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Abstract

Title: Decision Making Framework and Tools for Integrating Considerations on Sustainability in Technology Selection in the Semiconductor Industry

EPA Regional Office: Region 9 (the Pacific Southwest)

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Project Period: October 1, 2004 – September 30, 2007

Project Amount (EPA): $300,000

Total Project Amount: $300,000

Project Summary:
Environmental, Health and Safety (EHS) issues are an important determinant of the economic performance of the U.S. semiconductor industry. This sector of the economy and many other industries need rapid assessment methodologies to ensure the technological feasibility of new chemicals used in manufacturing, while human health, safety, and the environment being protected. All of these must be accomplished without delaying process implementation. The recent semiconductor Industry Roadmap (ITRS 2003) highlighted the need for decision support systems that can match the short innovation cycle and provide an integrated way to achieve environmentally sustainable production. Some of the required tools are: life cycle analysis, process modeling, decision theory, uncertainty analysis, cost-of-ownership analysis, value-of-information analysis, and risk management. A key aspect of this proposal is a software and database architecture that will be compatible with existing tools used for environmental analysis as well as those used for conventional process modeling. The key deliverables from the proposed research will be: a robust decision making framework, documented case studies and technology transfer to industrial collaborators. Progress will be tracked by regular reporting of results at annual meetings of semiconductor conferences, journal papers and conference proceedings. The database architecture and initial data will be made available on line to the general public. The semiconductor industry, which is highly concentrated in the Pacific Southwest Region (California, Arizona), Texas, and Oregon will benefit from this work.

Project Plan

1. Project Description

Environmental, health and safety (EHS) are of primary issues of concern to the semiconductor manufacturing industry. The recent technology roadmap (Semiconductor Industry Association 2003) highlighted the need for rapid assessment methodologies that will ensure the technological feasibility of new chemicals used in manufacturing, while human health, safety, and the environment being protected. All of these must be accomplished without delaying process implementation or the time-to-market, which is a critical aspect of commercial success. At present scientists and engineers who are responsible for new technology development face a critical need for explicit analysis methodologies, data sets, and case studies. Well documented case studies are needed to demonstrate the benefits of an environmentally conscious approach to process design where sustainability issues are treated as objectives not as constraints in business planning (Cano-Ruiz and McRae 1998). The essential concept in this proposal is the integration of tools and data bases needed to help evaluate the environmental impact of new production technologies and chemical systems before they are used in manufacturing.

1.1 Identification of Problem and Opportunity

There is an increasing recognition of need for semiconductor manufacturers to assess life cycle environmental impacts of their products. There are several driving forces, one of which comes from regulations. For example,

- The European Commission has recently issued an Integrated Product Policy (IPP) that advocates consideration of the whole of a product's life-cycle, from cradle to grave (EU 2003a).
- European union (EU) directives, such as the waste from electrical and electronic equipment (WEEE) directive, state reduction of life cycle impacts as a primary goal (EU 2003b).
- The Swedish Confederation of Professional Employees (TCO) has developed the detailed environmental requirements and an accompanying certification system for personal computers and monitors (TCO 95 and TCO 99). The initiative is widely recognized internationally (Gutowski, Murphy et al. 2001).
- EU restriction of the use of certain hazardous substances in electrical and electronic equipment (ROHS) (EU 2003c).

In addition to regulation some initial studies point to the economic benefits of a life-cycle approach that can lead to “win-win” solutions (Ford 2003). While there are many examples in the chemical industry, by comparison, there are only a relatively few published case studies of the electronics manufacturing industry. Set out below are a few examples.

- (Lashbrook and et al. 1997) identified processes which have superior environmental and economic performance from three options for deep ultraviolet lithography.
- Through water recycling strategies, Texas Instruments was able to save 260 million gallons every year, for a cost savings of $700,000/yr. (DeGenova 2000).
- Applied Materials has effectively used EHS decision tools to identify cost-effective options to treat wastewater contaminated with copper from chemical/mechanical polishing of wafers (Bauer, Krishnan et al. 2001).

There is clearly a need for more examples. As a preliminary study to this project a series of 14 interviews were carried out. A list of the key contacts at each organization is shown in Table 1. We visited these people to carry out a preliminary requirements analysis and in particular to identify critical research needs.

Table 1 - List of Companies Interviewed for EHS Needs and Concerns

Date of Visit	Organizations Visited	Type of Activity	Key Contact
01/12/04	Texas Instruments, TX	Device Manufacturer	Tim Yeakley, t-yeakley@ti.com,
01/13/04	Motorola, TX	Device Manufacturer	Brett Davis brett.davis@motorola.com
01/13/04	International SEMATECH, TX	Industrial Consortium	Walter Worth, walter.worth@intl.sematech.org,
01/13/04	TEL, TX	Device Manufacturer	Alan Krov, akrov@aus.telusa.com
01/14/04	DuPont, DE	Chemical Supplier	Mike Mocella, Michael.mocella@usa.dupont.com
01/27/04	AMD, CA	Device Manufacturer	Reed Content, reed.content@amd.com
01/27/04	Applied Materials, CA	Tool Supplier	Sebastien Raoux, sebastien_raoux@amat.com
01/27/04	SEMI, CA	Industrial Consortium	Rick Row, rrow@semi.org
01/28/04	Intel, PX	Device Manufacturer	Jim Jewett, Jim.jewett@intel.com
01/29/04	Novellus, CA	Tool Supplier	John G. Langan, John.langan@novellus.com
01/29/04	Silicon Valley Toxicity Coalition, CA	Advocacy Group	Ted Smith, tsmith@igc.org
01/30/04	Air Products, CA	Chemical Supplier	Ralph Richardson, RICHARRJ@airproducts.com
01/30/04	ATMI, PX	Tool Supplier	Mike Scherer, msherer@atmi.com,
02/24	BOC Edwards	Chemical Supplier	Ken Lykins, Ken.Lykins@bocedwards.com

Key findings from Interviews include:

- Technical performance is always the key issue. EHS enhancement cannot compromise technical performance.
- The system boundary for most of the companies is around the fab. The mindset of environmental protection is end-of-pipe type of downstream treatment.

- Most companies are focused on only one or a few aspects of the environmental impacts, rather than broad concepts like sustainability.
- EHS cost of ownership (COO) is often not included because it is considered small compared to equipment cost.
- Most research and development personnel and process engineers of the tool suppliers and IC manufacturers have limited or little understanding on the EHS impacts of their designs.
- Essentially all process engineers responsible for the selection of new chemistries or production technologies expressed the need for examples that demonstrate the benefit of "win-win" solutions.
- Most designers ignore the fact that much of the data needed for process analyses are also needed for performing environmental analyses. Typically the linkages between EHS groups and process designers were weak and EHS issues were simply treated as a go/no-go criterion.

One resounding conclusion was the need for better tools for anticipating potential adverse environmental impacts of new chemicals before they are used in large scale manufacturing. For example, if the adverse environmental impacts of perfluorooctanyl sulfonate (CFR 2000) had been identified much earlier, the high costs of abatement and identifying suitable replacements would have been avoided.

1.2 Use of Science – A New Decision Making Framework

The focus of this project is on the development of the metrics, the databases, and the algorithms needed to perform rapid EHS evaluations at the unit process level as well as at the fab level. The novelty of the work lies in considering in an integrated way how uncertainties in EHS and process economics can be reflected in decisions about technology choices being faced by the semiconductor industry. The detailed components are to

- Demonstrate the procedure and merits of integrating EHS evaluations in technology assessments;
- Design a procedure that shows the steps in evaluating a chemical, a device, or a process;
- Design a database that includes the crucial properties of a material to be studied before the material is applied to manufacturing;
- Develop metrics that are suitable for semiconductor industry;
- Evaluate the materials that may be of interest in the manufacturing processes;
- Transfer learning from case studies that show how to evaluate the environmental impacts when making decisions to the semiconductor industry.

Case studies are a key aspect of testing and refining the new methodologies. Three specific analyses have been performed: (1) NF_3 versus F_2 for chamber cleaning, (2) Cu chemical vapor deposition, and (3) direct patterning to produce low k dielectrics. Because of the concern about global warming, various approaches have been used to reduce the emission of PFCs. One example is the use of NF_3 as a substitute for CF_4 and C_2F_6. Figure 1 shows a comparison of the life cycle impacts of NF_3 versus F_2 using the methodology developed by (Cano-Ruiz 2000) and applied to the NF_3 vs. F_2 case by (Chen, Cano-Ruiz et al. 2004). In practice it has been found that it is possible to achieve a two to three times higher decomposition rate using NF_3 rather than CF_4 or C_2F_6. At the same time a reduction of operating costs for the abatement is possible. A key feature of the results shown in Figure 1 are the estimates of the uncertainties associated with the impacts. This information can be used to assess risk and in particular to identify areas where allocation of resources to reduce uncertainties can be most effective.

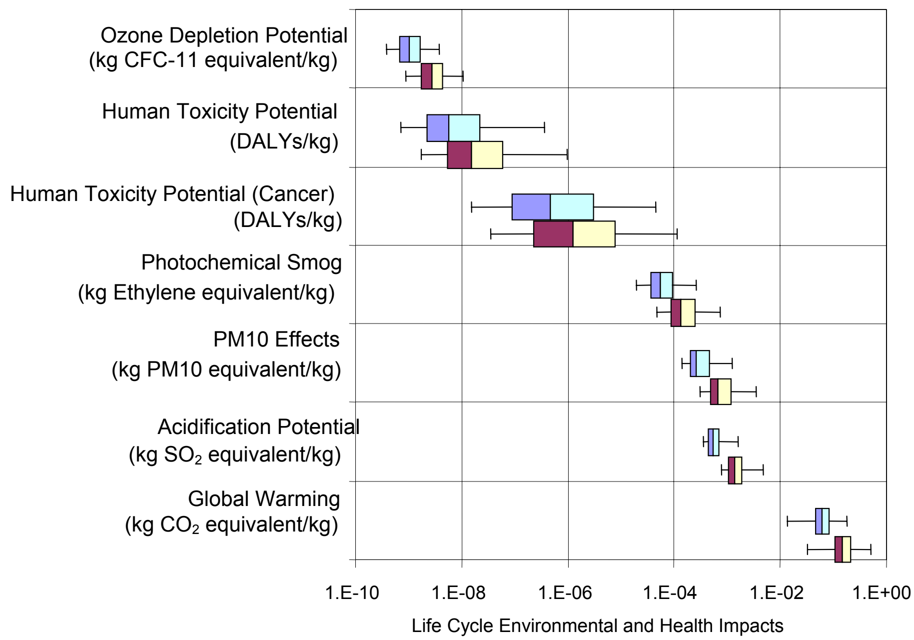

Figure 1. Example of Life Cycle Analysis of a NF_3 compared to F_2 Process.

The essence of the proposed decision making framework is shown in Figure 2. Value of Information (VOI) and decision tree concepts will used to assess the underlying data in the presence of uncertainties in the model, as well as the impact of further refinement in details that affect the decision outcome or risk (Clemen 1997).

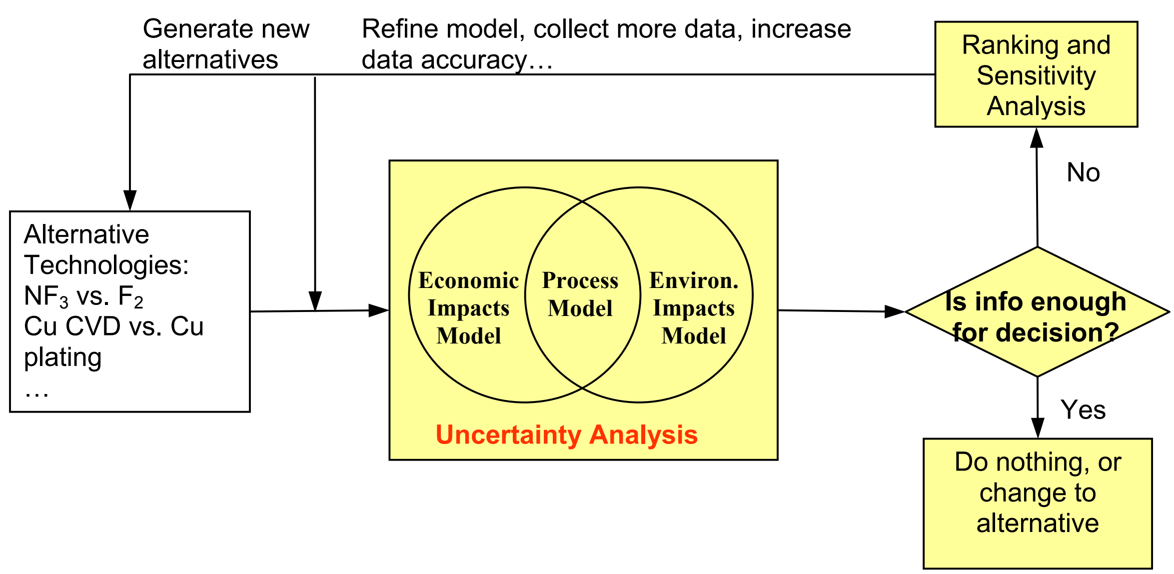

Figure 2. Decision Making Framework under Uncertainty

1.3 Tasks and Deliverables

Set out below are the proposed research tasks and deliverables. In the short term the goal is to develop the system architecture, identify the "best" analysis tools and propose a database structure for managing the data need for both economic and environmental analyses. We intend to publish the architecture and solicit feed back from our collaborators. In the latter part of the proposed project we propose to test the design concepts against a series of selected case studies. We expect to have considerable leverage on this project from our current involvement with the NSF/Semiconductor Research Center (SRC) Engineering Research Center (ERC) for Environmentally Benign Semiconductor Manufacturing at the University of Arizona. This center has participants from MIT, Stanford, University of California Berkeley, and the University of Arizona. It has focus on development of the basic science. We have access to much of the needed data and can interact with other researchers who are willing to supply case studies and test any proposed environmental assessment tools. In this proposal the goal is integration of the components not so much the development of new capabilities.

Task 1. User Requirements Analysis and Extension of Interview Base

We did not have the opportunity to meet with the regulatory community as a part of our screening survey. We propose to extend the results of the survey to include state and federal regulatory authorities in particular Region 9 where much of the semiconductor production facilities are located.

Deliverables: (1) A report summarizing the results from the user requirements analysis
(2) A summary of the regulatory requirements in the U.S. and the data needed to support environmental impacts of the type described in (Chen, Cano-Ruiz et al. 2004).

Task 2. Design Database Structures for Modeling of Manufacturing Equipment and Facility

Based on the results of the user requirements analysis the objective of this task is to develop the basic data architecture for environmental impact analysis. We proposed to design the data structures for an equipment centric approach that will support a library of models. An equipment centric approach offers a convenient way to build "bottom-up" environmental analyses for the entire manufacturing facility that can keep pace with technology changes. Since many manufacturing environmental impacts are tied to the design of equipment, such an approach also offers a practical way to quantify equipment cost and environmental performance and support equipment procurement decisions (Krishnan, Raux et al. 2004). For the purposes of this work, four key modules are identified, each consisting of a string of process steps – Shallow Trench Isolation (STI), gate stack, via and interconnect following a methodology developed by (Smati, Raux et al. 2002). The data architecture must accommodate (i) a library of recipes for individual process steps; (ii) a process tool library; (iii) a library of point of use infrastructure requirements in the subfab, such as pumps, abatement devices, monitoring equipment, gas panels, etc.; and (iv) a library of facilities infrastructure. Table 2 presents some examples of process tools and facility infrastructure requirements.

Table 2 - Summary of Key Process Tools and Facility Infrastructure Requirements

Process Tools	**Facility infrastructure**
Rapid Thermal Processing	Electrical System
Chemical Vapor Deposition	Ultra-pure water (UPW) system
Epitaxial/Polysilicon deposition	Process cooling water (PCW) system
Physical Vapor Deposition	Chilled water system (CWS)
Ion Implantation	Delivery of recycled water
Lithography	House scrubber for Acid Exhaust
Plasma Etching	VOC abatement for solvent exhaust
Chemical Mechanical Planarization (CMP)	Acid Waste Neutralization System
Electrochemical Plating (ECP)	Piping, plumbing of different wastes
Wet Cleaning	

Deliverables: A standard relational data base design implemented using standard structured query language (SQL) protocols. The implementation will be carried out using Microsoft Access.

Task 3. Design of Data Architecture for Life Cycle Environmental Impact Analysis

Figure 3 shows the data flow architecture for the life cycle environmental impact analysis system developed by (Cano-Ruiz 2000). The primary objective of this task is to convert the "research prototype" into an industrial strength modeling system using object oriented programming in C++ coupled with a standard SQL interface to the outputs from the equipment centric models, the environmental metrics derived from Task 1, and industry standard data bases for material, chemical and toxicity data bases.

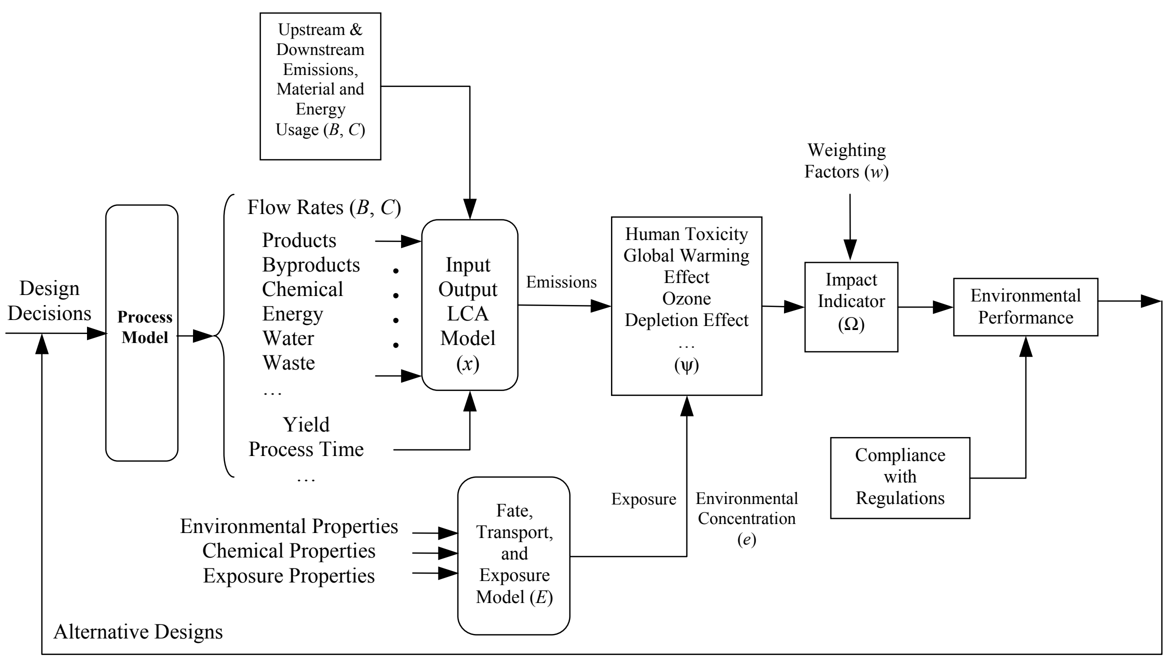

Figure 3 Components of an Environmental Evaluation Model

Up to now, most of the environmental evaluations of the semiconductor industry remain as adding up material and energy consumptions and emissions (Schischke, Stutz et al. 2001; Taiariol, Fea et al. 2001; Murphy, Kenig et al. 2003). However, as shown in Figure 4, there is great information overlap between the two. Our past work has shown that by building process models, we were able to extract technical performance, cost, and environmental information from a centralized and verifiable source (Chen, Cano-Ruiz et al. 2004).

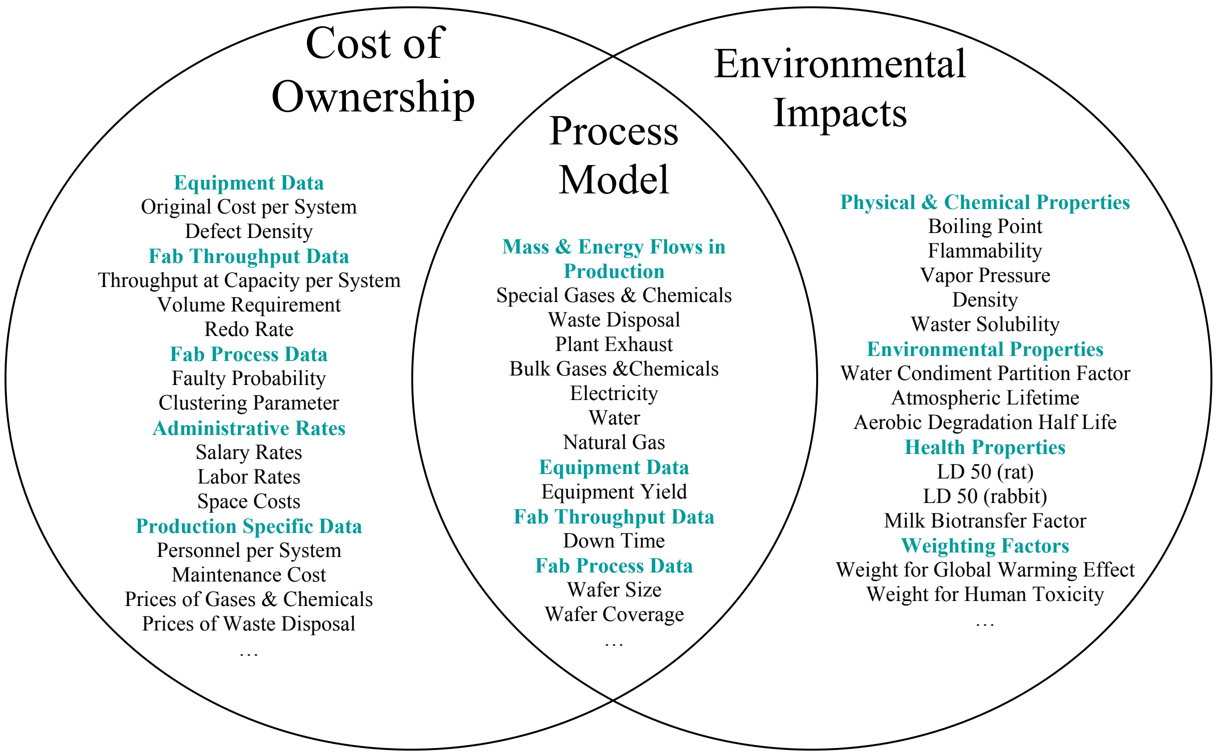

Figure 4. Overlapping of Data Requirements in an Economic Valuation and an Environmental Valuation

Deliverables: An environmental process modeling system that can link the outputs from the equipment centric models with the physical/chemical/toxicity data needed to carry out the life cycle environmental impact analysis using the methodology of (Cano-Ruiz 2000).

Task 4. Expand the Current Cost of Ownership (COO) models to Include Safety and Risk Management Costs

A major pitfall related to current hazard scoring of chemicals is the lack of adequate toxicity data as a result of rapidly changing chemistries in the semiconductor industry (Schuppe and Ho 2002; Semiconductor Industry Association 2003). The problem is particularly severe for the endpoints of systemic toxicity, developmental/reproductive toxicity and carcinogenicity which are often not well studied or characterized. To offset the current lack of health metrics, we propose to explicitly quantify certain costs associated with health and safety and risk management.

Deliverables: We propose to expand current COO models to include costs related to: (i) engineering controls required for health and safety reasons; (ii) facility infrastructure such as thicker piping, exhaust and ventilation, and equipment enclosures; (iii) personal protective equipment to protect workers from exposure to hazards during interventions etc.; and (iv) costs from workplace injuries (treatment, workers compensation data, etc.) drawn from Industrial Hygiene (private) and from OSHA (public) databases.

1.4 Definition of Success and Measurement of Progress

The project will be considered as a success if the tools, data architectures, process models, and life cycle environmental impact assessment tools are taken up by the industrial, academic, and regulatory communities. Given the pressing needs facing the semiconductor industry we foresee no major difficulties in the light of the enthusiasm expressed by our collaborators shown in Table 1 as well an additional set of people shown in the next section.

2. Qualifications and Collaborators

The principal investigator has considerable experience with lifecycle assessment methodologies and chemical process modeling. In addition, the proposed Ph.D. student (Yue Chen) and postdoctoral fellow (Dr. Nikhil Krishnan) have already worked with the semiconductor industry and were involved in the interviews described in Table 1. They are both are aware of current EHS practices, tools and databases. In addition to those shown in Table 1 set out below is a list of project partners who have agreed to work with us on the development and use of case studies.

Table 3 - Collaborators for Testing the Proposed System and for Development of Case Studies

Name	Organization	Title	Knowledge and Expertise	Role in This Project
Farhang Shadman	Arizona University, NSF/SRC ERC	Professor, Director of NSF/SRC ERC	Ultra-pure water generation and recycling for semiconductor manufacturing	Provide direction of this project, data on water consumption
Michael Overcash	Northern Carolina State University	Professor	Life cycle inventory	Provide data on upstream of chemicals and energy production
Paul Blowers	University of Arizona	Professor	Chemical process modeling	Provides data on supercritical CO_2
David Dornfeld	University of California, Berkeley	Professor	Mechanical process and equipment modeling and manufacturing systems	Provides data on Chemical Mechanical Planarization (CMP) processes and manufacturing systems modeling

3. Transferability

The means of transferring the lessons and results to the industry will include: (1) technology transfer documents following the standards of the industry consortium International SEMATECH; (2) presentations at trade show such as SEMICON WEST, TECHCON, and Electronics Go Green; (3) articles on trade magazines such as Semiconductor International, Electronic News, and Semiconductor Fabtech; (4) presentations at the NSF/SRC ERC semi-annual meetings; (5) training courses offered at the NSF/SRC ERC meetings. The means of transferring to the academia include: (1) papers on journals such as Institute of Electrical and Electronics Engineers (IEEE) Transactions, Environmental Science and Technology, Environmental Science, and Industrial Ecology; (2) presentations at conferences such as IEEE Electronics and the Environment, International Semiconductor Environment, Safety and Health, and American Institute of Chemical Engineers; (3) course modules for undergraduate and graduate studies. The results and methodologies will have direct applications to other industries as well.

4. Project Schedule

Oct. 2004 – May 2005:	Finish integration of individual tools. Complete the documentation of the case study of comparing chamber cleaning gases and procedure for applying methodology to technology selection. Construct the database structure.
Oct. 2004 – Feb., 2005:	Develop a module for training which will be conducted during the NSF/SRC Engineering Research Center meeting in February, 2005
June 2005 – June 2006:	Select and conduct 2 new case studies that are of future technologies upon which the industry is making decisions. Same knowledge-transfer methods as before.
July 2006 – Feb. 2007:	A suite of training modules and a short course on EHS assessment in semiconductor manufacturing and other process intensive industries
June 2005 – June 2007:	Populate databases with chemical and process recipe data.
June 2007 – Sept. 2007:	Document the learning and results during the 3-year period.

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Resume

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EDUCATION

B.E. (Honors) (1971)	Mechanical Engineering, Monash University, Australia
M.S., Ph.D. (1981)	Engineering, California Institute of Technology

PROFESSIONAL EXPERIENCE

1969 - 1975	Consulting Engineer, Kinhill, Melbourne Australia
1981-1983	Senior Research Engineer, Environmental Quality Laboratory, Caltech.
1983-1992	Assistant, Associate and Professor, Departments of Chemical Engineering and Engineering and Public Policy, Carnegie-Mellon University.
1992-Present	Professor of Chemical Engineering, Department of Chemical Engineering, Massachusetts Institute of Technology

CURRENT RESEARCH INTERESTS

Current activities include: atmospheric processes responsible for oxidant formation, acid deposition and global climate, chemical transport and transformations in multimedia environments. Other interests include: uncertainty analysis, nonlinear parameter estimation, molecular design, combinatorial optimization, application of mathematical models in the policy process and the design of cost effective environmental controls. Chemical process and product design to improve commercial and environmental performance.

MAJOR HONORS, AWARDS, AND FELLOWSHIPS

Foremost-McKesson Foundation Fellowship (Caltech)
Oscar Weigel Exhibition in Engineering, Monash University
Production Equipment Prize and Solid Mechanics Prize, Monash University
Presidential Young Investigator Award, National Science Foundation
George Tallman Ladd Research Prize, Carnegie-Mellon University
AAAS U.S. EPA Environmental Science Fellowship
Forefronts of Computational Science Award
Niccograph Scientific Visualization Prize
National Computer Graphics Prize

CURRENT TECHNICAL AND GOVERNMENT COMMITTEES

U.S. Environmental Protection Agency (Member of Review Panels)
National Research Council (Two current committees)
National Academy of Sciences (Panel on Destruction of Chemical Warfare Agents)
Member of Advisory Board of the Combustion Research Facility at SANDIA
U.S. DoE Science Advisory Board for Advanced Scientific Computing
Five editorial boards

SELECTED FILMS AND VIDEO TAPES

Visualizing Los Angeles Air Quality,[1] (video), Produced at the Pittsburgh Supercomputing Center and the National Center for Supercomputing Applications, Illinois. (1990)

Los Angeles Air Quality,[2] (video), Produced at the Pittsburgh Supercomputing Center, Pittsburgh. (1991)

SELECTED PUBLICATIONS (From over 150 referred articles, reports,…)

Five Publications Relevant to the Proposal

Cano-Ruiz, A. and G.J. McRae, “Environmentally Conscious Process Design,” Annual Reviews of Energy and Environment, 23, 499-536 (1998).

Hoffmann, V. H., Hungerbuhler, K. and McRae, G. J.;, “Multiobjective Screening and Evaluation of Chemical Process Technologies,” Ind. Eng. Chem. Res., **40**(21); 4513-4524 (2001)

Jiménez, J.L., J.B. McManus, J.H. Shorter, D.D. Nelson , M.S. Zahniser , M. Koplow, G.J. McRae, C.E. Kolb, “Cross road and mobile tunable diode laser measurements of nitrous oxide emissions from motor vehicles,” Chemosphere - Global Change Science, **2**, Issues 3-4, 397-4121 (2000).

Phenix, B.D., Dinaro, J.L., Tatang, M.A., Tester, J.A., Howard, J.B. and McRae, G.J., Incorporation of Parametric Uncertainty into Complex Kinetic Mechanisms: Application to Hydrogen Oxidation in Supercritical Water, Combustion and Flame, **112**, Issues 1-2, 132-

Pan, W-W, M.A. Tatang, G.J. McRae, and R.G. Prinn. Uncertainty Analysis of Direct Radiative Forcing by Anthropogenic Sulfate Aerosols, *J. Geophysical Research,* **102**(D18), 21,915-21,924, (1997)

Five Additional Closely Related Publications

Brugge, B., Riedel, E., Russell, A.G. and McRae, G.J., Developing GEMS: An Environmental Modeling System, IEEE Journal on Computational Science and Engineering, Fall, 55-68 (1995)

McRae, G.J., W.R. Goodin, and J.H. Seinfeld, "Development of a Second Generation Mathematical Model for Urban Air Pollution: I. Model Formulation," *Atmospheric Environment*, **16**, 679-696 (1982)

Milford, J.B., G.J. McRae, and A.G. Russell, "A New Approach to Photochemical Pollution Control: Implications of Spatial Patterns in Pollutant Responses to Reductions in Nitrogen Oxides and Reactive Organic Emissions," *Environmental Science and Technology*, **23**, 1290-1301, (1989).

Milford, J.B., A.G. Russell, and G.J. McRae, "Comparison of Condensed Mechanisms for Photochemical Air Pollution," *Environmental Science and Technology*, December, (1992)

Russell, A.G., G.J. McRae, and G.R. Cass, "Mathematical Modeling of the Formation and Transport of Ammonium Nitrate Aerosol," *Atmospheric Environment,* **17**, 949-964 (1983).

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[1] This visualization has won several awards for computer animation including: The Niccograph Scientific Visualization Prize (Japan), Science Category Prize at Festival International du Film par Ordinateur de Montreal (FIFCOM) competition, PIXEL INA Award (Monte Carlo), SIGGRAPH 90 Film and Video Show, First Place in National Computer Graphics Association for Scientific Visualization and Second prize in the 5th International Computer Animation Competition Images Du Futur 91 held in Canada.

[2]This visualization won the 1991 Computer Graphics Society of Japan award for scientific visualization.

Current and Pending Support

Budget

Budget Justification

Quality Assurance Statement

Individual Who is Responsible for Quality Assurance

Professor Gregory J. McRae, Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, mcrae@mit.edu

Activities for Hypothesis Testing

The key data collection activity in the proposed project is related to populating databases for semiconductor EHS decision support. We are interested life cycle environmental data and economic performance data for semiconductor manufacturing. In the short term (1 year), data related to two specific case studies will be collected. In the long term (3 years), a broader suite of data will be accumulated to provide a practical decision support tool for semiconductor manufacturing.

This project will rely on a wide variety of data from multiple sources. Environmental data will include various life cycle resource use and emissions factors. Economic data will include costs related to specific semiconductor manufacturing operations, materials, equipment and infrastructure. This project will involve some measurement activities, but will also rely heavily on secondary data sources.

Data quality of both measurements and secondary data will be examined and investigated through three primary methods. We will:

i. Use relevant data collection protocols, or, for secondary data, verify that proper protocols were employed [Myers et. al., 2001, Hinson et. al 2000].
ii. Cross-check data through use of multiple data sources where possible, such as similar data points from different companies, life cycle data from different databases data from multiple measurements at different sites, etc.
iii. Capture the uncertainty in datasets and propagate this through the analysis. We will also assess the value of specific information items to the specific decision problem. By explicitly modeling the uncertainty in data (through Monte Carlo methods), large uncertainties need not conflict with effective decision making. Details on uncertainty modeling and the value of information assessment appear in (Chen, Cano-Ruiz et al. 2004)

Study Design

Environmental and economic data will be collected under four key categories for semiconductor manufacturing: (i) Recipe level (ii) Platform level (iii) Point-Of-Use infrastructure and (iv) facilities infrastructure . Numerous secondary sources will be used to gather upstream life cycle environmental data ranging from commercial life cycle databases, Process-Product Input-Output LCA model and analysis based on first principles. Health hazard data, if collected, will be from publicly available databases or peer reviewed journals. Wherever possible, uncertainty in data will be assessed by comparing data from different sources following the description in the previous section. Numerous endpoints will be considered for environmental data. Some are highlighted below:

i. Electricity use: Semiconductor data collected or examined will use the SEMATECH utility use protocol [Hinson et. al 2000]
ii. Water use, Gaseous, Liquid emissions, Solid waste: Data will be collected for these and other key semiconductor EHS metrics [Dahlgren 2002]. For equipment data, we will use the SEMATECH equipment characterization guidelines wherever possible [Myers et. al. 2001].

Calibration Procedures

The key analytical instruments that may be used in this project are

i. Power meters for semiconductor equipment and facilities power measurement: A digital meter capable of reporting the true RMS value of the current waveform and of making current measurements with an accuracy of greater than 5% full scale will be used. Instrument specifications, calibration and use are detailed in a SEMATECH protocol [Hinson et. al. 2000].
ii. Fourier Transform Infrared Spectroscopy (FTIR) and Quadrupole Mass Spectroscopy (QMS). They will be used analyze semiconductor process gaseous emissions. Calibration and use will proceed as per the SEMATECH gaseous emissions protocol [Myers et. al. 2001].

Data Reduction and Reporting

The database structure and data collection methodology will be reviewed by two other collaborating researchers: Prof. Paul Blowers at the University of Arizona, Prof. Michael Overcash at NCSU and Prof. David Dornfeld at the University of California at Berkeley. The database structure will also be presented to the NSF/SRC Industrial Advisory Board and reviewed in February 2005.

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