# Implications of Nanomaterials Manufacture & Use

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USEPA Nanotechnology STAR Review
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# Outline

- Introduction
- Project background & approach
- Progress review
- Next steps
- Personnel

# Introduction

- *“Implications of Nanomaterials Manufacture and Use: Development of a Methodology for Screening Sustainability”*
- BRIDGES to Sustainability and Rice University
- Period: July 1st 2003 – June 30th 2005

# Underlying Question

*How can we incorporate sustainability considerations early in the development of an emerging technology?*

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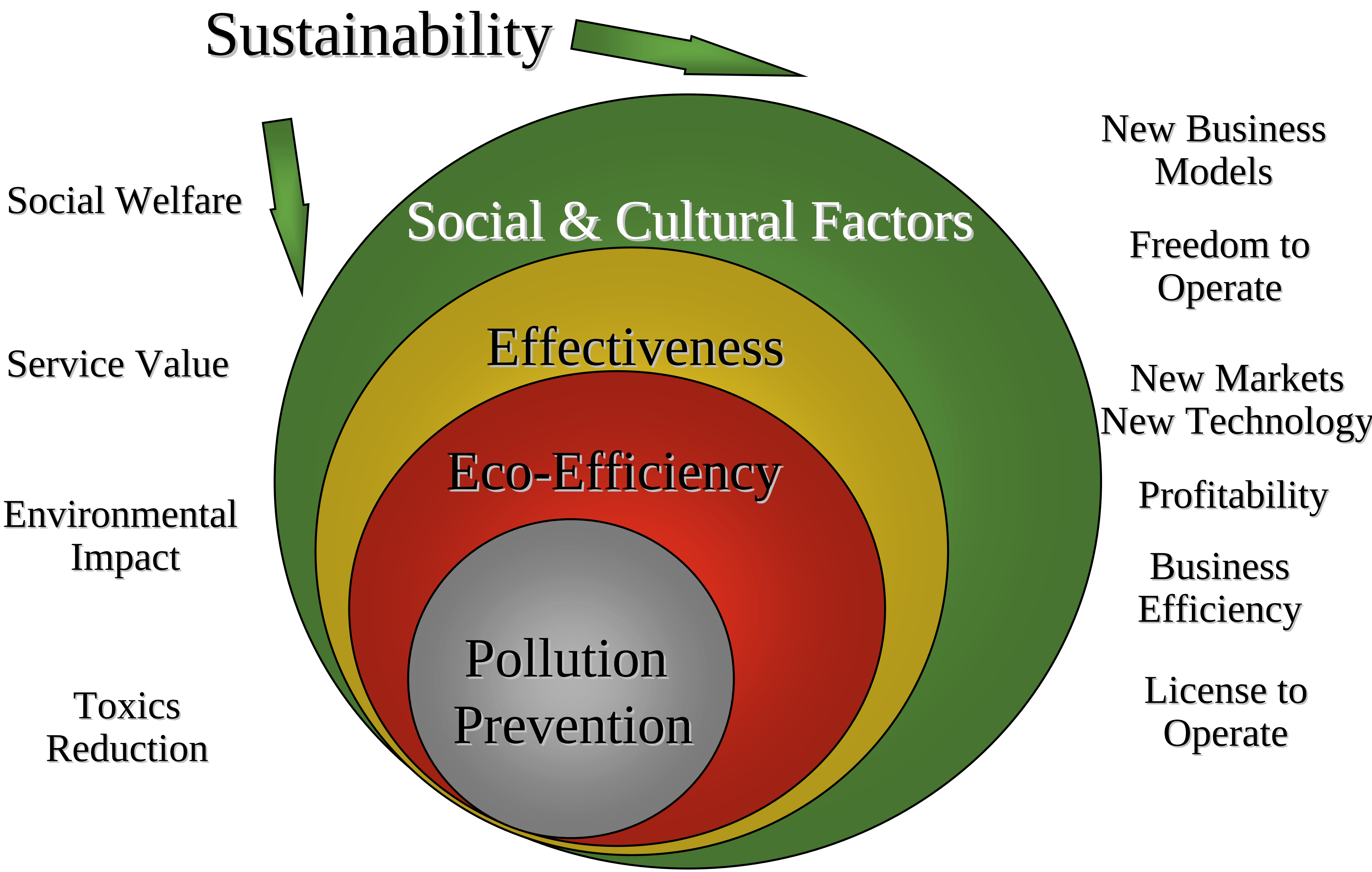
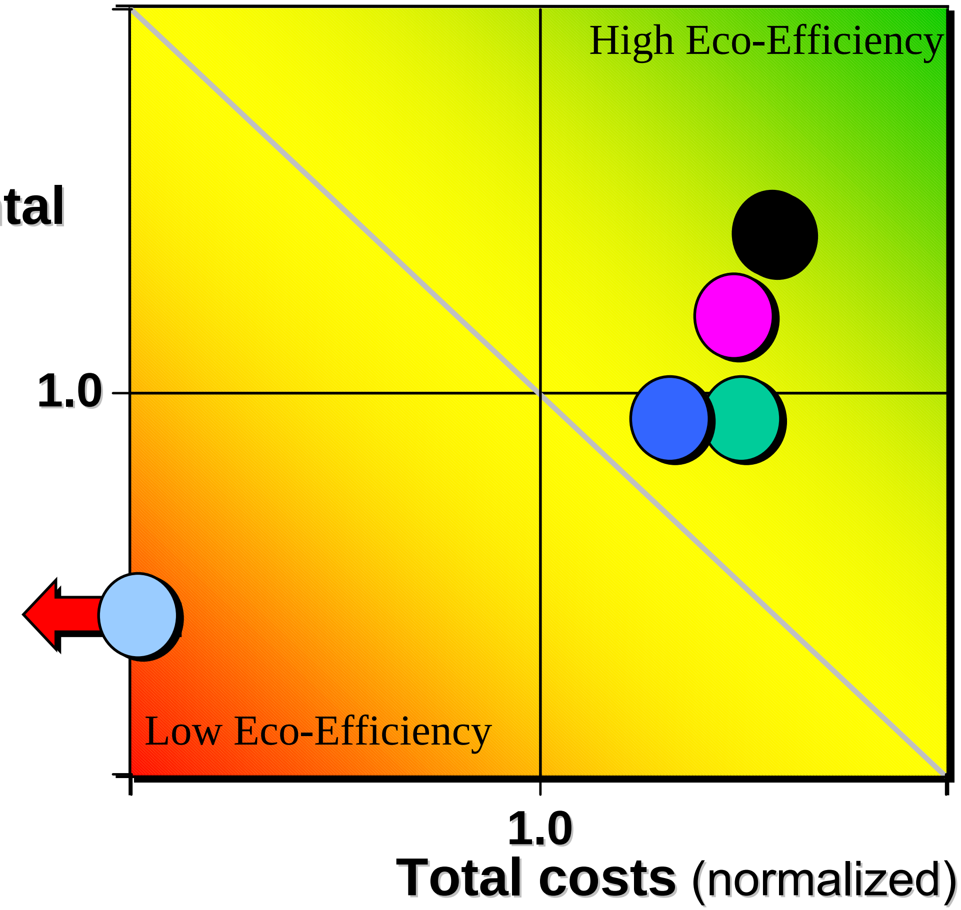
<u>Focus on near-term nanotechnology</u>

# Eco-Efficiency vs. Sustainability



# Eco-Efficiency at BASF

## Saling, Wall, et al., 2002



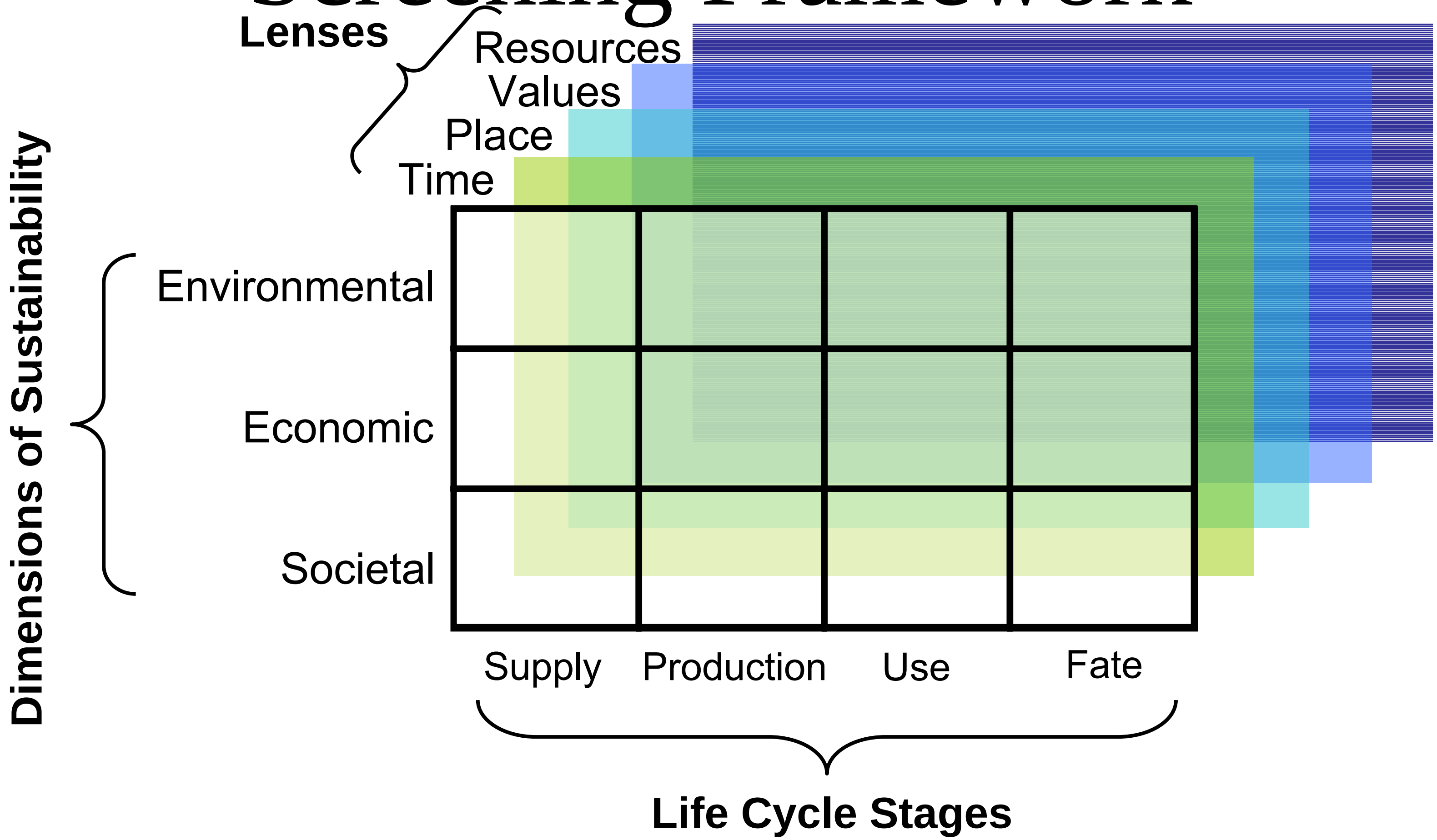

Single-score aggregate, includes

- Energy
- Raw materials
- Land area
- Emissions & waste
- Toxicity potentials
- Process risk

# Decision-Support Tools

- Sustainability metrics
- Lifecycle assessment
- Total benefit & cost assessment
- Thermodynamic analysis (exergy, etc.)
- Sustainability screen (list- and question-driven)

# Screening Framework



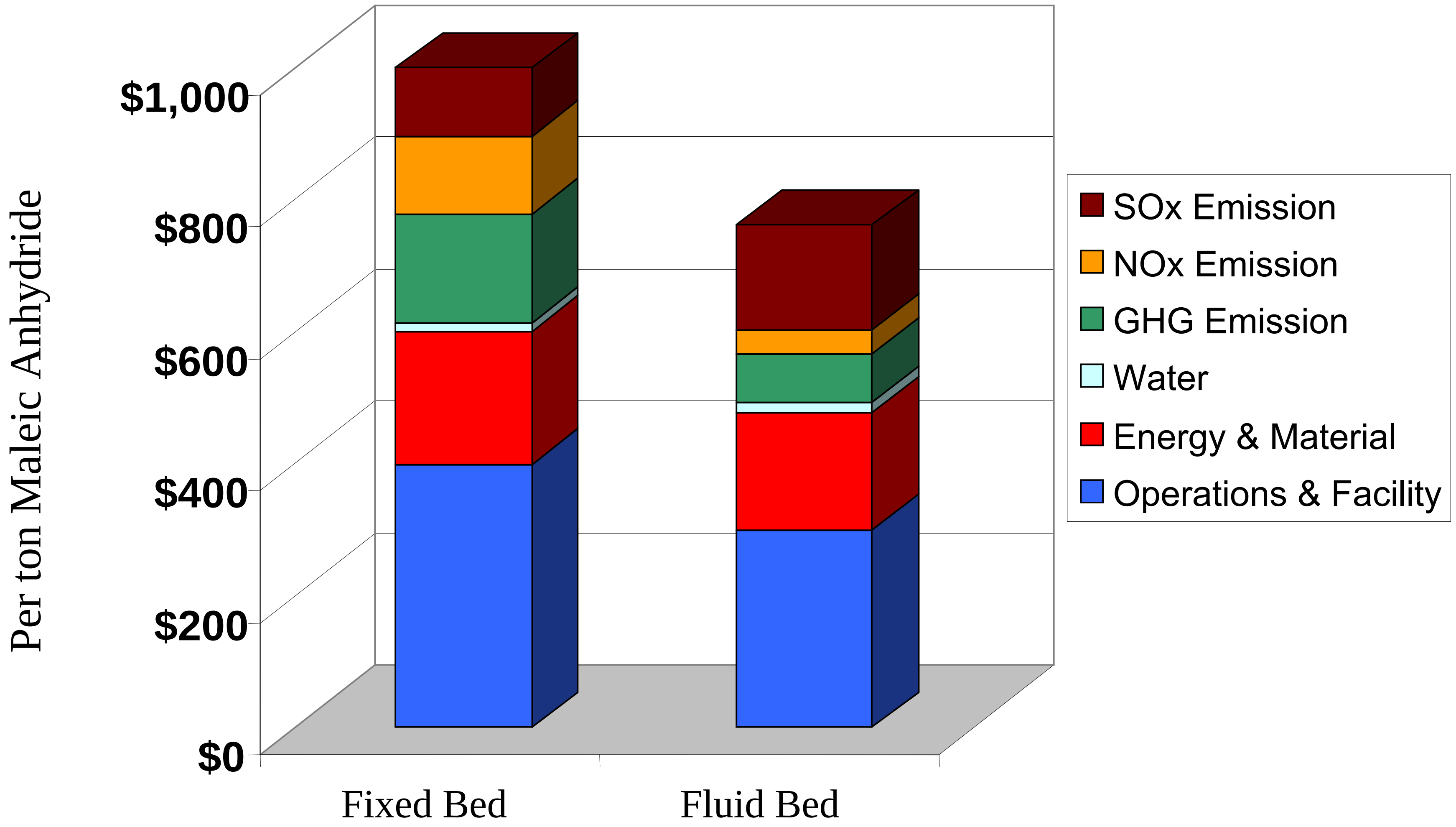
# Example Data Available

| Geographical Reference | Effects/Pathways | Costs Estimates, 2001$/ton | | |
|---|---|---|---|---|
| | | Low | High | Best |
| U.S. overall | Mortality & morbidity – 2nd nitrate PM10 | 1,326 | 21,533 | |
| | Mortality & morbidity - NO2 | 195 | 949 | |
| | Mortality & morbidity - ozone (50%) | 7 | 72 | |
| | Visibility - NOx | 247 | 1,443 | |
| | Total | 1,775 | 23,997 | 6,526 |
| U.S. urban | Mortality & morbidity – 2nd nitrate PM10 | 1,807 | 29,101 | |
| | Mortality & morbidity - NO2 | 247 | 1,248 | |
| | Mortality & morbidity - ozone (50%) | 13 | 91 | |
| | Visibility - NOx | 247 | 1,443 | |
| | Total | 2,315 | 31,883 | 8,590 |
| Los Angeles | Mortality & morbidity – 2nd nitrate PM10 | 7,867 | 98,601 | |
| | Mortality & morbidity - NO2 | 676 | 3,433 | |
| | Mortality & morbidity - ozone (50%) | 332 | 2,822 | |
| | Visibility - NOx **) | 247 | 1,443 | |
| | Total | 9,122 | 106,299 | 31,139 |

"McCubbin & Delucchi, 1999; Delucchi et al, 2001"

# Linking Metrics to TBCA

## Maleic Anhydride Production




Source: BRIDGES to Sustaianbility; SOx & NOx valuations based on So. California; GHG from IPCC

# Dimensions of Sustainability

## What is important?

| | | |
|---|---|---|
| **Environmental** | Resources | Material Intensity<br>Energy Intensity<br>Water Usage<br>Land Use |
| | Pollutants<br>Waste | Products / Processes / Services<br>Manufacturing Operations<br>Buildings / Sites<br>Effects: Ecosystems / Human Health |
| **Economic** | Internal | Eco-Efficiency<br>Costs<br>Revenue Opportunities<br>Access to capital / Access to insurance<br>Shareholder value |
| | External | Cost of externalities<br>Benefits to local community<br>Benefits to society |
| **Societal** | Workplace | Workplace conditions<br>Employee health / safety / well-being<br>Security<br>Human capital development (ed/train)<br>Aligning values |
| | Community | Social impacts<br>Stakeholder engagement<br>Quality of Life in community<br>Human rights |

# Project Issues

- Integrate both quantitative and qualitative aspects of sustainability assessment for emerging technology.
- The most important sustainability cost and benefit drivers for near-term nanomaterials.
- How to communicate with stakeholders.

# Near-Term Nano

- Very broad, hard to generalize
- Continuous improvements (c.f. disruptive technologies)
- Many unknowns/uncertainties
  - Nano-particle vs. bulk properties
  - Exposure in use
  - Fate at end-of-life (PBT concerns)

# Project Approach

- Identify sustainability aspects/impacts along the lifecycle of nanomaterials
  - Literature review
  - Focus on drivers of costs and opportunities

- Construct inventory of resource use, waste, and emissions in manufacturing
  - Focus on three case studies
  - Identify “preferred recipe” for each nanomaterial
  - Literature + expert “interviews”
- Expand analysis to upstream and downstream
  - Quantitative and qualitative

- Generalize approach

# Nanomaterials – General Manufacturing

- Eco-efficiency
  - Resource use intensity & impacts
  - Pollutant intensity & impacts
- Land use
- Economic value generation
- Workplace health and safety

# Nanomaterials – General Use

- Product performance/service value
- Eco-efficiency in use
- Consumer health & safety

# Nanomaterials – General End-of-Life

- Recyclability
- Release to the environment
  - PBT concerns
    - Low solubility favors persistence
    - Biological intake and possible bioaccumulation
    - Toxicity of nanoparticles (as opposed to their bulk counterparts) largely unknown

# Nanotechnology & Sustainability: Promises

- Better and more cost-effective technologies
  - Separation
  - Process sensors and control
  - Emission/effluent/waste treatment and remediation
- Greater material & energy efficiency
- Renewable energy (solar)
- …

# Health & Safety Concerns

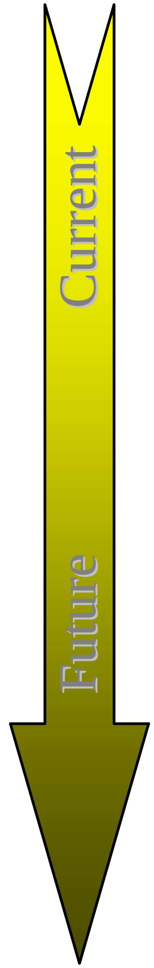
- Ultra-fine particles (< 100 nm)
  - More reactive
  - More potent in inducing respiratory inflammation
  - May cross blood-brain barrier
- Properties of nanoparticles (as opposed to bulk) largely unknown
- Workspace intake (inhalation, oral, …)
- Consumer intake/chemical trespass (inhalation, skin absorption, …)

# Nanotechnology & Sustainability: Threats

- “Nano-pollutants” and new exposure routes
- Changes faster than human ability to ponder and make necessary corrections
- Affordability leading to increased worldwide consumption
- Widening gap between rich and poor, North and South
- Pseudo-Science

# Cost Types


| | | |
|---|---|---|
| 1 - Direct | Capital, labor, raw materials and waste disposal | Operating and maintenance for treatment works |
| 2 - Indirect | Overhead costs not properly allocated to product or process | Community relations<br>Regulatory costs<br>Monitoring costs |
| 3 - Future & contingent liability | Unforeseen, but very real costs | Remediation, fines, restoration & penalties |
| 4 - Internal intangible | Image and relationship costs corporate costs | Employee turnover<br>Recruitment costs |
| 5 - External intangible | Public costs not yet borne internally | Consumer perception<br>Resource depletion |



# Sustainability Model

Societal Benefits
+
Business Revenues

Societal Costs
+
Business Costs

Invest when **Business revenues > Business costs**
and **<u>Total</u> benefits > <u>Total</u> costs**

# General Nanotechnology

| | Supplier | Production | Use | End-of-life |
|---|---|---|---|---|
| **Benefits** | Higher price<br>Less mass | Higher heat transfer<br>More uniformity<br>Less land<br>Less waste | Time to market<br>New products | Recyclability? |
| **Costs** | Higher costs | Workplace safety issues | Consumer safety issues | Disposal issues |

*Public Concern about Nanotechnology*

# Selected Cases

- Inorganic sunscreens – *bulk*- *vs*. *nano*-*sized titania*
- Ceramic membrane – *sol*-*gel vs*. *alumoxane nanoparticles*
- Fullerenes (buckyballs)

# Nano-tech vs Conventional Inorganic Sunscreens

| | Extraction | Production | Use | End-of-life |
|---|---|---|---|---|
| **Benefits** | ? | ? | • Aesthetic<br>• Broader protection spectrum | ? |
| **Costs** | ? | • Workplace inhalation? | • Skin absorption? | • Aquatic releases |

*Public Concern about Nanotechnology*

# Alumoxane vs. Sol-gel Membranes

| | Extraction | Production | Use | End-of-life |
|---|---|---|---|---|
| **Benefits** | ? | • Less energy<br>• No hazardous substances | ? | ? |
| **Costs** | ? | • Worker exposure to nanoparticle ? | ? | ? |

*Public Concern about Nanotechnology*

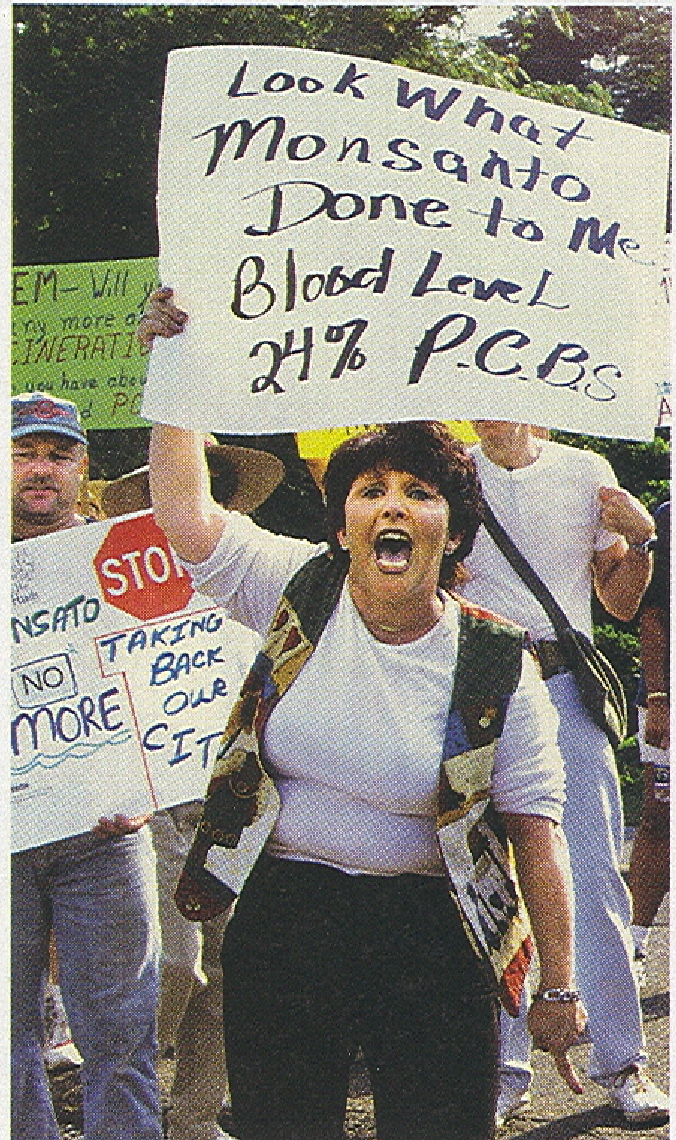



PHOTO BY TRENT PENNY/ANNISTON STAR

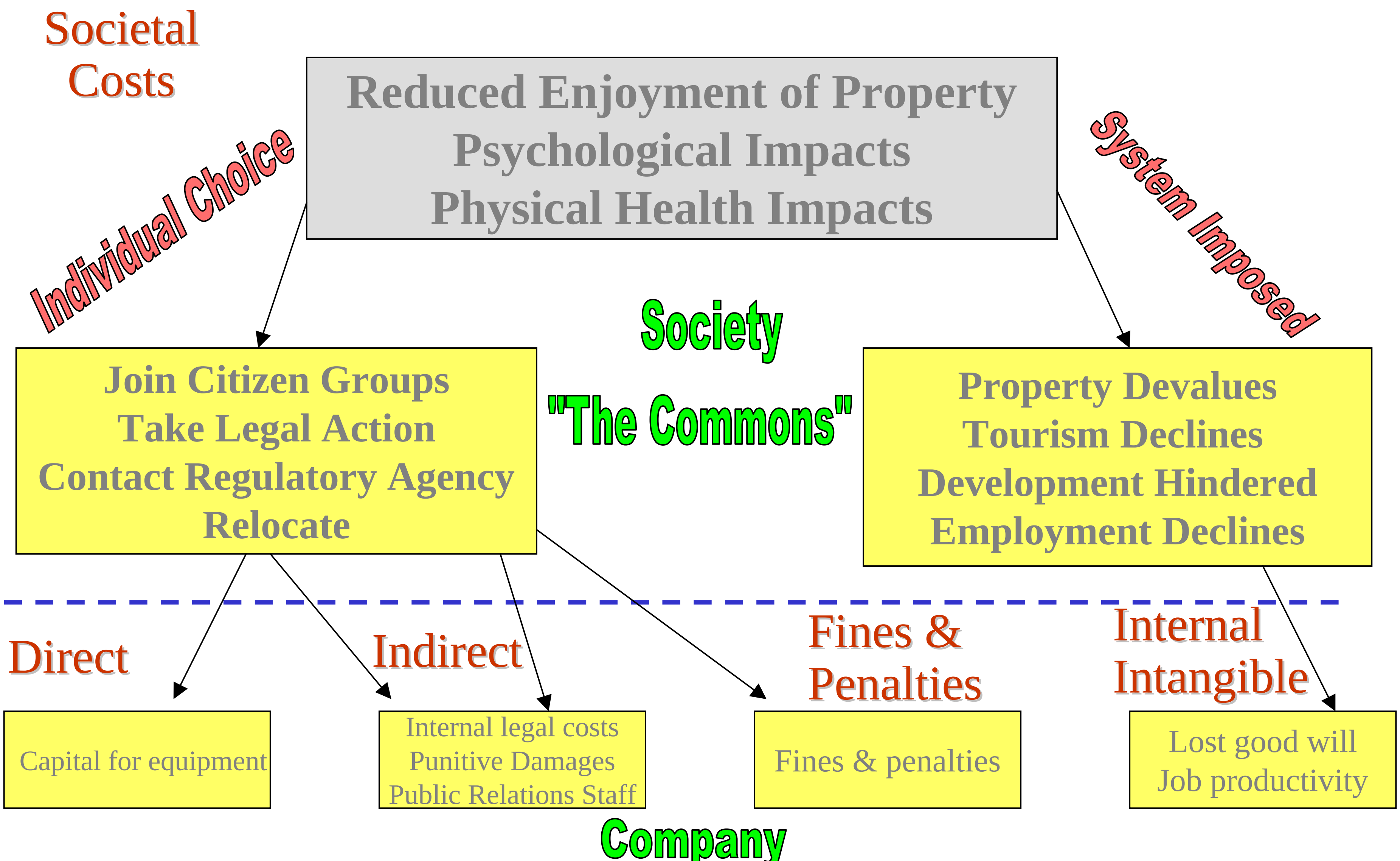
**ANGRY** Residents of Anniston, Ala., protested pollution from polychlorinated biphenyls.

Story: C&ENews December 22, 2003

# Sustainability Model


Invest when **Business revenues > Business costs**
and **<u>Total</u> benefits > <u>Total</u> costs**

# Evolution of Costs: “Harmless” Odors



# Next Steps

- Continue manufacturing inventory
- Collect safety and LCA data on materials used in manufacturing
- Expand analysis of cost/benefit drivers to extraction and end-of-life
- Solicit comments

# Implications of Nanomaterials Manufacture and Use: Project Plan

RICE

Identify key nano-materials

- Bucky balls (C60)
- Single-wall carbon nanotubes
- Quantum dots
- Alumoxanes & Ferroxanes
- Nano-Titanium Dioxide

# Implications of Nanomaterials Manufacture and Use: Project Plan

RICE

**Identify key nano-materials**

- Bucky balls (C60)
- Single-wall carbon nanotubes
- Quantum dots
- Alumoxanes & Ferroxanes
- Nano-Titanium Dioxide

**Research production methods & required materials**

- Preferred "recipe(s)" for each nanomaterial
- Process used with each recipe

# Implications of Nanomaterials Manufacture and Use: Project Plan

RICE

Identify key nano-materials

Research production methods & required materials

**Deliverables for Existing Project**

- Preferred "recipe(s)" for each nanomaterial
- Process used with each recipe

- Bucky balls (C60)
- Single-wall carbon nanotubes
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# Implications of Nanomaterials Manufacture and Use: Future

RICE

1. Identify key nano-materials
2. Research production methods & required materials
3. Project production volumes based on expected applications
4. Collect material characteristics of inputs, additives, and outputs
5. Model relative manufacturing risk of nano-materials

- Projected market uses
- Projected production volumes
  - Variety of opinions
  - Variety of time horizons

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RICE

1. Identify key nano-materials
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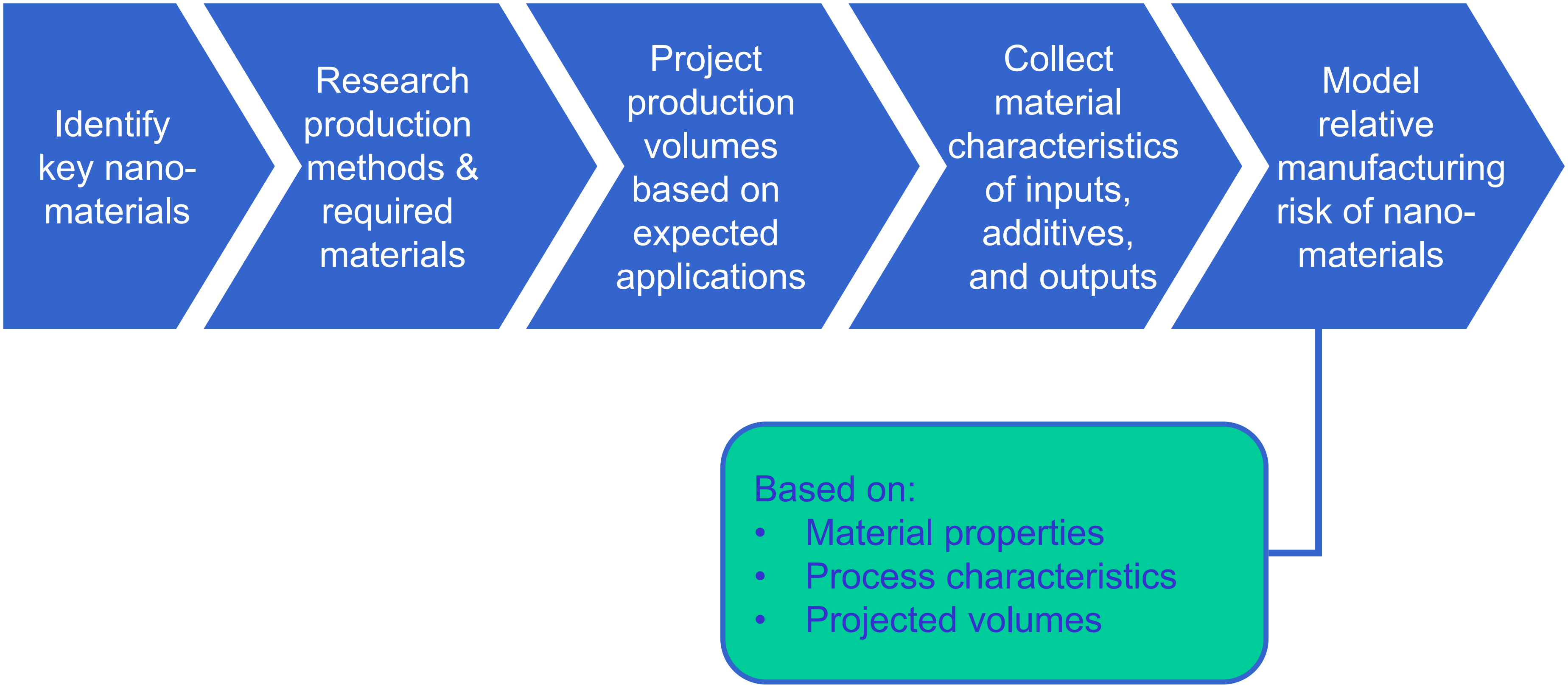
| **Materials:** | **Processes:** |
| --- | --- |
| • Octanol / Water partitioning coefficient | • Temperature |
| • Molecular weight | • Pressure |
| • Specific gravity | • Enthalpy |
| • pH tolerance ranges | • Duration |
| • Toxicity | |

# Implications of Nanomaterials Manufacture and Use: Future

RICE



# Project Personnel

- PI: Earl Beaver
- BRIDGES to Sustainability
  - Beth Beloff (co-PI)
  - Dicksen Tanzil (co-PI)
  - Balu Sitharaman (intern, Rice Dept. of Chemistry)
- Rice University
  - Mark Wiesner (co-PI)
  - Christine Robichaud
  - Maria Cortalezzi

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