An Integrated Economic and ESH Framework for Making Technology Choices

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NSF/SRC Engineering Research Center

Environmentally Benign Semiconductor Manufacturing
Tele-seminar 24th July 2003
Key Message

ESH – Environment, Safety and Health

COO – Cost of Ownership

They must be seamlessly integrated for effective decision making
**Why are Technology Choices Complex?**

**Example:** Choosing a chamber cleaning gas (NF$_3$ vs. F$_2$?)

<table>
<thead>
<tr>
<th>Decision Criteria</th>
<th>NF$_3$</th>
<th>F$_2$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorine usage rate at the same etch rate (mole/min)</td>
<td>0.15</td>
<td>0.17</td>
<td>This work</td>
</tr>
<tr>
<td>Cost/mole of Fluorine</td>
<td>$6</td>
<td>$0.8</td>
<td>[1]</td>
</tr>
<tr>
<td>LCA Global Warming Effect (kg CO$_2$ equivalent/kg)</td>
<td>3.3</td>
<td>2.4</td>
<td>This work</td>
</tr>
<tr>
<td>Toxicity LC$_{50}$ (ppm)</td>
<td>6700</td>
<td>180</td>
<td>[2,3]</td>
</tr>
</tbody>
</table>

**The Problem:** How to choose between technologies

- When there are conflicting decision criteria
- Many uncertainties
1. How much information do we need to know in order to get the sign right?

2. How do we decide where to allocate resources for more analyses, experiments and/or better data?
Industry recognition of need

“...There is a critical need for an integrated way to evaluate and qualify environmental impact of process, chemicals, and process equipment...”
-- ITRS, 2001 Edition, Environmental, Safety, and Health

Emerging Driving forces for Change

“...The European Commission Integrated Product Policy (IPP) will look at all stages of a product’s life cycle from cradle to grave...we are calling on industry to bring IPP to life”
-- M. Wallström, EU Environment Commissioner
Press release 18th June 2003
Outline of Presentation

- Review of Current Approaches
  - CARRI, EnV-S, TEAM,…

- Development of Decision criteria
  - System boundary choice
  - Cost of Ownership (COO)
  - Environment, Health and Safety (EHS)
  - Integration of COO and EHS

- Impact Assessment Models
  - Process models for mass and energy balances
  - Hierarchical representations
  - Treatment of uncertainties

- Example
  - $\text{NF}_3$ vs. $\text{F}_2$ case study

- Conclusions and Next Steps
## Comparison of Environmental Valuation Methods

<table>
<thead>
<tr>
<th>Impact Categories Considered</th>
<th>CARRI</th>
<th>S70</th>
<th>TEAM</th>
<th>EnV-S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Work space safety and health, broad characterization of environmental toxicity, regulatory, COO</td>
<td>Mass and energy consumed, transformed, and discharged</td>
<td>More than 50 categories such as global warming effect, human toxicity, aquatic/terrestrial ecotoxicity</td>
<td>COO, human health (cancer, acute toxicity, etc), regulatory</td>
</tr>
<tr>
<td>Applications</td>
<td>Relative risk of chemical usage</td>
<td>Determine the overall material and energy usage and waste products generated by the unit operations</td>
<td>Quantifying environmental impacts of the operations associated with products, processes, and activities</td>
<td>Tool design, choosing between alternative tools</td>
</tr>
<tr>
<td>System Boundary</td>
<td>Fab, downstream</td>
<td>Fab</td>
<td>Upstream, fab, downstream</td>
<td>Upstream, fab, downstream</td>
</tr>
<tr>
<td>Inputs based on database or model</td>
<td>Database</td>
<td>Static, averaged process model</td>
<td>Based on user input, databases</td>
<td>Process models</td>
</tr>
<tr>
<td>Site Specific</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Linked to Cost</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Include Uncertainty</td>
<td>Qualitative</td>
<td>No</td>
<td>User can set up limited probability distributions</td>
<td>PDFs, Monte Carlo simulations</td>
</tr>
<tr>
<td>Database availability</td>
<td>Inventories and impacts</td>
<td>Inventories</td>
<td>Inventories and impacts</td>
<td>Inventories</td>
</tr>
</tbody>
</table>
Key points from review of ESH models

- Widespread industry acceptance of SEMI COO model but it is not integrated into ESH methods
- Decision criteria are influenced by the choice of system boundaries but few methods look outside the plant boundaries
- No formalized treatment of uncertainties or means for identifying what controls decision outcomes
- Little consistency between databases used for analyses and there are many data gaps
- Little cross fertilization of good ideas from other industries
Operational Challenges

A new framework must:

- Be compatible with the short innovation cycle
- Show the value of treating environment as an objective in design and operations
- Handle different levels of understanding in the process and economic models
- Deal with the large EHS information uncertainties
  - ~1 orders of magnitude in air pollutant emission factors
  - 2 ~ 3 orders of magnitude in cancer toxicity indicators
  - 3 ~ 6 orders of magnitude in non-cancer toxicity indicators
Value of Treating the Environment as an Objective

- The Energy and Waste Reduction Contests at Dow Chemical

- A 180% annual return on $3 million invested in projects to reduce toxic waste generation and emissions (Midland site, Dow Chemical).
An Environmental Evaluation Model

Process Model

- Design Decisions
- Upstream & Downstream Emissions, Material and Energy Usage
  - Flow Rates
  - Products
  - Byproducts
  - Chemical Properties
  - Energy
  - Water
  - Waste
  - Yield
  - Process Time

Input Output LCA Model

- Human Toxicity
- Global Warming Effect
- Ozone Depletion Effect
- Respiratory Effect

Impact Indicator

Weighting Factors

Environmental Performance

Compliance with Regulations

Alternative Designs

- Fate, Transport, and Exposure Model
- Environmental Properties
- Chemical Properties
- Exposure Properties
- Emissions

LCA Model

Upstream & Downstream Emissions, Material and Energy Usage

Upstream & Downstream Emissions, Material and Energy Usage
Human Exposure Modeling: Complex Interactions*

Very complicated system, large number of parameters

Modified Mackay-type level III fugacity model

Human exposure model

Emissions

Vegetation

Ground soil

Root-zone soil

Air

Water

Sediments

Inhalation

Water ingestion

Food ingestion

Irrigation

transpiration

air exchange, particle deposition

BCF_{fish}

RCF

BTF_{beef}

BTF_{milk}

Ingestion

Food ingestion

Water ingestion

* Cano–Ruiz 2000
Mathematical Model

- Model Input Six: Price vector (p)
- Allocation matrix (G): for multiple product processes

\[ G_{ji} = \begin{cases} \frac{p_i}{\sum_k C_{kj} p_k} & \forall C_{ij} \neq 0 \\ 0 & \forall C_{ij} = 0 \end{cases} \]

G_{ji}: the amount of throughput of process j that is attributed to one unit of product i made in process j

- Throughput matrix (D)

\[ D_{ji} = F_{ji} G_{ji} \]

D_{ji}: the amount of throughput of process j that is attributed to the demand of one unit of product I at current price and market share

- Direct product requirement (q_{direct})

\[ q_{direct} = (I + BD)d \]

- Total product requirements

\[ q = (I + A_{prod} + A_{prod}A_{prod} + A_{prod}A_{prod}A_{prod} + \ldots) d = (I - A_{prod})^{-1} d \]

where \( A_{prod} \equiv BD \)
Mathematical Model

- Total process throughput requirements \((x)\)
  \[ x = Dq \]

- Life cycle environmental exchanges inventory \((e)\)
  \[ e = Ex \]

- Impact valuation by process \((\Omega_{\text{process}})\)
  \[ \Omega_{\text{process}} = \text{Diag}(x) E^T H w \]

- Impact valuation by emission \((\Omega_{\text{emission}})\)
  \[ \Omega_{\text{emission}} = \text{Diag}(e) H w \]
Cost of Ownership (CoO) Model

- Design Decisions
- Process Model
- Alternative Designs

Annualized Recurring Cost
- Footprint
- Prices
- Internal Charges
- Flow Rates
- Products
- Byproducts
- Chemical
- Energy
- Water
- Waste
- Throughput
- Unit Volume
- Equipment Yield
- Parametric Limited Yield
- Defect Limited Yield

Annualized Fixed Cost

Cost of Equipment Ownership

Cost of Ownership

Equipment Yield

Throughput per Year

Waste

Alternative Designs
Overlapping Data Requirements

There are many areas of overlap
Matrix Presentation of Cost-of-Ownership

- COO = Cost of Equipment Ownership (CEO) + Cost of Yield Loss (CYL)

- CEO = Fixed Cost + Recurring Cost

- Recurring Cost = $\begin{bmatrix} P_{NF_3} & P_{N_2} & P_{Ar} & P_{Energy} & P_{Water} & P_{WasteDisposal} & P_{Lbm} & \ldots & P_{Sp} & P_{Sc} \end{bmatrix} \times \begin{bmatrix} U_{NF_3} & U_{N_2} & U_{Ar} & U_{Energy} & U_{Water} & U_{WasteDisposal} & U_{Lbm} & \ldots & U_{Sp} & U_{Sc} \end{bmatrix}^{-1}$

- CYL = $\left( \frac{\text{annualized cost of wafers lost due to equipment yield}}{\text{good units per year}} + \frac{\text{annualized attributed cost of wafers lost due to defect & parametric yield}}{\text{good units per year}} \right) \cdot \frac{1}{\text{good units per year}}$
## Excerpt from an Life Cycle Assessment Calculation

<table>
<thead>
<tr>
<th>PRODUCT INPUTS</th>
<th>UNITS</th>
<th>PROCESS</th>
<th>USAGE MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>kg</td>
<td>Coal furnace</td>
<td>0.03</td>
</tr>
<tr>
<td>clean chamber</td>
<td></td>
<td>Coal production</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>kg</td>
<td>Coal-fired power plant</td>
<td>0.03</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>kg</td>
<td>F2 chamber cleaning</td>
<td>0.06</td>
</tr>
<tr>
<td>Electricity</td>
<td>MJ</td>
<td>F2 production</td>
<td>8.0 0.1 6.55 6.55</td>
</tr>
<tr>
<td>F2</td>
<td>kg</td>
<td>Industrial gas furnace</td>
<td>18.0 0</td>
</tr>
<tr>
<td>Fluorine from Chamber Cleaning</td>
<td>kg</td>
<td>Natural gas product</td>
<td>3.3 0.05 2.5 0.1 0.05</td>
</tr>
<tr>
<td>HF</td>
<td>kg</td>
<td>NF3 chamber cleaning</td>
<td>0.07</td>
</tr>
<tr>
<td>KF</td>
<td>kg</td>
<td>Oil furnace</td>
<td>0.01 10.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>N2</td>
<td>kg</td>
<td>Oil production</td>
<td>0.01 10.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>kg</td>
<td>Oil-fired power plant</td>
<td>0.01 10.0 0.0 0.0 0.0</td>
</tr>
<tr>
<td>NF3</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiF4</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy from coal furnace</td>
<td>MJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy from industrial gas furnace</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy from oil furnace</td>
<td>MJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal energy from utility gas furnace</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Usage Matrix values are illustrative and subject to change based on actual calculations.*
### Hierarchical Modeling

<table>
<thead>
<tr>
<th>Pro</th>
<th>Assumption</th>
<th>Likely distributions for gas usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Tolerable efficiency</td>
<td>Yield of $\zeta = \zeta$ ($\zeta$ is a very small number)</td>
<td></td>
</tr>
<tr>
<td>2 Stoichiometric</td>
<td>100% efficiency, extremely quick etching</td>
<td></td>
</tr>
<tr>
<td>2 Simple kinetics</td>
<td>Only a few key reactions</td>
<td></td>
</tr>
<tr>
<td>3 Detailed kinetics</td>
<td>First principles</td>
<td></td>
</tr>
<tr>
<td>4 Experiments</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hierarchical Modeling

<table>
<thead>
<tr>
<th>Process Model</th>
<th>Likely distributions for gas usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Simple kinetics</td>
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<td>3 Detailed kinetics</td>
<td>First principles</td>
</tr>
<tr>
<td>4 Experiments</td>
<td></td>
</tr>
</tbody>
</table>

Time and cost increase

- 100% efficiency
- ζ efficiency

100% efficiency

ζ efficiency

Experiments

First principles

Only a few key reactions

Simple kinetics
<table>
<thead>
<tr>
<th>Process Model Hierarchy</th>
<th>Distribution of Flows</th>
<th>Resources Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Simple stoichiometric yield</td>
<td>![Graph]</td>
<td>1</td>
</tr>
<tr>
<td>2 Lumped kinetics (3 reactions)</td>
<td>![Graph]</td>
<td>10</td>
</tr>
<tr>
<td>3 Detailed kinetics (60 reactions)</td>
<td>![Graph]</td>
<td>100</td>
</tr>
<tr>
<td>4 Model based experiments</td>
<td>![Graph]</td>
<td>1000</td>
</tr>
</tbody>
</table>
# Simple Stoichiometric Yield Model

<table>
<thead>
<tr>
<th>Gas</th>
<th>Model</th>
<th>gm of gas / mole SiO$_2$</th>
<th>$\eta = 5%$</th>
<th>$\eta = 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$NF_3$</td>
<td>$\frac{1}{\eta} \cdot \frac{4SiF_4 + HF}{3}$</td>
<td>1900</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>$F_2$</td>
<td>$\frac{1}{\eta} \cdot \frac{4SiF_4 + HF}{2}$</td>
<td>1520</td>
<td>76</td>
<td></td>
</tr>
</tbody>
</table>
Lumped Kinetics and CSTR Model

Key Assumptions

- Free electrons are generated mainly by ionization $X^2 + e \rightarrow X^2^+ + 2e$
- Electron loss and production are linear to electron concentration
- Diffusion of electrons dominates the transport of electrons.

\[
\begin{align*}
NF_3 + e & \rightarrow NF_2 + F^+ + e & k_3 = 2.06 \times 10^{-17} T_e^{1.7} \exp(-37274/T_e) \\
NF_2 + e & \rightarrow NF + F^+ + e & k_2 = 1.57 \times 10^{-17} T_e^{1.8} \exp(-27565/T_e) \\
NF + e & \rightarrow N + F^+ + e & k_1 = 1.57 \times 10^{-17} T_e^{1.8} \exp(-27565/T_e) \\
F_2 + e & \rightarrow F^- + F^+ & k = 1.02 \times 10^{-5} T_e^{-0.9} \exp(1081.8/T_e)
\end{align*}
\]

\[
F^+ + SiO_2 \rightarrow SiF_4, \quad r = (8.97 \pm 0.82) \times 10^{-13} n_F T_s^{1/2} \exp\left(-\frac{0.163 eV}{kT_s}\right)
\]

\[
\begin{align*}
n_{F,NF_3} & = \frac{\beta_3 \tau n_{NF_3,in}}{1 + \beta_3 \tau} + \frac{\beta_2 \beta_3 \tau^2 n_{NF_3,in}}{(1 + \beta_2 \tau)(1 + \beta_3 \tau)} + \frac{\beta_1 \beta_2 \beta_3 \tau^3 n_{NF_3,in}}{(1 + \beta_1 \tau)(1 + \beta_2 \tau)(1 + \beta_3 \tau)} \\
n_{F,F_2} & = \frac{\beta_{F_2} \tau n_{F_2,in}}{1 + \beta_{F_2} \tau} \\
\beta_i & \equiv k_in_e
\end{align*}
\]
Uncertainty Analysis for NF$_3$ Etch Rate

Assume 10% uncertainty in $A_i$ and $E_{ai}$, no uncertainty in $\beta_i$.

\[
\text{NF}_3 + e \rightarrow \text{NF}_2 + F + e \\
\text{NF}_2 + e \rightarrow \text{NF} + F + e \\
\text{NF} + e \rightarrow N + F + e \\
F + \text{SiO}_2 \rightarrow \text{SiF}_4
\]

\[
k_i = A_i \cdot T_e^{\beta_i} \cdot e^{-\frac{E_{ai}}{T_e}}
\]

\[
r = k \times n_F \times T_s^{1/2} \times \exp\left(-0.163 \times eV \left/ k_B T_s\right.^{-1}\right)
\]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rank Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept for $k_B T_e \sim E_e / p$</td>
<td>0.659466</td>
</tr>
<tr>
<td>Activation energy $E_{a3}$ for NF$_3$ decomposition</td>
<td>-0.65332</td>
</tr>
<tr>
<td>Rate constant $k$ for etch reaction</td>
<td>0.227614</td>
</tr>
<tr>
<td>Activation energy $E_{a2}$ for NF$_2$ decomposition</td>
<td>-0.10335</td>
</tr>
<tr>
<td>Pre-exponential coefficient $A_3$ for NF$_3$ decomposition</td>
<td>0.093827</td>
</tr>
</tbody>
</table>
Identifying Important Parameters to GWP

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rank Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF₃ Yield in NF₃ Production</td>
<td>-0.71</td>
</tr>
<tr>
<td>Energy Usage in F₂ production</td>
<td>0.42</td>
</tr>
<tr>
<td>Intercept for $k_B T_e \sim E = /\rho$</td>
<td>-0.39</td>
</tr>
<tr>
<td>Activation Energy $E_{a3}$ for NF₃ decomposition</td>
<td>0.34</td>
</tr>
<tr>
<td>Energy Usage in NH₃ production</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Assume 10% uncertainty in $A_i$ and $E_{ai}$, no uncertainty in $\beta_i$. 
Assume 10% uncertainty in $A_i$, $E_{ai}$, and $\beta_i$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rank Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power $\beta_3$ to the electron temperature for NF$_3$ decomposition</td>
<td>0.87</td>
</tr>
<tr>
<td>Activation Energy $E_{a3}$ for NF$_3$ decomposition</td>
<td>-0.27</td>
</tr>
<tr>
<td>Power $\beta_2$ to the electron temperature for NF$_2$ decomposition</td>
<td>0.267</td>
</tr>
<tr>
<td>Intercept for $k_B T_e \sim E_e / P$</td>
<td>0.24</td>
</tr>
<tr>
<td>Power $\beta_1$ to the electron temperature for NF decomposition</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Chamber Cleaning with NF$_3$/F$_2$

- NF$_3$/F$_2$, Ar, N$_2$
- Plasma Generator
- RF Power
- F, NF, NF$_2$, Ar
- N$_2$, F-, NF$^+$ ...
- SiO$_2$ Deposited on wall
- Chamber Wall
- CVD Reaction Chamber
- HF, SiF$_4$
- F, F$_2$, HF, N$_2$, SiF$_4$...
SiF$_4$, F$_2$, N$_2$…

- **Fuel Usage** – Similar
- **Water Usage** – 548 gallon/yr for NF$_3$, 566 gallon/yr for F$_2$
  - Insignificant compared to 1 million gallon/day
Case Study: NF₃ vs. F₂ as Chamber Cleaning Gas

- **Merits of NF₃**
  - High disassociation rate
  - High removal rate
  - High etch rate

- **Drawback of NF₃**
  - High cost

- **Merits of F₂**
  - Low cost

- **Drawbacks of F₂**
  - High toxicity
  - High reactivity
  - POU generation creates explosive H₂

- **NF₃ Cleaning Process in the Fab**

  ![Diagram](image)

  - Basis for Comparison – Same etch Rate $r_e$ for both processes
  - Strategy  – Same process parameters except $F_{\text{cleaning gas, in}}$
    - Vary $F_{\text{cleaning gas, in}}$ to achieve same $r_e$
• Similar in Environmental Impacts due to the Same Power, Cleaning Time, and Chamber Temperature
• Similar in Cost of Running the Process
Including Upstream Processes

Upstream of NF₃ Production

- H₂ Production
- N₂ Production
- NH₃ Production
- F₂ Production
- KF Production
- HF Production

1 kg NF₃

0.5 kg NH₃

3.35 kg F₂

1.27 kW-hr Electricity

Hydroelectric Plant

Gas-fired Plant

Coal-fired Plant

Gas-fired Plant

Coal

Gas

Coal Production

Nature Gas Production

Coal-fired Plant
Comparison in the Life Cycle Boundary

- NF₃ cleaning has higher impacts in all the areas than F₂
- Higher impacts due to energy generation for producing NF₃

![Comparison Chart]

- Ozone Depletion Potential (kg CFC-11 equivalent/kg)
- Human Toxicity Potential-NonCancer (DALYs/kg)
- Human Toxicity Potential-Cancer (DALYs/kg)
- Photochemical Smog (kg Ethylene equivalent/kg)
- PM10 Effects (kg PM10 equivalent/kg)
- Acidification Potential (kg SO2 equivalent/kg)
- Global Warming (kg CO2 equivalent/kg)
Relative Impact of Two Cleaning Processes

- Strong correlation between results of NF$_3$ case and F$_2$ case
- Reduce correlation effect by using relative values

\[
\left( \frac{\sum_i H_{i,GWP} E_i}{\sum_i H_{i,GWP} E_i} \right)_{NF_3} \rightarrow \left( \frac{\sum_i H_{i,GWP} E_i}{\sum_i H_{i,GWP} E_i} \right)_{F_2}
\]

- Uncertainty of relative impact is much smaller than inputs
Identifying Important Parameters

- Which parameters are important is also influenced by the goals of the analysis.

Top three parameters that contribute the most to the uncertainty of GWP of F_2 cleaning:

- GWP Effect of SO2 from Oil Furnace
- Energy Generated
- Emission of CO2 from Coal Furnace
Top three parameters are related to upstream production.

Identification of important parameters enables efficient allocation of data collection effort – **spend money and time in the most valuable place!**
Importance of Considering Multi-Boundaries

Upstream

Nature Gas Production
Coal Production
N₂ Production
H₂ Production
HF Production
KF Production

Gas-fired Plant
Coal-fired Plant

NH₃ Production
F₂ Production

NF₃ Production

Boundary I

F₂ Production

HF, CO₂…

Boundary II

SiF₄, F₂, N₂…

CH₄, Air

Recycled Water

Burner

SiO₂ to Sewer

Boundary III

Hydroelectric Plant

Gas-fired Plant

Plasma Generator

CVD Chamber

NF₃

Ca(OH)₂

CaF₂, HF(aq.)

CO₂, HF…

Cleaned Water

HF(aq.)

Central Treatment

SiF₄, F₂, N₂…

CO₂, HF…

Cleaning Process
Boundary of Environmental Analysis

- Boundary of the environmental analysis directly affects the results

![Bar chart showing relative impacts of Cu CVD, NF3 Chamber Cleaning, and F2 Chamber Cleaning inside and outside the Fab.](chart.png)
Framework of Decision-Making Process

- Generate new alternatives
- Refine model, collect more data, increase data accuracy...

Alternative Technologies:
- $\text{NF}_3$ vs. $\text{F}_2$
- Cu CVD vs. Cu plating...

Uncertainty Analysis:
- Cost of Ownership
- Process Model
- Environ. Impacts

- Info is enough for decision?
  - Yes: Do nothing, or change to alternative
  - No: Ranking and Sensitivity Analysis

...
Conclusions and Key Points

- The integration of process models, COO, and environmental evaluations is critical and doable.

- Large uncertainty in the inputs does not necessarily lead to low confidence in decisions.

- System boundaries strongly affect the outcomes of the evaluations.
Acknowledgements

• Laura Losey, David Bouldin, Mike Kasner, Tim Yeakley, Larry Novak, Daren Dance, Tina Gilliland – Texas Instruments

• Alejandro Cano-Ruiz and Pauline Ho – Reaction Design

• Joe Van Gompel – BOC Edwards

• Karen Gleason, Herb Sawin and Joel Clark – MIT

• Holly Ho – SEMATECH International

• Engineering Research Center for Environmentally Benign Semiconductor Manufacturing – NSF/SRC.
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End of Presentation