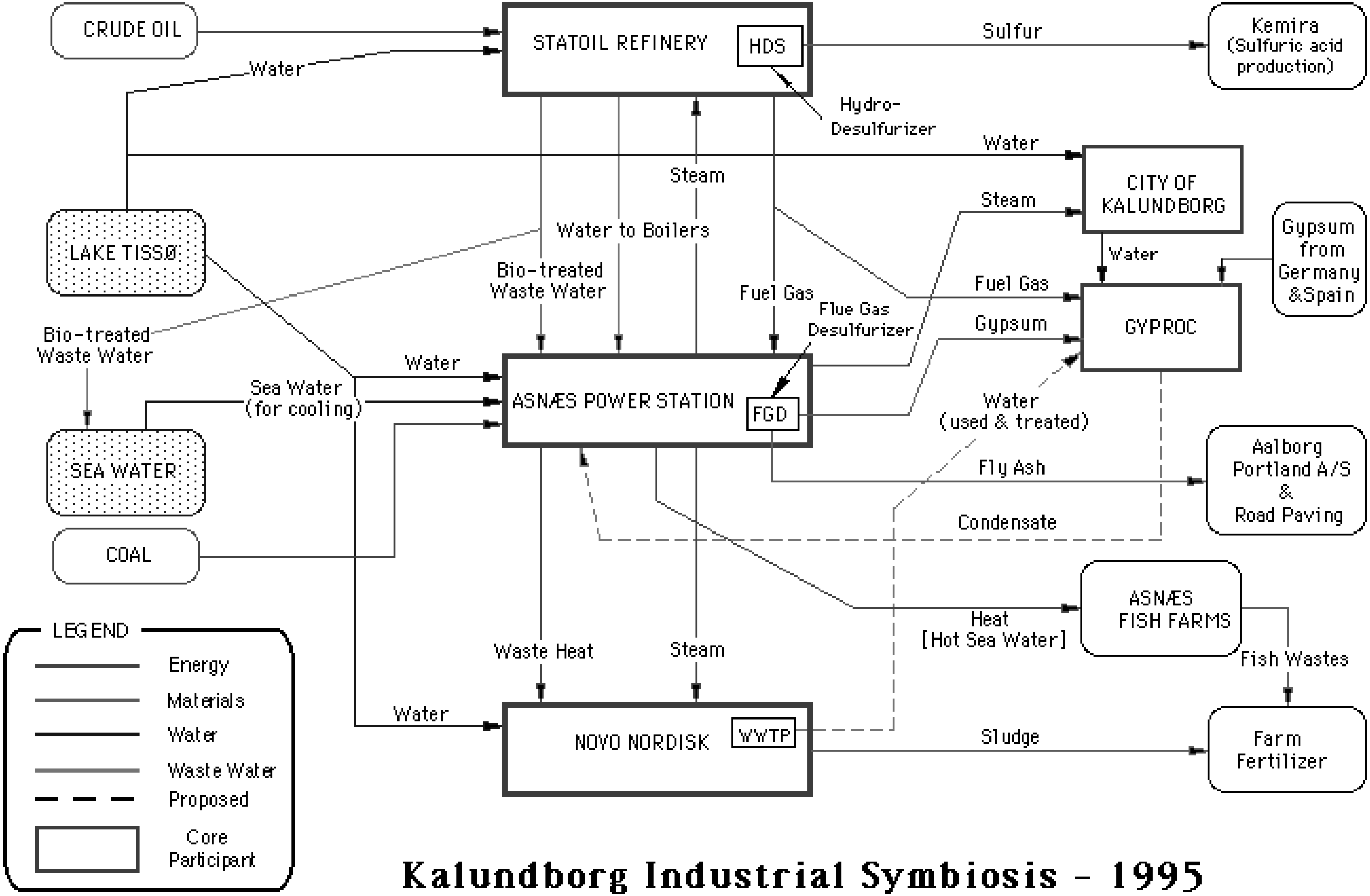
“design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows”

- Make use of what you’ve got available in process or on site

Kalundborg Industrial Park



A&S, 2002



Kalundborg Industrial Symbiosis - 1995

Drawn by D. B. Holmes based on information from various sources, including L.K. Evans, N. Gertler, and V. Christensen.

Principle 11

- Design for commercial afterlife

  "To reduce waste, components that remain functional and valuable can be recovered for reuse and/or reconfiguration".

Product Afterlife Examples

- Photodegradable polymers
- Conversion of old factories to housing
- Disassembly of equipment for reuse of components
- Creation of “plastic lumber” from used polymeric packaging material (molecular reuse)

- Uses for CO_2:

Oil recovery	Alternative solvent	Coffee decaffeination
Refrigerant	Food packing	Beverage additive
Antibacterial/fungal agent	Fire extinguishers	Water treatment
Raw material for chemical and material synthesis		

Principle 12

•Renewable rather than depleting

“Material and energy inputs should be renewable rather than depleting”

- Don’t want to deplete our natural resources
- Need resources to be there for future generations

- Energy: solar, wind, hydroelectric, geothermal, biomass, hydrogen (fuel cells)

Presidential Green Chemistry Challenge Award Winners
(selected examples)

2007

- Supercritical CO_2 for sterilizing medical equipment
- Alternative wood adhesive using soy flour

2006

- New synthetic path using enzymes for making Januvia™, a diabetes treatment (Merck)
- New enzymes for making active ingredients in Lipitor® (Codexis)
- Greenlist™ rates health/environmental effects of product ingredients (SC Johnson)

For more details, see: http://www.epa.gov/opptintr/greenchemistry/pubs/pgcc/past.html

References

- Allen and Rosselot, Pollution Prevention for Chemical Processes, 1997, John Wiley & Sons, Inc.
- Allen and Shonnard, Green Engineering, 2002, Prentice-Hall
- Seader and Henley, Separation Process Principles, 1998, John Wiley & Sons, Inc.
- Segars et al., ES&T, 2003, 37, 5269.

- Other sources:

  Various presentations by: **E. Beckman** (U. Pitt), **J. Brennecke** (U. Notre Dame), **R. Hesketh** (Rowan U.), **R. Keiski** (U. Oulu), and **D. Shonnard** (Mich.Tech)