Semiconductor DFE work at Berkeley:
Environmental Value Systems Analysis (EnV-S) and Future Work

NSF/SRC Center for Environmentally Benign Semiconductor Manufacturing

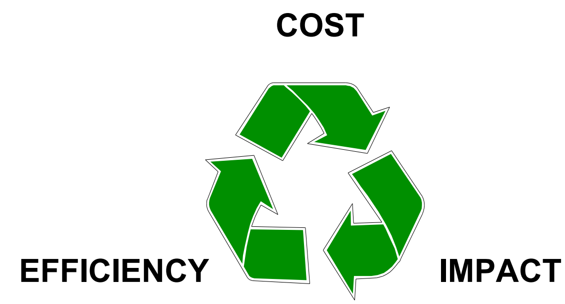
April 14, 2004

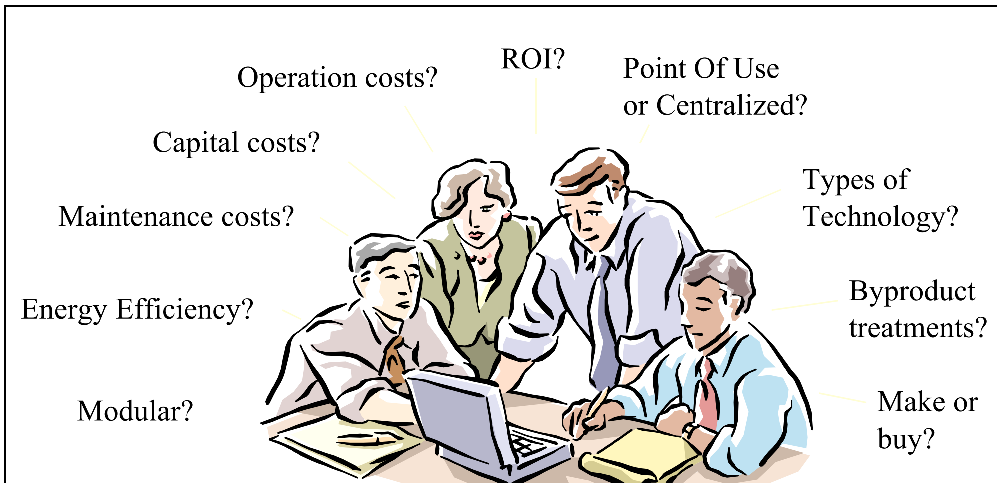
Outline of presentation

1. Semiconductor DFE Research at Berkeley - The Environmental Value Systems Analysis (EnV-S) Tool
2. Case Study 1 - Comparing Completed Systems (CVD Abatement)
3. Case Study 2 - Informing Design of Equipment (Copper CMP Wastewater Treatment)
4. Conclusions

Why Improve environmental performance?

- Responsibility towards sustainable industrial development - Corporate Responsibility
- Growing public and customer awareness - Image
- Preempt/inform future, regulations on waste generation, facilities operation - Avoid problems
- Increase revenues and emerge as market leaders through product differentiation - $$$





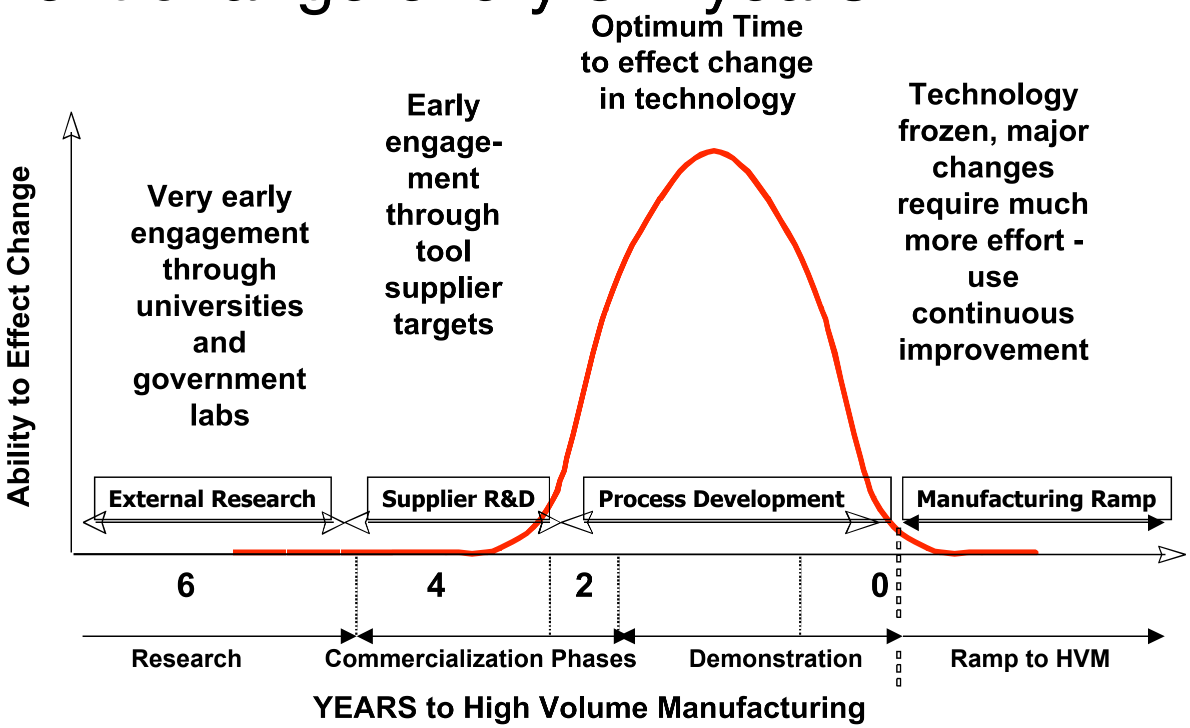
Adapted from Raoux. S and Woolston W., EnV-S Seminar, SEMICON West 2002

The need:

Effective environmental ***decision making*** in Product and process Design, Development, Purchasing, Sales, etc.

Challenges - Rate of change

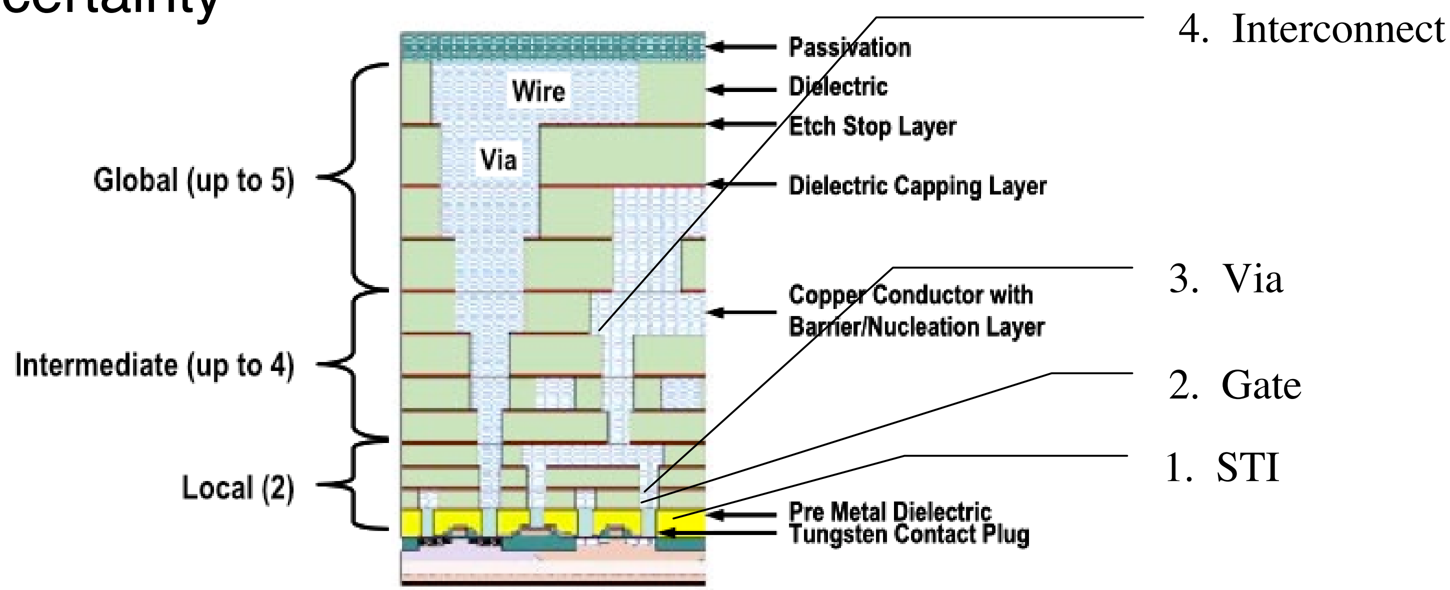
- Technology change every 18 months
- Equipment change every 3-4 years



Adapted from McManus, T. J. 2002, "Integrating EHS into the Business, Delivering a Market/Business Advantage," Presentation at U C Berkeley, Sept. 27th.

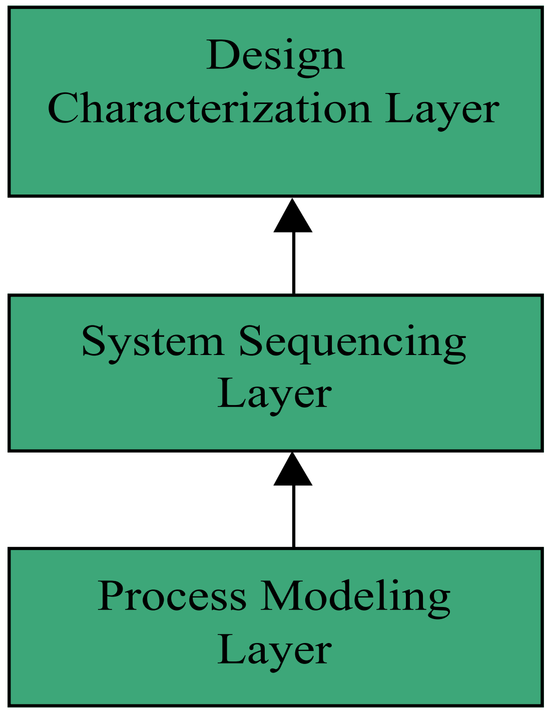
Challenges - chemical use and complexity

- Numerous process steps ~250
- Numerous chemicals used ~200 possible agents
  - New chemicals
  - Unavailable health data
  - Uncertainty

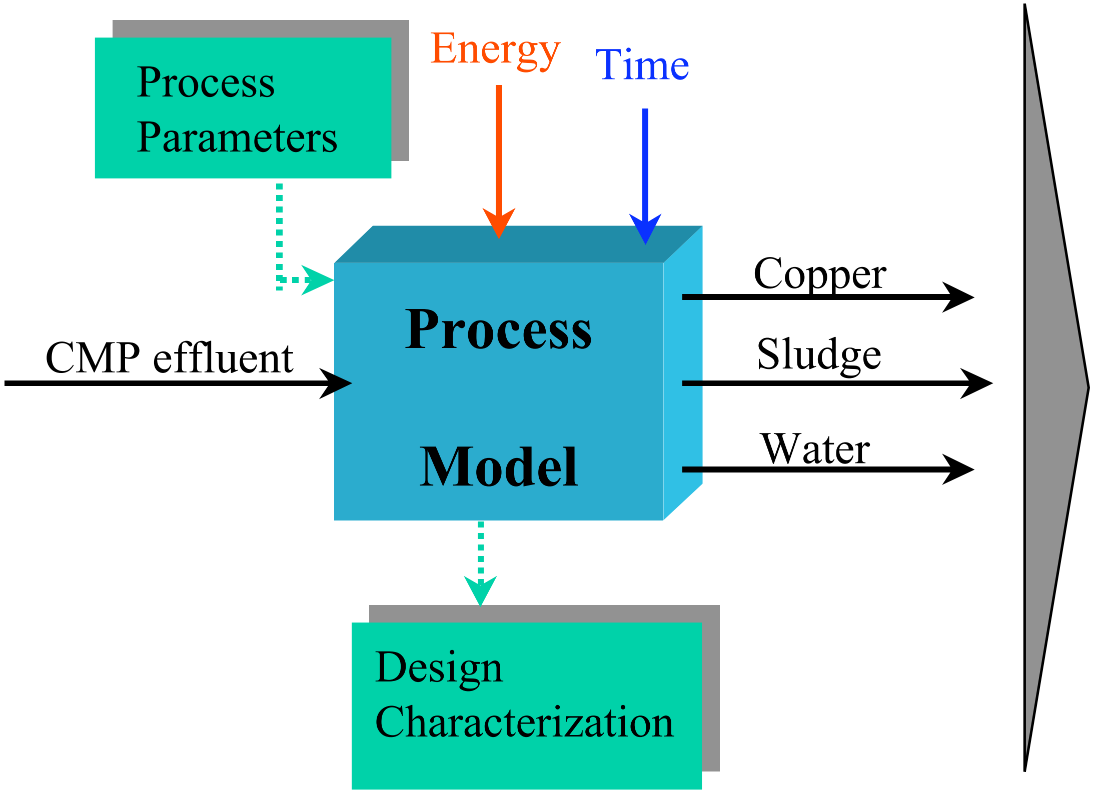


A “bottom-up” semiconductor DFE tool

- The Environmental Value Systems Analysis (EnV-S)
- Three layers



Process Modeling Layer: Unit process model approach



A set of analytical/empirical process models are used to describe the process.

Inputs include process parameters, mass/flow data, energy, unit costs, etc.

Output parameters include energy utilization, waste, generated, environmental and health impacts, cost

Equipment model library

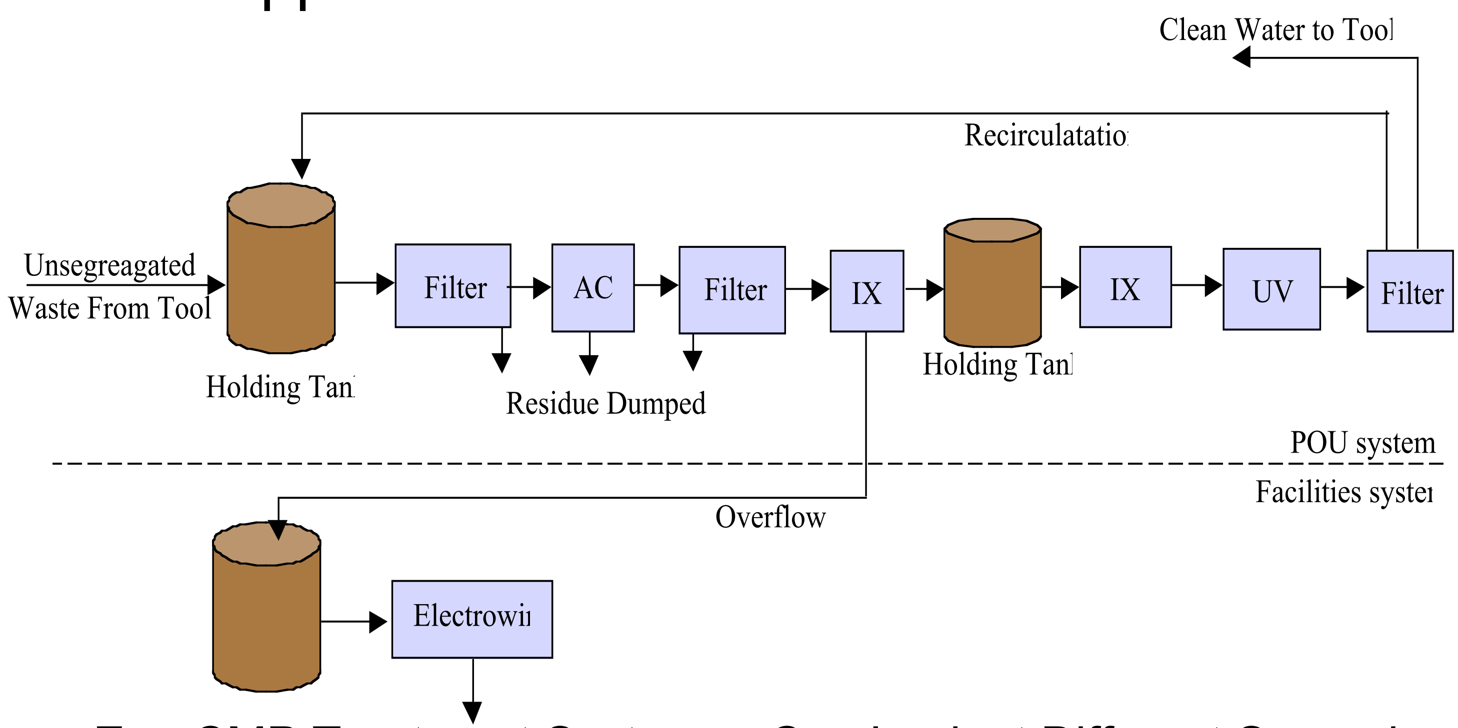
- Build a library of platform based models
  - Key platform models

Process Platform	Broad Function
Rapid Thermal Processing	Film growth/annealing
Chemical Vapor Deposition	Film growth
Epitaxial/Polysilicon deposition	Film/layer growth
Physical Vapor Deposition	Film growth
Ion Implantation	Charge
Lithography	Patterning
Plasma Etching	Contacts/vias
Chemical Mechanical Planarization (CMP)	Local/global planarity
Electrochemical Plating (ECP)	Copper plating
Wet Cleaning	Cleaning at various stages

Facility infrastructure	Broad function
Electrical System	Electricity delivery
Ultrapure water (UPW) system	UPW generation and distribution
Process cooling water (PCW) system	Cooling process equipment
Chilled water system (CWS)	Cool HVAC and PCW
Delivery of recycled water	Back to UPW front end/elsewhere
House scrubber for Acid Exhaust	HAPS removal
VOC abatement for solvent exhaust	VOC removal
Acid Waste Neutralization System	Meet discharge specifications
Piping, plumbing of different wastes	Miscellaneous

System Sequencing Layer

- To sets the boundary of the analysis
- Track primary and secondary flows
- Modular Approach: Can mix and match the models



Eg: CMP Treatment Systems: Can Look at Different Scenarios

Sequencing (contd.)

- Hierarchical organization of databases
  - Keep pace with technology change
  - Proprietary, public and shared information
- Can assemble different manufacturing sequences

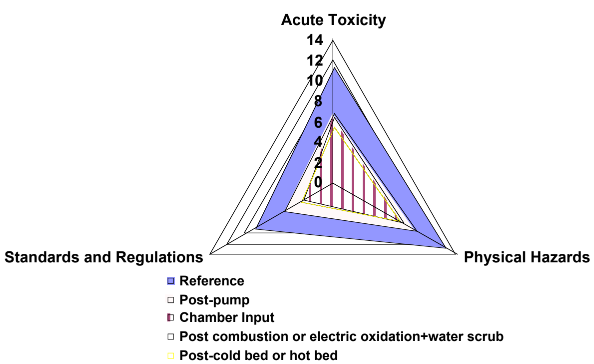
Recipe information	BPSG CVD Recipe	Contact Etch Recipe	MOCVD recipe	W Dep recipe
Platform models	Centura Platform (4 chambers)	Producer Platform (3 twin chambers)	MOCVD platform	Centura Platform (4 chambers)
Facility infrastructure models	Pumps (4) HAPS Abatement (combustion and water scrub) Downstream HF Treatment; House scrubber	PFC Abatement in Foreline (plasma) Pumps (3) House scrubber	Pumps (3) House scrubber	Pumps (3) House scrubber

Eg: Via module

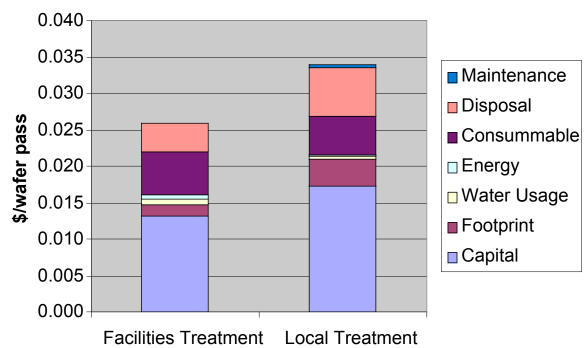
Design Characterization Layer

Environmental Value Systems Analysis

Health hazards
Interpreted through a Multi-Criteria Hazard (MCH) analysis



Cost of ownership
Interpreted through Environmental Cost of Ownership analysis



Environmental Performance
Track different environmental performance metrics

RESOURCES USED
Electricity (kWhr/year)
Industrial City Water (ICW) (Kgal/year)
Chemicals and Consumables, (tons/year)
EMISSIONS
AIR EMISSIONS
HAPs Loading (HF Equivalent Tons/Year)
Global Warming Emissions (tonsCE/year)
Criteria Air Pollutants (tons/year)
LIQUID
Liquid Waste (Kgal/year)
SOLID
Hazardous Solid Waste (tons/year)
Non-hazardous Waste (tons/year)

Three Applications for the EnV-S

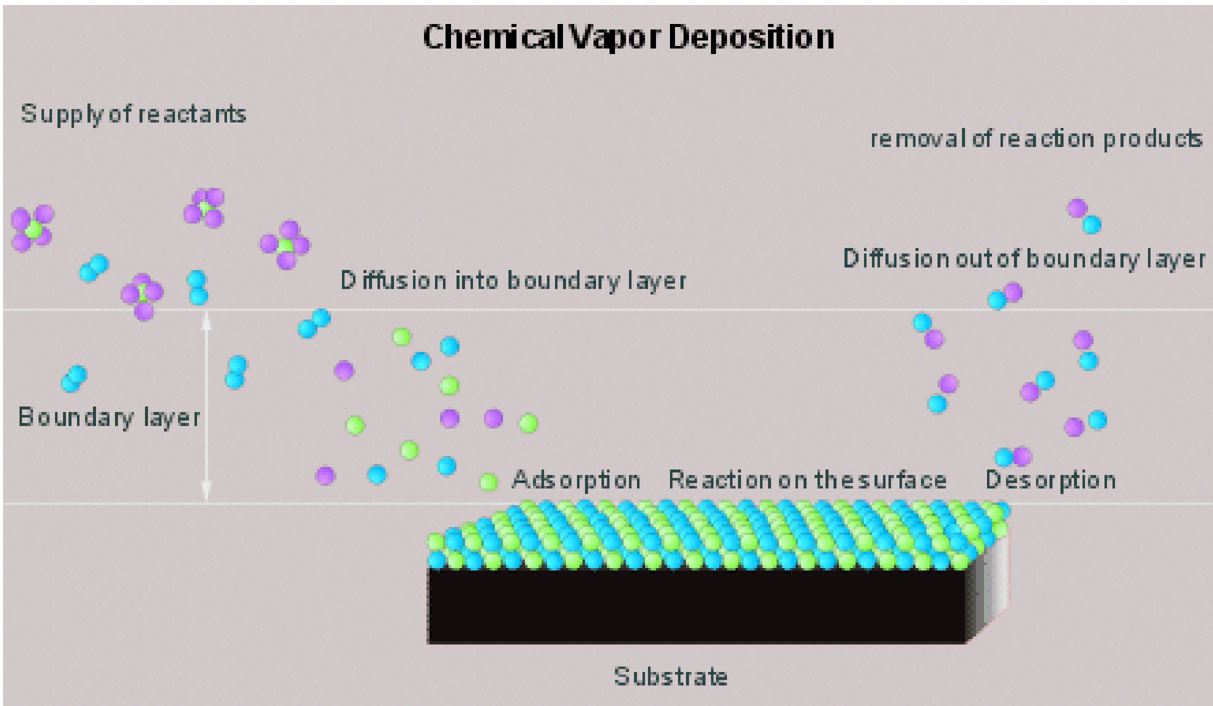
1. Comparing alternative equipment
   – Case Example: CVD Abatement
2. Design of equipment
   – Case Example: Copper CMP abatement
3. Examining industry-wide environmental ramifications of equipment/processes
   – PFC emissions issues

2. Case study 1: Comparing Alternative Equipment

- Eg: in purchasing decisions
- Compare dielectric chemical vapor deposition (DCVD) emissions abatement technologies

Application

- Deposit a dielectric film using Chemical Vapor Deposition (CVD)
- Material Deposited: Undoped Silicate Glass (USG)



Source: everest-coatings.com

Application (contd.)

- Equipment Utilized
  - Three CVD chambers

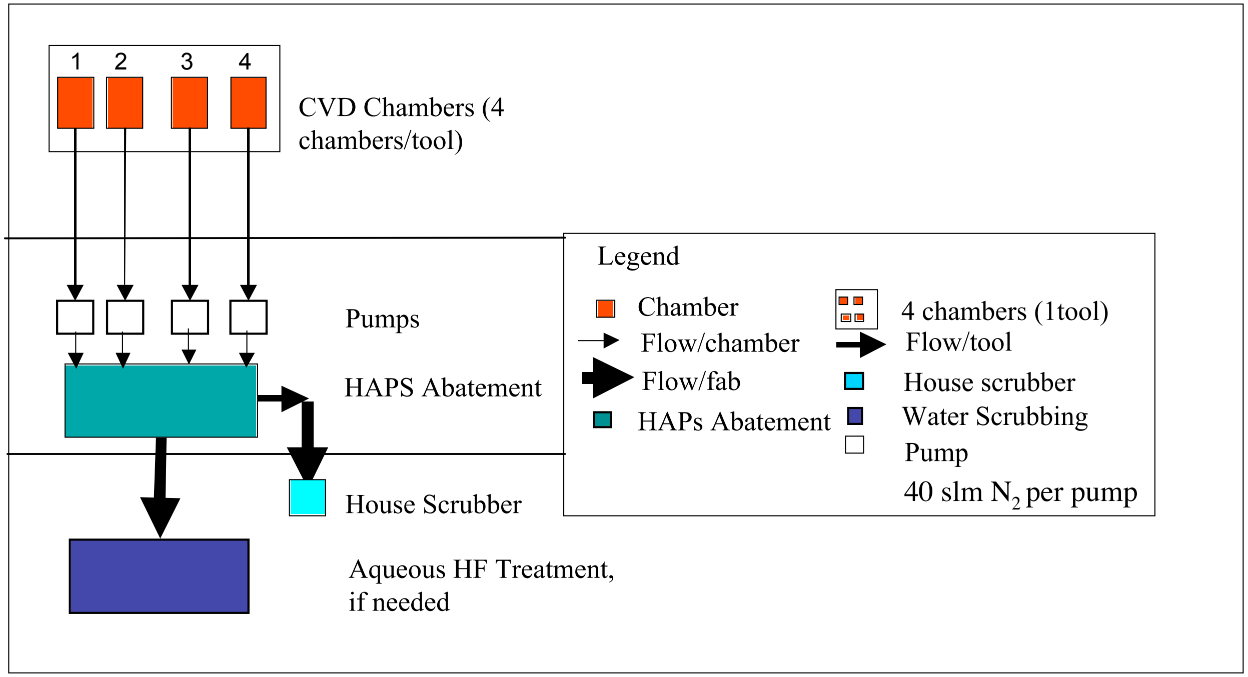
Source: http://appliedmaterials.com

Analysis scope

Cleanroom

Sub-fab

Facilities or Backpad



Chamber inputs

	Ar	O_2	SiH_4	NF_3
Deposition (g/wafer)	0.80	1.45	0.63	None
Clean and seasoning (g/wafer)	2.89	0.22	0.07	7.96

Post pump emissions

	SiH_4	NF_3	SiF_4	F_2	HF
Deposition (g/wafer)	<5.71E-3	None	None	None	None
Clean and seasoning (g/wafer)	None	0.06	0.46	5.89	0.05

Environmental Issues and Abatement

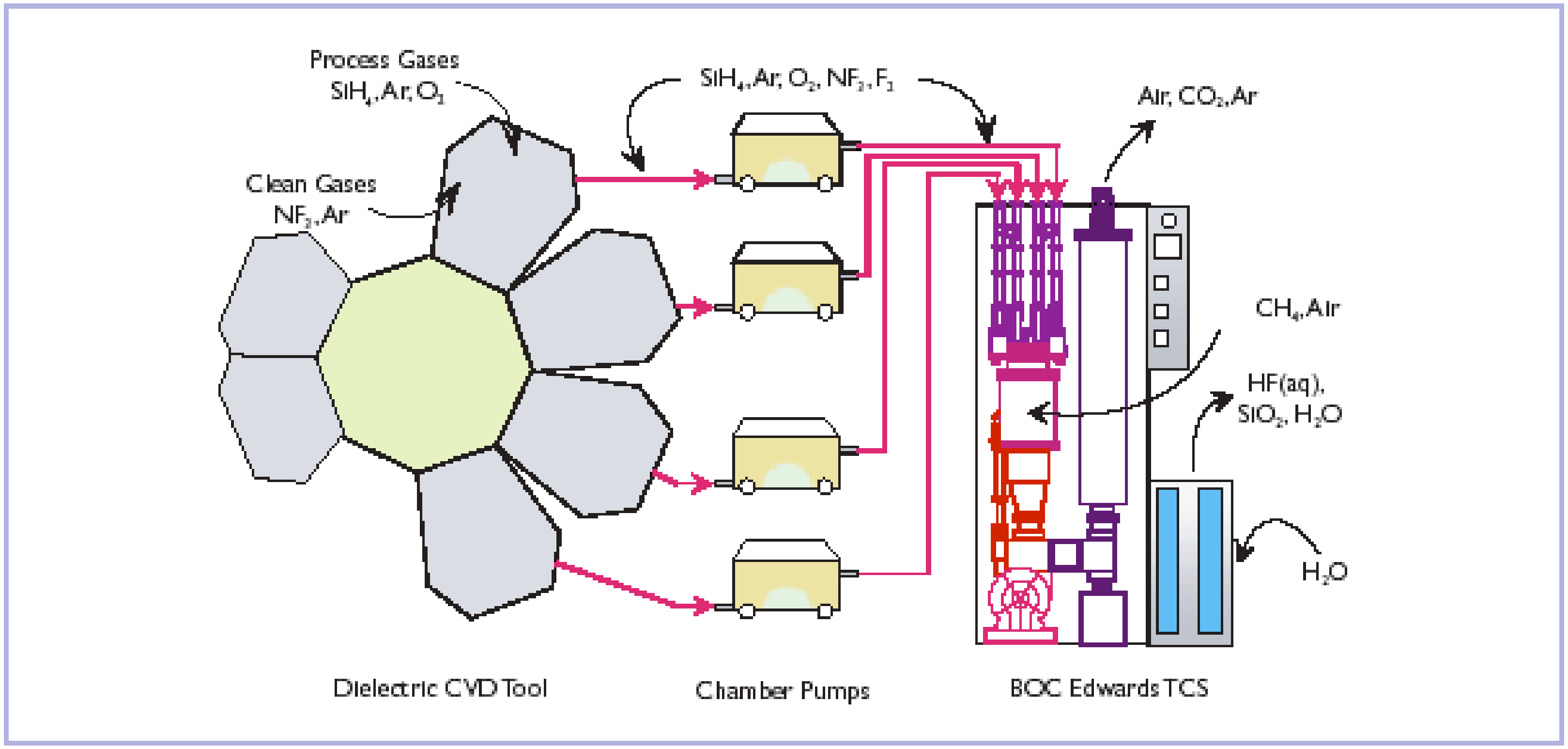
- Emissions include $F_{2,}$
  - Transporting F_2 is problematic
  - Could lead to release of HF (HAPs)
- Other potentially hazardous, toxic and flammable emissions (SiF_4, SiH_4, etc.)

Abatement Technologies	SiF_4	F_2	SiH_4	HF	NF_3	Selected for Analysis?
Catalytic and Water Scrub	Y	Y	N	Y	Y	N
Burn and Water Scrub	Y	Y	Y	Y	Y	Y
Burn and Dry Scrub (Hot or Cold bed)	Y	Y	Y	Y	Y	N[1]
Plasma	N[2]	Y	N[2]	Y	Y	N
Cold Bed	Y	Y[3]	Y	Y	Y	Y
Hot Bed	Y	Y[3]	Y	Y	Y	Y
Electric Oxidation and Water Scrub	Y	Y	Y	Y	Y	Y

Note:
[1]Not considered, because a dry scrubber could abate F_2 directly, without the need for a burner
[2]Can abate, but form solids that cause production problems and may require other technologies to remove.
[3] = low capacity

Abatement Technologies Considered

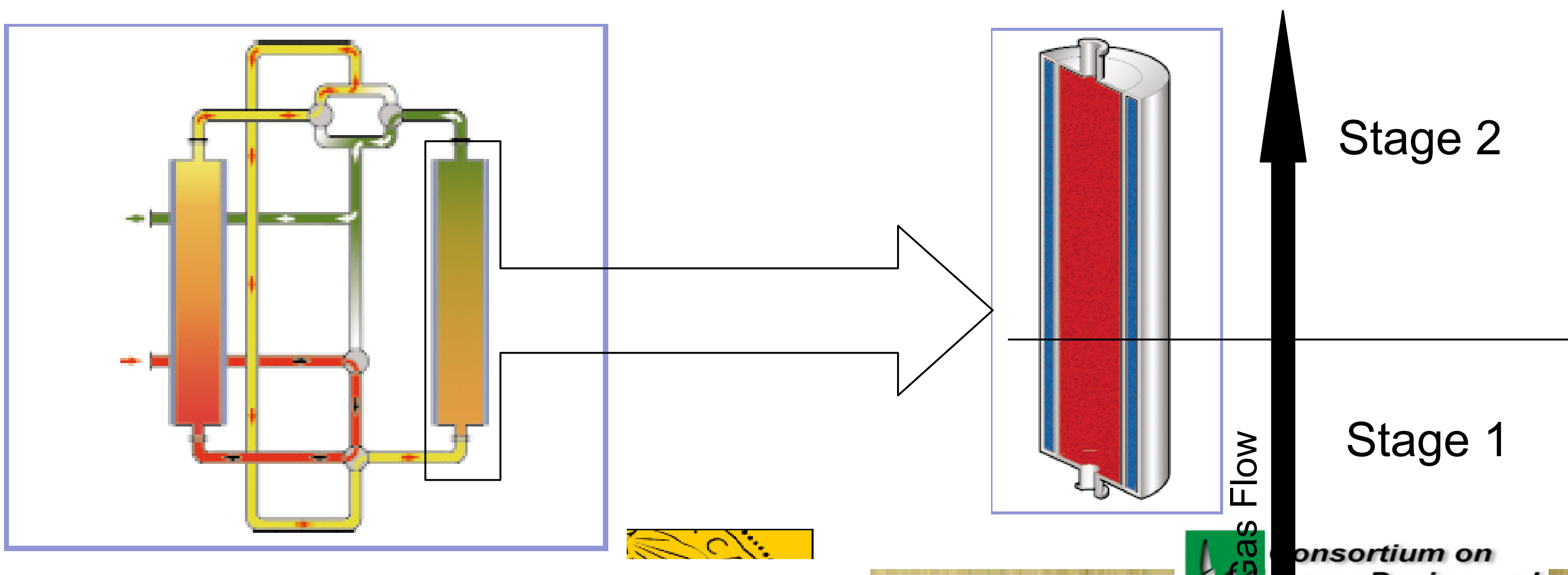
- Option 1. Combustion and Water Scrubbing
  - Use methane, or other fuel to burn flammable emissions and break down F_2 into HF



Source: Product data, Thermal Combustion System, BOC Edwards

Abatement Technologies Contd.

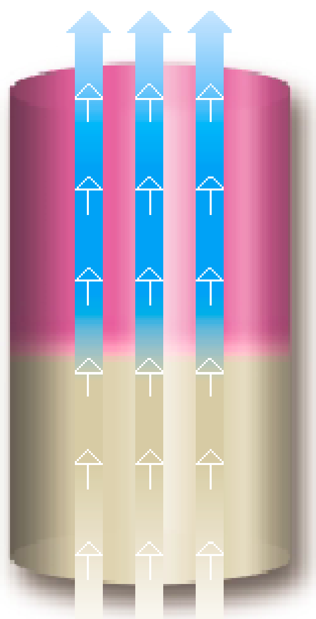
- Option 2. Hot Bed Technologies
  - Stage 1:
    - A mixture of metals for thermal decomposition (SiH_4) and heat transfer.
    - Strong oxidizing agents to form metal halides
  - Stage 2
    - CaO for removal of acid gases and metal halides. Form salts

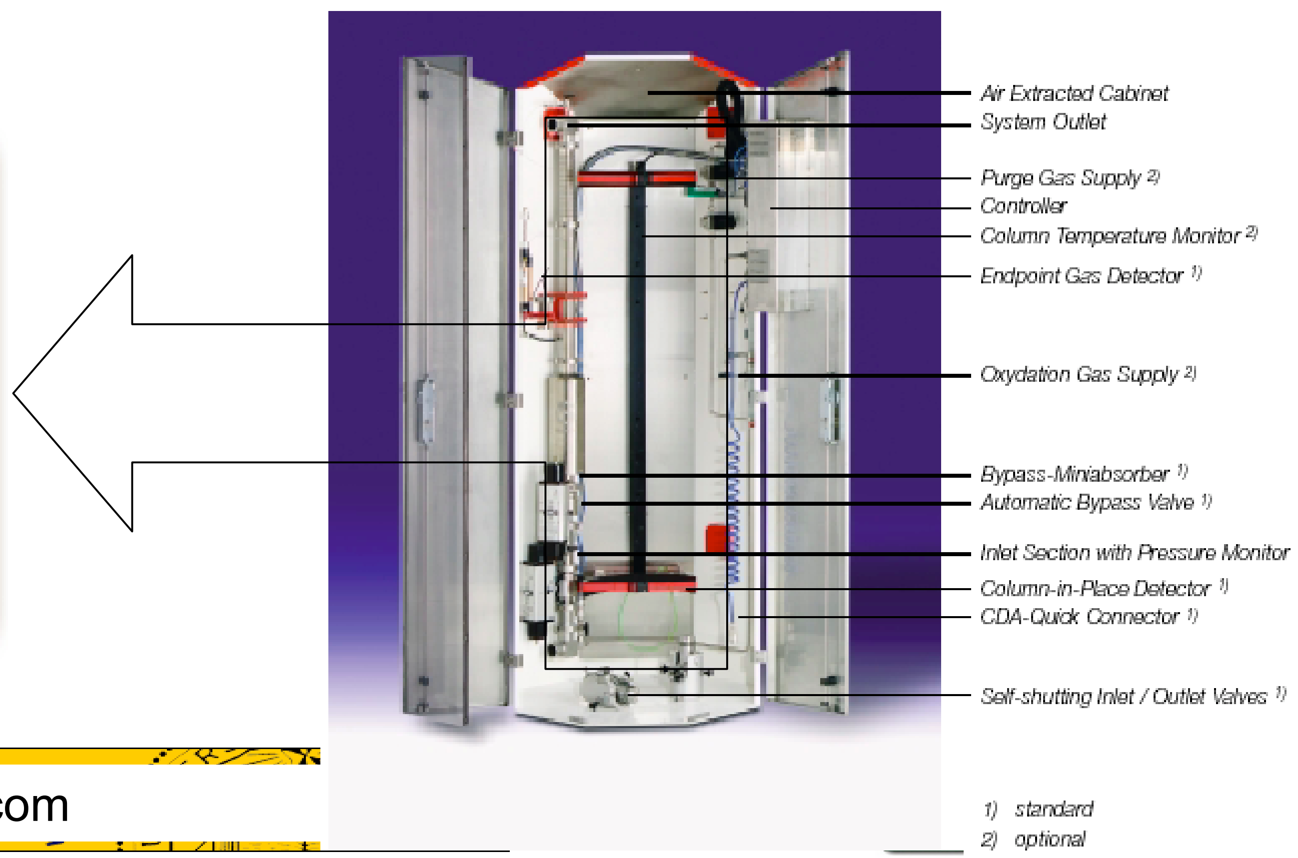


Source: Inline data sheet, BOC Edwards

Abatement Technologies Contd.

- Option 3. Cold Bed Technologies
- Dry-bed chemisorption using metal oxides
- Passive operation at ambient temperature

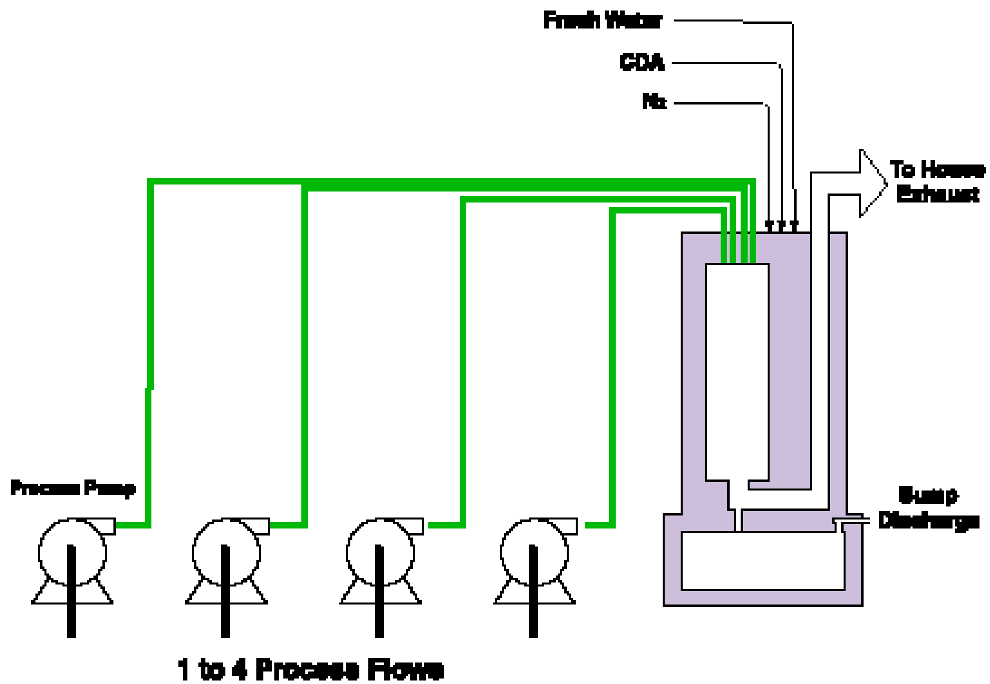




Source: csclean.com

Abatement Technologies Contd.

- Option 4. Electric Oxidation and Water scrubbing
  - Use electric heating
  - Addition of H_2 to reduce large F_2 flows into HF



Source: ATMI CDO 863 datasheet

Sample Data Used

Analysis Units	Combustion and Water Scrubbing	Hot Bed	Cold Bed	Fluoride Treatment	Oxid. and Water Scrubbing
Fixed Costs	~ $90,000, 200 slm flow rate	~$59,000 for ~9000 l HF capacity	~$78,000 for ~39,000 l HF capacity	$2,000,000 for a 100 gpm system	74,000, 200 slm flow rate
Electricity	~1.2 kW	~3 kW	~0.07 kW	13 kW (100 gpm system)	~5.6 kW
Water	City water use calculated based on ~0.2% F- concentration in drain; cooling water at 6 gpm	Cooling water at 6gpm, nominal fuel flow, same as combustion unit	No water use	No water use	City water use calculated based on ~0.2% F- concentration in drain; cooling water at 5 gpm
Consumables	Spares ~ $4000/year; fuel use ~37 slm CH_4	Cartridge capacity is ~9000 l HF, ~$1,800	Cartridge capacity is ~39000 l HF, ~$4,000	Average incoming HF at 290 ppm; 50 % excess $CaCl_2$ and ~400 lb of NaOH/day	Spares ~ $4000/year, hydrogen use is 1 to 1.5 times expected stoichiometric requirements for avg. fluorine loading (1.3 slm)

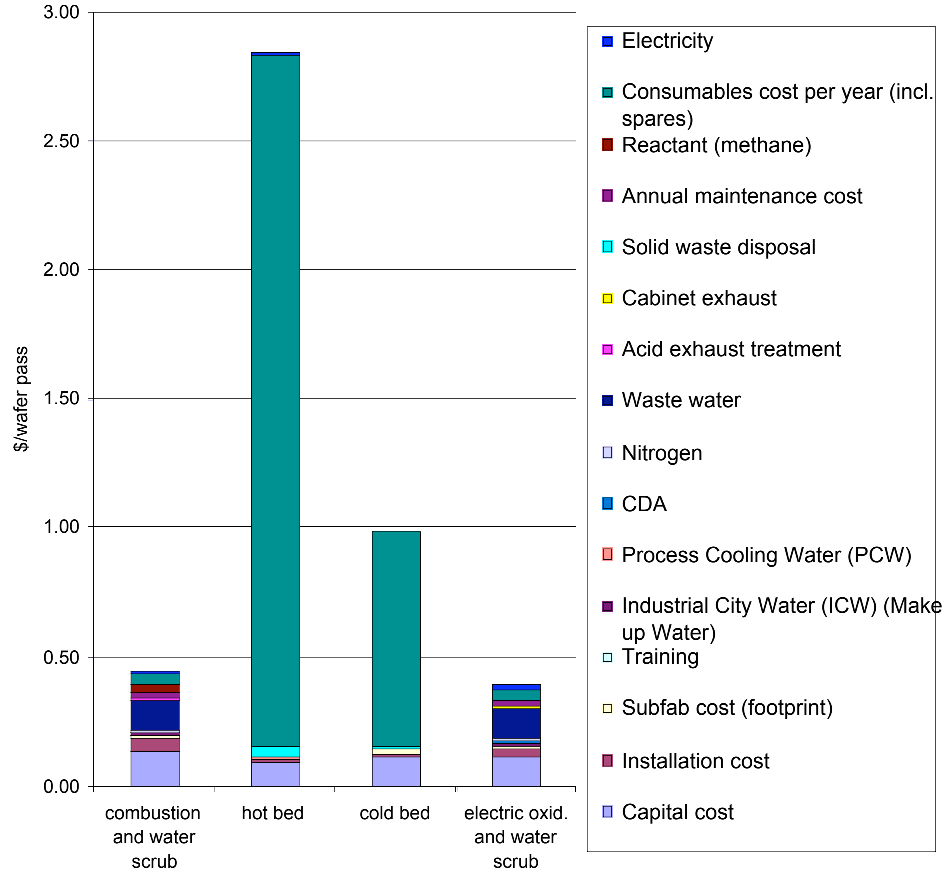
Process Data and Models Used (contd.)

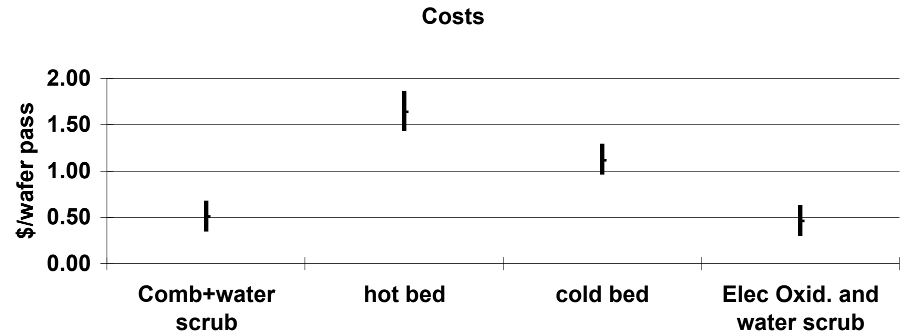
Analysis Units	Combustion and Water Scrubbing	Hot Bed	Cold Bed	Fluoride Treatment	Oxid. and Water Scrubbing
Disposal	Disposal costs relate to fluoride treatment models Exhaust costs calculated assuming complete combustion $XCH_4 + Y(O_2+3.76N_2) + ZN_2 = XCO_2 + 2XH_2O + (3.76Y+Z)N_2 + (Y-2X)O_2$ X and Z are known inputs	Spent cartridges are usually a mixture of lime and metal oxides, and are non-hazardous Disposal costs are based on ~30 min changeout time Disposal weight is based on ~4g/l HF capacity Exhaust flow volumes assumed similar to input volumes (largely N_2)	Spent cartridges are a mixture of silica and metal (usually iron) oxides, and are non-hazardous. Disposal costs are based on ~30 min changeout time Disposal weight is based on actual volume of ~200 l, and bulk density of iron oxides ~1.2g/cc Exhaust flows volumes assumed similar to input volumes (largely N_2)	16 ppm of HF in discharge; removed fluorine goes to CaF_2 sludge and pressed to 20% solids	Disposal costs relate to fluoride treatment models

Berkeley University of California

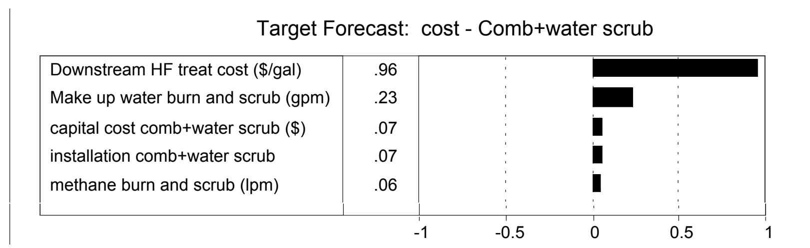
Consortium on Green Design and Manufacturing

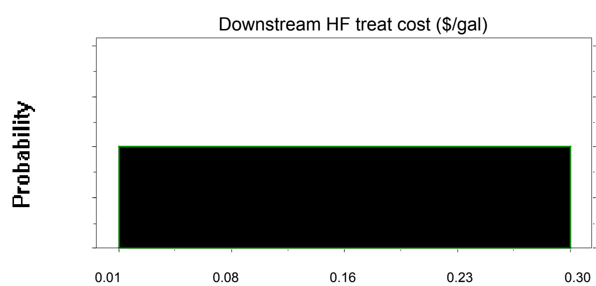
Results - CoO

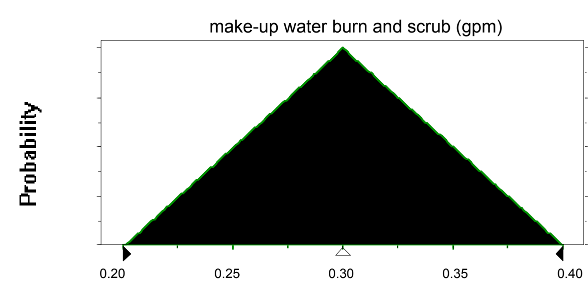




Oxidation and Water Scrub Systems are the most cost-effective







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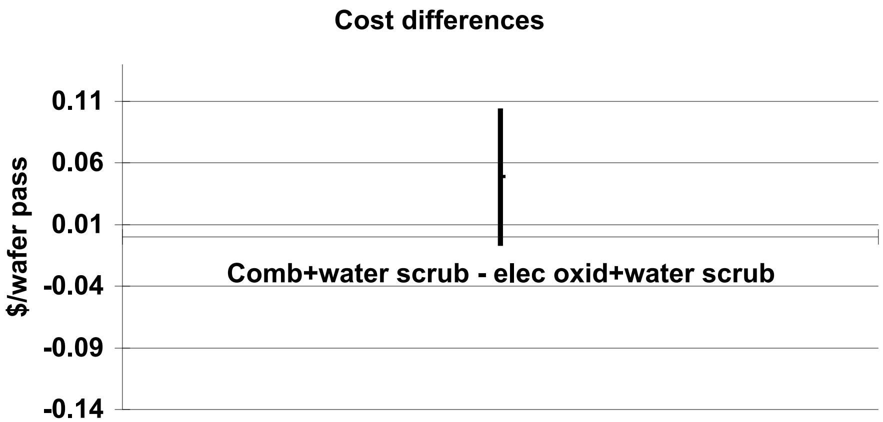
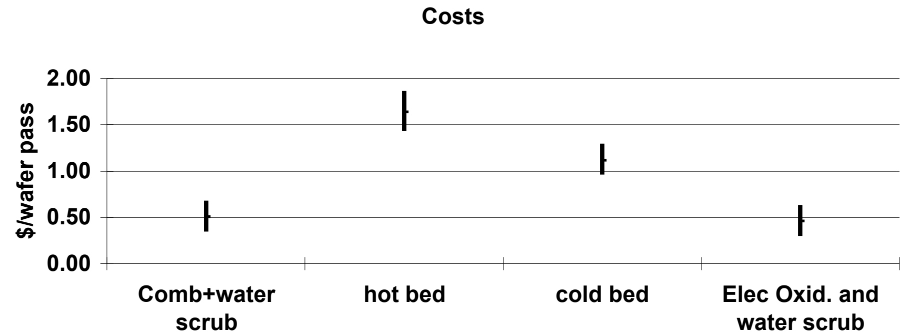
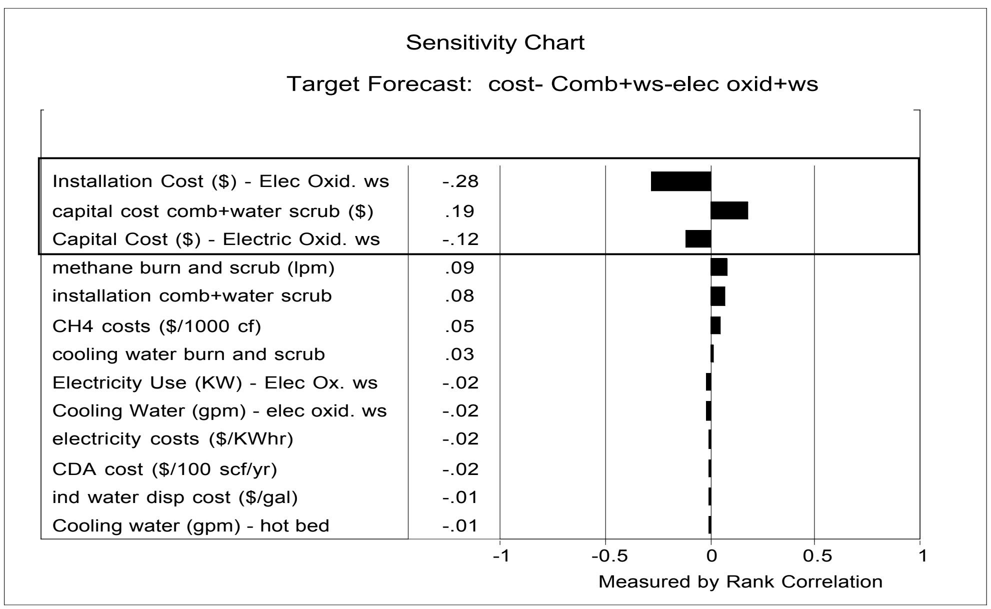
Results - CoO





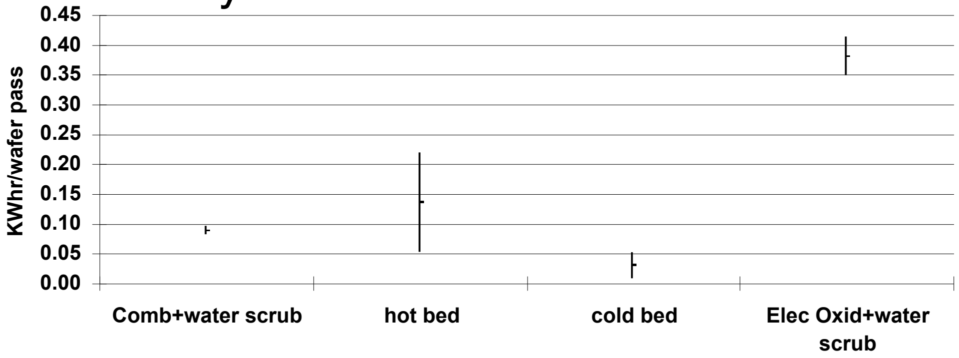


Oxidation and Water Scrub Systems are the most cost-effective

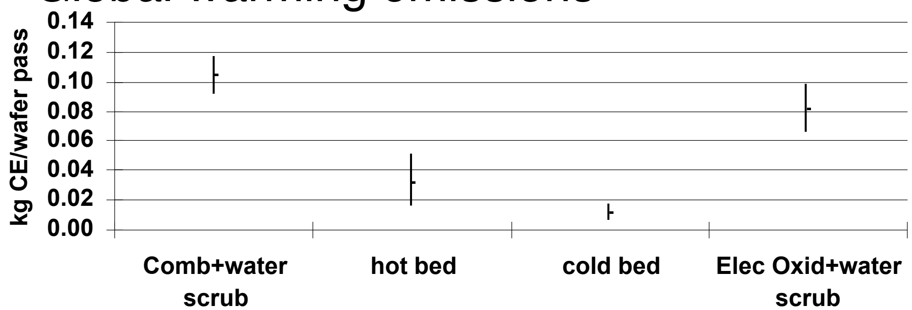
Need to examine capital and installation costs in more detail

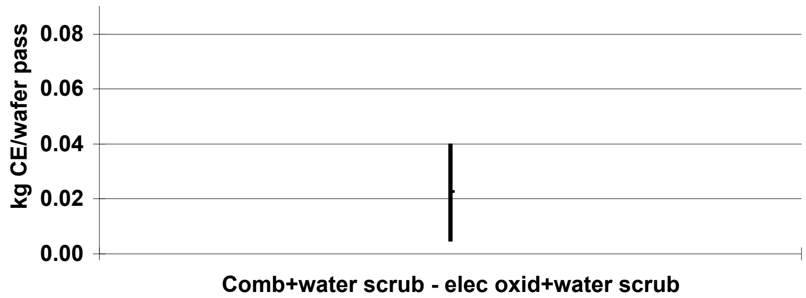
Environmental impacts

Electricity use



Global warming emissions





- Electric Oxidation systems use the most electricity -
- **Carbon intensity of electricity** could influence decisions between
    - combustion and electric oxidation and water scrubbing systems

Facility-Wide Environmental Impacts

- Water and Liquid Waste are higher for oxidation systems
- Solid Waste higher for bed systems

GENERAL FACILITY PARAMETERS	
Size of Wafer (inches)	12
Number of Wafer Starts per Week	5000
Number of USG Layers Considered	1

RESOURCES USED	Combustion And Water scrubbing	Hot bed	Cold bed	Electric Oxidation and Water Scrubbing
Total Electricity (kWhr/year)	16,168	36,809	859	98,836
Industrial City Water (ICW) (Kgal/year)	316	0	0	315
Chemicals and Consumables, (tons/year)	32	9	12	4
EMISSIONS				
AIR EMISSIONS				
HAPs Loading, No Abatement (HF Equivalent Tons/Year)	2	2	2	2
Global Warming Emissions (tonsCE/year)	26	9	2	22
Criteria Air Pollutants (tons/year)	1.27E-01	0	0	1.14E-01
LIQUID				
HF Discharged as Liquid (From POU Device) (tons/year)	0.02	0	0	0.02
Final Liquid Waste (Kgal/year)	315	0	0	315
SOLID				
Hazardous Solid Waste (tons/year)	N/A	N/A	N/A	N/A
Non-hazardous Waste (tons/year)	6[1]	9	12	6[1]

[1] Mainly CaF_2 After Fluoride Treatment

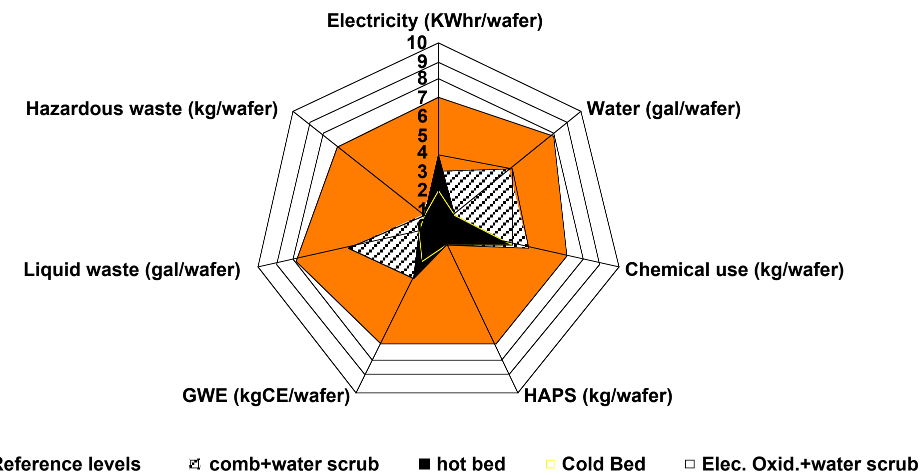
Facility-Wide Environmental Impacts

- Graphical Representation on a logarithmic scale of 1-10
- Can compare to facility reference levels

•Largest profiles for oxidation and water scrub systems

–But they have the smallest COO

Impacts/USG layer



GENERAL FACILITY PARAMETERS	
Size of Wafer (inches)	12
Number of Wafer Starts per Week	5000
Number of USG Layers Considered	1

Score	Electricity	Water	Chemicals Used	HAPs
1	<10 Whr/wafer	<1 mgal/wafer	<0.1 g/wafer	<1 mg/wafer
2	1-10 Whr/wafer	1-10 mgal/wafer	**0.1-1 g/wafer**	1-10 mg/wafer
3	0.01-0.1 kWhr/wafer	0.01-0.1 gal/wafer	1-10 g/wafer	0.01-0.1 g/wafer
4	0.1-1 kWhr/wafer	0.1-1 gal/wafer	10-100 g/wafer	0.1-1 g/wafer
5	1-10 kWhr/wafer	1-10 gal/wafer	0.1-1 kg/wafer	1-10 g/wafer
6	10-100 kWhr/wafer	10-100 gal/wafer	1-10 kg/wafer	10-100 g/wafer
7	100-1000 kWhr/wafer	100-1000 gal/wafer	10-100 kg/wafer	0.1-1 kg/wafer
8	1000-10000 kWhr/wafer	1000-10000 gal/wafer	100-1000 kg/wafer	1-10 kg/wafer
9	10-100 mWhr/wafer	10-100 Kgal/wafer	1-10 tonnes/wafer	10-100 kg/wafer
10	>100 mWhr/wafer	>100 Kgal/wafer	>10 tonnes/wafer	>100 kg/wafer

Score	GWP (CE)	Liquid Waste	Hazardous Waste
1	<1 g/wafer	<1 mgal/wafer	<0.1 g/wafer
2	1-10 g/wafer	1-10 mgal/wafer	**0.1-1 g/wafer**
3	0.01-0.1 kg/wafer	0.01-0.1 gal/wafer	1-10 g/wafer
4	0.1-1 kg/wafer	0.1-1 gal/wafer	10-100 g/wafer
5	1-10 kg/wafer	1-10 gal/wafer	0.1-1 kg/wafer
6	10-100 kg/wafer	10-100 gal/wafer	1-10 kg/wafer
7	100-1000 kg/wafer	100-1000 gal/wafer	10-100 kg/wafer
8	1-10 tonnes/wafer	1000-10000 gal/wafer	100-1000 kg/wafer
9	10-100 tonnes/wafer	10-100 Kgal/wafer	1-10 tonnes/wafer
10	>100 tonnes/wafer	>100 Kgal/wafer	>10 tonnes/wafer

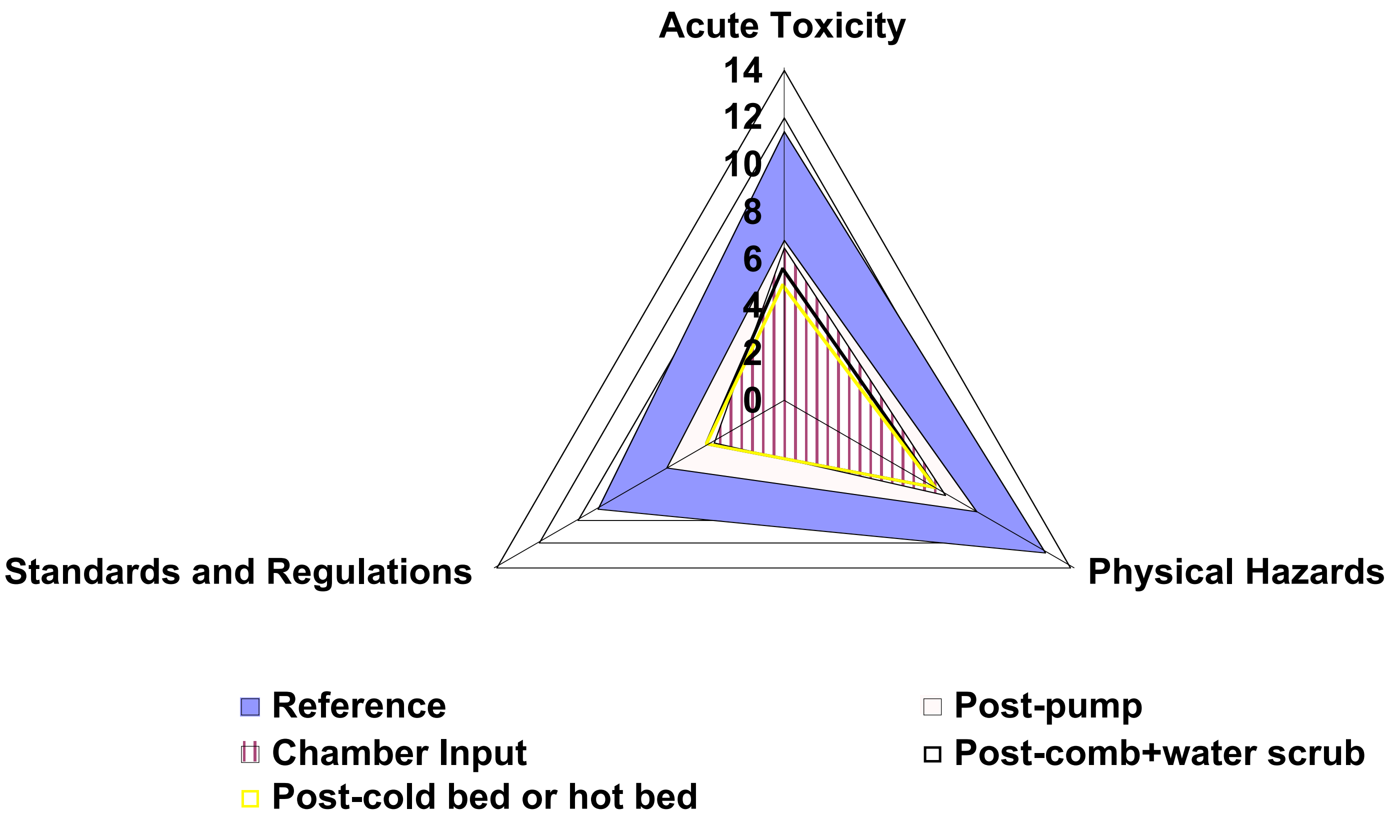
Health impacts

- Three categories
  - Acute toxicity, Physical Hazards, Standards and Regulations
- Compare chemical hazards to “worst-case” Reference chemical

Endpoints	Actual Value	Scaled Score	Reference Chemical
Category 1: Acute Toxicity			
Lethal Dose, 50% of Population (LD50) or Lethal Dose (LD)	15 ug/m3	9	Sarin
Lethal Concentration, 50% of population (LC50) or Lethal Concentration (LC)	5 mg/m3	8	Sarin
Threshold Dose Level (TDL)	2 ug/m3	9	Sarin
Threshold Concentration Level (TCL)	10 mg/m3	10	Lead
Irritation Dose in Eye (ID (eye))	50 ug	8	Mercury chloride
Irritation Dose on Skin (ID (skin)):	500 mg	5	Mercury chloride
OVERALL SCORE CATEGORY 1		8.17	
Category 2: Physical Hazards			
Flash Point (FP)	-49 °C	10	Pentane
Lower Explosive Limit (LEL)	1.5%	9	Aniline
Explosive Limit Range (EL Range)	22%	8	Aniline
Corrosivity (pH)			Hydrochloric acid
National Fire Protection Agency Flammability (NFPA FR)	4	10	Pentane
National Fire Protection Agency Reactivity (NFPA RR)	4	10	Nitroglycerine
National Fire Protection Agency Health (NFPA HR)	4	10	Hydrogen cyanide
Hazard Management Information System Flammability (HMIS FH)	4	10	Hydrogen cyanide
Hazard Management Information System Reactivity (HMIS RH)	4	10	Pentane
Hazard Management Information System Health (HMIS HH)	4	10	Nitroglycerine
Hazard Management Information System Personal Protective Equipment (HMIS PP)	4	10	Hydrogen cyanide
OVERALL SCORE CATEGORY 2		9.92	
Standards And Regulations			
OSHA Permissible Exposure Limit (OSHA PEL)	0.1 mg/m3	6	Mercury chloride
NIOSH Time Weighted Average (NIOSH TWA)	0.1 mg/m3	5	Mercury chloride
ACGIH Threshold Limit Value (TLV)	25 ug/m3	4	Mercury chloride
OSHA/ACGIH Short Term Emission Limit (STEL)	5 mg/m3	5	Hydrogen cyanide
National Ambient Air Quality Standard (NAAQS)	1.5 ug/m3	7	Lead
Maximum Contaminant Level (MCL)	10 ug/l	4	Antimony
Secondary Max Contaminant Level (SMCL)	0.2 mg/l	2	Hydrogen Cyanide
Reportable Quantity (RQ)	1 lb	9	Cyclophosphamide
OVERALL SCORE CATEGORY 3		8.10	

Health Hazards

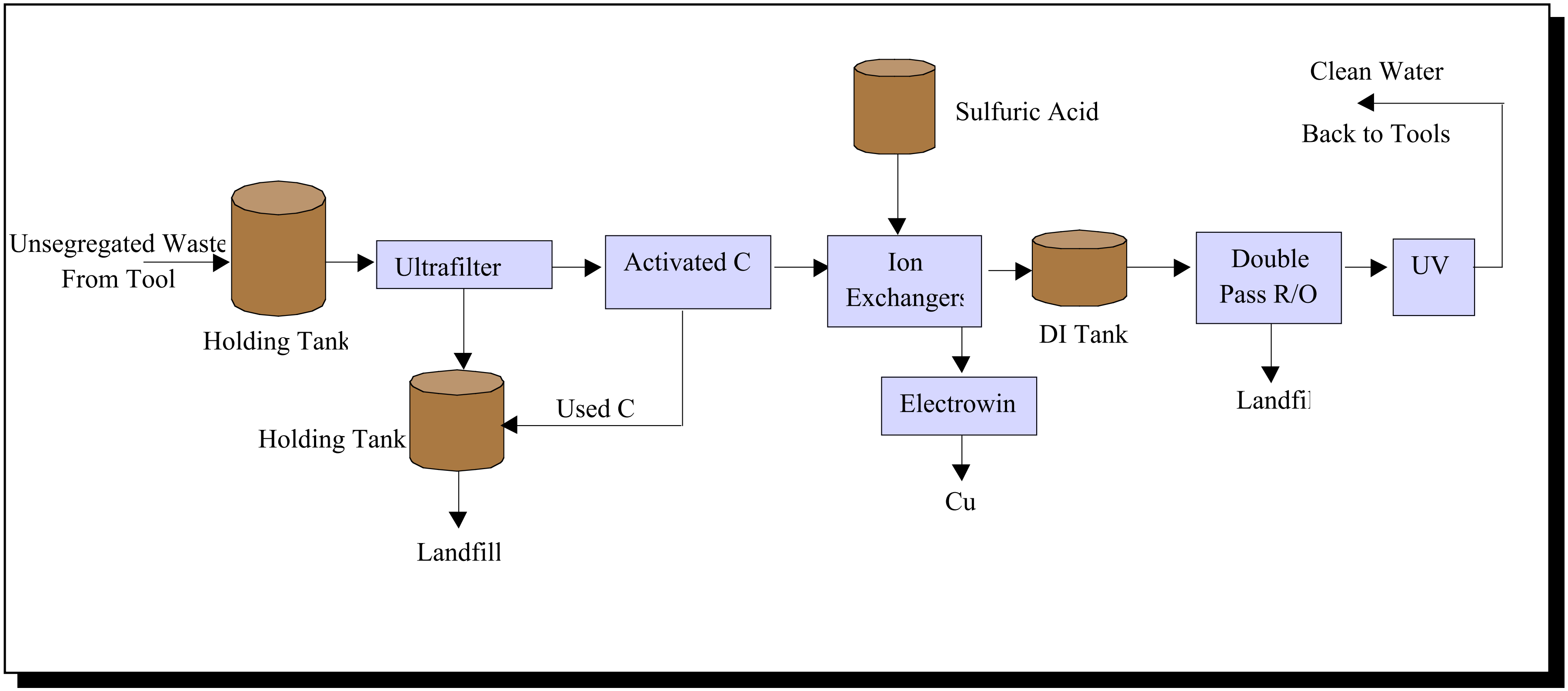
- Three categories
  - Acute toxicity, Physical Hazards, Standards and Regulations



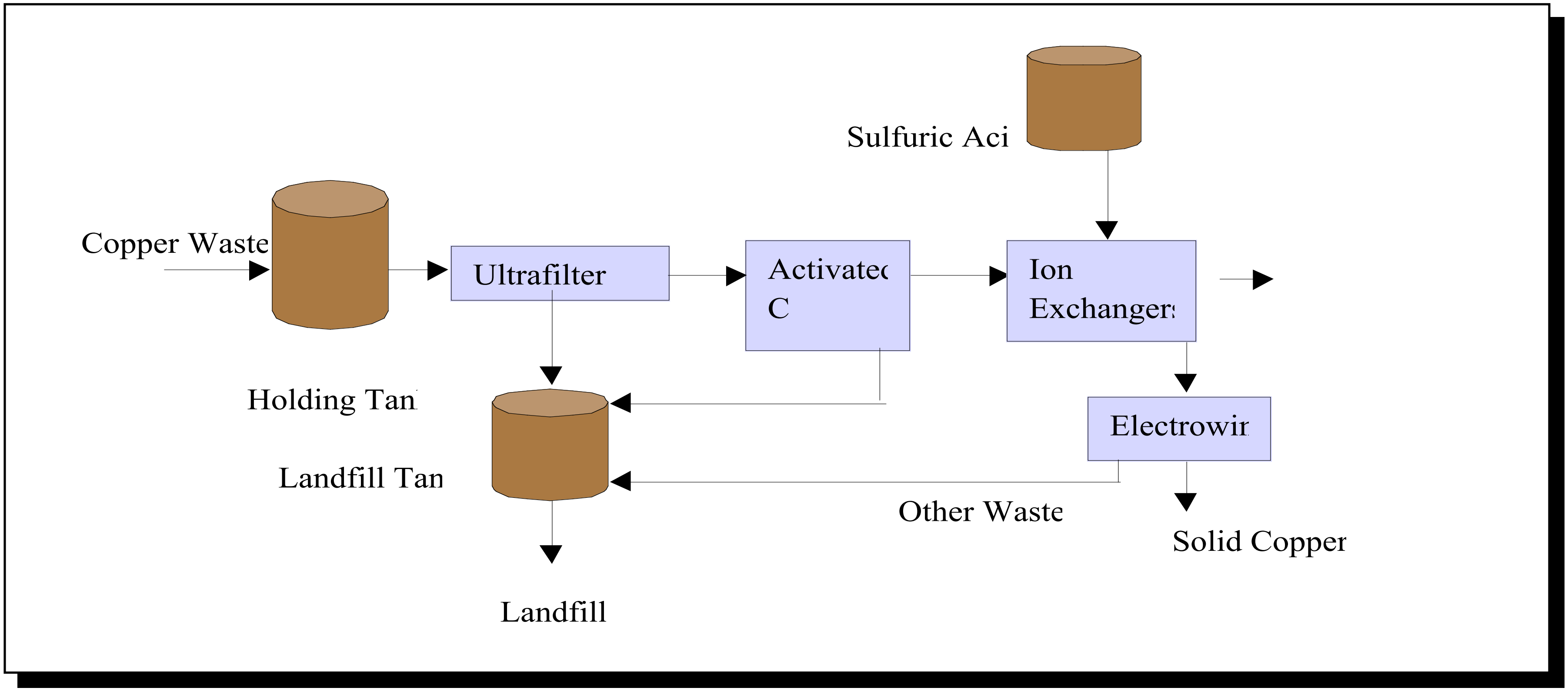
3. Case Study 2 - Informing Design of Equipment

- Copper CMP Waste Treatment
- Focus on how local regulatory and economic factors affect system design
- Examine Two Facility Waste Treatment Systems
  - Treat and Recycle
  - Treat and Discharge

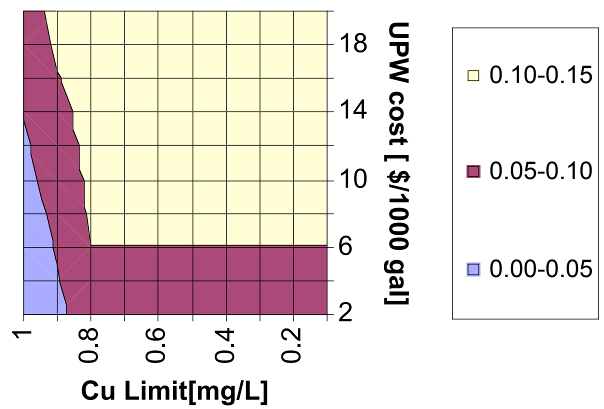
Facilities system: Treat and recycle



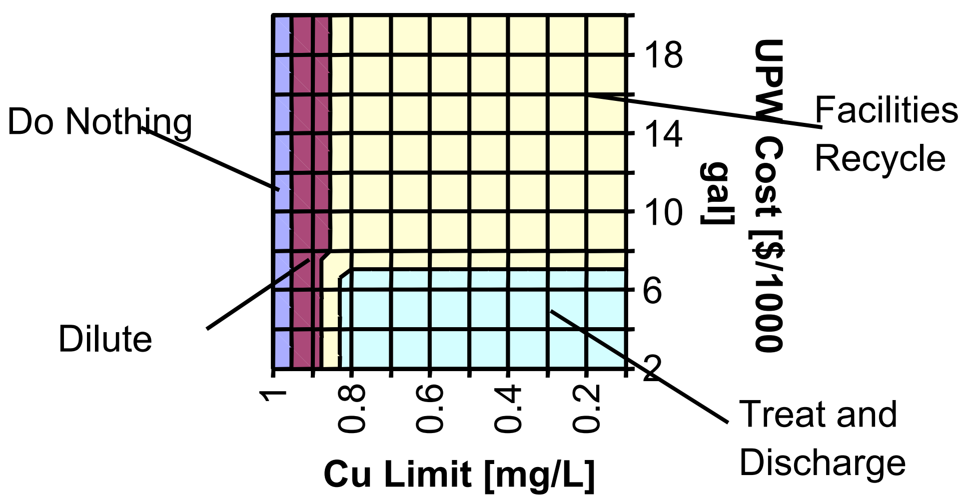
Facilities system: Treat and Discharge



Overall Decision Map



Incremental Cost over 'minimum' requirements (replacement of DIW+AWN discharge costs)



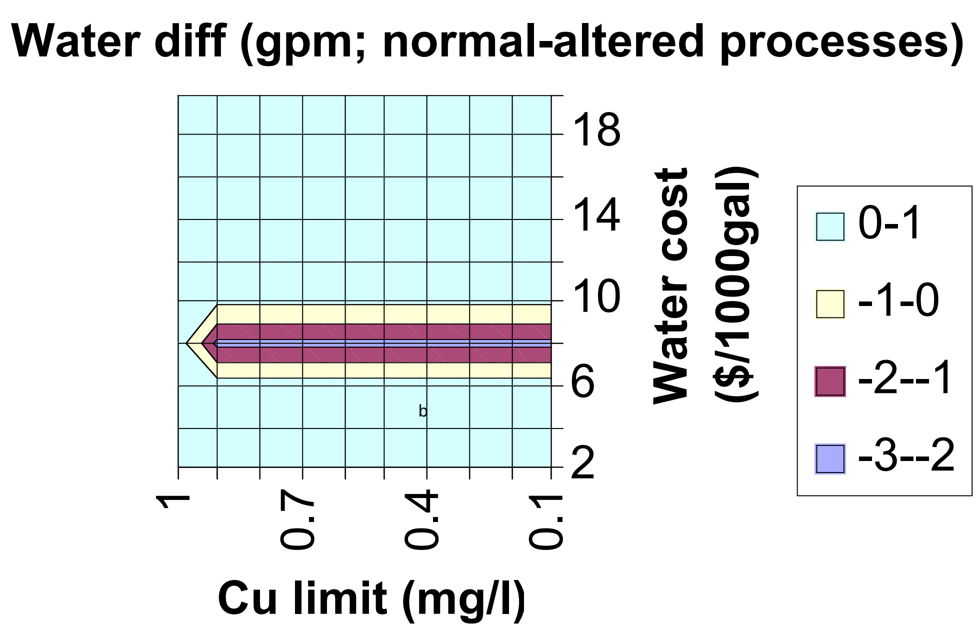
At Lax Cu Limits - Do Nothing

Low Water Costs - Discharge

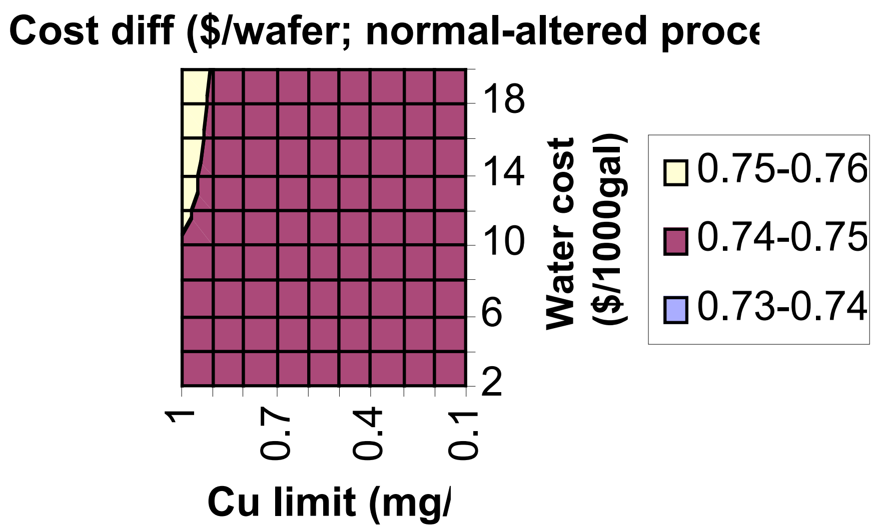
Intermediate Concentrations - Water Costs Decide Selection

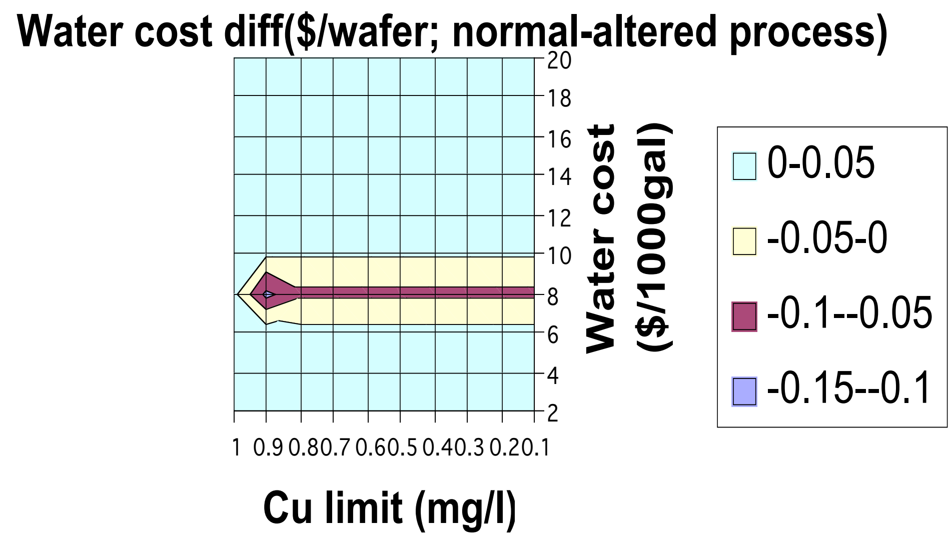
Copper CMP process alterations

- Scenario 1: Identify high water use steps
  - Decrease rinse times on platens (decreased water use) by decreasing unbalanced MRR.
  - Increased polish time, but decreased CoO
  - Increased water use with new process at $8/1000gal
    - owing to increased selection of T&D as most cost effective option



CMP process alterations: Scenario 1





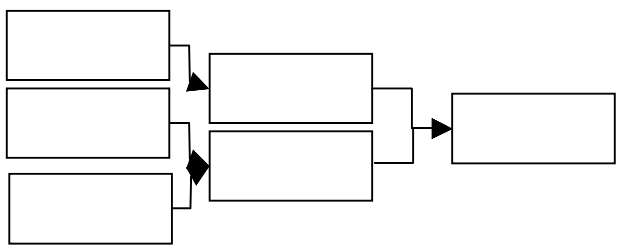
4. Conclusions

- Expand the library of models and data to cover all the fab operations (costs, resource use, emissions)
  - Use the hierarchical data structure
- Run more detailed case studies
- Combine fab-level analysis to upstream and downstream life cycle cost and environmental data - hybrid approaches
  - Collaborate with MIT, U of A, NCSU
- Other directions - QSAR, chemical screening, etc.

Additional Slides

Upstream life cycle impacts

- Main LCA obstacles
  - Effort and time for detailed SETAC life cycle inventory analyses
  - several months of data collection efforts
  - Boundary problems remain
  - Studies revisited with changes in equipment/processes and chemical sets,
  - Track comprehensive environmental impact data throughout the supply chain.



SETAC LCA

- Therefore, use a hybrid LCA approach

Economic Input Output LCA

What is the EIOLCA approach?

Developed by Carnegie Mellon University

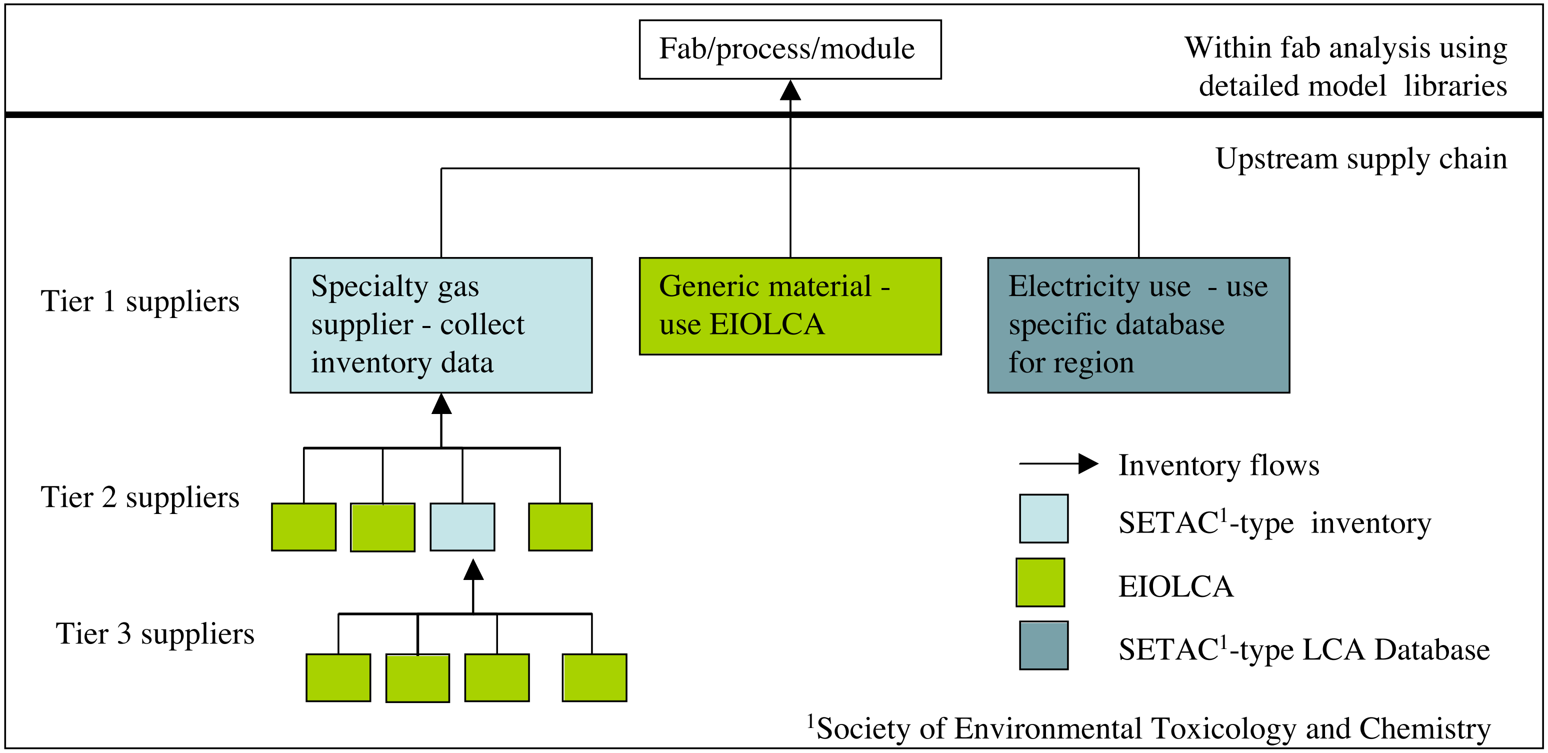
- Sectoral approach using Leontief Matrices
- Basis of matrix - unit economic output of one sector links to economic outputs of many other sectors.
- The Department of Commerce's 485x485 commodity input-output model of the US economy serves as basis.
- Potentially more inclusive than typical SETAC based LCA methods.
- Dollar values are translated to environmental impacts using several different available databases.

Output from sectors	**Input to sectors**				**Intermediate output *O***	**Final demand *F***	**Total output *X***
	1	**2**	**3**	**n**			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	F_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	F_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	F_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	F_n	X_n
Intermediate input *I*	I_1	I_2	I_3	I_n	□	□	□
Value added *V*	V_1	V_2	V_3	V_n	□	**GDP**	□
Total input *X*	X_1	X_2	X_3	X_n	□	□	□

Source: www.eiolca.net

Upstream life cycle impacts (contd.)

- So - adopt a hybrid approach



Hazard Scaling

Category 1: Acute Toxicity						
	Endpoints					
Scaled Score	LD$_{50}$ or LD	LC$_{50}$ or LC	TDL	TCL	ID (eye)	ID (skin)
1	>1 kg/kg	>10 kg/m^3	>100 g/kg	>1 kg/m^3	>100 ml, 100 g	>1 L, 1 kg
2	<1 kg/kg	<10 kg/m^3	<100 g/kg	<1 kg/m^3	<100 ml, 100 g	<1L, 1 kg
3	<100 g/kg	<1 kg/m^3	<10 g/kg	**<100 g/m^3**	<10 ml, 10 g	<100 ml, 100 g
4	<10 g/kg	<100 g/m^3	<1 g/kg	<10 g/m^3	<1 ml, 1 g	<10 ml, 10 g
5	<1 g/kg	<10 g/m^3	<100 mg/kg	<1 g/m^3	<100 μL, 100 mg	<1 ml, 1 g
6	<100 mg/kg	<1 g/m^3	< 10 mg/kg	<100 mg/m^3	<10 μL, 10 mg	<100 μL, 100 mg
7	< 10 mg/kg	<100 mg/m^3	<1 mg/kg	< 10 mg/m^3	<1 μl, 1 mg	<10 μL, 10 mg
8	<1 mg/kg	< 10 mg/m^3	<100 μg/kg	<1 mg/m^3	<100 nl, 100 μg	<1 μL, 1 mg
9	<100 μg/kg	<1 mg/m^3	<10 μg/kg	<100 μg/m^3	<10 nl, 10 μg	<100 nL, 100 μg
10	<10 μg/kg	<100 ug/m^3	<1 μg/kg	<10 μg/m^3	<1 nL, 1 μg	<10 nL, 10 μg

Category 3: Standards and Regulations								
	Endpoints							
Scaled Score	STEL (OSHA/ACGIH)	OSHA PEL (8 hr)	NIOSH TWA (8 hr)	TLV (8 hr)	NAAQS	RQ (lbs)	MCL/MCLG	SMCL
1	>10 g/m^3	>1 g/m^3	>1 g/m^3	>10 mg/m^3	>1 g/m^3	□	>1 g/L	>1 g/L
2	<10 g/m^3	<1 g/m^3	<1 g/m^3	< 10 mg/m^3	<1 g/m^3	□	<1 g/L	<1 g/L
3	**<1 g/m^3**	<100 mg/m^3	<100 mg/m^3	<1 mg/m^3	<100 mg/m^3	□	**<100 μg/L**	<100 μg/L
4	<100 mg/m^3	< 10 mg/m^3	< 10 mg/m^3	<100 μg/m^3	< 10 mg/m^3	5000	<10 μg/L	<10 μg/L
5	< 10 mg/m^3	<1 mg/m^3	<1 mg/m^3	<10 μg/m^3	**<1 mg/m^3**	<5000	<1 μg/L	<1 μg/L
6	<1 mg/m^3	<100 μg/m^3	<100 μg/m^3	<1 μg/m^3	**<100 ug/m^3**	<1000	<100 ng/L	<100 ng/L
7	<100 μg/m^3	<10 μg/m^3	<10 μg/m^3	<100ng/m^3	**<10 ug/m^3**	<100	<10 ng/L	<10 ng/L
8	<10 μg/m^3	<1 μg/m^3	**<1 μg/m^3**	<10 ng/m^3	<1 ug/m^3	<10	<1 ng/L	<1 ng/L
9	<1 μg/m^3	<100ng/m^3	<100ng/m^3	<1 ng/m^3	<100ng/m^3	1	<100 pg/L	**<100 pg/L**
10	<100ng/m^3	<10 ng/m^3	<10 ng/m3	<100 pg/m^3	<10 ng/m^3	<1	<10 pg/L	<10 pg/L

Category 2: Physical Hazards											
	Endpoints										
Scaled Score	FP (C)	LEL	EL Range	pH	HMIS HH	HMIS FH	HMIS RH	HMIS PP	NFPA FR	NFPA RR	NFPA HR
1	> 121	□	□	□	□	□	□	A,B	□		□
2	<121	□	□	**pH<6,>8.5**	□	□	□	C	□	□	□
3	□	□	□	□	1	**1**	1	D	1	1	1
4	<87.8	□	<5%	pH<5,>9.5	□	□	□	E	□	□	□
5	□	>5%	>5%	□	2	2	2	F	2	□	2
6	<60	<5%	>10%	pH<4,>10.5	□	□	□	G	□	2	□
7	□	<4%	>20%	□	□	□	□	**H**	□	□	□
8	<37.8	<3%	>30%	pH<3,>11.5	3	3	3	I	3	3	3
9	□	<2%	>40%	□	□	□	□	J	□	□	□
10	<22.8	<1%	>50%	pH<2,>12.5	4	4	4	K	4	4	4

Hazard Equations

Category Score, j, of a chemical i:

$$C_{i,j} = \sum_{k=1}^{m} \frac{X_{i,j,k}}{m}$$

With m endpoints with scores X

Process Score, I, for category j

$$PC_{i,j} = \log M_p + \log \sum_{i=1}^{L} \left(m_i \cdot \log^{-1} C_{i,j} \right)$$

m_i is the mass fraction of chemical i

Reference calculation, for category j

$$PC_{\mathrm{Ref},j} = \log M_{\mathrm{Ref}} + C_{\mathrm{Ref},j}$$

M_{Ref} is the largest process mass compared