UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

April 4, 2002

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OFFICE OF THE ADMINISTRATOR
SCIENCE ADVISORY BOARD

Honorable Christine Todd Whitman
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW
Washington, DC 20460

Subject: Industrial Ecology: a Commentary by the EPA Science Advisory Board

Dear Governor Whitman:

At its November 1997 retreat, the EPA Science Advisory Board's Executive Committee encouraged its standing committees to undertake more self-initiated efforts. This commentary is one of several Environmental Engineering Committee (EEC) initiatives undertaken in response to that guidance.

This commentary addresses Industrial Ecology, a systems approach to environmental analysis. Industrial ecology seeks to address not just industrial emissions, and not just specific products, but the complex networks of services, products, and activities that make up our economy. It emphasizes opportunities for new technologies, new processes, and economically beneficial efficiencies.

The purpose of this Commentary is two-fold: first, to bring industrial ecology to the attention of a wider audience within EPA and other agencies as an approach to meeting their missions, and second, to articulate key research needs. The SAB believes that industrial ecology could help EPA to address some of the core challenges of environmental policy, from climate change to waste management to land use policy. Achieving this potential will require rigorous research and a firm grounding in science and engineering.

This identifies the need for better understanding of the potential and limitations of a range of promising approaches including:

a) technological innovation

b) voluntary and cooperative approaches to environmental management

c) substitution of services for products

d) recycling and reuse

e) reduction in the amounts of materials used in products

f) substitution of scarce resources with those that are plentiful

We look forward to your written response to the ideas set forth in the commentary. Please contact us if we may be of further assistance.

Sincerely,

/ Signed /

Dr. William Glaze, Chair
EPA Science Advisory Board

/ Signed /

Dr. Domenico Grasso, Chair
Environmental Engineering Committee
EPA Science Advisory Board

/ Signed /

Dr. Thomas Theis, Co-Chair
Subcommittee on Industrial Ecology and Environmental Systems Management
Environmental Engineering Committee
EPA Science Advisory Board

/ Signed /

Dr. Valerie Thomas, Co-Chair
Subcommittee on Industrial Ecology and Environmental Systems Management
Environmental Engineering Committee
EPA Science Advisory Board

U.S. Environmental Protection Agency
EPA Science Advisory Board
Environmental Engineering Committee*
Fiscal Year 2002

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Dr. Bruce Rittmann, Northwestern University, Evanston, IL

Dr. Thomas Theis, University of Illinois at Chicago, Chicago, IL

Dr. Valerie Thomas, Princeton University, Princeton, NJ

SCIENCE ADVISORY BOARD STAFF
Ms. Kathleen Conway, USEPA Science Advisory Board (1400A), 1200 Pennsylvania Avenue, NW, Washington, DC

Ms. Mary Winston, USEPA Science Advisory Board (1400A), 1200 Pennsylvania Avenue, NW, Washington, DC

* Members of this SAB Panel consist of SAB Members: Experts appointed by the Administrator to serve on one of the SAB Standing Committees.

U.S. Environmental Protection Agency
EPA Science Advisory Board
Environmental Engineering Committee
Subcommittee on Industrial Ecology and Environmental Systems Management*

CO-CHAIRS
Dr. Thomas Theis, University of Illinois at Chicago, Chicago, IL

Dr. Valerie Thomas, Princeton University, Princeton, NJ

EEC MEMBERS
Dr. Domenico Grasso, Smith College, Northampton, MA

Dr. Byung Kim, Ford Motor Company, Dearborn, MI

CONSULTANTS
Dr. James N. Galloway, University of Virginia, Charlottesville, VA

Dr. Catherine Koshland, University of California-Berkeley, Berkeley, CA

Dr. Reid Lifset, Yale School of Forestry and Environmental Studies, New Haven, CT

Dr. Robert Pfahl, Motorola Advanced Technology Center, Schaumburg, IL

Dr. Clifford S. Russell, Vanderbilt University, Nashville, TN

SCIENCE ADVISORY BOARD STAFF
Ms. Kathleen Conway, USEPA Science Advisory Board (1400A), 1200 Pennsylvania Avenue, NW, Washington, DC

Ms. Mary Winston, USEPA Science Advisory Board (1400A), 1200 Pennsylvania Avenue, NW, Washington, DC

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Commentary on Industrial Ecology
EPA SAB Environmental Engineering Committee

1. Introduction

Over the past decade, a new approach to environmental analysis has developed. Although the scope and definition are not yet completely fixed, the new field of "industrial ecology" focuses on reducing the environmental impacts of goods and services, and on innovations that can significantly improve environmental performance. The scope of industrial ecology includes the entire lifecycle of products and services, drawing on and extending a variety of related approaches including systems analysis, materials flow analysis, pollution prevention, design for environment, product stewardship, energy technology assessment, and eco-industrial parks (Ausubel and Sladovich, 1989; Proc. Natl. Acad. Sciences, 1992; Allenby and Richards, 1994; Socolow et al. 1994; Graedel and Allenby, 1995; Wernick and Ausubel, 1997; Kates et al. 2001).

A report from the National Academy of Sciences identifies this area as one of the eight Grand Challenges of Environmental Science (NAS, 2001). Recent reports from the Science Advisory Board (SAB), including "Integrated Environmental Decision-making" and the EEC Commentary, "Overcoming Barriers to Waste Utilization," indicate increasing interest within SAB in this type of approach (SAB 2000a, 2000b).

The purpose of this Commentary is two-fold: first, to bring industrial ecology to the attention of a wider audience within EPA and other agencies as an approach to meeting their missions, and second, to articulate key research needs. We believe that industrial ecology offers great potential for US environmental policy. Achieving this potential will require rigorous research and firm grounding in the physical and social sciences and engineering.

Industrial ecology emphasizes innovation. It emphasizes the opportunities for new technologies and new processes, and the opportunities for economically beneficial efficiencies. It provides a long-term perspective, encouraging consideration of the overall development of both technologies and policies for sustainable resource utilization and environmental protection into the future.

Industrial ecology can complement and enhance the single-pollutant risk-based framework of traditional environmental policy. It could help EPA address some of the core challenges of environmental policy, from climate change to waste management to land use policy.

a) Climate Change: Technological innovation will be key to any number of approaches to climate change, from renewable energy technologies to energy efficiency to carbon sequestration.

b) Waste Management: Innovations in industrial systems and processes have the potential not only to reduce wastes, but also to make the remaining wastes more economically useful and environmentally benign. With insights gained from Industrial Ecology, the nation's waste management program (RCRA, the Resources Conservation and Recovery Act) could be redesigned as an innovative program that actually fits its name: to conserve and recover resources through closing loops in the lifecycle of materials and minimizing material use (Fagan et al., 2000).

c) Land Use: The interconnected issues of land use policy, transportation systems, urban air quality, and economic and technological infrastructure require a long-term strategic approach to environmental policy. Industrial ecology seeks to address not just industrial emissions, and not just specific products, but the complex networks of services, products, and activities that make up our economy (Powers and Chertow 1997; Stern et al. 1997).

In the following sections we discuss related policy developments (section 2), research needs for the foundations of industrial ecology (section 3), and research needs for applications of industrial ecology (section 4).

2. Policy Applications of Industrial Ecology

Historically, US environmental regulation of industry has emphasized point source controls, especially of gaseous, liquid, and solid emissions from manufacturing plants. In the past few years, the US EPA has initiated a number of innovative policies of the industrial ecology type (US EPA, 2001). Elsewhere in the developed world, however, these new approaches have been adopted more quickly and more fully. In Europe, environmental policies increasingly address the overall environmental impacts of a product over its entire life cycle (raw materials extraction, product manufacturing, product use, and disposal or recycling). One example is the European Union's proposed Integrated Product Policy (IPP), which seeks to stimulate demand for greener products and to promote greener design and production (Commission of the European Communities, 2001). In Japan, the emerging emphasis is on the environmental design of products, driven both by concern over scarce resources and by business strategy. The emphasis is on extensive recycling of products and environmental attributes such as energy efficiency and use of non-toxic materials (National Academy of Engineering, 1994; Life Cycle Assessment Society of Japan, 1998; Gutowski, 2001).

These developments signal an international shift in emphasis from managing individual manufacturing waste streams to managing the overall environmental impacts of a product over its life cycle. In response, global industrial firms, participating in commerce in the US, Europe, and Japan, are beginning to apply these concepts to their products, manufacturing processes, and environmental programs.

These developments pose opportunities for and challenges to US policy. They challenge US policy both because there is the possibility of inconsistent regulatory obligations across national borders, and because the analytical and policy framework is different from the traditional US approach. The growing diversity of environmental policies for products could raise trade issues; on-going activities in the European Union and other countries could place the US in a reactive mode.

US policy adaptations of industrial ecology might be somewhat different from the approaches that have been taken in Europe and Japan. With its often litigious and adversarial approach to environmental policy, the US has developed an emphasis on quantification of environmental risks in particular and on the scientific evaluation of environmental policy in general. This emphasis is likely to be reflected in US policy adaptations of industrial ecology as well. Moreover, as the importance of both information technology and the technological infrastructure are increasingly recognized, application of industrial ecology may progress from its initial emphasis on specific products and materials to a broader emphasis on infrastructure and technological systems. Thus the early policy adoptions of industrial ecology ideas in Europe and Japan provide an opportunity for US policy. They present a portfolio of strategies and experiences from which the EPA can draw in its efforts to protect environmental quality in a cost-effective manner.

3. Fundamental Research Needs

If industrial ecology is to provide a basis for environmental policy, it needs a well-developed scientific foundation. In the same way that fundamental scientific research supports technological development, and fundamental economic research supports the development of both economic policy and the economic system, fundamental research in industrial ecology is needed to provide a robust framework for understanding the interaction of technological systems and environmental protection.

Fundamental research in industrial ecology focuses on the long-term relationships between materials and energy use, the environment and human health, and economic well being. The examples below focus on materials and energy efficiency and substitution, the role of innovation, and the role of the private sector. The emphasis is on economy-wide consumption of materials and energy, and on how this will change in the future. Concern over resource use includes consideration of environmental impacts and ecosystem services as well as the narrower issue of resource availability and longevity (Ayres 1993; Daily 1997).

Materials and Energy Efficiency and Substitution

Since the 1970s a growing body of research has suggested that greater material efficiency, use of better materials, and the growth of the service economy are contributing to the "dematerialization" of the economy. Yet the extent of this phenomenon remains unclear. Simon's (1980) analysis of worldwide trends in natural resource use and the environment has been widely criticized as overly optimistic (Holdren et al. 1980). Undertaking a more limited analysis, Larson, Ross and Williams (1986; Williams et al. 1987) argued that economic growth in developed countries is no longer accompanied by increased consumption of basic materials. This dematerialization has been investigated for a range of materials, including steel, plastics, paper, cement and a number of metals.

Despite these promising results, neither the extent of dematerialization nor its implications are yet understood. Wernick et al. (1996) pointed out that some products, such as personal computers and beverage cans, have become lighter over the years, but use of other materials, such as paper, have increased. Although primary materials use is not rising as fast as economic productivity, there are no signs of net dematerialization among consumers or of saturation of individual material wants. In a review of the dematerialization literature, Cleveland and Ruth (1998) argued that knowledge of the extent and mechanisms behind the patterns of material use are limited largely to individual materials or specific industries.

A related body of research suggests that expensive, scarce, or environmentally harmful resources can be substituted by resources that are cheap, abundant, and environmentally benign. For example, Goeller and Weinberg (1976) used a geologic and chemical analysis to argue that, with the important exception of fossil fuels, the use of scarce minerals can be substituted with other minerals that are essentially inexhaustible. Their analysis refuted the "Limits to Growth" report, which had argued that growing consumption would inevitably deplete basic materials (Meadows et al. 1972). "Substitution" can be seen in the changes in energy sources that have occurred over the past century. As the sources of energy have shifted from wood and coal to petroleum and natural gas, the average amount of carbon per unit energy produced has fallen, resulting in a "decarbonization" of world energy use (Nakicenovic, 1996). Overall, however, the potential for and limitations of substitutability remain unresolved (Tilton, 2001).

It is often suggested that "loop closing" – the recycling and reuse of products, materials, and wastes – has significant environmental potential. Graedel and Allenby (1995) have suggested that the goal of industrial ecology is to accomplish the evolution of manufacturing to a system in which all wastes are recycled. Understanding of the potential to reach this goal, and the environmental risks and benefits, is needed.

One strategy for reducing environmental impacts is the substitution of services for products. The notion is that people seek not physical products, but rather the services provided by those products. For example, an integrated pest management service might provide crop protection rather than selling pesticides per se. By emphasizing the service instead of the physical product, firms have an incentive to be more efficient with materials and energy. Product-to-service strategies hold potential for innovative environmental strategies and considerable environmental gain, but they need further conceptual analysis and systematic empirical testing (Stahel, 1994).

Role of Innovation

Other researchers have used biological analogies to suggest that "industrial ecosystems" have vast potential for improved efficiency through innovation and integration (Ayres, 1989). Frosch and Gallopoulos (1989) argued that

> "the traditional model of industrial activity – in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of – should be transformed into a more integrated model: an industrial ecosystem. In such a system, the consumption of energy and materials is optimized,

waste generation is minimized, and the effluents of one process – whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products – serve as the raw material for another process."

The biological, evolutionary analogy of industrial ecology suggests that the focus of environmental policy should increasingly emphasize innovation, and the diffusion of innovations into industry and society (SAB 2000c). This also suggests an increasing research emphasis on the development of environmentally beneficial technologies. In addition, there is a need for research on the innovation process itself and on the role of government in that process.

The Role of the Private Sector

A number of researchers look to industrial firms to take a leading role in environmental management and policy. There are two dimensions to this premise:

a) optimism that voluntary approaches can be effective in bringing about environmental improvement, and

b) reliance on industrial firms as the locus of technological expertise which in turn is seen as crucial to strategies emphasizing design for environment (DfE).

Industrial firms are clearly a locus of technological expertise. But use of ecodesign by businesses is both partial and uneven (Tukker, 2002). A more thorough understanding of the factors that influence the adoption of ecodesign is needed. In addition, clarity about what constitutes a green product is needed so that companies that are inclined to use their technological expertise to this end can have confidence that their efforts are well targeted.

It is often argued that cooperative approaches are more cost effective, more conducive to innovation, and better able to promote fundamental attitudinal change than traditional "command and control" regulation. On the other hand, skepticism about the effectiveness of voluntary approaches remains. The claim that there are extensive unexploited win-win opportunities in environmental policy is similarly the subject of active research and debate (Esty and Porter, 1998).

Incentive-based approaches to improved environmental management are also controversial because of debate over which approaches are best for different applications and because of disputes about their policy implications (WRI 2000; Tietenberg, 1997).

Better understanding is needed of the potential and limitations of industry's role and of the specific circumstances which can encourage industry to be environmentally proactive. There is a need to understand what motivates change. There is a need for greater attention to program evaluation, and examination of the effectiveness of the new policy instruments in comparison with traditional regulatory and market-based incentives (O'Rourke et al., 1996; Harrison, 1998; Andrews et al. 2001).

4. Applied Research Needs

Whereas the fundamental research needs address questions of how the industrial system can evolve to reduce environmental impacts, the applied research needs focus on the methods and data needed to assess specific products, facilities or industries. The examples below emphasize the need for critical evaluation and peer review of an ensemble of software, databases, and metrics.

Software and Databases for Life-cycle Assessment

A life-cycle assessment (LCA) evaluates the entire environmental impact of a product through its life-cycle, including manufacturing, use and disposal. A great deal of work has been done to develop the technical foundations for LCA of products and processes, and to develop the databases necessary to support these assessments. The International Organization for Standardization (ISO) is working to formalize LCA methods. Efforts within the United States to develop LCA methods are being led by the Society for Environmental Toxicology and Chemistry (SETAC) and the US EPA (US EPA, 2000).

There are now a large number of competing software packages for LCA and related applications (de Caluwe, 1997). Because of the wide range of tools, it is difficult for users even to determine which tool is best suited to a particular situation (Wilgenbusch, 2000). These software tools are often complex, opaque in their technical assumptions, and use data that are difficult to verify.

Methods to validate LCA results have yet to be established (Hendrickson et al. 1998). Both conventional peer review of the LCA methods and software, and development of standardized “test-beds” (data sets or protocols) could provide users with increased confidence that actions based on the tools would indeed lead to overall environmental improvements. One of the main issues of LCA has been the validity of available life cycle inventory (LCI) databases, which are the basis for any LCA studies but are neither standardized nor peer-reviewed. There is a need for a comprehensive, national-level LCI database that is open and peer-reviewed, and that contains reliable industrial data. Some efforts to address this need are currently underway; continued support of work in this area is needed (NREL, 2001).

Weighted Metrics

Applied industrial ecology aims simultaneously to reduce a range of environmental impacts, including not only the mass of emissions and wastes, but also impacts on human health and ecosystems. In order to integrate across diverse dimensions of environmental performance, a number of weighted environmental metrics have been developed. For example, a scoring system called eco-indicator is a measure of overall environmental impact; human toxicity potential has been developed as a measure of the toxicity of chemical compounds over a range of human health endpoints; and the “triple bottom line” is a measure being used by some industrial companies to combine business, environmental, and social accounts (National Academy of Engineering, 1999; Huisman et al., 2001; Luo et al., 2001; Hertwich et al. 1997). Some weighted metrics are being considered in the European Union and elsewhere for use in environmental legislation.

The validity and limitations of such weighted metrics need to be clarified. The key questions are the commensurability of the attributes that are being combined, and the validity of the weighting scheme. For example, the toxicity of a chemical is a function of dose, the medium of exposure, the duration of exposure, the state of the receptor (condition, characteristics and activity level), the route of exposure and the chemical and physical state of the pollutant. A weighted measure of the toxicity of different compounds must make assumptions about all of these factors, and indiscriminate application of such a metric may lead to non-representative outcomes. Hence there is a need for deeper understanding of how weighted metrics are developed, of the impacts of uncertainty and variability, and of the limitations and benefits of their application.

Simplifying Assumptions

Industrial ecology has generated an ensemble of simplifying assumptions used in calculations and analysis. For example, lifecycle analyses (LCAs) are often simplified by assuming that mass is a reasonable proxy for environmental impact, or by only assessing materials that comprise at least 5% of the product mass, or by not including some of the upstream pre-manufacturing steps such as materials extraction and processing (Hertwich et al. 1997; Curran, 1996; ISO 14041, 1998). The effects of these simplifications are not known, but it is often assumed that streamlined LCA captures 70 to 80% of the opportunities for environmental improvement (Graedel and Allenby, 1995). However, one recent evaluation concluded that streamlined LCAs can have truncation errors as high as 50% (Lenzen 2001). Further quantitative evaluation of claims that underlie these assumptions could define both when such assumptions provide reliable guidance and the type and extent of uncertainty that arises when they are used (Sousa et al., 2001).

Recommendations for Research

A rigorous scientific foundation will be essential for the development of an environmental policy that may be increasingly linked to technology and economic policy. The US EPA and the National Science Foundation have already begun to support research related to industrial ecology.[1] Significant advances in industrial ecology will require new theoretical developments, quantitative models, empirical research, and field-scale experiments. Neither a quantitative theoretical foundation nor a substantial body of experiment – in science or in policy – have yet been developed for this new field. The potential for scientific experiments has hardly yet been conceived, with most efforts currently at very small scales. The potential for policy experiments is somewhat more developed, with state-level policy innovations increasingly viewed as a venue for policy experimentation and adaptive learning.

[1] These include the joint NSF/EPA programs on Technology for a Sustainable Environment, Decision Making and Valuation for Environmental Policy, Green Chemistry, Design For the Environment and Green Engineering, and Interagency Opportunities in Metabolic Engineering. In addition, the National Science Foundation’s programs in Environmentally Benign Chemical Synthesis and Processing, Environmentally Conscious Manufacturing, and New Technologies for the Environment also address industrial ecology themes.

Specific research needs are summarized in Table 1.

Table 1: Research Needs in Industrial Ecology

Materials Efficiency and Substitution

Better understanding is needed of the potential for and limitations of

- Dematerialization (reduction in the amount of material per product or activity),
- Substitution of scarce or harmful resources with those that are plentiful and benign,
- Recycling and reuse, and
- Substitution of services for products.

Innovation

- Research on a wide range of environmentally beneficial technologies should be encouraged and supported.

Better understanding is needed of

- The innovation process and how government can encourage innovation and adoption.

Role of the Private Sector

- Private sector design-for-environment activities should be encouraged.

A better understanding is needed of the potential for and limitations of

- Voluntary approaches to environmental management.

Life-Cycle Analysis and Related Environmental Evaluation Approaches

There is a need for

- Peer review of methods and software,
- Standardized tests for methods and software, and
- Development of a comprehensive life-cycle inventory database.

Better understanding is needed of the validity and limitations of

- Metrics used to compare different environmental effects, and
- Common simplifying assumptions.

To develop the scientific foundation for industrial ecology, the Agency should emphasize quantitative and theoretical developments, empirical research, and experimental approaches including pilot projects. Key topics include the impact and potential for all forms of resource efficiency and substitution, and the potential for innovation, new technologies, and proactive measures to achieve environmental goals. To strengthen the ongoing applications of industrial ecology, the Agency should support evaluation and technical review of the working assumptions, metrics, and lifecycle assessment tools that are currently in use.

Acknowledgments

The Subcommittee gratefully acknowledges Kathleen White of the EPA Science Advisory Board staff for her work and support throughout the development of this Commentary. This Commentary benefitted from comments from members of the public, including Brad Allenby of AT&T, Clint Andrews of Rutgers University, Vince Anigbogu of Clark-Atlanta University, Jesse Ausubel of Rockefeller University, Tim Considine of Penn State University, Suren Erkman of the Institute for Communication and Analysis of Science and Technology, John Harte of the University of California, Victor Ibeanusi of Spelman College, Greg Norris of Sylvatica, Matt Polsky of the New Jersey Department of Environmental Protection, Delcie Durham of the National Science Foundation, and from US EPA personnel including Derry Allen, Diana Bauer, Maryann Curran, Barbara Karn, Angie Leith, April Richards, Steve Lingle and Walter Schoepf. The subcommittee thanks Roger Kasperson and Rhodes Trussell of the SAB Executive Committee for helpful reviews of this Commentary.

Appendix A - Biosketches

Thomas L. Theis is the founding director of the Institute for Environmental Science and Policy at the University of Illinois at Chicago. Formerly, Theis was the Bayard D. Clarkson Distinguished Professor and Director of the Center for Environmental Management at Clarkson University. Professor Theis' areas of expertise include the mathematical modeling and systems analysis of environmental processes, the environmental chemistry of trace organic and inorganic substances, interfacial reactions, subsurface contaminant transport, and hazardous waste management. He has been principal or co-principal investigator on over forty funded research projects totaling in excess of six million dollars, and has authored or co-authored over eighty papers in peer review research journals, books, and reports. He is a member of the USEPA Science Advisory Board (Environmental Engineering Committee), is past editor of the *Journal of Environmental Engineering*, and serves on the editorial boards of *The Journal of Contaminant Transport,* and *Issues in Environmental Science and Technology.* He has served on numerous professional committees including the Scientific Committee on Problems in the Environment (SCOPE), and the World Bank funded team of scholars for advising the Universidad Nacional Del Litoral (Argentina) on environmental engineering education. From 1980-1985 he was the co-director of the Industrial Waste Elimination Research Center (a collaboration of Illinois Institute of Technology and University of Notre Dame), one of the first Centers of Excellence established by the USEPA, and is currently Principal Investigator on the NSF-Sponsored Environmental Manufacturing Management Program at Clarkson.

Valerie Thomas received her Ph.D. in theoretical physics from Cornell University. She is now a Research Scientist at Princeton University at the Center for Energy and Environmental Studies and the Princeton Environmental Institute. She is also a Lecturer in Princeton's Woodrow Wilson School of Public and International Affairs, where she teaches the graduate course of Methods in Science, Technology and Environmental Policy. Her research is in the areas of Industrial Ecology and Environmental Policy. Recent research topics include mercury exposure, dioxin sources, the economic demand impacts of second-hand markets, electronics for product recycling, environmental policy in the former Soviet Union, and ethanol as a gasoline lead replacement in Africa. She is co-author of the book "Industrial Ecology and Global Change," (Cambridge University Press, 1994). She is a Member of the Environmental Engineering Committee of the EPA Science Advisory Board, and she participated in the SAB reviews of the dioxin reassessment, the mercury report to congress, and the integrated risk project. She is a Fellow of the American Physical Society.

Domenico Grasso is the Rosemary Bradford Hewlett Professor and Founding Chair of the Picker Engineering Program a Smith College and holds adjunct faculty appointments at the Universities of Connecticut and Massachusetts and Yale University. Prior to joining Smith, Dr. Grasso was offered and declined the position of Professor (with tenure) and Chair in the Department of Earth and Environmental Engineering at Columbia University. An environmental engineer who studies the ultimate fate of contaminants in the environment and develops new techniques to destroy or otherwise reduce the risks associated with these contaminants to human health or natural resources, he focuses on molecular scale processes that underlie nature and behavior of contaminants in environmental systems.

He holds a B.Sc. from Worcester Polytechnic Institute, an M.S. from Purdue University and a Ph.D. from The University of Michigan. He is a registered Professional Engineer in the states of Connecticut and Texas, and was Professor and Head of Department in Civil & Environmental Engineering at the University of Connecticut prior to joining Smith. He has been a Visiting Scholar at UC-Berkeley, a NATO Fellow, and an Invited Technical Expert to the United Nations Industrial Development Organization in Vienna Austria. He is currently a member of the United States Environmental Protection Agency Science Advisory Board, President of the Association of Environmental Engineering & Science Professors, and Editor-in-Chief of *Environmental Engineering Science*. He has authored more than 100 technical papers & reports, including four chapters and two books. Federal, state and industrial organizations have supported his research work.

Reid J. Lifset is the Associate Director of the Industrial Environmental Management Program and a member of the faculty at the Yale School of Forestry and Environmental Studies. He did his graduate work in political science at the Massachusetts Institute of Technology and in management at Yale University. His research focuses on the application of industrial ecology to solid waste problems and the evolution of extended producer responsibility. He is the editor-in-chief of the *Journal of Industrial Ecology,* an international quarterly on industry and the environment, headquartered at and owned by Yale University and published by MIT Press. He is member of the steering committee of the International Society for Industrial Ecology (ISIE), the Science Advisory Board of Material Flow Analysis for Sustainable Resource Management (MFAStorM) of the Scientific Committee on Problems of the Environment (SCOPE) and the editorial advisory board for the Kluwer book series on Eco-efficiency. He has been a Javitts Fellow and a Graduate Fellow at the Program in Science, Technology and Society at MIT and a J.D. Rockefeller III Fellow at Yale.

Byung R. Kim received his Ph.D. in Environmental Engineering from the University of Illinois, Urbana, IL. He is now Staff Technical Specialist in the Chemistry and Environmental Science Department of Ford Research Laboratory, Dearborn, MI and is a professional engineer. His current research interest is in understanding various manufacturing emission issues (physical/chemical/biological waste treatment processes and the overall environmental impact of manufacturing processes). He also has worked on the adsorption of organics on activated carbon and water quality modeling. He has served on the EPA SAB Environmental Engineering Committee and was Editor of the Journal of Environmental Engineering, American Society of Civil Engineers (ASCE). He served on the advisory board for the National Institute of Environmental Health Superfund Basic Research Program at the University of Cincinnati. He received a Richard R. Torrens Award for editorial leadership from ASCE and two Willem Rudolfs Medals from Water Environment Federation on his publications.

Catherine P. Koshland is the Wood-Calvert Professor in Engineering at the University of California, Berkeley, and Professor in Energy and Resources and in Public Health (Environmental Health Sciences). Professor Koshland graduated with a B. A. in Fine Arts from Haverford College, studied painting at the New York School of Drawing, Painting and Sculpture, and received her M. S. in Mechanical Engineering in 1978 and her Ph.D. in 1985 from Stanford University. She joined the U. C. Berkeley faculty in 1984. Professor Koshland's research is at the intersection of energy, air pollution and environmental (human) health. It is conducted at multiple scales, from mechanistic analyses of combustion products in flow reactors to control strategies in urban airsheds to improved management of the global industrial production system, addressing the conception and assessment of environmental and health dimensions to improve energy and manufacturing technologies. Prof. Koshland is Associate Director of the UC Berkeley Superfund Basic Research Program, and Director of Health Effects of Modern Technologies, the Berkeley component of the UC Toxic Substances Research and Teaching Program. At Berkeley, she is Vice-Chair of the Academic Senate, and served on the Commission on Undergraduate Education. She is a director and Secretary of the Combustion Institute and serves on the editorial board of Combustion Science and Technology. She is Vice Chair of the Board of Managers of Haverford College.

Robert C. Pfahl, Jr., received his B.M.E., M.S., and Ph.D. degrees from Cornell University where he majored in heat transfer and fluid mechanics. Dr. Pfahl is Director of International and Environmental Research and Development at Motorola's Corporate Manufacturing Research Center where he is responsible for globalizing Motorola's Corporate Manufacturing Research Center and in leading Motorola's Environmental Technology R&D. He holds eight U.S. patents in electronics manufacturing technology and invented the Vapor Phase reflow soldering process while at Lucent Technologies' Engineering Research Center. Dr. Pfahl is Co-Chair of the National Electronics Manufacturing Initiative (NEMI) Technical Committee and led the U.S. Electronics Industry in the preparation of the 1994 and 1996 NEMI Roadmaps. The NEMI Roadmaps are recognized as the definitive documents in the electronics industry for future technology requirements. He has published extensively in the areas of heat transfer, materials, and environmental technology. In recognition of his efforts to eliminate the use of CFCs in the electronics industry, Dr. Pfahl received the 1991 United States EPA Stratospheric Ozone Protection Award for "Executive Leadership and Industry Organizing." He chaired the American Electronics Association's CFC Task Force.

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