International Technology Research Institute
World Technology (WTEC) Division

WTEC Panel Report on

ENVIRONMENTALLY BENIGN MANUFACTURING

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WTEC PANEL ON ENVIRONMENTALLY BENIGN MANUFACTURING (EBM) TECHNOLOGIES

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WTEC's mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology in a manner that is timely, credible, relevant, efficient and useful. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The ITRI staff at Loyola College help select topics, recruit expert panelists, arrange study visits to foreign laboratories, organize workshop presentations, and finally, edit and disseminate the final reports.

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FINAL REPORT

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ABSTRACT

This report reviews the status of "environmentally benign manufacturing" (EBM) technologies, applications, and policies in Europe and Japan in comparison to those in the United States. Topics covered include metals and metal manufacturing, polymers, automotive applications, electronics, and energy-related issues. In addition to reviewing specific technologies and applications in the above areas, the report covers broader issues of government policies affecting environmental issues in manufacturing, corporate strategies and vision with respect to these issues, economic drivers influencing the development of EBM, and relevant research infrastructure. The panel's findings include the following: Europe leads in most governmental activities, Japan in industrial activities, and the results for research and development are mixed. The United States leads in financial and legal liability concerns, water conservation, decreased industrial releases to air and water, and research in polymers and long term electronics, but follows in all other areas. In the area of university educational activities, and both industry and government sponsorship of these, it is clear that Europe leads, followed by the United States and then Japan. Overall, therefore, the United States ranks third behind Europe and Japan. Additional findings are outlined in the panel's executive summary.

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EXECUTIVE SUMMARY

Timothy Gutowski

INTRODUCTION[1]

Is "environmentally benign manufacturing" an oxymoron? Or is it possible to align business needs with environmental needs? This is the central issue addressed in this report. What follows is a summary discussion, which outlines the current state of environmentally benign manufacturing (EBM). These findings are based upon the observations of a panel of U.S. experts during visits to Japan, Europe and the United States, as well as the panelists' substantial expertise in the various areas of this broad and challenging field. Because of the breadth of this topic, panelists focused their attention on two key areas: processing and products. In processing, the focus was on metals and polymers, since by far the vast majority of products are made from these materials. Among products, the focus was on automobiles and electronics**,** two products with significant environmental activity. Details of the panel's 52 site visits can be found in the appendices of this report. This summary has five remaining sections: The Problem, Major Findings, U.S. Competitiveness, Barriers to Progress, and the Technology Summaries for Metals, Polymers, Automobiles, and Electronics.

THE PROBLEM

The area of environmentally benign manufacturing addresses the central long-term dilemma for manufacturing: how to achieve economic growth while protecting the environment. The conflict is fundamental, rooted in part in the materials conversion process, which takes from the earth and gives to the customer, the stockholder, and to those who make a living or derive support from this enterprise, and in part in consumerism, which focuses on current needs often with disregard for the future. The resolution of this conflict is a serious issue for society to address, for in the near future it will threaten our well-being. The question then for environmentally conscious manufacturers is how to incorporate both economy and environment into their business plans.

Once a firm is motivated to address environmental issues, what then are the right things to do? The answers are not simple. There are many aspects to this problem, including: toxic materials, waste and wastewater, emissions and greenhouse gases, energy usage, and material and product recycling. Furthermore, at the root of all environmental issues are people—people with different values, goals and needs, and people from different generations. The development of an environmental strategy needs to address all of these issues and translate this understanding into an effective program of action.

The panelists' work, then, was to sort out these complex and intertwined issues, and to organize them in a way that is both understandable and inclusive. Often, the issues went far afield from the original engineering focus of the panelists. But the overwhelming importance of these broad issues requires that they be included here to accurately represent the nature of our findings.

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[1] The views expressed in this summary are the consensus views of the entire panel. References can be found in the original chapters from which this summary is derived.

MAJOR FINDINGS

1. **Motivation at the corporate level:** The panel saw a clear trend towards the “internalization” of environmental concerns by manufacturing companies, particularly large international companies. For a variety of reasons, large companies like Sony, Toyota, Hitachi, Volvo, DaimlerChrysler, IBM, Motorola, Ford, DuPont and others profess to behave in environmentally responsible ways and provide reports and data from self-audits to demonstrate this commitment. The motivations for this behavior are many, including cost reduction, risk mitigation, market advantage, regulatory flexibility, and corporate image. At the core though, the panel was convinced that many companies really do understand the problem: any long term sustainable business policy must address the relationship to the environment.

2. **Strategies at the national level:** The development of a strategy is a critical part of EBM. In general, companies develop strategies that are compatible with their national strategies, while multinational companies need to respond to the strategies of many countries. The strategies of the EU, Japan and the United States are strongly influenced by their national concerns and societal structures. In capsule form, the main issues are as follows:

   – In Japan: (1) a focus on the conservation of resources including reductions in energy, materials, solid wastes, and greenhouse gases; (2) an alignment of internal resources by public education, environmental leadership, consensus building, and tools development including LCA (Life Cycle Assessment), DFE (Design for the Environment), and ISO 14000 certification; and (3) a systematic implementation of EBM as a competitive strategy.

   – In Europe: (1) a concern for solid wastes and toxic materials; (2) a product take-back focus; (3) a systems orientation built upon interdisciplinary agenda setting and tools development; and (4) a strong political basis for environmental concerns.

   – In the United States: (1) a regulatory focus on pollution by medium; (2) a materials, process, technology, and cost orientation; (3) a reliance on free enterprise to solve system level problems; and (4) a tendency toward adversarial positions which are solved by litigation.

3. **Systems-level problem solving:** To be successful, progress in EBM requires integration of technology, economic motivation, regulatory actions and business practices. Examples abound of missed opportunities when any element is missing. Fundamental to this systems approach is dialog and cooperation between stakeholders. In the most effective firms a clear strategy is developed and woven into business practices. The setting of targets and constancy of mission are essential to this process. By far the most highly coordinated efforts seen by the panelists were in Japan. For example, Toyota views “lean manufacturing” and “green manufacturing” as essentially the same thing.

4. **Analytic tools for addressing products:** The emphasis in Europe and Japan is shifting to the environmental consequences of products in all of their stages of life. Along with this shift, there is a clear need for analytic tools to assist in the assessment of life cycle consequences of actions and policies and to guide design decisions for new products and processes. The Japanese have a national program to develop LCA, and are integrating these tools into engineering design practice. The Europeans have large coordinated projects within industries and run by academics to develop LCA tools, and they are ahead in educating university students to develop these tools.

5. **Technology highlights:** While the panel saw no “silver bullet” technologies to solve environmental problems, technology clearly plays a central role. The main feature required is that the technology must work in an integrated systems approach to the problem. Some technology highlights include: a complete system for recycling PVC from construction materials in Japan; a strong emphasis on technology development and transfer in Japan and Europe; the use of plastics as reducing agents in steel making in Japan and Germany; a steel can production facility in Japan that increases recyclability, reduces wastes and reduces costs; and car doors reinforced with natural fibers in Germany. Four technology areas are treated in more detail at the end of this summary.

U.S. COMPETITIVENESS

Based upon observations from the site visits as well as the experience of the panelists, the three regions visited are ranked in three areas: (1) governmental activities; (2) industrial activities; and (3) research and development. These are shown in Tables ES.1, ES.2, and ES.3. Overall, Europe leads in most governmental activities, Japan in industrial activities, and the results for research and development are mixed. The United States leads in financial and legal liability concerns, water conservation, decreased industrial releases to air and water, and research in polymers and long term electronics R&D, but follows in all other areas. In the area of university educational activities, and both industry and government sponsorship of these, it is clear that Europe leads, followed by the United States and then Japan. Overall, across all these areas, the United States ranks third behind Europe and Japan.

Table ES.1
Government Activities—Relative Competitiveness*

Activity	Japan	U.S.	Europe
Take-back legislation	**	*	****
Landfill bans	**	*	***
Material bans	*	*	**
LCA tool and database development	***	**	****
Recycling infrastructure	**	*	***
Economic incentives	**	*	***
Regulate by medium	*	**	*
Cooperative/joint efforts with industry	**	*	****
Financial and legal liability	*	****	*

*Number of asterisks indicate comparative strength, and are intended to be indicative of level of effort and emphasis as much as actual level of success.

Table ES.2
Industrial Activities—Relative Competitiveness

Activity	Japan	U.S.	Europe
ISO 14000 certification	****	*	***
Water conservation	**	***	*
Energy conservation/CO2 emissions	****	**	**
Decreased releases to air and water	*	***	**
Post Industrial solid waste reduction/recycling	****	**	***
Post-consumer recycling	**	*	****
Material and energy inventories	***	*	**
Alternative material development	**	*	***
Supply chain involvement	**	*	**
EBM as a business strategy	****	**	***
Life-cycle activities	**	**	**

Table ES.3
Research and Development Activities—Relative Competitiveness

Activity	Japan	U.S.	Europe
Relevant Basic Research (> 5 years out)			
Polymers	**	***	**
Electronics	**	***	*
Metals	***	*	**
Automotive/Transportation	**	*	***
Systems	**	*	***
Applied R&D (< 5 years out)			
Polymers	*	***	**
Electronics	***	**	**
Metals	***	*	**
Automotive/Transportation	***	*	***
Systems	**	*	***

BARRIERS TO PROGRESS AND IMPLICATIONS FOR RESEARCH

1. **Motivation, policy and education:** It was the panelists' impression that many people in manufacturing are not yet aware of the potential magnitude of the effect that the environment will have on their business. In fact, the U.S. public as a whole is somewhat behind in awareness of environmental issues. It can be argued that this is due to different conditions in the United States, namely more room and lower population densities. But population densities on our East Coast are generally quite similar to those in Europe, and our rates of waste production and energy usage are beyond those of all other countries both in absolute terms and on a per capita basis. Environmental education in the U.S. is now largely confined to the early years of education. Much needs to be done to inform manufacturers and the public, and to educate university students. Future engineers need both more depth and more breadth. This can only happen with the generation of new knowledge that can symbolically represent the complex issues of EBM.

   On the policy level, a clear trend seen by the panelists was the move away from "command and control" policies toward more cooperative goal setting. Early results indicate clear advantages, both in terms of economic outcomes as well as environmental consequences, when companies are given more flexibility in their modes of response to environmental concerns.

2. **Strategic planning:** EBM presents a bewildering array of issues and opportunities to the manufacturer. In order to align business and environmental issues it is important for a company to develop a strategic plan. A first step in doing this is to identify objectives along with stakeholder needs and economic incentives. Although objectives will vary by region and firm, the panel found five common environmental themes emerging: (1) reducing energy and material consumption; (2) waste reduction and reduced use of materials of concern (i.e., potentially harmful); (3) reducing the magnitude and impacts of product packaging; (4) managing products that are returned to manufacturers at the end of their designed use; and (5) customer demands for documented environmental management systems (EMS).

   Strategic planning requires that conflicts among objectives be resolved, priorities set, and the environmental goals be integrated into the management system and technology development plan. It is the panel's observation that firms who do this see the benefits of EBM, while those who do not do this see only the costs. This process can be greatly aided by technology roadmaps such as those developed under the DOE's program for "Industries of the Future." More interdisciplinary planning, as well as working with trade and industrial groups, is needed, however, in particular to help small and medium sized businesses.

3. **EBM implementation:** EBM is a system of goals, metrics, technologies, and business practices. In some ways its implementation is similar to the implementation of any effective business system. The

WTEC panel's impression is that companies that already have effective business practices can readily incorporate EBM into their system. For others, EBM implementation is a learning process that could pay dividends by enhancing business practices for other objectives as well as the environment. Many firms have been helped in their strategy implementation by the ISO 14000 certification process. For those who participated in the ISO 9000 process and the quality movement, they will see that much previous learning will apply to EBM implementation. The critical areas for attention are: (1) the development of high performance business practices that will enhance EBM; (2) the application of these practices with particular reference to small and medium businesses; and (3) the development of tools and technologies that will enable effective EBM.

4. **System-level tools and data:** Analytical tools along with supporting data and metrics are essential to effective planning and implementation of EBM. The primary needs are tools that assess environmental impact and identify areas for improvement. Specific issues are: (a) LCA, (b) data, (c) metrics, and (d) DFE.

    (a) A complete picture or assessment of the environmental consequences of an action requires both temporal and spatial tracking of multiple impacts. However, over ambitious pursuit of these goals could render the tools to do this too complex and useless. This is the current dilemma of life cycle assessment, or LCA. Much work in this area needs to be done. Particular needs are consistency, transparency, and integration with other engineering tools.

    (b) Good data are urgently needed for LCA and all other EBM tools. Data are necessary to set the agenda, identify priorities, calculate metrics, and for use in models. The issues are the ease of acquisition, and proprietary and liability concerns.

    (c) Metrics can be enormously helpful in communicating and aligning goals; however, they are value laden and potentially contentious. Work needs to be done in developing scientific underpinnings of a number of existing and proposed measures.

    (d) "Design for the environment," or DFE, is a broad category of tools that could include avoidance of banned materials, design for reuse, design for disassembly, design for recycling, etc. These tools are clearly tied to regulations, business practices, and end-of-life technologies. Hence there is a need to keep these tools current, and to integrate them into the design process. Together they represent enormous leverage for EBM at the product development stage.

5. **Technology development:** Technology remains a strong suit for the United States, and EBM represents a vast array of technology opportunities. Of particular importance are technology solutions that integrate well into a complete systems concept. Key areas for attention are: (a) new processing technology; (b) new materials; (c) new energy and propulsion systems; and (d) technologies that address the many aspects of the end-of-life treatment, including: identification, sorting, cleaning, separating, neutralizing contaminants, shredding, reprocessing and recycling. At the same time the panel did see some shortcomings to the U.S. approach to technology. The United States appears to be under-funded in the area of technology transfer when compared to Japan and Europe. Because of an often narrow focus on invention, the U.S. is in jeopardy of losing its competitive advantage at the development stage, and to some extent squandering its efforts even at the invention stage. Technology development—and in particular technology transfer—needs serious new attention in the United States. The four main technology focus areas of this report are treated in more detail in the remainder of this summary.

TECHNOLOGY SUMMARIES

Metals

Metals represent a recycling success story. Structural, precious, and base metals are all recycled at rates that are near or above 50%. However, metal usage is slowly being eroded by competition from other materials, especially polymers. The challenge to metals is to compete with these alternative materials while maintaining and improving recyclability. Trends towards higher strength metals and alloys, used in thinner sections, while improving the competitiveness of metals, will make their recycling more difficult. To preserve and expand the benefits of metals, new technologies will have to be developed along with new materials. These include new methods to identify and sort alloys, remove coatings, and to eliminate and neutralize contaminants.

Metals processing remains a significant source of environmental problems. Many of these problems are associated with waste materials and related emissions from the basic processes of refining, machining, forming, casting and forging. The wastes include contaminated cuttings and chips, waste coolants, lubricants, casting sands, parts washing fluids, etc. Because of the high disposal costs for each of these, manufacturers are self-motivated to reduce, reuse and eliminate, but they need new technologies from which to choose. Examples of needed EBM research include: dry machining, bioactivity monitoring and control of machining coolants, true net shape component forming methods, alternative methods to control friction in metal forming, new casting sand binders, etc.

In addition, the primary processing of metals remains a serious threat to the environment. New work to reduce energy requirements and related CO_2 and greenhouse gas emissions is needed. Currently, both the steel and aluminum industries have been designated as "industries of the future" by the U.S. Department of Energy, and as such have developed cooperative research programs to address these issues.

Polymers

Polymers compete against other materials by virtue of their light weight and low cost. This can make them desirable, and in fact environmentally friendly, during the "use phase" of the product. For example, the use of polymers and composites in automobiles has helped to lower weight and therefore lower fuel consumption. But these same attributes conspire to make recycling a difficult economic challenge. A lower material density actually increases transportation costs per kg of material, and the low cost of virgin materials makes recycling targets very difficult to meet. The primary problem is with the details of the reverse logistics stage, especially with streams that are extremely heterogeneous (mixed plastics) or dirty (contaminated with metal and paper). Major attention needs to be focused on the collection, transportation, cleaning and sorting of a sufficiently pure waste stream to make plastics recycling economically viable. To accelerate recycling, new technologies can help. For example, small scale recycling technologies would lessen transportation and infrastructure needs; new bulk-handling, cleaning and sorting techniques are also necessary.

Composites also pose a challenge. These materials can provide enormous benefits at the use phase, but equally enormous challenges at the end-of-life phase. One possible route to recyclable composites could involve organic and/or biodegradable fibers. Other strategies could be based upon new materials with designed-in "disassembly" schemes. Polymers and polymer composites can also be used in various materials exchanges and as fuels. For example, there are pilot programs in Japan and Germany to use polymers as a reducing agent in steel making.

The processing challenges for polymers are in some ways quite similar to metals, in that many of the benefits should be self-motivating for the processors. However, there is a need for new technologies that concentrate on energy efficiency, and the reduction in volatile organics. These can include new efficient heating and cooling methods, new tooling, closed-loop control, and new materials and additives to reduce solvents, residual organics and other materials of concern.

One particularly interesting area is that of bio-polymers and bio-materials. There is significant activity worldwide in such areas as biodegradable polymers synthesized from petroleum, organic fibers and fillers, and biodegradable polymers derived from various crops and biomass. While this work looks very interesting, the overall effect of these materials on the environment is still not well known. For example, a recent analysis has shown that some new routes from crops to bio-polymers are actually more energy intensive than the conventional routes from petroleum. Much new work is needed to follow through the entire life cycle for these materials.

Finally, the primary production of polymers from petroleum remains a serious challenge to the environment. These processes, contained in the petroleum and chemical industries, are subject to several initiatives to move from end-of-pipe treatments to proactive "clean technologies" approaches. Several studies sponsored by the United States' Environmental Protection Agency have shown the combined economic and environmental gains that can be obtained by these means.

Automobiles

In automobiles we see the plastic, glass, ceramic and metal parts coming together to make a product that has been growing worldwide three times faster than the population, and in the United States six times faster than the population. This type of growth and the potential new growth, as the worldwide standard of living increases, not only threatens the environment, but can threaten the automobile itself. For if infrastructure and roadway construction does not keep pace (and it cannot in the already high population density regions of the world) then the automobile may ultimately fail as a viable form of transportation in these regions. It is this type of scenario that has helped to focus the attention of some of the automobile companies on their environmental impact.

Many of the major environmental impacts associated with automobiles actually come during the vehicle use phase. In fact, transportation in general constitutes about one-third of all the energy needs in the U.S.—and is growing. Furthermore, autos and light vehicles contribute significant amounts of air pollutants and smog producing agents to the atmosphere. Legislation has helped to motivate vehicle improvements, but increases in fuel consumption per car, cars owned, miles traveled and congestion have counteracting effects. For one to three months each year many major U.S. cities still cannot meet minimum air quality standards. This is an area that begs for leadership, public education, and policies that reflect the true cost of vehicle ownership.

New directives from Europe that simultaneously set serious new fuel economy goals (on the order of a 40% improvement in seven years) and strict product take-back requirements (95% recycle for model year 2015) should help by encouraging the development of new technologies and design strategies. Furthermore, Europe is providing a role model of environmentally responsible behavior for the rest of the world. Effects from the European initiative have already diffused to other parts of the world, both in terms of national legislation as well as international design strategies for firms that sell autos to Europe and elsewhere in the world.

Vehicle recycling already exists as a successful free enterprise activity in the U.S., but its performance and viability has been declining as the volume of metals used in automobiles declines. It is critically important that auto recycling be improved to reclaim automobile shredder residue (ASR), including various polymers, rubber and glass components. This will require coordinated and intentional design and materials selection decisions on the part of the automobile manufacturers. Technology needs include identification of both materials and contaminants, sortation and reprocessing technologies, life cycle analysis tools, new materials, and coatings removal technologies.

During manufacturing, much of the waste and wastewater used over the lifetime of a car is produced, significant amounts of energy are consumed, and various emissions are released to the atmosphere. Perhaps leading the list of environmental focus areas for automobile manufacturing is vehicle painting. Various technologies can be implemented to reduce the environmental load from painting, including wastewater cleaning and recycling, and emissions treatment. New paint technologies now also offer water-based paints and powder sprays. In addition, new approaches are looking at prepainted steel sheets and molded-in class A finishes for plastic parts. This work needs further support, plus a thorough systems-level assessment that includes the potential impacts of increased inventories and scrap rates due to off-color results.

Many other areas of automobile manufacturing also need attention; some of them have already been mentioned in the sections on metal and plastics parts manufacturing. In addition, however, a few areas stand out for further attention. These include technologies for parts washing and glass manufacturing, as well as the environmental effects of various manufacturing systems designs. During the visit to Toyota, panelists saw examples of “lean” manufacturing, which by virtue of the emphasis on the reduction of waste were clear emulations of “green” manufacturing. For example, one Toyota assembly plant in Tsutsumi produced only 18 kg of landfill waste per vehicle.

Finally, WTEC panelists are concerned that the divestiture of parts manufacturing plants by the big six automakers will have a deleterious effect on the environment unless there is significant support for environmental technology development aimed at second and third tier suppliers.

Electronics

The growth of electronics in our society is an impressive story. On the one hand it has led to an enormous boost to the economies of many countries, providing convenience, entertainment, and ready access to information and services, but on the other hand many of the manufacturing processes to make electronic devices are both seriously wasteful and use and emit toxic and dangerous materials. Furthermore, the dual trends of growing consumption and decreasing product life spans present a serious end-of-life issue. For example, the trend for PCs is a projected six-fold increase in the obsolescence rate over a six year span to about 65 million PCs/year in 2003. Furthermore, as the PC has evolved, there is a tendency toward material compositions that are less easy to recycle. Silicon chips are no longer gold-backed, the volume of precious and base metals used on printed wiring boards (PWBs) has decreased, and the housings are more commonly made of engineering thermoplastics than steel.

However, by and large, the metals in electronics products can still be recycled, while the chips, which are expensive to produce, cannot be recycled or reused. A major problem in the recycling of electronics is the presence of flame retardants in the plastics, required by U.S. fire-prevention regulations. In Japan and Europe, plastics are incinerated rather than recycled and the presence of brominated flame retardants (BFRs) raises the concern of dioxin formation during the burning process. Unfortunately, BFRs are very difficult to detect economically in a recycling process. Since most products sold in the United States contain these substances, and plastics cannot effectively be sorted by whether or not they contain BFRs, it is assumed that most recycled plastic from electronic products, particularly ABS, contains flame retardants. Consequently, many OEMs are reluctant to include recycled plastics in new products that may be sold in Europe. This dilemma has inspired a variety of responses from industry ranging from skepticism concerning the particular BFRs and the mechanisms by which they could become harmful, to enthusiastically embracing this problem as a “green” marketing opportunity should a viable alternative be found. This particular issue clearly illustrates the complexity of EBM for international markets.

In addition to the end-of-life issues surrounding electronics, there are significant environmental impacts associated with electronics manufacturing, particularly from wafer fabrication processes. These processes, which are characterized by gaseous deposition, ultra-clean manufacturing environments, and in some cases low yields, result in high amounts of waste and wastewater, high usage of energy, and the emission of materials of concern including perfluoro compounds. Because of the importance of these issues they have received research support through a variety of programs sponsored by SEMATECH, NSF and the EPA. Strategies to address issues at the wafer fab level have been outlined in the SIA (Semiconductor Industry Association) roadmap.

A separate set of environmental issues is also encountered at the PWB and board level assembly steps. These include laminate manufacture and processing, cleaning, plating, etching, and various through-hole-plating and interconnect technologies. However, a current major focus is on lead-free solders. Driven primarily, if not exclusively, by the European Union’s WEEE Directive, there has been a strong incentive for electronic companies worldwide to develop alternatives to tin-lead (Sn-Pb) solder.

There is, however, resistance to converting to Pb-free solders. One of the challenges with Pb-free solders is the difficulty in achieving satisfactory reliability during the use phase. A second problem with Pb-free solders is that they typically have higher melting temperatures and therefore require increased process temperatures. Since this is one of the final processes seen by the PWB, all the materials and components on the board must be able to withstand the increased thermal exposure. This means that alternative, and probably more expensive, components and substrates will need to be used.

In addition, many of the Pb-free alternatives are difficult to control (leading to scrap), and difficult to rework (leading to additional scrap) or disassemble. Some contain elements that are incompatible with recycling processes.

Finally, if a full life-cycle analysis is done it is unclear that Pb-free solders are actually more environmentally friendly. If material availability, impacts of extraction, increased processing difficulties, and end-of-life issues are accounted for, Sn-Pb solder may actually be a better choice. Ultimately the best solution may be completely new attachment technologies that do not use solder, such as adhesive flip chip.

CLOSING COMMENT

For many people, the concept of EBM presented here requires a change in basic thinking. EBM is much more than preventing pollution and waste. It is a business opportunity and a social responsibility that are intimately intertwined. As U.S. Senator Gaylord Nelson said on the first Earth Day, 1970, “The economy is a wholly owned subsidiary of the environment. All economic activity is dependent upon that environment with its underlying resource base. When the environment is finally forced to file under Chapter 11 because its resource base has been polluted, dissipated and irretrievably compromised, then the economy goes down with it.”

CHAPTER 1

INTRODUCTION

Timothy Gutowski

BACKGROUND

Is "environmentally benign manufacturing" (EBM) an oxymoron? Some may think so. Others, particularly those involved in manufacturing, may feel that many processes such as injection molding, thermoforming of polymers, and sheet metal forming are already quite environmentally benign. What does EBM mean and how much attention should we pay to it? How do EBM practices differ in various regions of the world? Are there things we should be doing in terms of future research to promote EBM in the United States?

The above questions are the topics of this report, which is the culmination of a year-long study sponsored by the National Science Foundation, with additional support from the Department of Energy. The work was conducted by an interdisciplinary panel of engineers and scientists, who are experts in various aspects of EBM, the environment, and manufacturing. Short biographies for the panel members can be found in Appendix A. In addition, the panelists were assisted by representatives from the sponsoring agencies, in particular Dr. Delcie Durham (NSF), who was personally responsible for the development of this panel, as well as Dr. Fred Thompson (NSF) and Dr. K.P. Rajurkar (NSF), and Dr. Toni Marechaux (DOE). This project was administered by WTEC at Loyola College, where Geoff Holdridge, Bob Williams and Roan Horning provided additional assistance.

For the purpose of this study the panel started with the idea that EBM enables economic progress while minimizing pollution and waste and conserving resources. As the study progressed, however, it appeared that the concept of EBM embodied much more. If one takes the long view of things, the problem is much more complex than just drawing a box around a manufacturing process and responding to what goes in and comes out. Decisions in manufacturing, including design, can have profound implications throughout the entire product life cycle, from *raw materials* production, through the *use phase* of the product and into its *end-of-life* treatment. Hence a major portion of the environmental impact of a manufactured product could occur hundreds, or even thousands, of miles from its original point of manufacture. Furthermore, the consequences of these decisions could occur over a time span affecting generations. One simple way to state this is to say that "environmentally benign manufacturing" does not compromise the environment, or the opportunities for development, for the next generation. In other words, it focuses on integrating manufacturing into a sustainable society. Hence the panel's view of the problem was in terms of a large system with interconnecting parts. While alternative definitions of this term are possible, the panel took these concepts as the guiding premise for this study.

This broad interpretation of environmentally benign manufacturing drew our attention to a wide range of issues and actions, and challenged the panel to organize this subject in a meaningful way. Perhaps of immediate concern is how to explain the motivation of industry to participate in EBM. Many see EBM in conflict with the financial responsibilities companies have to their owners. Hence the panel became keenly interested in sources of motivation for the firm—both internal and external (including motivational governmental policies)—to pursue an EBM approach. Then, once the firm is motivated, the next question is, "What is the right thing to do?" When viewed as a large system, environmental issues are complex. During the course of the study the panel learned of several instances where well meaning firms apparently did the wrong thing. This was usually due to a lack of information or tools to help in the analysis of complex data and interactions. In many cases people learn by doing, so it was of utmost importance that current practices be understood. Consequently, the interests of the panel moved from policy, to general motivation, to data gathering and tools, and to industrial practice. The components of the solutions focused attention on goal setting, metrics, and assessments, and the basic components of infrastructure, technology and methodology. Throughout this entire project, the panel had an overarching interest in identifying potential research projects that might develop these various components.

As can be seen, the range of issues for EBM is quite large. In order to make the panel's mission manageable, the inquiries needed to be focused. Early in the study, and with the guidance of the NSF, it was decided to focus primarily on manufacturing processes (including design) with an emphasis on the processing of metals and polymers. In terms of applications of these processes, two key areas, automotive and electronics, were selected, in large part because of these industries' publicly stated goals in the area of EBM.

METHODOLOGY

After an initial kickoff meeting on July 13, 1999, a U.S. industry review was held in Arlington, Virginia, on Oct. 5, 1999. At that meeting the panel was presented with reviews and technology roadmaps for steel, aluminum, casting, electronics, automotive, polymers and composites. Representatives from industry (manufacturers, consultants, and trade associations) and from several U.S. governmental agencies, including the EPA, DOE, and NSF, participated in the proceedings and provided their perspectives.

One of the goals of the study was to benchmark global trends. In addition to the U.S., Japan and northern Europe were chosen as countries/areas to visit, and to include in the benchmarking process, in part because they both have high population densities and high per capita GDP (gross domestic product)—two critical factors that generally indicate both the potential for environmental problems and the resources to address them. And, both areas are known for their international leadership in environmental issues. A trip to Japan was made during October 17-25, 1999 and a trip to Europe took place during April 1-9, 2000. A series of visits to U.S. firms were made between January and June of 2000.

In each country, the panel attempted to visit a mix of sites, including governmental agencies and laboratories, academic institutions and companies. In the United States visits focused exclusively on companies. There were several goals for all site visits. These were: (1) to advance the understanding of environmentally benign manufacturing, (2) to establish a baseline and document best practices in environmentally benign manufacturing, (3) to promote international cooperation, and (4) to identify research opportunities.

A total of 52 different locations were visited in Japan, Europe and the United States. In addition, several telephone conference calls were made. These visits and interviews were conducted by members of the panel and by accompanying representatives from NSF and WTEC. The sites visited in Japan, Europe and the United States are listed in Tables 1.1, 1.2 and 1.3. For each site a report was written to document what was learned. These reports were then reviewed by the hosts and revised if necessary. The final versions are contained in Appendices C, D, and E of this report. In most cases only a subset of the panelists were able to go to any one site. But afterwards, summary meetings were held to share information and observe trends. On July 13, 2000 a public workshop was held in Arlington, Virginia, to present the findings. The meeting was well attended, and many useful comments and constructive criticisms were received.

Writing this report represents the last task for the panel. In the following chapters we present our findings. The report starts with a high level overview of the key differences that were found between Japan, Europe and the United States (Chapter 2). This is followed by a discussion of the strategic issues that face firms and those who develop the area of EBM (Chapter 3). The fourth chapter discusses systems level issues. One of our key findings is that the Japanese and Europeans both view EBM as a systems problem and have put in place various aspects of systems solutions. There is no evidence that this problem was solvable by a "silver bullet" technology. This conclusion is not too different from what was found years ago when the Japanese economy was surging based in part on their new production systems. When the outside world went to investigate the "Toyota Production System" it was found that their success was not based on technology *per se* but rather a systems based solution, which integrated technology. The next chapter, Chapter 5, is by far the largest, focusing on materials (metals and polymers) and product applications (automotive and electronics), and with a special section on energy. Chapter 6 discusses cross-cutting issues between firms, and the final chapter (Chapter 7) makes observations and recommendations for research (Chapter 6). This report is intended to promote discussion among industry, government and academia, and to guide future research activities in the United States.

Table 1.1
Sites Visited: Japan

Fuji Xerox	NIMC
Hitachi PERL	Nippon Steel Corporation
Horiba, Ltd.	NIRE
Institute of Industrial Science	NRIM
Kubota Corporation	Polyvinyl Chloride Industrial Association
Mechanical Engineering Lab., MITI	Sony Corporation
Nagoya University	Toyo Seikan Kaisha
NEC Corporation	Toyota Motor Corporation
New Earth Conference & Exhibition	University of Tokyo

Table 1.2
Sites Visited: Europe
(Belgium, Denmark, Netherlands, Germany, Sweden, Switzerland)

DaimlerChrysler AG	ICAST
Delft University of Technology	IVF
EC Directorate for Science, R&D	MIREC B.V.
EC Environment Directorate-General	Siemens AG
EX-CELL-O GmbH	Technical University of Berlin
Fraunhofer IGB (Stuttgart)	Technical University of Denmark
Fraunhofer IPT (Aachen)	University of Stuttgart (IKP)
Fraunhofer IZM (Berlin)	University of Technology, Aachen
Hoogovens Steel	Volvo

Table 1.3
Sites Visited: U.S.

Applied Materials	General Motors Corporation
Caterpillar Inc.	IBM
CERP	Interface Americas, Inc.
Chaparral Steel/Texas Industries	Johnson Controls Inc.
DaimlerChrysler Corporation	MBA Polymers, Inc.
DuPont	Midrex Seminar
Federal-Mogul Corporation	Micro Metallics Corporation
Ford Motor Company	NCMS

MANUFACTURING AND THE ENVIRONMENT

Among industrial activities in the U.S., manufacturing's impact on the environment is enormous. Manufacturing industries are dominant in their environmental impact in such areas as toxic chemicals, waste, energy, and carbon emissions. Manufacturing is also a heavy user of water, and there have been many cases of air, water and soil contamination which have led to such actions as Superfund cleanups, class actions suits and a variety of other corporate liabilities.

Among the industries selected by the EPA for toxic materials monitoring, manufacturing releases are larger than all other activities, with the one exception of metals mining, which is closely related to manufacturing. This is shown in Figure 1.1, which gives the 1998 EPA Toxic Release Inventory (TRI) results by industrial categories (EPA 1998).

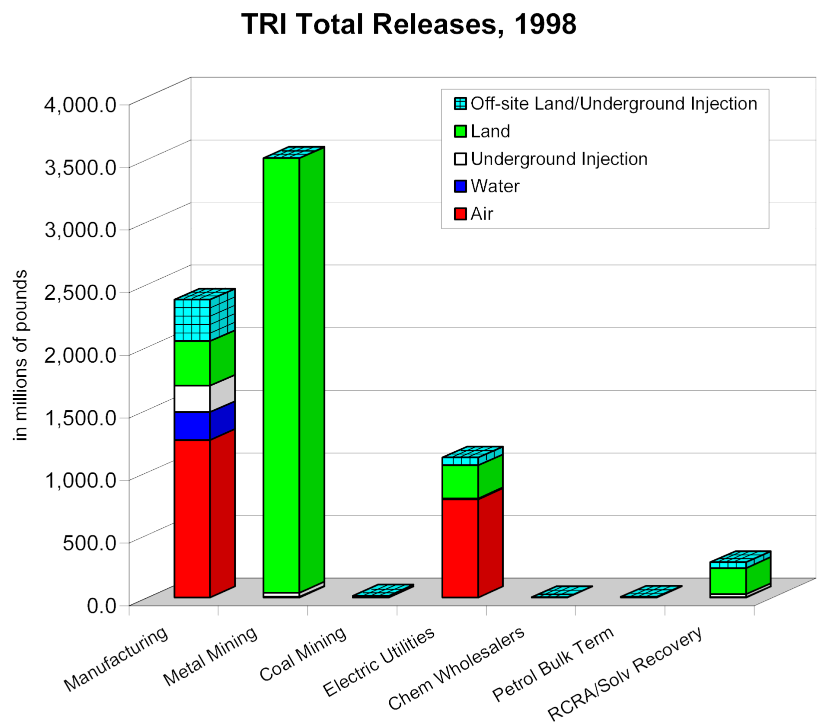

Fig. 1.1. TRI releases for 1998 by category (EPA 1998).

Figure 1.2 shows the major waste types by weight in the U.S. using data taken from the Office of Technology Assessment (Wernick 1996). These figures become even more significant when one realizes that the United States produces more waste than any other country in the world. This is true both on an absolute scale and per capita (Park and Labys 1998). Hence, U.S. manufacturing might be characterized as the most wasteful industrial activity, in the most wasteful nation. Note also that a large portion of this waste is water waste. This too is extremely significant because water usage both in the United States and throughout the world exceeds supply. That is, we and others are pumping ground water out faster than it can be replenished by nature (McNeil 2000). Globally there is an estimated 160 billion cubic meter overdraft of groundwater per year (Brown, Runner and Halwell 2000).

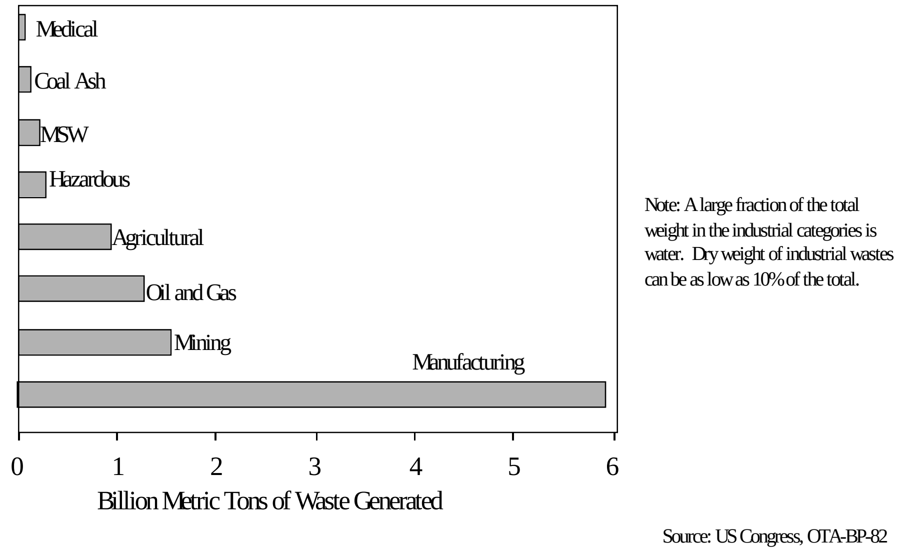

Fig. 1.2. Major waste types by weight in the United States (1985) (Wernick et al. 1996).

In terms of energy usage, manufacturing again dominates all other industrial activities, taking up 80% of the total. And, because most of our energy consumption in the U.S. is from carbon-based fuels—oil, natural gas, and coal—manufacturing's contribution to carbon emissions is roughly the same, around 80%, again dominating all industrial activities (DOE/EIA 1998). Hence, when all of these factors are considered, we see that manufacturing is perhaps the most significant industrial activity in terms of potential environmental impact.

The nature and extent of the environmental impact varies within the manufacturing sector. However, for the industries, which we are most interested in for this report, metals and polymers (often categorized as chemicals), the environmental impacts are often quite large. For example, in terms of TRI totals, plastics, chemicals, primary metals and fabricated metals collectively account for 63% of all of the "manufacturing" releases (Figure 1.1). Similarly, chemicals and primary metals and "others," which includes fabrication, play a primary role in carbon emissions and energy usage (Figure 1.3). Hence, it is fairly clear that manufacturing—and in particular metals processing and polymer processing—deserve our attention for their potential impacts on the environment.

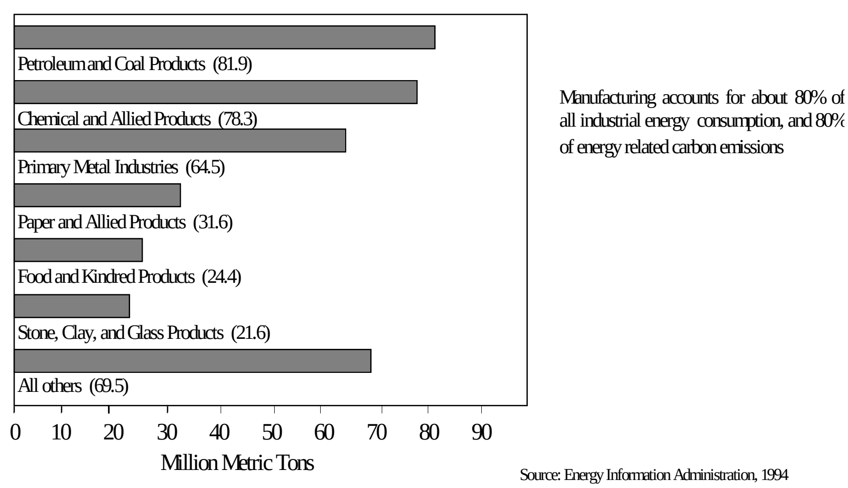

Fig. 1.3. Total energy-related carbon emissions for selected manufacturing industries, 1994 (DOE/EIA 1999).

SYSTEMS VIEW OF MANUFACTURING

Up to this point, we have thought of manufacturing as a simple open system into which flows various resources for conversion, and out of which flows products, wastes and pollution. However, one could take a much more extensive view of this problem. If we take the systems view of manufacturing, and track the consequences of manufacturing and design decisions throughout the entire product development cycle, this would take us through (1) raw materials production, (2) manufacturing, (3) the use phase, and finally to (4) the end-of-life phase. This is a far broader view of manufacturing than the one that simply looks at the consumption, wastes and pollutants occurring at the factory. These two different views of manufacturing can be seen in Figure 1.4. The overall view is of the “closed” systems view of manufacturing, showing all of the major activities and the connecting paths for reuse and recycling. In the center of the figure one can see the “open” systems view of manufacturing, which features only the box labeled ”Mfg.,” along with two input arrows representing design and raw materials, and two output arrows representing wastes and products. It has become clear to us that integrating manufacturing into a sustainable society requires the broader systems view.

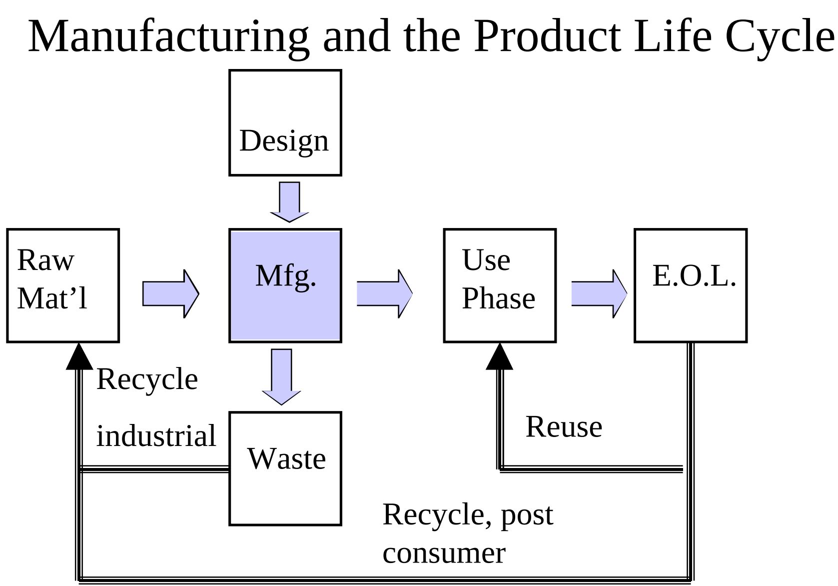

Fig. 1.4. A closed systems view of manufacturing showing all of the major activities and reuse and recycle paths.

How big is the systems problem? One way to illustrate the magnitude of the problem we are faced with is to write out environmental impact in terms of population, per capita GDP and impact per unit of GDP. This is often called the “master equation” in industrial ecology texts (Graedel 1995). To be concrete about this, one might think of a unit of GDP as a manufactured product, such as a car. Then the impact due to a car would be the sum total of all activities to make, use and dispose of the car. So here we are using the extended definition of manufacturing to illustrate our point. The equation would be

$$Impact = Population \times \frac{GDP}{person} \times \frac{Impact}{unitGDP} \qquad (1)$$

Now we can speculate about how the first two terms of the equation will change over, say the next 50 years. Of course nobody knows for sure, but short of a truly cataclysmic event, we can estimate the range of possibilities for these terms. For example, the U.S. Census Bureau “Middle Series” population estimate for 2050 is 402,420,000 (U.S. Census Bureau 2000). This constitutes an increase from today by a factor of 1.48. GDP estimates can be made from a variety of sources. For example the 1998 *World Factbook* (CIA 1998) gives the U.S. 1997 GDP growth rate as 3.8%. If we keep this up for 50 years, GDP will grow by a factor of 6.45. Using these two estimates in Equation (1), one can show that to maintain our current level of environmental impact we would need to reduce the impact per unit of GDP by a factor of 9.55, or about one order of magnitude. Obviously one can consider many alternative scenarios and then redo this calculation, but just about anyway you do it, the result is a significant factor. For example, when the calculation is done using worldwide estimates one gets a factor from 6 to 10 (Graedel 1998). In other words, the problem that faces us is large, but the stakes are equally large. In order to maintain our standard of living and enjoy a healthy environment, significant changes in manufacturing are required. History shows that mankind is both adaptable and inventive. We have faced other difficult challenges and succeeded. To be successful here we must start now to channel our inventiveness to solve this problem.

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CHAPTER 2

GEOGRAPHIC TRENDS

Cynthia F. Murphy

SUMMARY

Cultural, geographic, and business needs strongly influence environmentally benign manufacturing in the three regions that this panel studied, making direct comparisons somewhat challenging. In order to summarize the trends in each geographic area, four categories were considered: government, industry, research and development, and education. Government in both Japan and Europe appears (at least outwardly) to operate at a greater level of interaction and cooperation with the private sector than does government in the United States. As a result, both of these regions tend to have a more proactive approach to problem solving. The U.S., largely in response to financial and legal liabilities associated with a significant amount of regulatory action, tends to solve problems in a more reactive manner. Based on the panel's observations, U.S. industry is focused on the reduction of liability, decreased resource consumption (especially water), and pollution prevention. Corporations in Japan are concerned with energy conservation (reduced CO_2 emissions), decreased solid waste, and incorporation of environmental issues into business strategies. EU industries are very involved in end-of-life issues. Research in the U.S. is heavily focused on materials and process technologies. Japan's efforts are more closely aligned with applications and manufacturing systems. European research is heavily weighted in the area of systems engineering, particularly in the areas of design for the environment (DFE) and life-cycle assessment (LCA). Higher education has begun to address EBM to a much greater degree in the European countries than in either the U.S. or Japan.

INTRODUCTION

One of the goals of this study was to benchmark and compare trends in Japan, northern Europe and the U.S. The motivation for doing this was to understand how well the U.S. is performing in the area of environmentally benign manufacturing relative to the EU and Japan in the areas of research and development, industrial strategies and priorities, governmental policies and regulations, and educational activities. A key finding is that cultural, geographic, and business needs strongly influence the focus areas in each of these regions, making direct comparisons rather challenging. At a technical level, the tendency noted for each of the regions is as follows. The U.S. appears to be most heavily involved in materials and processes and in avoiding litigation. Japan is focused on applications that incorporate EBM into business strategies, introduction of new products (primarily to gain market share), and resource conservation. The EU is concerned primarily with product end-of-life, infrastructure (supply chain and reverse logistics), elimination of materials of concern, and systems level modeling.

DRIVERS AND MOTIVATION

United States

The United States has a significant history in the area of environmental protection. Conservationists and activists such as John Muir (the Sierra Club), Theodore Roosevelt (national monuments/parks), Rachael Carson (*Silent Spring*), Pete Seeger (Hudson River Sloop), and the Environmental Defense (Fund) (ED(F)) foundation (banning of DDT through legislation) have reached the population through a variety of media. In most cases, these activities were in response to acute and highly visible problems. These efforts led to the formal recognition of environmentalism through the passage of the National Environmental Policy Act of 1969 (NEPA), Earth Day at the request of U.S. Senator Gaylord Nelson of Wisconsin on April 22, 1970, and the subsequent formation of the Environmental Protection Agency (EPA) a few months later by executive order under President Nixon. This was followed by the Clean Air Act (CAA) in 1970, the Resource Conservation and Recovery Act (RCRA) and the Toxic Substances Control Act (TSCA) in 1976, and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) in 1980, and many more. (Interested readers are referred to the EPA web site at http://www.epa.gov/epahome.)

The result of this "emergency" response approach was the formation of "go-no-go" type legislation that assumed that big business would not voluntarily act in an environmentally responsible way. The threshold type of regulations that resulted are largely focused on protection of specific media (air, land, and water) from toxic substances rather than resource conservation (despite some of the names) or tackling of systemic problems, such as CO_2 emissions. In addition, the litigious culture of the U.S. encourages risk management and minimization. This tends to produce a defensive posture within industry and encourages an emphasis on accountability (focus on things that might or do go wrong), rather than fostering a proactive culture between industry and government that focuses on improvements and system level solutions. It also reflects a general distrust of government, as pointedly illustrated by Ronald Reagan's winning a presidential election by arguing that government in and of itself was bad—"Get the government off the backs of the people and out of the economy" (Thurow 1985). Lastly, the U.S. has always had a representative government where the government is held accountable to the people, making the populace resistant to situations where the reverse appears to be true.

Business management techniques that are common in the U.S. may also make it difficult to implement EBM. Large companies are often divided into small business units (SBUs) that may be encouraged to compete with one another. This can act to discourage cooperation across SBUs, which is critical to effective implementation of design-for-environment practices. Strong economic drivers (including the stock market) require companies to immediately correlate cost-savings with environmental benefit. This may not be an easy task, especially with short-term accountability fostered by quarterly accounting and reporting practices. Most of the companies that have notable EBM programs either have a strong, motivated individual acting as a champion, such as with Interface, or they are large, international corporations, such as Ford or IBM, that can more readily justify a corporate EBM program (see Appendix E).

Large geographic areas and many individual state and municipal governments make infrastructure a challenge in the U.S. The United States covers a total of 9.6 million square kilometers, while the 15 EU countries cover only 3.2 million km^2, and Japan has a very small area with only 378 thousand km^2 (Figure 2.1).

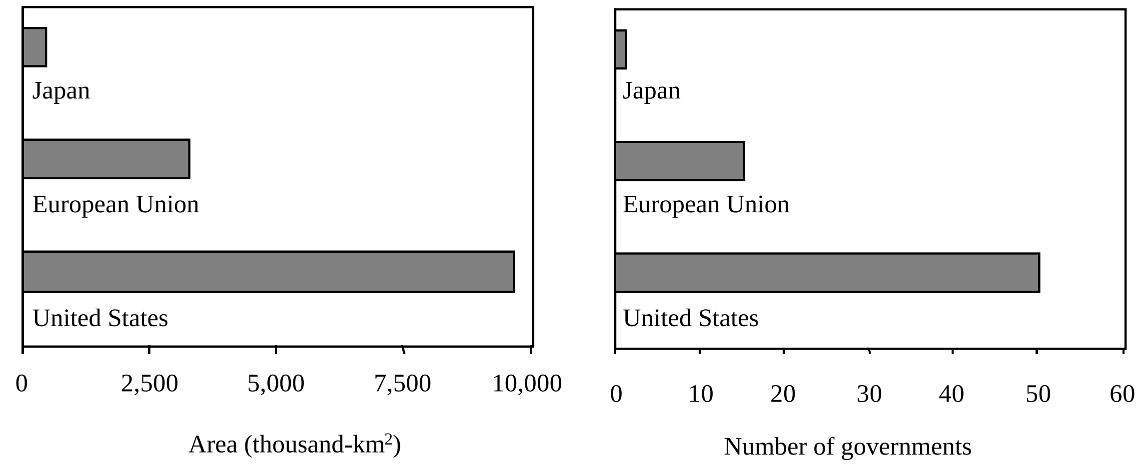

Fig. 2.1. The U.S. has almost three times as much area as the EU and nearly 30 times the area of Japan. In addition, the U.S. government must represent the needs and desires of 50 states, the EU substantially fewer (with 15 member states), and Japan has a single central government.

In addition, a diverse ethnic and socio-economic character (Figure 2.2) and the need for companies to appeal to many different stakeholders challenge consensus building in the U.S.

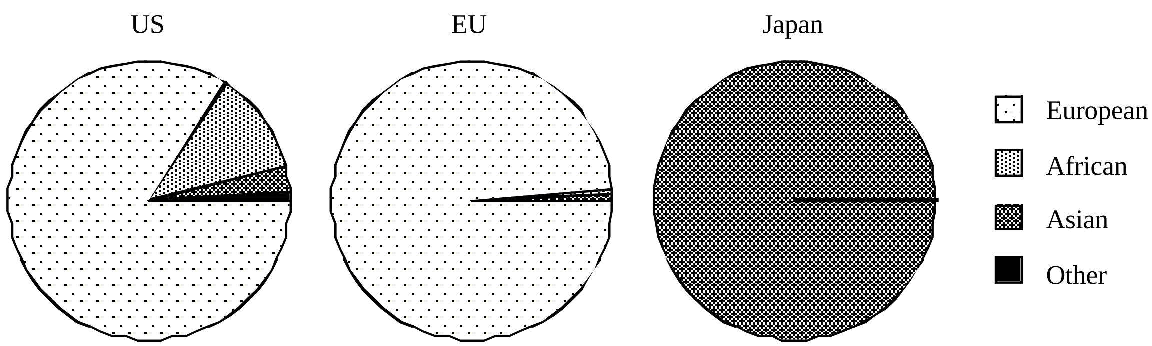

Fig. 2.2. The U.S. has significantly more ethnic diversity than either the EU or Japan, where ethnic groups are defined as people of European, African, Asian, or other heritage. Data from the U.S. Central Intelligence Agency's *The World Factbook (2000)* (see www.cia.gov).

European Union

The European Union (EU) currently consists of 15 member states, but this number is expected to grow. The members as of this report writing are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden, and The United Kingdom. Since the purpose of this study was to benchmark best practices, the panel made site visits in countries that have especially notable activities in the area of EBM. However, given the time constraints of the trip, we were unable to cover all of the leading nations. The observations made in this report are therefore based largely on activities in Belgium, Germany, The Netherlands, and Sweden. However, Denmark, The United Kingdom, and Finland are also leaders in this area, and there is significant literature from these nations the findings of which (to the extent possible) are incorporated into the following evaluations.

The EU enjoys a rather unique position in that the relatively new cooperative efforts associated with its formation facilitate adoption of established "best practices" from its member nations. The European Environment Agency (EEA) has been functional for only a little more than five years. The decision to form the EEA was made in 1990 and the decision to locate it in the Danish capital of Copenhagen was made in October 1993. In 1999, the agency had a staff of 70 and a budget of 18.1 million EUR. The EEA covers three main areas: networking, monitoring and reporting, and acting as a reference center. More can be found at its Web site (http://org.eea.eu.int/documents).

The European Union has a relatively low amount of imports and exports (Table 2.1). Only 8% of the total GDP is exported to the U.S. and Japan, and imports are equal to only slightly more than that. In contrast, imports into Japan from the U.S. and the EU are equivalent to 38% of its GDP and exports to the same regions are equal to 48%. Since the movement of products in and out of its sphere of influence is low relative to the other two regions, it is suggested that this would allow the EU to more efficiently focus on supply stream and end-of-life product management than the U.S. and Japan.

Table 2.1
Imports and Exports between Regions as a Share of GDP

% GDP Exported		**% GDP Imported**	
From the U.S. to		Into the U.S. from	
Japan	10.0%	Japan	14.0%
EU	21.0%	EU	18.0%
Japan plus EU	31.0%	Japan plus EU	32.0%
From Japan to		Into Japan from	
U.S.	30.0%	U.S.	24.0%
EU	18.0%	EU	14.0%
U.S. plus EU	48.0%	U.S. plus EU	38.0%
From the EU to		Into the EU from	
U.S.	7.3%	U.S.	7.4%
Japan	0.9%	Japan	1.8%
U.S. plus Japan	8.2%	U.S. plus Japan	9.2%

Data from U.S. CIA, *The World Factbook (2000).*

Europe has a relatively high population density and most of the EU nations have well-established transportation systems that are critical in the development of take-back infrastructure. This has made recycling more logistically and economically viable. In addition, there is minimal space for landfill and resistance to incineration for plastics disposal. A relatively high unemployment rate (Table 2.2) and workers' rights have led to more acceptance of manual disassembly. All of these factors are critical to the development of well-defined end-of-life policies, especially for electronics and vehicles.

Japan

Formal governmental control over environmental issues is relatively new in Japan (as compared to the United States). In 1989, the Japanese government established the Council of Ministers for Global Environment Conservation to work on global environmental issues, and in November 1993, the "Basic Environment Law" was enacted. The focus was almost exclusively on reduction of greenhouse gases (carbon dioxide emissions) through energy-saving technologies within the industry sector. The government has assisted in this effort through special taxation measures and low-interest financing for energy-saving capital equipment. The Web site for the Environment Agency, Government of Japan (http://www.eic.or.jp/eanet/en/index.html) concentrates on information related to energy conservation and CO_2 emissions. Japan must import significant amounts of natural resources including fossil fuels for energy production. Japan also has the highest cost of energy in ODEC. So while there is a significant emphasis on CO_2 emissions (since this is seen as a direct function of energy consumption and the typical metric) there are clear economic as well as environmental incentives to conserve energy.

In addition to energy, the overall limited natural resources throughout this island nation's history has resulted in a cultural aversion to wastefulness. Japan's economy is a value-added one: natural resources are imported and products are exported. Almost half of Japan's GDP is exported to the U.S. and the EU (Table 2.1). Consequently, corporations must be very product oriented and must be responsive to both market activities and policies in Europe and the U.S. For this reason, ISO 14000 is viewed as a critical competitive issue.

Table 2.2
Population and Unemployment (late 1990s)

Country	Population	Unemployment
Austria	8,139,299	7%
Belgium	10,182,034	12%
Denmark	5,356,845	6.5%
Finland	5,158,372	12%
France	58,978,172	11.5%
Germany	82,087,361	10.6%
Greece	10,707,135	10%
Ireland	3,632,944	7.7%
Italy	56,735,130	12.5%
Luxembourg	429,080	3%
Netherlands	15,807,641	4.1%
Portugal	9,918,040	5%
Spain	39,167,744	20%
Sweden	8,911,296	6.3%
U.K.	59,113,439	7.5%
Total EU (mean)	374,324,532	10.9%
U.S.	272,639,608	4.5%
Japan	126,182,077	4.4%

Data from U.S. CIA, *The World Factbook (2000).*

One of the strongest drivers in Japan is the high population density. The overall population density of Japan (333 people per km^2) is about twice that of the EU (117 people per km^2), but 85% of the land in Japan is uninhabitable, primarily due to steep-sided mountains. Consequently, the effective population density in Japan is nearly four times that of the Netherlands and twenty-six times that of the U.S. (Figure 2.3). This forces a strong emphasis on solid waste management.

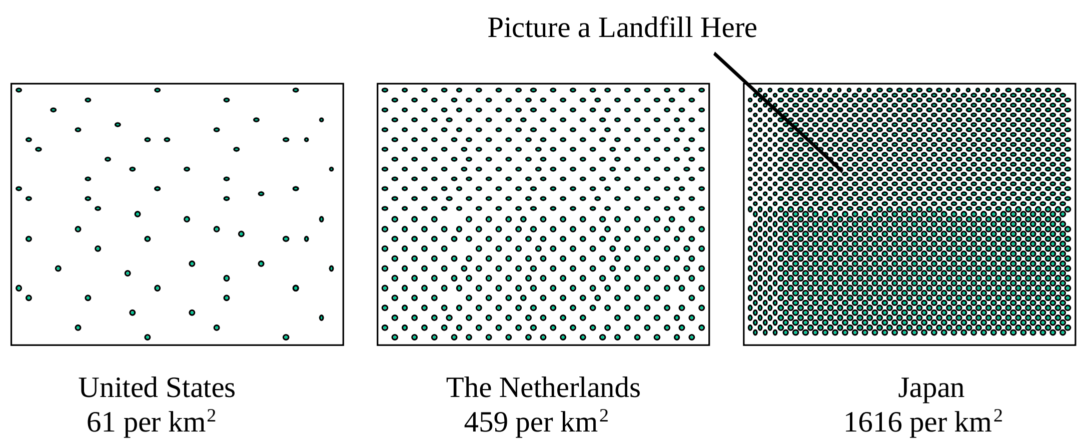

Fig. 2.3. Japan has an extremely high population density, especially if adjusted for inhabitable area (as above). This contributes to a concern for solid waste management (Rogers and Feiss 1998).

In 1998, the Japanese government passed a law calling for the recycling of specified kinds of electrical home appliances, to take full effect by 2001. Under this law, manufacturers of television sets, refrigerators, washing machines, and air conditioners, that operate in Japan, are required to recycle a specified percentage of these discarded appliances. Hitachi (Appendix D) discussed this during the panel's site visit. While there is some interest in materials recycling technology, most of the research efforts that address recycling appear to be at the design level, with disassembly concerns receiving the highest priority. This appears to be the case in both the electronics (Yokoyama and Iji 1998) and automotive industries (Yamamoto et al. 1999).

Another factor that contributes to Japan's ability to embrace environmentally benign manufacturing is that it can be viewed as simply another permutation of the quality movement that developed in Japan following World War II. In addition to the engineering systems that it spawned, the focus on quality was also critical in the development of methodologies and metrics to measure continuous improvements and in promoting excellent data management. By requiring an emphasis on the supply chain (through monitoring of incoming quality) and the use and end-of-life phases (as functions of product reliability), the quality movement also facilitated the understanding of basic life-cycle principles. Environmental issues can be viewed as simply another set of product "qualities" to manage.

Japan has a history of adopting best practices from abroad and improving upon them. This tendency was especially drawn upon during the last half of the 19th century when Japan, after nearly three centuries of isolation, made a rapid transition from a feudal, agrarian culture to an industrial one by means of quick adaptation of Western ideas and technologies (Yamazaki 1985; Clark 1979). This has significantly affected Japanese manufacturing practices and contributes to their focus on applications, in both industry and in research. Traditionally, Japanese industry is quite skilled at importing the results of fundamental research from the U.S. and making successful use of them in their products.

Japan also has a culture of consensus building, which promotes interaction between government, universities, and industry, and indeed within industry itself. This can be attributed to a variety of influences, including a Confucian-Buddhist heritage where community benefit and harmony are a high priority (in contrast to the Western Judeo-Christian focus on individual accountability and responsibility). It may also be an artifact of the rapid industrial expansion that took place in the late 1800s. During this short period the Imperial Japanese government presented private enterprise with opportunity, subsidies, and tax breaks in order to accelerate insertion of technology. This is in sharp contrast to the Western industrial revolution where there was virtually no government involvement. The type of relationship that exists between Japanese companies and the central government also has roots in the feudal Japanese "house" system, where households were separate political, economic, and legal units and the chief role of the Shogunate government was to support and protect rather than to control (Clarke 1979).

OBSERVATIONS

United States

Most of the EBM focus in the U.S. is on materials and processes within the traditional manufacturing environment. This may be viewed as a logical response to media-based regulations and policy since these areas and activities most directly affect air, water, and solid waste. The automotive industry has concentrated on the materials and processes used in structural metals and for paint application; the electronics industry has concerns over a number of materials and processes (Chapter 5). Those issues specific to the semiconductor industry are noted in the AMD site report (Appendix E). However, where there are market drivers that encourage consideration of products and end-of-life solutions, there are activities in U.S. industries within these areas as well. For example, large international firms such as Ford and IBM are responding aggressively to EU directives focusing on these areas (specifically the Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicle (ELV) directives). Ford has designed a car specifically for European take-back. IBM has a strong electronics products recycling effort (http://www.ibm.com/environment) and has produced a computer using 100% recycled plastic housing.

Metrics and supply chain management are of concern in the U.S. but not nearly to the degree that was observed in Europe. In addition, the motivation appears to be different. Often it can be linked to concern over potential future liability (especially with large chemical and electronics companies) or in response to a customer (such as Johnson Controls responding to the automakers, Appendix E). However, there are some exceptions. Within large companies (e.g., DuPont, Ford, IBM, AT&T, HP) there are typically small groups that are very focused on systems level environmental issues. In addition, there are some smaller companies that view a systems level approach to managing environmental issues as a key strategy, such as Interface (Appendix E).

Kalundborg, Denmark is recognized as the premier site in the world for material exchanges, however there is also significant interest and activity in the U.S. in this area. Of note are the activities that are occurring at TXU's Chaparral Steel (Appendix E). Cornell University's WEI program (http://www.cfe.cornell.edu/wei) focuses on eco-industrial park development. Its most recent conference (in February 2000) was at Red Hill, Miss., where a power plant is being built directly next to a lignite mine. Since virtually all transportation costs are thus eliminated, this will allow a marginally economic, low-grade coal to be used. In addition, a nursery grower plans to build greenhouses to make use of waste heat from the power plant. The U.S. Department of Energy (DOE) is working in cooperation with the Polymer Alliance Zone of West Virginia to establish an eco-industrial park in Parkersburg, West Va., with a focus on recycling of electronics. Similar efforts are underway in Austin, Texas (funded by the Department of Commerce, EDA) and in Broome County, New York (the Aurora Project, backed in part by IBM).

Recycling efforts in the U.S. are subject to the free market with variable results. (Note that for the purposes of this study, the discussion of recycling efforts is limited to engineered metals and polymers, and to automotive and electronic applications). The U.S. continues to be the largest producer of solid waste, even when normalized (Figure 2.4). However, until landfill space and/or costs become critical, as they have in Japan and Europe, it may be difficult to develop viable material recycling processes, except where there is clear economic advantage (such as for steel, aluminum, and precious/base metals). There are significant efforts in the U.S. to recycle certain polymers. DuPont has a pilot facility to recycle polyester and MBA Polymers is developing methods for recovering engineering thermoplastics such as acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) (see Appendix E). However, the economics of both of these facilities was or is a challenge. In all cases within the U.S., companies must rely on their own initiative to collect and consolidate materials, to recover materials in a cost-effective manner, and to find markets for their output streams.

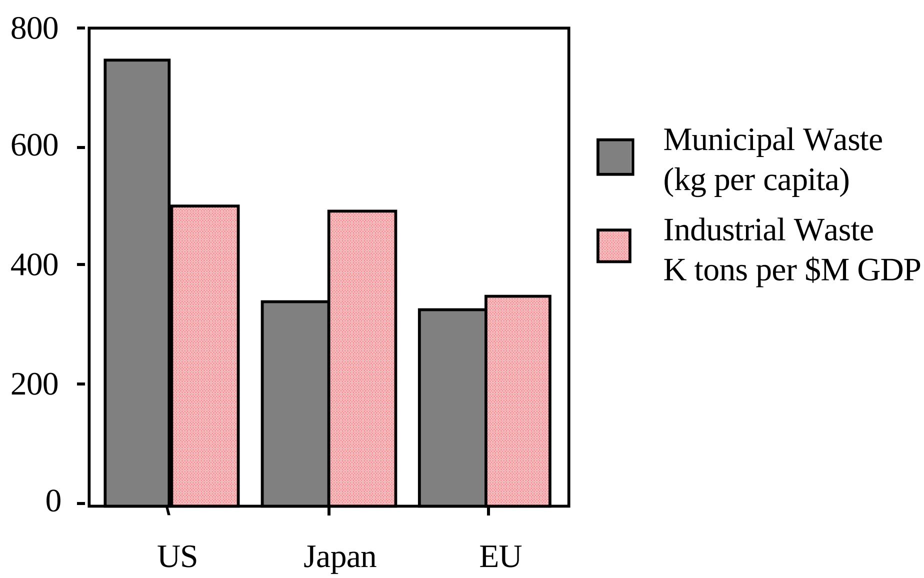

Fig. 2.4. When normalized (per capita for municipal and dollar for industrial), the U.S. is still the world's biggest producer of solid waste, with Japan producing nearly the same amount of industrial waste; data are for 1990 (Park and Labys 1998).

At the research and development level, there is a much greater effort to investigate the recycling of engineering thermoplastics that are a predominant material in both electronics and automotive applications. Perhaps this is because incineration is not as acceptable an option in the U.S. as it appears to be in Japan and Europe. The Society of Plastics Engineers (SPE) holds an annual conference with a very strong emphasis on separation and recovery technologies. Options include separation by hydrocyclone (used by MBA Polymers in California and Butler-MacDonald in Indianapolis) and electrostatic properties, with systems available from U.S. companies such as Carpco (http://www.carpco.com) and from the German company Hamos (http://hamos.com). The barriers to recycling of engineering thermoplastics has been the subject of ongoing "stakeholder dialogues" at Tufts University. This is discussed in greater detail in Chapter 5, Materials and Products: Section D, Electronics.

European Union

The EU is concerned primarily with product end-of-life, infrastructure (supply chain and reverse logistics), elimination of materials of concern, and systems level modeling. This is in large part made possible by its insular nature, with the majority of imports and exports being between EU member states (Table 2.1). Take-back infrastructure is especially well developed in the Netherlands, as seen at MIREC (Appendix C) and other countries are expected to develop similar programs in the near future. These efforts are being driven in large part by the WEEE (Waste Electrical and Electronic Equipment) Directive and by the ELV (End-of-Life Vehicle) Directive.

The EU is also a world leader in the area of life cycle assessment (LCA). An excellent reference to LCA can be found at the EEA Web site (http://org.eea.eu.int). Indeed, there are a number of documents available that discuss incorporation of LCA into business practices (Moll and Gee 1999; Skillius and Wennberg 1998), and DFE/LCA software tools were first introduced in the United Kingdom (Boustead) and France (Ecobilian or Ecobalance). Delft University of Technology, in cooperation with Philips Electronics (Appendix C), has also done a significant amount of work in this area.

The only encounter the panel had with industry attempting to use renewable resources was at DaimlerChrysler in Stuttgart (Appendix C), where they had looked at using flax, sisal, and hemp as the reinforcing fiber in composites. One of the most intriguing aspects of this project was an attempt to look at this from a life-cycle viewpoint, including working up the supply chain with the flax growers in order to ensure a uniform material.

There appeared to be evidence of more collaborative relationships between government, industry, and universities in the EU countries the WTEC panel visited. Certainly, there seem to be more attempts at using "carrots" rather than "sticks." And while some of the policies are met with skepticism (e.g., the WEEE Directive) if not downright refusal to cooperate, the government appears to offer more room for post-policy negotiation than in the U.S.

One interesting trend is the introduction of environmental taxes by member states (Table 2.3) on environmentally harmful products and activities (Roodman 2000). While the shifts have been small (Figure 2.5) and the bulk of the revenue is from energy taxes (Figures 2.6 and 2.7), including transport fuels which make up more than three-quarters of energy taxes, there are clear indications that this is an increasing trend. In 1980, 5.84% of total revenue was derived from environmental taxes. This number had increased to 6.17% in 1990 and to 6.71% by 1997 (EEA 2000b). The tax base is also being broadened from "polluter pays" to the more comprehensive "user pays." For example, there are taxes on groundwater extraction in France, Germany, and the Netherlands. In addition to directly penalizing undesirable behaviors, it is hoped that these taxes will provide some level of social engineering and increase general awareness of environmental issues.

Table 2.3
Examples of EU Environmental Taxes

Country, First year in effect	Taxes Cut On	Taxes Raised On	% Revenue Shifted
Sweden, 1991	Personal income	Carbon and sulfur emissions	1.9
Denmark, 1994	Personal income	Motor fuel, coal, electricity, and water sales; waste incineration and landfilling; motor vehicle ownership	2.5
Spain, 1995	Wages	Motor fuel sales	0.2
Denmark, 1996	Wages, agricultural property	Carbon emissions from industry; pesticide, chlorinated solvent, and battery sales	0.5
Netherlands, 1996	Personal income and wages	Natural gas and electricity	0.8
UK, 1996	Wages	Landfilling	0.1
Finland, 1996	Personal income and wages	Energy sales, landfilling	0.5
Germany, 1999	Wages	Energy sales	2.1
Italy, 1999	Wages	Fossil fuel sales	0.2
Netherlands, 1999	Personal income	Energy sales, landfilling, household water sales	0.9
France, 2000	Wages	Solid waste; air and water pollution	0.1
UK, 2001	Wages	Energy sales to industry	0.3

Source: Brown, Renner, and Halwell (2000).

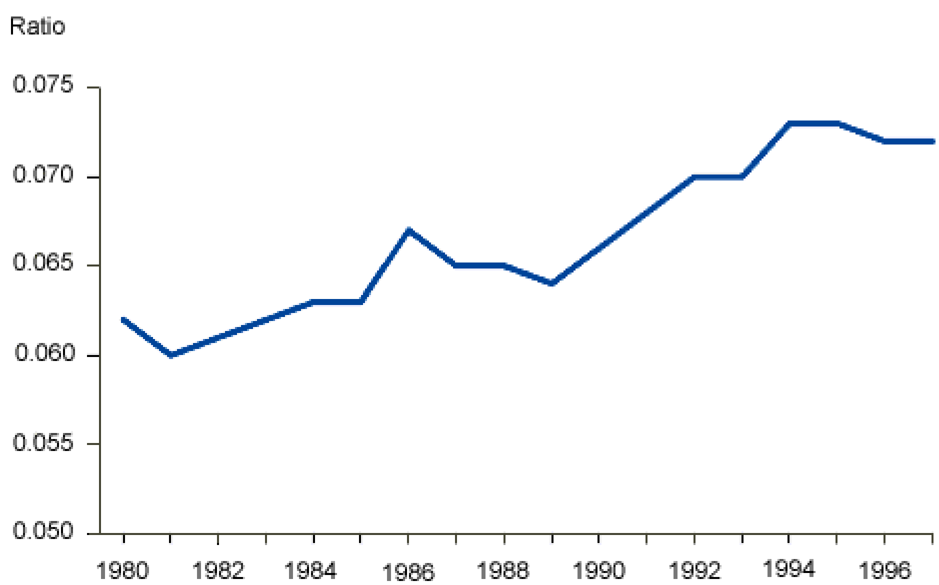

Fig. 2.5. In the EU, the ratio of revenue from environmental taxes, compared to revenue from other taxes and social contributions, steadily increased, 1980-96. Environmental taxes are defined as energy taxes (including taxes on transport fuels), transport taxes, and dedicated pollution taxes (EEA 2000a).

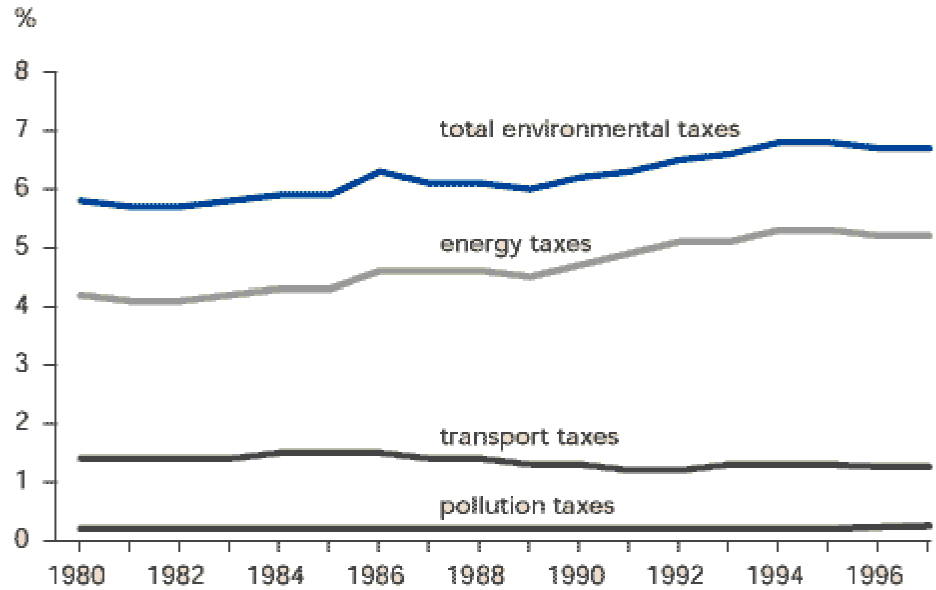

Fig. 2.6. Most of the environmental taxes, and most of the increase in taxes, in the EU are from energy taxes, including transport fuels, which make up more than three-quarters of energy taxes (EEA 2000a).

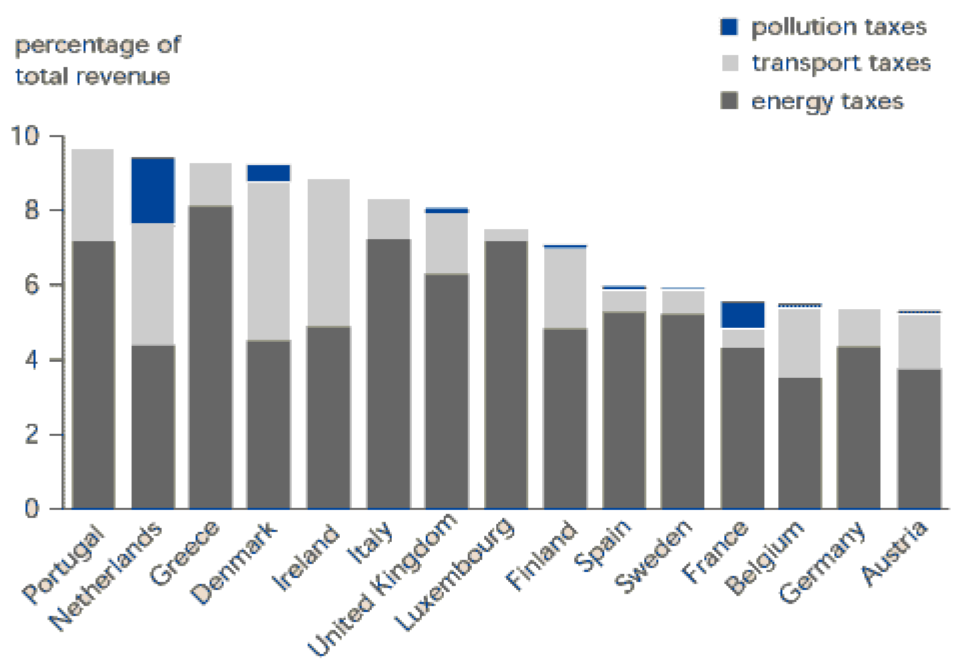

Fig. 2.7. 1997 revenue from environmental taxes in EU member states, as a percentage of total revenue and social contributions, shows that only the Netherlands, France, and Denmark have significant pollution taxes, and that energy taxes are the most significant type in all 15 member states (EEA 2000a).

Japan

In the traditional manufacturing environment, Japan is focused on applications and products, and technical solutions tend to be at the operations level. One example of this is Toyo Seikan's waste minimization program and use of pre-coated steel in the manufacture of beverage cans. There is also evidence of early adoption of emerging (non-Japanese) technologies in new products; for example, Honda and Toyota were the first to introduce hybrid cars, and Sony and Hitachi manufacture a significant volume of printed wiring boards that use micro-via interconnects and bromine-free flame retardants (Appendix D). The manufacture of vinyl window frames using triple co-extrusion with a recycled PVC core demonstrates an innovative application of existing materials and equipment (Appendix D). Progressive implementation of technology was evident with the use of plastic as a reducing agent (also done in Germany).

As a country that relies heavily on marketing high-value-added consumer products to countries all over the world, Japanese industry must be highly responsive to global policies. The most striking example of this is the strong emphasis on ISO 14000, which was seen advertised in public areas, including mass transit systems. Japanese electronics companies were the first to develop lead-free solders and offer bromine-free printed wiring boards in response to the EU's WEEE Directive. Japan's limited amount of natural resources and limited landfill space evokes a strong awareness of the relationship between conservation and economics (lean = green), as observed at Toyota and Toyo Seikan (Appendix D). Toyota claims that its highly efficient assembly line at Tsutsumi produces only 18 kg landfill waste per automobile. Fuji Xerox has a very well implemented program of component reuse.

Of the three regions studied, Japan appears to have the greatest concern with CO_2 emissions and global warming. CO_2 emissions are measured as a function of energy consumption, and since Japan has extremely high energy costs, there is clear economic incentive as well as environmental incentive to be concerned with this issue. However, given that most of Japan's populace lives at or near sea-level, there may be concern over rising sea-levels as well.

Japan demonstrates a strong alignment of internal resources not seen in the other two regions. This manifests itself as a unified response to EBM and is evident in the areas of public education, environmental leadership, and consensus building. There is also a commitment to public development of data and software tools such as its national LCA project. In this effort the Japanese government is trying to develop a large LCA database that is specific to Japan and which is viewed as a national project (see the MITI site report, Appendix D). Hitachi representatives were particularly outspoken in their strong interest in systems integration.

The emphasis on recycling in Japan lies somewhere between that of the U.S. and the EU. Government is invested in developing infrastructure for recycling (e.g., PVC from construction sites) and industry is beginning to establish standards for recycled materials, such as PVC for non-pressurized wastewater pipes (Appendix D).

The WTEC panelists did not see much evidence of activity in the area of pollution prevention. This was somewhat unexpected in light of Japan's historical problems with industrial pollution. Rapid industrialization in the last half of the 19th century contributed significantly to this problem; however, contamination of soil with base and heavy metals continued to be a problem well into the 20th century (McNeill 2000).

SUMMARY MATRICES

The following matrices were developed by consensus within the panel after completion of the site visits. They are subjective; but based on observations made during the year-long investigation, it is believed that they represent the relative trends within the three different regions in the areas of government, industry, research and development, and education. The number of asteriks in each cell are intended to be indicative of level of effort and emphasis as much as actual level of success.

Table 2.4
Government Activities

Activity	Japan	U.S.	Europe
Take-back legislation	**	—	****
Landfill bans	**	*	***
Material bans	*	*	**
LCA tool and database development	***	**	****
Recycling infrastructure	**	*	***
Economic incentives	**	*	***
Regulate by medium	*	**	*
Cooperative/joint efforts with industry	**	*	****
Financial and legal liability	*	****	*

Table 2.5
Industrial Activities

Activity	Japan	U.S.	Europe
ISO 14000 certification	****	*	***
Water conservation	**	***	*
Energy conservation/CO2 emissions	****	**	**
Decreased releases to air and water	*	***	**
Decreased solid waste/post-industrial recycling	****	**	***
Post-consumer recycling	**	*	****
Material and energy inventories	***	*	**
Alternative material development	**	*	***
Supply chain involvement	**	*	**
EBM as a business strategy	****	**	***
Life-cycle activities	**	**	**

Table 2.6
Research and Development Activities

Activity	Japan	U.S.	Europe
Relevant Basic Research (> 5 years out)			
Polymers	**	***	**
Electronics	**	***	*
Metals	***	*	**
Automotive/transportation	**	*	***
Systems	**	*	***
Applied R&D (< 5 years out)			
Polymers	*	***	**
Electronics	***	**	**
Metals	***	*	**
Automotive/transportation	***	*	***
Systems	**	*	***

Table 2.7
Educational Activities

Activity	Japan	U.S.	Europe
Courses	**	**	***
Programs	*	*	**
Focused degree program	—	—	*
Industry sponsorship	*	**	***
Government sponsorship	*	*	**

CONCLUSIONS

It is clear that cultural, geographic, and business needs all strongly influence practices in environmentally benign manufacturing in the U.S., EU, and Japan. In the area of government, environmental regulations are relatively new to both the newly formed EU and Japan, and there are historical precedents for cooperative efforts between government and industry (in many areas, not just in the environment). Consequently, both of these regions tend to have a more proactive approach to problem solving than does the U.S. This approach lends itself well to long-term, systems-level efforts such as development of life-cycle inventory tools and data. Take-back legislation and recycling laws in the EU and Japan are made possible by small, densely populated areas and the limited number of local governments within which consensus needs to be reached. These laws are also driven by the limited amount of area available for landfills. The U.S. has a long history of environmental regulations that are focused on pollution of specific media (air, soil, and water). This, combined with a tendency towards litigation, is much more likely to produce "point" rather than systems solutions. The governments of Japan and the EU are involved in infrastructure development and extended producer responsibility, which are almost completely absent at the Federal level in the U.S.

Corporations in the U.S. are very material and process oriented, and tend to place emphasis on decreased resource consumption (especially water) and pollution prevention. While some of the larger, international firms have started to incorporate environmental issues into business strategies, it is not nearly at the level seen in Japan and the EU. Included in these strategies is a high priority placed on ISO 14000 certification. In the U.S., life-cycle analyses are becoming more prevalent, but they are done in a much more limited capacity than in the EU and might more properly be described as mass-energy balance activities. Japanese industry, in cooperation with the government, is very concerned with energy conservation (reduced CO_2 emissions) and decreased solid waste, and this is reflected in the type of life-cycle analyses that are performed there. However, there are clear economic as well as environmental drivers, including high energy costs and limited opportunities to landfill waste. European corporations are interested in alternative material development, especially as these activities relate to systems level issues, including life-cycle assessment (LCA), particularly in the area of supply chain management and design for the environment (DFE), typically for end-of-life issues. Post-consumer recycling has a high priority in light of take-back regulations and decreased landfill space.

Research in the U.S. is heavily dependent upon industry objectives (especially introduction of new technologies) and is therefore focused on materials and processes. Japan's efforts are more closely aligned with applications, implementation, and manufacturing systems. European research is heavily weighted in the areas of implementation and systems engineering, particularly DFE and LCA.

In the European countries, higher education has begun to address EBM to a much greater degree than in either the U.S. or Japan. The panel did not identify any degree programs in the U.S. There are a few formal programs within conventional engineering programs, and courses at the graduate level are becoming more common.

Overall, it appears that environmentally benign manufacturing in the U.S. is somewhat behind that of the EU and Japan. However, because activities are more privatized within industry, and in many cases are viewed as competitive (both technically and from a marketing perspective), the level of effort may be less obvious. The U.S. government is more reactive, rather than proactive, and as such there is less willingness to publicize its activities, and more reluctance on the part of industry to collaborate on big-picture issues. It should be remembered, however, that the U.S. is a nation of crusaders. It does best when it has "an enemy." There are numerous instances where, largely through technical innovation and collaborative efforts, the U.S. has come from behind to mount a successful challenge. Examples are the automobile industry in the early 1980s and the electronics industry in the early 1990s. In both cases there was a significant amount of industry and government collaboration. It will simply take the U.S. government and industry, in cooperation with educational systems, to determine that environmentally benign manufacturing is critical to our global economic status and extended quality of life.

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CHAPTER 3

STRATEGIC VISION

David T. Allen

INTRODUCTION

In order to identify critical research needs in environmentally benign manufacturing (EBM), it is first necessary to define the objectives of EBM and to identify the forces driving its implementation. If this strategic framing of goals is not done, then EBM becomes just a collection of loosely connected technologies. The panel observed, worldwide, that many companies are struggling with the challenges of defining and implementing key facets of EBM. Yet, common issues and approaches emerged, and this chapter will report on those elements. Specifically, these include identification of environmental objectives that are viewed as strategic by companies worldwide, the forces that are driving companies to address these issues, the metrics with which to measure improvement, and the response of the research community in identifying knowledge gaps. An excellent discussion of this, as it applies to any industry sector, is included in the 1994 *Electronics Environmental Roadmap* (MCC 1994).

EBM ENVIRONMENTAL OBJECTIVES

An almost infinite array of environmental objectives can be considered in designing products and manufacturing systems that are environmentally benign. These objectives may address concerns at the manufacturing level, such as avoiding hazardous waste generation and reducing the emissions of smog precursors, or they may address larger life cycle issues such as designing products that are easily disassembled for parts and material recovery at end-of-life. In a workshop held at the Microelectronics and Computer Technology Corporation (MCC) in 1997, a panel of original equipment manufacturers (OEMs) developed the following list of environmental objectives (MCC 1997):

- Disposition (planning for recovery): maximum recovery/reuse at the end-of-life
- Energy conservation: reduced energy consumption throughout the product's life cycle
- Materials of concern: reduced use of materials of concern through the product's life cycle
- Natural resource conservation: increased materials efficiency throughout the product's life cycle and reduced reliance on non-renewable or resources that are not obtained through sustainable processes
- Product life extension: increased product life (reduced use of resources per unit of service delivered)
- User health and safety: products present no health or safety hazards to the user

These are in close alignment with the observations made by the panel during the course of this study. The common EBM objectives worldwide were noted to be:

- Reducing energy and material consumption
- Waste reduction and reduced use of materials of concern

- Reducing the magnitude and impacts of product packaging
- Managing products that are returned to manufacturers at the end of their designed use
- Customer demands for documented environmental management systems (EMS)

Because of the wide variety of environmental objectives that could be considered, an equally wide array of technologies might be required to achieve EBM. For example, if hazardous waste minimization were the desired objective, then chemical reaction and separation technologies would be critical. In contrast, if dealing with products at the end of their designed use were the desired objective, then disassembly algorithms would be critical. Thus, to identify critical technologies and knowledge gaps, the panel examined the types of environmental objectives driving EBM.

DRIVERS FOR EBM ENVIRONMENTAL OBJECTIVES

Many different forces drive environmental policy and strategy. In some cases the demand for these objectives comes from the manufacturers themselves (e.g., increased material and energy efficiency). In other cases, the demand comes from customers (e.g., demand for EMS systems) or through environmental regulation (e.g., end-of-life product take-back). Motorola has developed a table that maps environmental objectives against drivers (Figure 3.1)(Pfahl 2000).

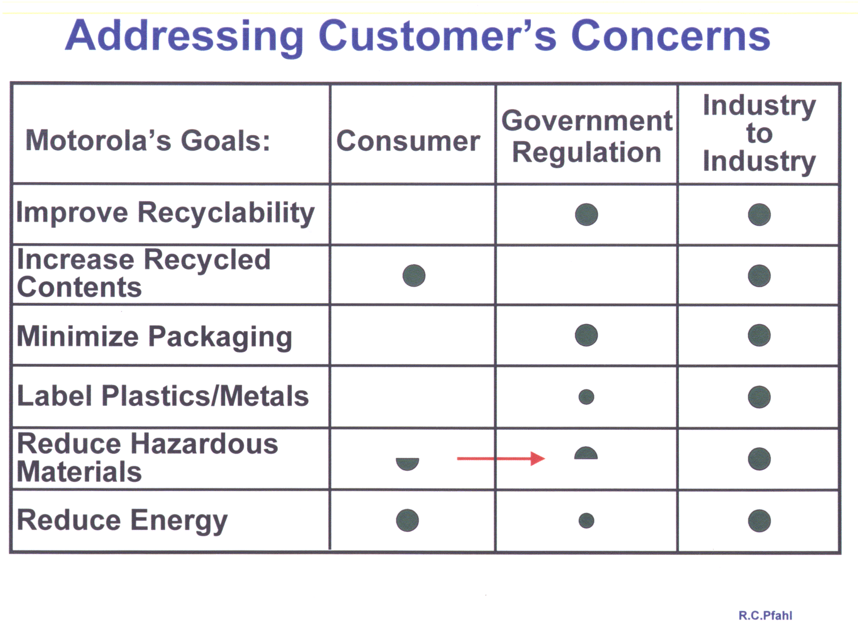

Fig. 3.1. Motorola has developed the above matrix to map EBM environmental objectives against drivers.

While perhaps not laid out in this specific format, this general approach appears to be behind much of the development of EBM strategies worldwide. Thus, expanding upon the Motorola example, the issues and driving forces shown in Table 3.1 are the key ones identified by the panel during site visits in the U.S., EU and Japan. The elements within Table 3.1 are intentionally left blank, since the panel found that the importance of various environmental objectives, as well as the forces driving companies toward these objectives, varied from region to region and from sector to sector. For example, in the EU, new regulations requiring the take-back of electronic products by original equipment manufacturers and material recovery regulations for scrapped automobiles are driving product design in these sectors. Since Japanese and U.S. manufacturers of electronic products and automobiles have a large market share in the EU, this emphasis is seen worldwide. Other industry sectors not addressed by this panel (such as pulp and paper) would likely have minimal concern with this environmental objective. Within the sectors studied (automotive and electronics) reduced use of materials of concern is currently a much more important objective in the electronics industry than in the automotive industry. This is largely due to the EU directive that calls for virtual elimination of cadmium, lead, and certain brominated flame retardants (see Chapter 5, electronics section). Globally, energy and material consumption is much more of a concern in Japan (in large part due to economic drivers) than in the U.S. (see Chapter 2 for more discussion).

Table 3.1
Issues and Drivers for EBM

	Consumers	Government Regulations and Policies	Non-government Organizations	Supply Chain	Economics
Energy and material consumption					
Waste reduction and reduced use of materials of concern					
Product packaging					
Producer responsibility and take-back					
Environmental management systems (ISO 14000)					
Integrated product policy					

METRICS FOR MONITORING EBM ENVIRONMENTAL STATUS AND PROGRESS

In addition to defining the objectives and drivers within an EBM strategy, the means with which to measure continuous improvement in environmental quality are often complex and challenging. Bridges to Sustainability, a non-profit organization with a focus on the chemical industry, has a metrics project developed in cooperation with DOE’s Industries of the Future program. In May 2000, the group hosted a two-day workshop entitled “Sustainability Metrics.” A summary of the workshop is available online at http://www.bridgestos.org/news.htm#workshop. In another workshop hosted by MCC, “Making Design-For-Environment and Life-Cycle Assessment Work” (MCC 1997), a list of metrics was agreed upon by a large group of electronics OEMs and suppliers (Table 3.2).

Table 3.2
List of EBM Metrics Recommended by Electronics OEMs and Suppliers

- commodity material value
- composition of materials of concern (including persistent, mined, and regulated materials)
- disassembly time and cost
- emissions (e.g., EMF) during use
- energy consumption during production
- energy consumption during use
- ergonomics
- expandability/upgradability
- landfill fraction
- material identification/ marking
- number of materials
- process efficiency relating to material balance
- public perception/opinion (as in the cases of PVC, radiation, and perceived toxicity)
- recoverability
- recyclability
- recycled content
- reliability
- resource consumption
- reusability
- serviceability/service requirements
- size
- standardization of parts
- toxicity in processing
- toxicity in product
- use of material of concern in processing
- use of renewable/non-renewable resources
- useful life (MTTR, MTTF)
- volume/nature of maintenance materials
- weight

The National Academy of Engineering (NAE) has also explored this issue in four different sectors: automotive, chemical, electronics, and pulp and paper. It divides metrics into four groups: supply chain, facility centered, product centered, and sustainability. As is typical in the U.S. (Chapter 2 of this report), the NAE approach is very media centered and emphasizes impact on air, water, and land. The study also makes a number of recommendations including the following overarching goals (CIEPM 2000).

- Adopt quantitative environmental goals
- Improve methods of ranking and prioritizing environmental impacts
- Improve the comparability or standardization of metrics
- Expand the development and use of metrics
- Develop metrics that keep pace with new understanding of sustainability

IMPLEMENTING EBM: IDENTIFYING RESEARCH NEEDS

Given the sets of environmental objectives driving EBM, companies are responding by creating and implementing new design tools and new technologies. The panel observed a number of common elements among companies, worldwide, that are attempting to implement EBM. These knowledge and tool gaps include:

- lack of tools to examine trade-offs between environmental issues, and between environmental issues and issues such as cost and quality
- lack of consistent data and metrics on the environmental attributes of materials
- need for certain key technologies, specific to individual industrial sectors

(Note that this list could be expanded if the development of new high performance business practices to address EBM were included as well. These topics, which include such issues as supply chain coordination and communication, goals alignment, performance tracking, etc., are discussed later in this report in Chapters 4 and 6.)

These research needs have been articulated in research roadmaps that define key gaps, opportunities and priorities. The development of research roadmaps and strategic planning documents has become increasingly common in both public and private sectors, particularly in interdisciplinary areas such as environmentally benign manufacturing. The panel found a number of examples in the United States and Europe of roadmaps and strategic research plans focusing either directly or peripherally on EBM. (A summary of these is given at http://itri.loyola.edu/ebm/usws/ind_summary.htm.)

In the United States, the Department of Energy's Office of Industrial Technologies has been developing a variety of research roadmaps through its Vision 2020 program. This program, called "Industries of the Future," focuses on a group of energy intensive industrial sectors (agriculture, aluminum, chemicals, forest products, glass, metal casting, mining, petroleum, and steel). With DOE sponsorship and coordination, leaders in these industries and researchers in industrial, governmental and academic laboratories have created a strategic vision of the future of these industry sectors and have identified critical research needed to achieve the vision. The form of the reports is exemplified by the documents generated by the chemical industry sector. For the chemicals sector, the overall vision is articulated in a single document ("Technology Vision 2020: The U.S. Chemical Industry," available at www.oit.doe.gov/chemicals). In addition, specific research needs have been identified in a series of documents, ranging in coverage from new process chemistries to separations technologies. Topics covered include alternative media, conditions, and raw materials, catalysis, computational chemistry, computational fluid dynamics, and separations. A complete list of documents is available from the DOE's Industries of the Future Web site (www.oit.doe.gov/industries.shtml). While these roadmaps are not exclusively focused on environmentally benign manufacturing, much of the strategic vision for these energy and material intensive industries involves decreasing energy consumption and reducing wastes.

The electronics industry has also developed a set of research roadmaps that define critical research needs in environmentally benign manufacturing. Examples are:

- 1996 Electronics Industry Environmental Roadmap (MCC) (available at www.mcc.com/projects/ env/roadmap/roadmap.toc.html)
- National Electronics Manufacturing Technology Roadmaps (1998) (NEMI) (www.nemi.org/Roadmap/ index.html)
- National Technology Roadmap for Semiconductors (1999) (SIA) (public.itrs.net)
- Lead-free soldering roadmap (1998) (JEIDA) (www.leadfree.org)
- National Technology Roadmap for Electronic Interconnects (1999) (IPC) (www.ipc.org/)

Among the features that distinguish these roadmaps from others in the United States is their use of data on environmental impacts throughout product life cycles (raw material extraction to final product recycling or disposal) and their promotion of life cycle tools as part of the research agenda. The 1996 Electronics Industry Environmental Roadmap, for example, draws upon a prior study which looked at a streamlined life cycle study of a computer workstation (MCC 1993). A computer workstation is a complex product involving an enormous range of materials and components. It would be extremely difficult to conduct a full assessment of all of the environmental impacts of all of the material use, energy use and emissions associated with a product such as a workstation. Yet, these data can prove extremely useful in identifying areas for environmental improvement. The workstation components considered in the MCC study included the cathode ray tube (display), plastic housings, semiconductors, and printed wiring boards. A streamlined life cycle assessment was able to identify, for a variety of environmental categories, which workstation components were of primary concern. For example, product disposal was a dominant issues for cathode ray tubes. Hazardous waste generation was dominant in semiconductor manufacturing. Energy use was dominant in the consumer use stage of the life cycle. Surprisingly, considering the final size of an integrated circuit, semiconductor manufacturing was identified as a significant factor in material use (due to material that is wasted rather than what is included in the actual product).

Results for the manufacturing phase are summarized in Figure 3.2. The study was used to guide research and technology development for the microcomputer industry.

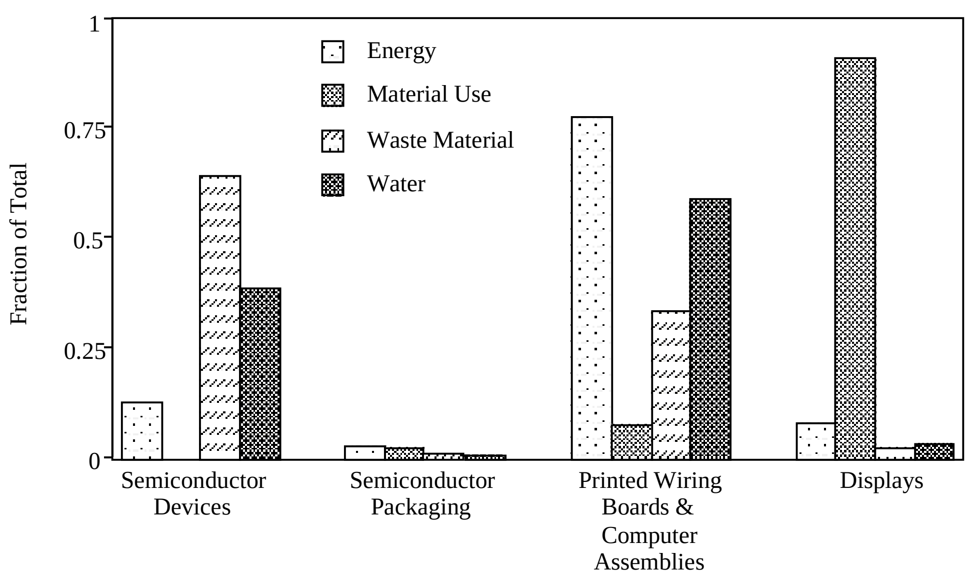

Fig. 3.2. Relative energy use, material use, waste generation, and water use are shown for the manufacturing phase of the computer workstation life cycle.

The automotive industry is currently working with the American Plastics Council to develop a roadmap for plastics used in automobiles. It will include a section on recycling of engineering thermoplastics and inclusion of recycled plastic into new components. The Automotive Part Rebuilders Association (APRA) has developed a roadmap facilitated by DOE's Office of Industrial Technology (OIT), which can be obtained online at APRA's Web site (www.apra.org/Promoting_Industry/Roadmap/roadmap.htm). The Steel Industry Technology Roadmap has a strong focus on environmental issues including recycling for the automotive industry (www.steel.org/mt/roadmap/roadmap.htm). The automotive consortium, USCAR, has a number of excellent references available electronically (Table 3.3).

Table 3.3
USCAR Websites

Topic	Website	Comments
General description	http://www.uscar.org/consortia/con-erc.htm http://www.USCAR.com	
CERP metal casting project	http://www.uscar.org/techno/cerp.htm	see CERP site report, Appendix E
Mist reduction project	http://www.uscar.org/techno/mist.htm	see Ford site report, Appendix E
Specific technologies	http://www.uscar.org/techno/index.htm	many are environmentally oriented
Recycling reuse and recovery	http://www.uscar.org/techno/rrr.htm	
Vehicle Recycling Partnership	http://www.uscar.org/consortia/con-vrp.htm	
U.S. Automotive Materials Partnership	http://www.uscar.org/techno/lciwrapup.htm, http://www.uscar.org/techno/lci.htm, http://www.uscar.org/techno/env_7-97.htm	Several articles on life-cycle studies

During their site visits, panelists learned of a number of research roadmaps focusing on EBM that have been developed in Europe. Among the most comprehensive were plans developed by the European Commission's Directorate for Science Research and Technology. The plans are described in detail at the Directorate's Web site (www.cordis.lu). As an example of the type of strategic planning conducted by the Commission, consider one of the Directorate's programs that is most relevant to EBM—the program on "Competitive and Sustainable Growth," which is described in detail at www.cordis.lu/growth/src/cwp_en. The program has a set of "key actions" that concentrate research and technology development on clearly defined social and economic challenges. The four key actions are:

- Efficient production including design, manufacturing and control
- Intelligent production
- Eco-efficient processes and design
- Organization of production and work

The projects address these key areas and fall into the categories of:

- Products of the future
- Advanced functional materials
- New generation of machines
- The extended enterprise
- The modern factory
- Infrastructures

The EC Directorate uses a number of tools to set strategic direction. To provide an overview of research needs, the directorate funds "virtual research institutes" that suggest strategic directions for research. These are complemented by a number of industrial/academic networks that provide more technical insight and direction on research needs. Approximately 100 of these networks exist; many are Web based; many of the Web sites are cited at the directorate home page. Finally, most research is funded in the form of consortia, which generally include industrial partners who help fund the research (approximately 50% in a typical consortium) and set research directions.

Other models for setting EBM research directions were observed in the German Fraunhofer institutes. The institutes visited by the panel were, in general, focused on specific technologies or industry sectors. For example, the panel visited institutes for polymer testing and polymer science, reliability and micro-integration, manufacturing, and chemical technologies, among others. While the institutes were not specifically directed at environmental issues, virtually all of these institutes had some level of effort aimed at collecting life-cycle environmental data. In some institutes the life-cycle data were used to identify research opportunities. For example, at the Institute for Polymer Testing and Polymer Science, a series of life-cycle studies of automotive parts made of steel, aluminum and plastics helped identify part systems for which plastics use would be advantageous. Similar life-cycle studies of construction and building materials helped identify new opportunities.

In Japan, some of the most comprehensive strategic planning has been developed within companies. For example, Toyota has developed environmental purchasing guidelines for its suppliers, has identified painting operations and machining as high priorities for manufacturing waste reduction, and tracks and controls more than 200 substances. Toyota's approach was consistent with that of other Japanese companies, where environmentally benign manufacturing, and energy and resource utilization efficiency are regarded as natural extensions of lean manufacturing.

SUMMARY

To summarize, the panel found that in Japan companies were driving the strategic development of environmentally benign manufacturing, with the involvement of government and universities. In Europe, university based research institutes and governmental organizations, in collaboration with the private sector, are driving research and development in EBM. The United States uses a combination of both the Japanese and European approaches; some of the most exciting innovations are occurring in companies, and some government/industry partnerships, such as the DOE's Vision 2020 program, are developing research roadmaps. Unlike in Europe, however, U.S. universities remain relatively disengaged from the research planning and roadmapping process.

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CHAPTER 4

SYSTEMS LEVEL ISSUES

Deborah Thurston and Bert Bras

SUMMARY

This section describes the systems level issues that were discovered by the panel, and a set of recommendations for further research. First, the motivating factors are discussed, focusing on the joint effects of legislation, economic efficiency, and marketing. Next, the need for a systems approach is illustrated through the complexity of environmentally benign manufacturing (EBM) issues. The next section describes several general approaches to EBM observed by the panel, along with the current limitations of each approach. The final recommendations section summarizes and describes specific needs for further research in modeling, economics, information and the technological components of systems analysis.

INTRODUCTION

"System" is defined as "a regularly interacting or interdependent group of items forming a unified whole" (Webster's 1974). Within the context of environmentally benign manufacturing (EBM), the group of items includes environmental, technical, economic and legislative issues, as well as human aspirations and values, which form the unified whole of the global environment. Table 4.1 lists the motivating factors for interest in environmentally benign manufacturing. Early regulatory mandates focused on control of emissions, employing a media-based (air, water and solid waste) approach. Manufacturers' early efforts in environmentally conscious behavior were thus focused on "end-of-pipe" treatment and waste disposal systems. Similarly, worker exposure motivated point-of-contact worker protection systems, which prevented or minimized worker exposure to harmful materials and/or processes. A new trend is product take-back legislation, which places the logistic and economic burden of product disposal on the manufacturer. This has recently been enacted by the Dutch, with the European economic community soon to follow.

Economic forces further motivate pro-active EBM behavior beyond simple regulatory compliance. One consistent theme the panel observed was interest in the correlation between environmentally benign manufacturing technologies and economic efficiency. At several site visits, the host stressed that the EBM technology developed was also more profitable. This is accomplished in several ways. First, if "end-of-pipe" emissions can be decreased, significant savings in waste treatment and disposal costs can be realized. The "Pollution Prevention Pays" program at the 3M company sought to exploit such opportunities. U.S. manufacturers currently spend approximately $170 billion per year in waste treatment and disposal costs.

Second, some manufacturers have realized that products and processes that generate large amounts of waste are, by definition, inefficient and costly. Many EBM technologies consume less raw materials and/or energy, resulting in simultaneous environmental protection and cost savings. In other words, "lean = green." While this is extremely promising, it is also a much more complex "concurrent engineering" problem than simply treating waste at the "end of pipe" in response to regulations. It requires thoughtful analysis long before the manufacturing process begins, and even long before the product is designed. Another economic motivator is that the manufacturer that is first to develop a cost-effective product or system that complies with anticipated product take-back legislation will have a competitive advantage in the marketplace, as well as an enhanced corporate image.

Table 4.1
Motivating Factors for EBM

Regulatory Mandates
Emissions standards (air, water, solid waste)
Worker exposure standards
Product take-back requirements, banned materials
Competitive Economic Advantage
Waste treatment and disposal ($170 billion/year in U.S.)
Resource consumption and costs—energy, water, materials
First to achieve cost-effective product take-back system, reduced liability
Green Marketing
Corporate image
ISO 14001
EPA Toxic Release Inventory (TRI)
Market value of company Dow Jones Sustainability Group Index Investor Responsibility Research Center
Eco-labeling, employee satisfaction

Beyond the immediate economics of the manufacturing process, larger scale marketing considerations also motivate EBM. Factors cited by leading EBM manufacturers include the importance of maintaining an environmentally responsible corporate image, high level directives from a corporate leader and customer demand. The regulatory complexities of an increasingly global economy have motivated several EBM leaders to define their own pro-active environmental goals that go far beyond minimum compliance with varying local regulations. Another motivating factor is investors. The correlation between the market value of the company and its environmental management program is only beginning to be studied, but several groups have begun gathering data to help identify companies that emphasize social responsibility, such as the Dow Jones Sustainability Group Index and the Investor Responsibility Research Center. Initial analyses indicate a correlation between social responsibility and long-term profitability.

Because of the intricate interplay between regulatory, technical, economic and other factors, environmentally benign manufacturing requires a systems level approach. Technological competence and good intentions alone do not assure success; a systems approach is essential. For example, Volvo succeeded in developing and implementing technology for "the world's cleanest paint line," utilizing water-based chemistry. However, energy price increases forced a more comprehensive systems analysis, which revealed that the cost and environmental impact resulting from the "clean" paint line's energy consumption arguably outweighed the decrease in paint line emissions. Another example is the failure of German recyclers who, although technologically competent, were financially unsuccessful because the enactment of product take-back regulations came too late to provide feedstock. Lessons learned include the necessity of including all environmental impacts in the analysis, including those of energy consumption, energy costs, timing and location of regulations.

The next section further discusses the complexity of systems issues in EBM. Section three describes systems-based approaches and their limitations, and the final section describes specific recommendations for needs in the systems area.

THE COMPLEXITY OF SYSTEMS ISSUES

The increasing complexity of EBM is illustrated in Figure 4.1, which compares the environmental and organizational scales of environmental protection approaches (Bras 1997). The vertical scale indicates the scope of organizational concern, ranging from the manufacturing facility at the origin, through a group of X manufacturers, to society as a whole. The horizontal scale indicates the corresponding length of the time scale, ranging from the time during the manufacturing process, through the product life cycle, to the span of civilization. The scales are not linear but indicate important distinctions between approaches.

In the lower left corner, traditional pollution prevention efforts are mapped that most often focus on elimination of pollutants from existing products and process technologies—the temporal scope is on the order of manufacturing process and the organizational scope is usually the manufacturing group/department. Traditional environmental engineering, although broadening, is primarily concerned with managing the fate, transport, and control of contaminants at the end of the manufacturing process ("end of pipe"), but still requires involvement of the entire manufacturing group.

Figure 4.1 indicates the complexities that must be overcome if one wishes to move from the lower left corner (pollution prevention) to the upper right corner and achieve sustainable development. Sustainable development is defined as "development that meets the needs of the present generation without compromising the needs of future generations" (UN "Brundtland" Commission 1987). Both the Europeans and the Japanese have progressed further than the United States. beyond the lower left corner and are indeed taking a more comprehensive, systems view of environmentally benign manufacturing. Specifically, (1) product take- back and recycling are actively pursued to avoid landfill disposal, (2) life-cycle analyses are performed to reduce environmental impact over the entire product life, and (3) strong collaborations between stakeholders (suppliers, recyclers, governmental bodies, etc.) are established. One might argue that these steps are easier to take where transportation distances are shorter and the culture is less diverse (see Chapter 2).

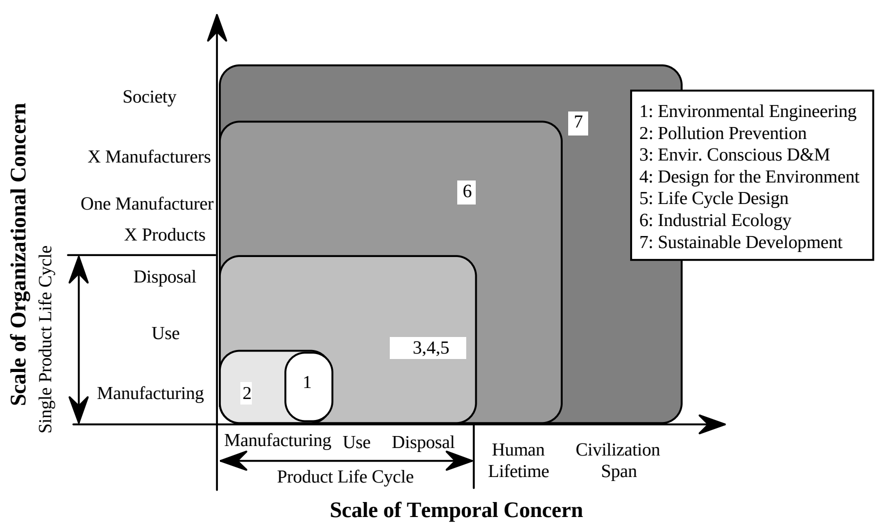

Fig. 4.1. Environmental and organizational scales of environmental impact reduction approaches (Bras 1997).

CURRENT SYSTEMS APPROACHES

Product Take-Back and Recycling

Current Status

One of the best examples of a systems approach is product take-back and recycling operations. Here, many elements of an inter-connected system must be put into place and coordinated in order to assure success. Clearly, the Dutch initiatives in requiring product take-back and recycling systems in order to reduce landfill have demonstrated that it is possible to implement a working take-back system for electronics (see the MIREC site report). Furthermore, the European Commission legislation on electronics take-back will most likely follow the Dutch model, except EC legislation is expected to be stricter—for example, including medical equipment. Hence, in Europe it was observed that manufacturers no longer question the issue of product take-back, but rather are focusing their energies on identifying the best approach. Japanese manufacturers are similarly focused on cost-effective compliance with pending European, as well as Japanese, take-back legislation. While the Japanese are perhaps even more space-limited in general than the Europeans, their primary motivation appears to be European legislation, since that is a large portion of their market.

Lessons learned are that a successful take-back system must be rooted in an economically viable approach to be self-sustaining. For example, MIREC's recommendation was to find markets for materials first, then recycle. A successful system also requires cooperation between many stakeholders, including the government, communities, consumers, manufacturers, and recyclers.

The Dutch also learned that consumers did not object to paying a "disposal fee" at point of purchase. A 25 guilder fee (approximately $10) on a $300 refrigerator or TV did not appear to affect consumers' purchasing decisions. One reason cited was that it was a relatively small increase compared to the cost of the product. Furthermore, the fee was levied on all products, hence, no competitive disadvantage was created.

Regarding the recycling process itself, it was observed that state-of-the-art reprocessing is still highly dependent on low-skilled manual labor (for sorting, disassembly, inspection). As such, the recycling/reuse industry is also seen as an opportunity to create new jobs to lower unemployment, especially in Germany. The U.S. appears to lead in mechanical separation technologies (see MBA Polymers site report).

Limitations

There are several difficulties encountered when developing a product take-back and recycling system. First, setting up the "reverse logistics" network can be very challenging. There is a need for better reprocessing technologies, particularly for polymer composites. Specialty materials and reinforcing materials in polymer composites often create a nuisance in the recycling process. Standardizing material types would facilitate recycling, but would also inhibit development of new materials that might improve product performance.

Use of recycled materials in the manufacturing process poses a number of problems. Some recycled "raw" materials are more expensive than their virgin counterparts, particularly for some polymers. Quality control is made more difficult when the range of material properties is greater due to contaminants and varying feedstocks.

Only a handful of products are currently designed to facilitate recycling. For example, flat-panel displays have been developed and are gaining wide market entry without consideration of their recyclability. Finally, the recycling process can also create its own environmental impact, resulting from transportation, facilities construction, facilities operations and waste generation.

Design for Environment Observations by Region

The increased emphasis on systems thinking, driven in part by the fact that end-of-life issues are now to be taken into consideration during product design, has led to what is often referred to as "design for environment" (DFE). Synonymous phrases include "environmentally conscious design" or "green design."

The interest in DFE is growing worldwide. In Japan, DFE is strongly correlated to a culturally ingrained sense of avoiding waste and conserving limited resources, as observed during visits to Toyota and Toyo Seikan (see site reports). Lack of space is a key motivator in Japan. This explains the emphasis on avoiding landfills by means of incineration and take-back initiatives.

In Japan, there is a strong emphasis on the development of DFE tools. Hitachi demonstrated several examples, as did the governmental laboratories. One of Hitachi's most active projects is inverse manufacturing, supported by MITI. Several tools shown were focused on design for disassembly and design for recycling, and NEC is also developing its own life-cycle analysis tool. One goal is to integrate life-cycle analyses into CAD systems. A key reason for in-house development is, interestingly enough, the language barrier: in order to introduce DFE and LCA tools, Japanese companies need a tool written in Japanese rather than English. Lead-free soldering methods are also being investigated.

Another key problem observed was the lack of integration with other design and management tools and practices. The sense of priority seems still to be with cost and quality at the engineering level, and hosts at Hitachi and other sites indicated that DFE is not completely adopted and prevalent throughout Japanese corporations. The connection with management tools also is lacking (still). It was very interesting to note that NEC had never investigated the economic payoff of its environmental R&D laboratory in its 29 years of existence, until last year. Instead, management sees environmental efforts as part of "being a good citizen."

In Europe, DFE was also prevalent, but several industrial sites that the WTEC team visited also emphasized that DFE should not be a stand-alone activity, but integrated throughout the product realization process. Still, there was no "magic" solution for how to integrate it throughout the business. At Volvo, this was cited as being a problem. Along similar lines, DaimlerChrysler representatives stated that having experts at the corporate level only did not work; experts need to be at the business unit level, close to the engineers and managers who are directly involved with the product and process design and management issues. It seemed that for most companies a primary motivator was "success stories" where environmental thinking was also beneficial to the bottom line in some way.

In general, EBM is seen by many in Europe and Japan as a natural extension of lean manufacturing and/or concurrent engineering, whereas in the United States, it is still often viewed as a separate activity with no "value-added." The European EBM/DFE support strategies appear to have evolved into a group of experts at the corporate R&D level, with few dedicated DFE/EBM experts at the business unit/manufacturing plant level. Integration with company-wide information systems (and beyond to suppliers) is being pursued.

In Europe, two studies were performed which focused on small and medium-sized enterprises (SMEs) that highlighted the importance of economic and environmental win-win situations even more. In a Dutch study, it was reported that SMEs were frequently eager to be helped, but that as soon as the consultants left, the motivator seemed to have gone as well. The reasons cited were that SMEs tend to think short-term and do not have many resources to spare. A recent Swedish study confirmed this (see IVF site report). An unresolved issue, therefore, is how to create the motivation for self-sustaining efforts after initial analyses have been performed by an external party.

From an education perspective, European universities seemed to be further ahead in integrating DFE into their curricula. Both in Europe and Japan, there are several ongoing research efforts, major national initiatives, and conferences addressing DFE issues. However, in Japan, DFE is not yet integrated into the curricula, and is mainly driven by elective courses and individual faculty interest.

In DFE and EBM alike, typical questions posed are:

- What is the environmental impact?
- Where does it occur most?
- What should we do about it?
- What is it going to cost us?

Hence, assessment tools are crucial and should ideally be easily validated, easy to use, objective, reproducible and enhance understanding. Throughout, it is generally agreed that one should not focus on one life-cycle aspect solely, but take a systems and life-cycle perspective.

Life-Cycle Analysis

Current Status

Life-cycle assessment (or analysis) is defined in ISO 14040 as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life." It was observed that LCA is widely used in Europe. In Japan it is less widely used, although there are apparent national efforts to develop LCA tools. A key motivator is ISO 14000 certification. To support LCA, there are a wide variety of software packages available—e.g., Volvo's Environmental Priority System, the Dutch-developed Eco-Indicator (embodied in Simapro software), and several extensive databases plus software tools (e.g., Gabi) that have been developed in Germany. However, LCA is mostly done by experts, either internal (e.g., corporate R&D) or (hired) external consultants. Furthermore, the LCA tools are not integrated with other analyses yet. Siemens cited this as being a problem.

Limitations

A problem with LCA that was mentioned during the visit to the Technical University of Delft is that there is no general consensus on a "standard" metric for measuring environmental impact, and thus a wide variety of interpretations are possible. In Europe, some companies have been promoting a "universal" single impact measure as provided by the Dutch Eco-Indicator, but this was met with strong opposition because many felt that this would result in using LCA more as a competitive tool than as a tool for true environmental impact improvement. Nevertheless, common criticisms regarding LCA are that it is not tied to business perspectives, too academic, too vague, difficult to perform, etc. Key, of course, is lack of data. In the Netherlands, the opinion was voiced that LCA has a problem in that it does not capture "value." Nevertheless, there does not appear to be any viable alternative, and LCA seemed to be well established in all major companies visited. Even more, certain Scandinavian governments now require that an LCA study be performed as part of a bid on a contract.

Win-Win Situations

Current Status

One of the most promising aspects of the systems approach involves strategies that simultaneously decrease pollution and improve profitability. One example commonly cited is the Xerox Corporation, which was able to realize a $200 million profit by spending $10 million to recycle toner cartridges. Another example was observed during the Toyo Seikan site visit, where the panel observed a new stretch drawing process for forming thin-walled steel cans. A tin-free steel is laminated with polyester film, eliminating the need for painting, lubricants, coolant water and subsequent wastewater discharge. The absence of tin facilitates recycling of the steel, and the laminated polyester film reportedly discharges no toxic fumes when burned off for recycling. The process is more profitable and consumes less space, steel, water and energy than the conventional method.

In Japan, a longer range economic perspective is taken than in the United States, with firms being more patient about investing for expected longer term payoff. An example is the Fuji Xerox plant visited (see Fuji Xerox site report)**,** which integrates a product take-back and disassembly unit within an assembly facility. The disassembled components are cleaned, inspected and reassembled into new products. While the assembly plant is profitable overall, the disassembly unit is still not cost-effective compared with the option of using all new components. However, Fuji Xerox continues improving its efficiency in anticipation of future regulations, expecting to realize a competitive advantage by being first to achieve cost-effective disassembly and reuse.

Limitations

While anecdotal evidence of “win-win” situations is inspiring, there is a great deal of controversy regarding the impact of environmental controls on the *overall* profitability of the firm (Porter and van der Linde 1995; Portney 1998). Some assert that there is no tradeoff between pollution prevention and “the bottom line” for the firm; that measures taken to prevent pollution also increase efficiency and profits (Hawken et al. 1999). Others argue that if EBM technologies always simultaneously decreased cost and improved product quality, the marketplace would have already achieved its “lowest polluting” potential without government intervention. They point out that although initial efforts to reduce pollution very often result in some savings for the firm, there often comes a point where increasingly stringent regulations incur unavoidable cost increases. (However, noncompliance might result in an even more significant cost increase.)

Interestingly, few (if any) companies have yet quantified the link between environmental assessments and business/economic assessments. Even companies that take a pro-active stance by going beyond mere compliance present the economic assessment mostly on a case-by-case, anecdotal basis and not systematically. Some promising initial research has determined that firms that adopt a single stringent global environmental standard, regardless of local standards, have higher market values (Dowell et al. 2000). These types of analyses are in their infancy, and rely heavily on self-reported assessments of general managerial practices. More in-depth analysis of the correlation between specific technologies and their economic impact is needed.

Collaboration Between Stakeholders

Current Status

The most striking distinguishing feature of the European approach is the way in which environmental protection legislation is formulated. Regulators, citizens, academia, industry and consultants interact in a more cooperative, less adversarial manner than in the United States.

In Europe, the Dutch are often cited as having the best cooperation between industry and government, followed by the Scandinavians. As can be seen in the TU Delft site report, in 1989 a shift occurred in the Dutch Ministry of Housing and Spatial Planning (the equivalent of the U.S. Environmental Protection Agency) when it shifted from the classical media (air, water, land) based approach to an industry-sector-based approach. Furthermore, the Ministry of Economic Affairs began to cooperate directly with the Ministry of Housing and Spatial Planning. The result is that, in governmental policy decisions, the correlation between economic and environmental issues is much better understood and managed

Limitations

Some limitations to this approach are details regarding implementation (which can be easily overcome) while others may be more intractable. Lucent Technologies (see TU Delft site report) emphasized the crucial role of a trusting and long-term relationship with suppliers. Cooperation with other partners in the supply chain is critical. Furthermore, a comprehensive strategy must be pursued, such as developing a set of recommended alternatives rather than simply “black-listing” certain materials.

Two more serious limitations to employing this approach in the United States are the traditionally adversarial relationship between government regulators and industry, and the litigious nature of our society. While managing a cooperative interaction in a small country with a rather homogeneous population is admittedly much easier than doing so in a country as large and diverse as the United States, there is much to be gained from improving collaborations between U.S. stakeholders.

Symbiotic Thinking and Industrial Ecology

Current Status

Several companies clearly have evolved beyond “business as usual” and can be viewed as “thinking outside the box.” At Interface Flooring Systems, the approach is centered on “quantification, qualification, symbiosis." This means that once a waste stream's amounts have been defined (quantification) and their severity assessed (qualification), an attempt is made not just to reduce it, but to find an outlet that can actually use the waste as a feedstock. These outlets can be other industries, and a symbiotic industrial ecosystem (as promoted by industrial ecology) can be obtained.

However, this symbiotic approach can also take place more directly with nature. Interface Flooring is using natural materials for some of its carpet products, e.g., animal hair and, recently, corn based fibers. Similarly, DaimlerChrysler is using natural reinforcing fibers (flax or sisal, depending on location) instead of glass fibers in some of its polymer composite components because these natural fibers can be more easily decomposed, both when recycling production scrap and also at the end of the useful life of the vehicle.

Limitations

This paradigm shift of viewing groups of industries, and even nature, as a large interconnected system does pose some problems. Both Interface and DaimlerChrysler noted that an entirely new supply chain had to be setup. For example, DaimlerChrysler had to ensure consistent crop quality, which even meant redesigning farming equipment and developing quality control systems to deal with unavoidable variations in the natural fiber "manufacturing" process, such as the influence of the amount of rainfall on fiber strength. Another example is efforts by Archer Daniels Midland in identifying a use for waste fly ash (similar to cement) generated by its fluidized bed coal combustion system. The fluidized bed system successfully decreases air pollution, but the chemical composition of the waste fly ash depends in turn on the composition of the coal, which varies greatly. As a result, the fly ash is unsuitable for many applications. In essence, the same manufacturing process quality control systems that have only recently been embraced by individual manufacturers will need to be embraced on a much larger scale.

Paradigm Shift from Selling a Product to Selling a Service

Current Status

The technical and economic difficulties with recycling described above can be avoided though product reuse and component remanufacturing (at least temporarily). Component reuse is well established in a number of sectors (e.g., automotive components, manufacturing equipment) and is pursued primarily when it makes good business sense. Most remanufacturing is performed by third-party remanufacturers, with a few exceptions. Caterpillar, Xerox, Kodak and Dell actively pursue remanufacturing and reuse as part of their business strategy. All three major U.S. automobile manufacturers offer numerous remanufactured parts, including complete engines, through their dealer networks. There is a substantial aftermarket business in remanufactured parts as well.

Caterpillar's "Reman" offers remanufactured engines and engine components at prices below that of comparable new components. Engine blocks are first disassembled, flushed and inspected, then resurfaced. Crankshafts are reground, polished and checked. Bearings, seals, gaskets, etc., are replaced with new components.

Dell's "remanufactured" computers are those that have been returned by the consumer within the 30 day total guarantee period. These computers are disassembled, rebuilt to original specifications and then tested. Dell's remanufactured systems cost $100-$600 less than comparable new models, and come with the same warranty. However, they do not allow for modification of predetermined system configurations. Dell does not currently offer a standard leasing option, but it does offer to dispose of end-of-use systems for business consumers.

In Europe and the U.S., such reuse and remanufacturing have long been part of the replacement parts business. In the U.S. remanufacturered automotive parts are a $36 billion per year industry. However, European OEMs appear to be more directly involved in remanufacturing—for example, at DaimlerChrysler's European engine remanufacturing facility, whereas in the U.S. most remanufacturing is done by third party or independent firms, although sometimes under OEM contract and distribution. The next logical step would be to improve the cost-effectiveness of disassembly and remanufacturing technologies.

In addition, there is growing interest in a paradigm shift from selling a product to selling a service. In such an arrangement, the customer essentially leases the product for a predetermined time period, or perhaps pays a monthly fee for the defined service. The Dutch government has sponsored several studies to determine how a shift toward selling services would promote sustainable development. Japanese electronics companies use the phrase “inverse manufacturing” to refer to this concept, and are exploring concepts involving modular consumer electronics systems, where one module (such as a monitor) might serve the function currently fulfilled by two or more consumer products (such as a television and personal computer).

Such leasing arrangements have been in place for automobiles and copying machines for some time. For the manufacturer, advantages of this approach include far greater control over the condition and timing of the products’ return to the manufacturer. For example, the Fuji Xerox system described above includes a system for keeping maintenance, repair and reliability records for each product, which is considered at the time of disassembly.

Limitations

There is an untapped potential for “design for component reuse.” The panel observed few examples of product components being designed specifically for easy disassembly so that certain components that can be cost-effectively cleaned, remanufactured and re-assembled into “new” products. One important example of this is internal combustion engines, which in the past could be relatively easily disassembled and serviced, but were not necessarily designed with remanufacturing in mind. Caterpillar, on the other hand, has developed a newer design strategy that does specifically look forward to the remanufacturing process, e.g., through use of piston bore sleeves in its engines that are designed to be removable, hence eliminating the need for bore machining in the remanufacturing process.

As for the service paradigm, it is not yet clear how customers will respond to this new approach. So far, leasing arrangements have been successful for high-cost, high-maintenance products such as photocopying machines. It remains to be seen whether customers will be satisfied with merely renting other types of products where “pride of ownership” is an important attribute.

SUMMARY AND RECOMMENDATIONS FROM SYSTEMS VIEWPOINT

One of the major findings of the panel is that a systems approach to EBM is essential. Our findings indicate several opportunities for specific advances in systems analysis that would facilitate EBM.

Overall Modeling and Information Needs

The most pressing needs from the systems perspective are fundamental data, and modeling of the joint technical, economic and environmental impacts of product and manufacturing process design. Table 4.2 shows a matrix of information for modeling needs. Each column refers to the set of engineering design and manufacturing decisions throughout the life cycle. Each column category contains many separate decisions. For example, “manufacturing” might include material forming processes, chemical processes, temperatures, line speeds, type of solvents employed, etc. Each row indicates the resulting impacts and objectives, such as cost, quality and environmental impact. Again, each row category might contain many separate impacts, such as capital investment costs, labor costs, taxes, etc. Each element within the table indicates the cause and effect relationship between the engineering decisions and each impact. As one moves from the upper left corner of the table to the lower left, the general trend is that the availability of information and analytic models decreases. Manufacturers currently employ relatively good models and data for cost estimation as a function of material choice and manufacturing process. More recently, quality estimation and control models have been developed.

Table 4.2
Modeling and Information Needs

	Engineering Design and Manufacturing Decisions			
Impacts and Objectives	**Design and Materials**	**Manufacturing**	**Consumer Use**	**Post Use**
Cost	√√√	√√	√√	?
Quality	√√	√	√	??
Environment				
solid waste	√	?	?	?
water	?	?	??	??
air	?	??	??	???

In contrast, the lower right corner of Table 4.2 indicates that the life-cycle environmental impacts of many manufacturing processes, consumer use patterns and post-use options are still very poorly understood. Even when manufacturing processes are well understood, the environmental impacts might be closely tied with proprietary manufacturing processes. As a result, several companies, such as Volvo, have developed proprietary life-cycle analysis tools for in-house use. If pro-active environmental management does give firms a marketplace advantage, that advantage is lost if they share data or new technology with their competitors. In the United States, a further concern is exposure to liability in the case of future litigation, if the manufacturer can be shown to have been aware of environmental impacts.

The second most pressing need is standardization of life-cycle analysis. Even when the environmental impacts of a particular manufacturing process can be estimated from commercially available or proprietary software, the results are quite complex. In order to convert the myriad impacts of air emissions, wastewater discharge and solid waste disposal, many subjective tradeoff judgements must be made. Further judgements must be made to define temporal boundary conditions; how far back in the supply chain and how far forward in time should impacts be considered? The final, and perhaps most intractable, problem is judging the appropriate tradeoffs between the environment, cost and quality.

Other modeling and information needs include education and regulatory system analysis. Education (curriculum development) is needed for both engineers and non-technical majors, to enable understanding of environmental complexities. In regards to regulatory systems, much more information is needed to determine the set of regulatory approaches that maximize the economic incentive for EBM.

Technology Needs

The most critical technology need from a systems viewpoint is integration of standardized life-cycle analyses into computer aids to product and manufacturing process design. Several attempts at such tools exist, but they are most often “add-ons” that are employed by a specialized environmental group, or by the engineer in a time-consuming iterative fashion.

The significant data requirements for such an effort are often cited as a major stumbling block. As mentioned above, another difficult and contentious aspect is comparing or “weighting” environmental impacts that accrue to different media (air, water, solid waste) and occur at different points in time, affecting different stakeholders. These impacts are referred to by economists as “externalities,” or impacts suffered by parties other than the decision maker. Many environmental protection regulations seek to “internalize the externalities,” and manufacturers lack a standardized toolkit for their analysis. As a result, manufacturers develop and/or utilize a wide variety of tools, which results in a duplication of effort and/or questionable assumptions.

Business Needs

One key finding was the close interrelationship between environmental protection and the business aspects of product design and manufacturing. The most pressing need is to *adopt a business paradigm* when considering EBM technologies, rather than citing anecdotal evidence that “pollution prevention pays” or that it doesn’t. A business paradigm would include developing a strategic long-range plan for expending capital, incurring operating expenses, measuring effects and reaping profits.

In addition to the information needs described above, marketing data related to “green consumerism” is needed. While many companies highlight their concern for the environment in advertising campaigns, few appear to possess quantitative information that would enable them to more effectively target these market segments. Many companies appear to be satisfied with the “halo effect” of their green products on sales of all their products, such as that of hybrid electric vehicles on overall fleet sales. Information about the size of the market is needed, along with information about customers’ willingness to pay in terms of cost, performance or convenience for environmentally superior products.

A related need is for development of consumer product labeling to convey environmental information to the consumer. Many argue that such labeling would be much more complex than nutrition information labeling since there is no environmental equivalent to nutrition requirements, environmental impacts are externalities, and there is currently no method for comparing environmental impacts over the entire product life cycle in a way that consumers could understand.

Summary

In summary, three key elements were identified as systems needs:

- Fundamental data that support standardized life-cycle environmental analyses
- Technology that fully integrates life-cycle analyses directly into computer aids to product and manufacturing process design
- Business models which more accurately predict the economic implications of environmentally benign manufacturing

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CHAPTER 5

MATERIALS & PRODUCTS

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METALS AND METAL MANUFACTURING (T. PIWONKA)

Summary

Much of the concern over the environmental burden of manufacturing processes is focused on traditional methods of producing metal and metal parts. Traditional metal manufacturing involves mining and beneficiation, casting, machining, forging and surface protection (painting and coating), which traditionally have been less than benign. There have been substantial improvements made to these processes to ameliorate their impact on the environment, and research is continuing to decrease their environmental load. These efforts are driven by a variety of pressures, but all are focused on more efficient use of metals, alloys, and energy, as well as the total costs of production.

Introduction

To most people, "manufacturing" means heavy manufacturing, represented by integrated steel mills, foundries and automobile plants. Thus the term "environmentally benign manufacturing" sounds oxymoronic, since such plants are regarded as dirty, noisy, hot, dangerous, smelly, and inherently polluting. However, the panel found that significant progress has been made in metal manufacturing processes to reduce the environmental burden of metal processing, and there is active and creative research going on to produce further improvements. Opportunities for further research were also identified.

The three major contributors to environmental problems from metal manufacturing are machining (lubricant aerosols and metal dust in the air and water, as well as chips, turnings and machining waste), casting (effluents from mold binder decomposition, spent sand solid waste) and surface protection (paint vapors). Complicating the problem is that most firms that specialize in these manufacturing techniques are small and medium sized enterprises (SMEs), whose small size constrains the assets that they can devote to the development of environmentally benign manufacturing methods. There is a clear need to support these firms in the development of technology to lessen the burden their processing methods place on the environment.

The panel noted that in many countries sustainable development, which includes the implementation of environmentally benign manufacturing technologies, is considered to be the mutual responsibility of the entire society, including industry, government and the communities in which the industrial plants are located. A recurring theme from industrial personnel in Japan and Europe was their dismay at the adversarial position of the U.S. Environmental Protection Agency (EPA) towards U.S. industry. While federal and state legislation and regulations often require an adversarial relationship, it is appropriate to question whether such a posture is truly beneficial for environmental improvement. In other countries governmental environmental agencies are seen as facilitating clean manufacturing techniques by working cooperatively with companies and communities to develop and implement environmentally benign manufacturing technology.

Primary Metal Production

Primary metal production is the separation of metal from its ore. Most ores are oxides or sulfides of the metal, and the metal winning process consists of reacting the ores with other compounds that combine preferentially with the oxygen or sulfur in the ore. For example, iron ores are compounds of iron and oxygen. In conventional steel production, the ore is first reacted with carbon in the form of coke in a blast furnace. The product, pig iron, contains little oxygen, but does contain about 4.5% carbon. Since the carbon level in steel is much less (0.01 to 2%), it is necessary to remove the carbon from the iron to convert the iron into steel. This is done by reacting the molten iron with oxygen in an oxygen converter. The reaction of oxygen and carbon is exothermic: it gives off energy, heating the molten bath of metal. It also produces carbon dioxide, CO_2, a greenhouse gas.

An alternative method of separating a metal from its ore is by electrochemical means: the ore is dissolved in a solution and a current is passed through the solution. Metal ions flow to one electrode, plating out on it. The electrode is then removed from the solution and the metal is processed. For example, aluminum ores are dissolved in molten cryolite to which fluoride salts have been added to produce aluminum cathodes for further processing. Electrical consumption requirements are large, and carbon dioxide is emitted at the carbon anodes used in the process.

The Role of Carbon in Metals Production

Winning metal from ores requires energy to melt the ores and fluxes (solid materials added to control chemical reactions or the physical form of the waste products from the furnace, such as slag), and to keep the metal molten. The energy can be chemical (produced by heat liberated during an exothermic reaction) or electrical, and is often a combination of both. Since most energy in the world is generated as a result of combustion processes, and a large percentage of ores, especially iron, are reduced with carbon, the production of primary metals yields large amounts of greenhouse gases, primarily carbon dioxide.

Carbon for metallurgical reactions is usually produced in the form of coke. Coke is coal that has been heated in an oven from which oxygen is excluded. During heating volatile gases in the coal are driven off. These gases are either burned or collected and used as feedstocks for other organic chemicals.

Alternative forms of carbon may be used, including recycled organic products such as thermosetting plastics. This allows the thermochemical energy of the plastics to be recovered, and is preferable to landfill disposal. Thermosetting plastics are more attractive for this application than thermoplastics, as thermoplastics can be recycled by melting, while thermosetting plastics decompose instead of melting when exposed to heat. However, many thermosetting plastics contain elements in addition to hydrocarbons, such as fluorine compounds added as flame retardants or chlorine compounds added to give strength. These compounds are often pollutants or are corrosive to metallurgical plants when they are burned. Burning the compounds yields carbon dioxide; Japan has currently banned the burning of plastics, unless they are being recycled for their chemical values (i.e., as necessary reactants in a chemical reaction) to avoid the creation of unnecessary greenhouse gases. At Nippon Steel, we learned that Japanese steel companies have been burning plastics as alternatives to coke (Japan has only one active coal mine, and thus must import nearly all its metallurgical coke). The steel industry in Japan is therefore at pains to emphasize to the public that carbon must react with iron oxide to produce steel, and the formation of carbon dioxide is an unavoidable consequence of this.

Aluminum

Because of the light weight of aluminum compared to steel, aluminum production is expected to grow substantially in the near future. Much of this growth will come from the use of aluminum in automobiles, not only in engine and chassis components, but as body panels as well. Audi has introduced an all-aluminum car in production, and is expected to be followed by other manufacturers. (There is, however, a price penalty associated with the use of aluminum, and the steel and cast iron industries are investing in programs to make their products competitive in weight and performance in automotive applications.)

The U.S. aluminum industry has been designated an "Industry of the Future" by the U.S. Department of Energy (as have the steel, mining, glass, forest products, foundry, forging and other basic industries).[2] Under this program, cooperative research and development agreements are written with industrial consortia to carry out research focused on improvements in energy usage and reduction of environmental pollutants. The consortia combine industry, government laboratories and academic institutions; at least half of the funding must be generated by industry. The Industries of the Future program requires that industry develop a roadmap through the year 2020. The aluminum industry roadmap targets a goal of eliminating CO_2 emissions by 2020, and decreasing energy use to 13 kWh/kg by 2010 and 11 kWh/kg by 2020. Another goal of the aluminum industry worldwide is to reduce the production of perfluorocarbons, a family of greenhouse gases generated in the aluminum production process.

Production of aluminum is highly dependent on inexpensive electrical power, which is why aluminum plants are found concentrated in the United States in the Tennessee Valley and the Pacific Northwest, where water power is available. The aluminum industry in the United States formed the Voluntary Aluminum Industrial Partnership (VAIP) in 1995 with 12 of the 13 primary aluminum producers and 94% of U.S. production capacity represented. The object of VAIP is to reduce energy consumption, perfluorocarbon emissions, and greenhouse gas generation by the industry. The goal is to reduce perfluorocarbon emissions 40% by the end of 2000; by 1997 they had already achieved a 41% reduction.

In Europe, Corus Holland (Hoogovens Steel) has installed equipment to capture 98% of the airborne particulates emitted in primary production, and has also opened a plant to remelt scrap aluminum for secondary ingot production. Remelting of aluminum to secondary ingot consumes only 5% of the energy required for primary ingot production. Indeed, this is one reason that aluminum beverage cans are economical in the U.S.; voluntary recycling of used cans is so high in the U.S. that some can scrap is diverted to other industries. (The reason for this is different alloys are used in the can bodies and tops, as the tops must be strong enough to support an opening mechanism. The alloy used in the top, in the quantities generated in can recycling, eventually alters the composition of the body alloy so that it cannot be used, thus limiting the number of cans that can be recycled into bodies.)

Recycling of aluminum alloys into secondary ingot will increase over the next decade as the aluminum content of automobiles increases. However, recycling must be done with care, as the three or four most popular alloys must be accurately identified in the recycling process to avoid contaminating each other during remelting. A further concern in recycling these alloys is that after a number of recycles, trace elements increase in the aluminum to levels such that the properties of the recycled alloy are degraded and the alloy can no longer be used. Research is needed to develop economical methods of removing these trace elements in the production of secondary ingot.

Steelmaking

The manufacture of steel has traditionally been carried out in large integrated steel mills, where iron ore, coke and limestone enter the plant, and finished steel mill shapes (bar, rod, billet and sheet) leave the plant, along with the waste stream of slag, wastewater and greenhouse gases. In the last twenty years, however, a revolution in steelmaking has taken place: mini-mills, which melt primarily scrap and focus on only one or two mill products, have taken over much of the steel production in the United States. Mini-mills generally use electric arc furnaces (EAFs) instead of blast furnaces and oxygen converters to produce their steel. Integrated mills still dominate in much of the world, especially in countries with emerging economies, where they are seen as emblematic of industrial strength.

While mini-mills have less intense environmental impact than integrated mills, their dependence on scrap as a primary charge material can exhaust the supply of quality scrap needed for their product. Indeed, the entire question of recycling steel is confounded by two problems:

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[2] More information on the "Industries of the Future Program" at the U.S. Department of Energy can be found at www.oit.doe.gov.

- Steel oxidizes (rusts) easily. Thus steel must be protected in service with some kind of coating. The coating must be removed prior to or during remelting. As stronger steels are developed, thinner sections (less weight) can be used, as their performance equals that of thicker, weaker steels. However, the percentage of the scrap represented by the protective coating increases, decreasing the yield of the recycling process.
- Many alloying elements cannot be removed easily from steel once they have been added. These include tin and copper, which is commonly found in automotive scrap, although it has recently been reported (*Materials Progress* 2000) that the addition of aluminum to the bath neutralizes their effect. Other alloying elements (such as nickel and molybdenum) deliberately added to specialty steels are also difficult to remove.

In 1997 the European Union published a report (Roederer and Goutsoyannis 1997) that reviewed the then-current (1996) situation in Europe on environmental problems/accomplishments of steelmakers. The report highlighted problems in common methods of data gathering in different European countries, and concluded that most European steelmakers were attempting to use BAT (best available technology) to mitigate the environmental effects of their process.

One section of the report dealt with research and development projects that would improve the steelmakers' ability to operate in an environmentally benign manner. Among the suggestions were the following:

- Better methods of particulate filtration
- Removal of zinc and lead dust from blast furnace, EAF and sinter plants
- Treatment of scale, sludges and grinding dust for recycling
- Continuous methods of monitoring wastewater discharge
- Oil extraction from wastewater and from grinding dust and scales
- Better sensors for air emissions
- Theoretical understanding of the thermodynamics of hazardous waste gas generation

The steelmakers we interviewed are not enthusiastic about the concept of life-cycle assessments. Although some steelmakers will provide input data to customers for them, they are aware that steel is heavier than aluminum or magnesium and this usually extracts a life-cycle cost and energy penalty during the use phase. This is especially true for transportation equipment where energy consumption and pollutant and greenhouse gas generation during the use of the product far exceed what is used and generated in manufacturing.

Direct Reduction Iron. The steel industry today is increasingly using methane (CH_4) rather than pure carbon to reduce iron ore. The process conserves energy, as it takes place in the solid state rather than the liquid state, and eliminates one of the greenhouse gas reactions, as well as using a greenhouse gas, methane, as a reactant. The process produces small spheres of nearly pure iron, known as “direct reduction iron” or DRI; if the spheres are briquetted into larger pieces (measuring 5” x 3” x 2”), they are known as “hot briquette iron,” or HBI. DRI is primarily used in electric arc furnaces. EAFs were designed to operate on solid charges of steel, generally scrap. DRI, which consists of pure iron with a small amount of residual oxide, is an attractive addition to the charge mix of EAFs.

When DRI is used as feed metal in EAF production of primary steel, CO_2 generation is cut 25 to 35% over basic oxygen furnaces, and a similar amount when it is substituted for pig iron in electric furnaces. When it is used to produce steel in mini-mills that combine it with scrap, CO_2 generation is cut nearly 90%. However, the need to minimize power costs and shorten heat times makes it economically attractive to deliberately add carbon to the bath, and then remove it with oxygen, to get the benefit of the exothermic (heat producing) reaction between carbon and oxygen. The reaction produces carbon dioxide gas as a by-product. Projections are that future furnace designs will move towards a hybrid EAF/basic oxygen furnace to accelerate the steel making process while decreasing the use of electrical energy.

Integrated Steel Mills. Integrated mills must conform to environmental regulations in each of the countries in which they are located. However, at the present time, each country has a different approach to the establishment of environmental regulations, and each country has different environmental priorities.

For instance, the Dutch steel and aluminum producer Hoogovens has recently merged with British Steel to form Corus. In Holland the elimination of NOx is of high priority, so Hoogovens has developed a NOx scrubber for its operations. However, in Great Britain, NOx is not as important, so there is less interest on the part of the British part of the new company in the technology.

In both Japan and Holland, emphasis is placed on developing environmental technologies that improve the local conditions around the plant. In Japan plant environmental personnel work closely with local governments to satisfy the neighbors and keep the local environment acceptable. In Holland, Corus Holland reported that it sponsored university research into ways of eliminating the odor in order to meet local concerns over the odor given off by the company's slag granulation plants.

In a large integrated mill there is sufficient solid waste to justify installation of a sinter plant to recover the iron values. The charge into the plant contains baghouse dust, sweepings, etc., that contain iron mixed with other materials. One advantage to sintering the solid waste in one operation is that all effluents are concentrated in one source that can be treated before being released to the atmosphere. Other attempts to recover metal from steel plant wastes include a Japanese government research effort to recover zinc from EAF baghouses.

Steelmakers attempt to recover as much material and energy as possible. In integrated steel plants in the United States, the energy recovered from burning flue gases is generally used on-site or the gas is "flared," or burned off. At Corus Holland's steel plant the excess energy generated is sold to a nearby power plant; the steel plant receives a credit against its electric bill. In Japan, Nippon Steel is attempting to improve heat recovery from warm (150–200°C) heat sources such as water and air.

Chaparral Steel's Midlothian (Texas) plant, which includes a steel mini-mill, an automobile shredding facility, a cement plant and an electric power plant, is a highly successful example of material exchanges between facilities. Slag from the steel mill is ground into small aggregate and sent to the cement plant. Here it is fed directly into the kiln, where it reduces the need for some endothermic reactions, reduces the need for lime (CaO) derived from calcium carbonate (a greenhouse gas producing reaction), and reduces the generation of solid waste. (For more detail, see the site report on Chaparral in Appendix E.)

Other Primary Metal Production

The need to develop environmentally benign ore beneficiation methods is less urgent in developed countries today than a century ago, as most mines in North America and Europe have been worked to their economic limit. As a result, most active mines are located in third world countries, where there is less emphasis on environmental and energy concerns. Nevertheless, there is a need to develop ore treatment procedures that are more environmentally friendly.

At the National Institute for Resources and Environment in Japan, a "soft metallurgy" project is in progress to develop methods for recovery of copper from $CuFeS_2$, methods that do not create sulfur dioxide gas or slag.

Metal Shaping (Net-shape Manufacturing, Casting, Forging, Dry Machining, etc.)

As part of environmentally benign manufacturing, it is necessary to reduce the amount of materials and energy used, as well as the number of components used to make an assembled product. The concept of "net-shape" manufacturing thus becomes essential to environmentally benign manufacturing (EBM).

Research into net-shape manufacturing began in the Department of Defense in the 1970s. The emphasis was initially on machine tools and machining operations, leading to the development of numerically controlled and computer numerically controlled tools. (Ironically, although the development work was carried out in the United States, today most machine tools are imported from Japan or Europe.) Research efforts were also funded to improve the dimensional capabilities of near-net-shape technologies such as precision forging (which led to the development of creep-forging), powder metallurgy, and investment casting. However, dimensional control and as-produced surface finish of castings and forgings is generally not good enough to allow a significant reduction in machining operations. Research into net-shape manufacturing techniques is currently not a priority.

There is a tendency to regard “precision engineering and manufacturing” as the science of making tiny components. Indeed, at least two laboratories the panel visited in Japan clearly indicated that such was their interpretation. There does not appear to a widespread acceptance of the definition of precision engineering as “the capability to control dimensions to plus or minus one part in 10^4 or 10^5.” Thus machining of castings and forgings continues, although a European machine tool executive expressed the opinion that machining added very little value to a product. Nevertheless, it is accepted in metalforming operations that combining the original manufacturing method (such as forging or casting) with final machining operations is essential for maximum profitability. It would appear that a major effort to develop highly accurate and precise methods of making large cast and/or forged components (such as those that are found in internal combustion engines) to net-shape would significantly reduce the environmental impact of metal manufacturing on the environment. Reaching such a goal depends on combining the disciplines of design and manufacturing, a trend we noticed in a number of industries (especially automotive) worldwide.

Many metal shaping concerns are small and medium size enterprises (SMEs) that are first or second tier suppliers, who sell to other manufacturers, not to the public. A growing trend worldwide is for the large customers of these suppliers to insist that the suppliers operate state-of-the-art green manufacturing plants. In the words of the panelists’ hosts at international truck manufacturer Volvo, “We are world class, and we expect our suppliers to be world class also.”

One disturbing trend was noted in the United States. Large manufacturers, such as automobile companies, are increasingly divesting themselves of their metal manufacturing operations. When asked, representatives of one company explained that such moves allowed the manufacturing to be done by specialists in the area (such as casting, forging, or machining). However, most suppliers are much smaller than their customers, and they have fewer resources to devote to address environmental problems created by their manufacturing processes. Their environmental departments emphasize compliance, not development. This suggests a need for a national initiative to address the environmental problems faced by these smaller companies as they attempt to meet their customers’ demands for lower costs in an environmentally responsible manner.

Casting

At DaimlerChrysler (Germany), casting was described as the manufacturing process of the future, because components could be combined in castings, thus eliminating machining and assembly operations. For casting to reach its full potential, however, dimensional control and reproducibility must be substantially improved. The foundry industry in the United States has realized this and is sponsoring a number of benchmarking studies to determine current casting dimensional capabilities.

Sand foundries comprise about half of the metalcasting establishments in the United States. These foundries make the molds (into which the molten metal is poured) from sand, held together with a mixture of clay and water. In ferrous foundries finely divided bituminous coal is added to the mixture to improve the surface finish of the casting. Cores, which make the hollow parts of castings, are made of sand bound with thermosetting resins. When molten metal is poured into the mold, the thermal decomposition products from the coal and resins are released into the atmosphere. These decomposition products include greenhouse gases and other gases that are listed in the EPA’s list of hazardous air pollutants. The foundry industry is actively pursuing binders and mold additives to reduce effluents from the mold. One promising approach is the addition of oxidizing agents to the mold to more completely combust the decomposition products. Current research shows that the addition of these products not only cleans the air, but also reduces the amount of clay needed to bond the sand.

To help develop more environmentally benign metalcasting technology, the Department of Defense and the metalcasting industry have built a modern sand foundry to study low emission products and processes in green sand foundries. The $50 million facility, called the Casting Emissions Reduction Program (CERP) facility, at the closed McClellan Air Force Base in Sacramento, CA, permits the measurement of air quality at various stages in the production process. It is currently being used to carry out a number of research projects that call for dedicated foundry production of a shift’s worth of castings. The projects include both environmental and dimensional studies that would otherwise disrupt production in a commercial foundry. This is a unique facility that is not found in other countries. CERP's Cooperative Research and Development Agreement (CRADA) is being transferred from the Air Force to the Army's National Defense Center for Environmental Excellence, and CERP is becoming a private company. It is seeking support from and collaborations with industry and government agencies.

Non-ferrous casting methods have recently been expanded to include semi-solid casting methods, in which an alloy is heated to a temperature between its liquidus and eutectic temperatures and then injected into a steel die. Both aluminum and magnesium alloys are made this way. Dimensional control is excellent, and castings often need no machining to be used. There have also been substantial improvements in the quality of pressure die castings in recent years. This net-shape process is now capable of producing dimensionally accurate parts with high property reliability. The success of semi-solid casting methods for non-ferrous alloys suggests that more efforts should be made to extend this method to ferrous metals and alloys. The initial attempts to develop ferrous die casting 25 years ago were commercially unsuccessful; it may be time to revisit this technology.

Foundries are often the recycling method of last resort. Large manufacturers such as DaimlerChrysler briquette oily turnings, grinding swarf and other metal wastes into charge materials for foundries. In Europe, high zinc ferrous scrap is sold to iron foundries for the manufacture of low tensile strength gray iron.

Machining, Forming, Joining and Coating Processes

Machining. Machining operations are ubiquitous in materials manufacturing. The coolants and lubricants used in machining generate water pollution and air quality problems, and can contaminate scrap used in re-melting. As a result there is a major effort worldwide to develop methods of reducing or eliminating coolants in machining processes. It is generally conceded that complete elimination of lubricants is unlikely, although it is feasible to reduce their use substantially. Techniques include improved thermal management of the workpiece and chips, and focused application of the coolant on the tool/workpiece face. Another approach is to add a polymer that resists shear to the cutting fluid, thus substantially reducing the formation of the small droplets and aerosols that cause environmental and health concerns in machining operations.

A further problem is chip removal: in the absence of coolant flow, chips tend to accumulate on the machine ways. The opinion was expressed both in Europe and Japan that the fundamental solution is the development of net-shape forging, casting and powder processing techniques so that subsequent machining is unnecessary. EX-CELL-O has a demonstration project using dry machining in a transfer line in Cologne, Germany, and Fraunhofer IGB in Stuttgart has developed a closed loop system for monitoring and replenishing coolants during cutting.

Dry (or almost dry) machining is a major research emphasis in Japan and in Europe. In the United States, we were told by all three automobile manufacturers that developing dry machining is an environmental priority for their companies.

Another approach is to eliminate machining wherever possible. For instance, at Volvo, holes in the truck chassis are punched instead of drilled. This is done to facilitate recovery of the metal removed, as punchings are easier to re-melt than turnings. The punchings are sold to Volvo's supplier foundry.

Metal Forming and Forging. The Saitama plant of Toyo Seikan (a steel beverage can manufacturer in Japan) is a good example of a factory developed to minimize its effect on the environment. The entire plant was designed to minimize use of energy and materials, and uses a stretch draw and ironing process with no lubricant to produce a steel can only 0.18 mm thick at the bottom. The key technology is the use of steel sheet laminated with 20 micron polyester on both sides. The polyester, needed to prevent corrosion, also aids in the drawing process. A further improvement is redesign of the can geometry to thin the wall even more. The total can making process consumes only about a fourth of the energy of a standard can making process.

The forging industry in the United States has identified a number of areas where research can lead to a more environmentally benign manufacturing process. These are identified in its *Forging Industry Roadmap*, part of the Department of Energy's Industries of the Future program. Among the environmental needs identified are the development of baseline data on energy and environmental usage and impact (in other words, a life-cycle assessment), development of environmentally safe lubricants for forging, and better ways to manage thermal energy in forge plants. Better die materials and better ways of protecting dies from oxidation were also identified as research needs.

Joining. Joining processes represent an interesting problem in environmentally benign manufacturing: if products are joined too well (as in welding) they cannot be disassembled for repair, or reuse. Hence the decision to join two components permanently must be approached with care. Mechanical joining usually requires that surfaces be carefully machined to obtain satisfactory fits. Adhesives may be used, but care must be taken that they do not degrade in the application environment.

A new joining process for aluminum is currently under study that may prove useful in marine applications and other large aluminum assemblies. Developed in Great Britain and known as "friction stir welding" it is a solid state joining method in which two sheets of aluminum are placed adjacent to each other. A solid rod is then rotated into the joint between them, heating them by friction, and stirring the metal together. The metal is not melted, thus preventing those defects such as porosity and inclusions that form during solidification, less energy is used, and no filler metal is necessary. The process is currently under study in a number of countries to optimize its use and operating parameters.

Other joining methods that are under development include laser welding, which is currently used for high precision welding, but suffers from low energy efficiency. Nevertheless, Audi introduced laser welding for its A2 aluminum-body mass production car in the summer of 2000. Each car has 30 m of laser welding on the body.

Coating. Surface protection of metal, which includes coating and plating, is a major contributor to environmental problems. Plating operations were an early target of state and federal environmental enforcement agencies. To a large extent, the plating industry is no longer considered to be a major polluter. However, painting is now being recognized as a major environmental problem.

The primary problem in painting has been the use of organic solvents as the vehicle for the pigments. These solvents require extensive treatment of the exhaust air from the painting operations before the air can be released to the atmosphere. Although there are methods that clean the solvents from the air, they require extensive use of fans, filters and other treatment equipment. The systems are expensive to build, and expensive to operate. (One European OEM installed such a system, only to discover that changing the coating method from solvent to water base would have accomplished the same goal at a fraction of the cost.) Water base systems have been developed, but they also present problems, both in the product quality and in treatment of effluent.

One technology that has been "almost" developed is the coating of steel sheet in the steel mill. The coatings are sufficiently pliable that the sheet can be stamped using conventional stamping dies. But stamping companies are reluctant to use the process. They are concerned about scratches on the surface as a result of handling problems during stamping, edge cracking of the coating during trimming, and color match from coating batch to batch. Nevertheless, the application of the clear coat in automobile and appliance factories could be done using this method, if methods were developed to eliminate these concerns.

Surface protection and preparation is key to obtaining long life in metallic (and especially ferrous) components. In view of the environmental problems involved with coating systems and applications, the need for increased research into surface protection methods should be clear.

Alloy Development

Lightweight Alloys and Composites

Increasing metallurgical knowledge is showing that impurities and trace elements can substantially degrade alloy properties. Sulfur has been identified as a deleterious element in a number of alloys, and oxygen levels are being controlled in ferrous alloys. Most alloy development today is focused on eliminating those elements that reduce alloy properties.

Composite materials are attractive because it is possible to combine material properties in ways not found in nature. For instance, a strong but easily oxidized fiber such as graphite can be encased in a corrosion resistant matrix such as aluminum. Although these materials have been extensively studied in the last four decades, their acceptance has lagged. (It is significant, however, that current advanced military and commercial airframes are making use of a number of resin-matrix composites for control surfaces and structural members.) Composites are attractive because they often permit a lightweight structure to have high stiffness and tailored properties for specific applications, thus saving weight and reducing energy needs.

Composites are, however, expensive to fabricate and inspect. In addition, they present serious problems in recycling, as it may be impossible to separate the reinforcing material from the matrix. Metal-matrix composites can also have a performance limitation: the moduli of the matrix and the reinforcing phases are usually different, leading to the possibility of fatigue failures at the interfaces between them unless they are carefully designed. A further problem, shared by all newly developed materials, is that extensive mechanical and environmental testing, under static and dynamic conditions, is required before designers will use the material. Thus alloy design efforts, once a mainstay of primary metal producers, have become much less important, and efforts are focused instead on the use of existing alloys. This trend is a barrier to the introduction of new and useful material systems. It was also important that evaluation of the recyclability of a new material be included in the material database.

Acceptance by designers of new material systems based on lightweight intermetallics has for the most part been disappointing. Titanium aluminides have seen some applications, but acceptance of other intermetallic systems has lagged: they are hard to fabricate, and frequently have properties that are little better than existing alloys. Magnesium alloys, once popular in the automobile and aircraft industry (but suffering from severe corrosion from salt in the atmosphere near seacoasts, or applied to de-ice roadways) are making a comeback, and a number of research initiatives exist in the United States and Europe to improve their processing, especially casting.

Concern was expressed by a number of companies that highly engineered tailored materials (such as graded powder metallurgy tool steels where the composition varies over small areas) cannot be recycled without losing their structure. Other recent areas of materials technology emphasis, such as nano-materials, present similar problems: because the alloying elements are so finely dispersed in the alloy, it is not currently possible to recover these alloying elements during recycling.

Iron, Steel and High Strength Alloys

In view of the importance of achieving light weight in all applications that use energy during their life cycle (such as cars and trucks), iron and steel face a challenge. Although iron and steel are stronger and stiffer than aluminum and magnesium, they are not attractive if they result in a weight and energy usage penalty to the final product. Thus there are a number of research projects aimed at making them lighter.

In the United States, a consortium of iron foundries and their suppliers is sponsoring research on the production of “thin-wall” iron, that is, iron castings having wall thicknesses down to 3 mm. Research is needed because if the proper melting and pouring procedures are not followed, cast irons solidify with a hard, brittle structure in thin sections, which is not useful in engineering applications. The research also focuses on the molding technology required to control wall thickness.

Research into very high strength steels is going on in a number of organizations worldwide. In Japan, researchers at the National Research Institute for Metals are developing high strength steels, supported by Japanese steel companies. One project is investigating thermo-mechanical treatment of low-alloy steels to obtain micron-sized grains to yield steels with strengths in the 800 MPa range. Similar studies are underway in European and U.S. laboratories. Another project is to develop martensitic steels with 1500 MPa strengths by removing hydrogen and coarse carbides from grain boundaries. Among the problems posed are those of joining the material without altering its microstructure. Some possible solutions include the use of extremely narrow gap arc-welding techniques, one-pass laser welding, and low temperature joining techniques.

In Japan the importance of diminishing the effect of corrosion on steel is recognized as a major need. One project seeks to develop steels that do not require chrome plating. Another project aims to develop corrosion-resistant steels for marine application that contain reduced amounts of chromium, nickel and molybdenum. The approach being taken is to produce ultra-pure steels, alloyed with nitrogen and melted in a cold-crucible levitation melting furnace.

One interesting approach in alloy development that was suggested to the panel is to limit the systems investigated to those containing elements that can be easily recycled. It remains to be seen whether such systems will have economic value.

Implications of Take-back Laws on Materials Design

Current legislation in Europe requires manufacturers to take back their products at the end of their useful life, known as “Extended Producer Responsibility” laws (Williams et al. 2000). For automobiles, this will begin in 2006. In practice, this may encourage manufacturers to lease the product to the consumer for its useful life, as no provision is made in product price for the cost to the manufacturer for take-back. In effect, the manufacturer would sell “use” instead of “product.” The lease price for a new item would be higher than the price for an older item, and when the item could no longer be leased, it would revert to the manufacturer, which would be responsible for recycling or remanufacturing the materials it contained. This is not revolutionary: most office equipment is leased, and very high percentages of other products, such as automobiles and golf carts are also leased. Even commercial aircraft are often leased. However, the concept is not popular with European automobile manufacturers.

The implications of take-back laws bear consideration. In the case of automobiles, the average car lasts for 12–13 years in the United States, and has traveled about 110,000 miles when it is scrapped. From the standpoint of the metals industry, this means that scrap that met the specifications of the industry 13 years previously must be accommodated in the recycling procedure. Another implication of the changing material composition of the automobile is that conventional scrap markets, based primarily on ferrous materials, will be faced with dislocations over the next two decades. There are implications for the entire infrastructure of scrap collection, sorting and distribution, if metal recycling becomes the responsibility of the original equipment manufacturer, instead of the scrap yard. The current efforts of Ford to acquire expertise in dismantling (see the Ford site report in Appendix E), and the support of DaimlerChrysler (Germany) for a German program in dismantling automobiles, is evidence of concern for this issue.

This may imply that alloy compositions would have to be frozen, as development of a new alloy for an engine block may leave the manufacturer with large quantities of the old engine block material—and no market for it—at some point in the future. Modern alloys are made to more stringent specifications than those used previously, even when the alloy designation does not change. Also, as noted above, most alloys can only be recycled a few times before they have dissolved unacceptable levels of impurities. (Each time an alloy is melted it dissolves minute quantities of the crucible or mold material; eventually these add up and the alloy no longer conforms to specification.)

This could possibly lead to more robust design of components, so that they could be remanufactured and re-installed in rebuilt assemblies. However, the need to use older components might inhibit innovation in design. Also, the use of more robust designs may add weight to the final product, requiring increased energy usage in its life cycle. Thus the possibility of take-back laws appears to complicate the picture for metals and alloys.

Summary

Metal manufacturers have always been intensely interested in recycling and reduction in the use of energy and materials. As material requirements become more stringent, and pressures increase to minimize energy usage and greenhouse gases, the metal manufacturing industry continues to look for improved manufacturing methods. Today there is an emphasis on the use of new, lighter weight materials instead of traditional ferrous materials. There are implications for the scrap/recycle stream that need to be considered, as well as implications in material development. These implications include alloy and part processing, logistics of scrap collection, sorting and shipment, and methods of recovering advanced materials either in their original form, or in separating the individual metal values from the material.

It is important to understand that component design often defines the manufacturing method that is used. Thus environmentally benign manufacturing begins with an understanding of *design* for environmentally benign manufacturing. This concept needs to be recognized in university design and manufacturing courses.

Research needs include:

- Methods of removing contaminants and trace elements from recycled alloys
- Methods of economically recovering and reprocessing composite materials
- Development of true net-shape metal casting and forging methods
- Methods of recycling and recovering alloying elements in highly engineered materials
- Evaluation of the recyclability of new materials and new material systems

In terms of priorities, it was pointed out by a number of companies that the three largest contributors to pollution in metal manufacturing are machining (the use of lubricants), casting (air pollution from binders) and surface conditioning (cleaning, painting and plating). Focusing developmental work in these areas would have the greatest impact on facilitating environmentally benign metal manufacturing.

POLYMERS (T. GUTOWSKI)

Summary

Polymers have a poor environmental image in large part due to their contribution to litter and landfills. But major environmental impacts also occur early in their life cycle in the petroleum and chemical industries and during processing, where they contribute to volatile organic compounds, hazardous air pollutants, waste, wastewater, and energy related impacts. In contrast, polymers often save energy and associated carbon emissions during their use phase by supplying light-weight components in transportation applications and insulating properties for thermal applications. Here we review major trends for polymers through all phases of their life cycle. The singular unmet challenge of polymers, however, is the development of sustainable end-of-life scenarios. Approaches for end-of-life scenarios include reuse, recycling, incineration for energy, by-product synergies, and the development of biomaterials.

Introduction

United States polymer production continues to grow and is now on the same order as metals. For example, primary plastics, rubbers, cellulose fibers, paints and adhesives now total about $71 billion in shipments, while steel, aluminum, copper, and non-ferrous metals total about $73 billion. However, over the last ten years the plastics segment has been growing at three times the rate of the metals (Darnay 1998). When the extended polymer industry[3] is considered, the value of shipments is enormous, exceeding $274 billion in 1996, a 55% increase since 1991 (SPI 1997). Similar trends exist worldwide where the total volume of plastics produced exceeds that of metals and is expanding at a rate faster than the rate of expansion of the economy (McCrum et al. 1997). Primary production and consumption of polymers is centered in the United States/North America, Europe and Japan (SPI 1997; *Modern Plastics* 2000).

This success is due to the low cost, light weight and excellent properties of polymers for such applications as food containers, packaging materials, textiles, films and engineered parts. In spite of their ever expanding use, however, polymers retain an image of being environmentally unfriendly. The potential environmental impacts associated with the different life-cycle phases of polymer products are listed in Table 5.1.

In Table 5.1 several reccurring themes are noted. At various stages in their life, polymers exist as low molecular weight hydrocarbons, and various hydrocarbon solvents are often employed in their processing. Consequently, there is always a threat for leaks or spills to occur, or for the escape of volatile organic

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[3]Primary producers, product manufacturers, machinery companies, mold makers, wholesale distributors and plastics processors

compounds (VOCs) and hazardous air pollutants (HAPs). Furthermore, in the case of some polymers, the precursor chemicals, the intermediates, or the catalysts can be quite hazardous. In fact the chemical industry, which produces the polymers, has historically been one of the leading toxic waste sources in the United States (EPA 1998).

Table 5.1
Some Potential Environmental Problems with Polymers

Phase	Problem
Petroleum extraction, refining,	Leaks, spills, releases, solvents, energy, HAPs, VOCs, waste and wastewater, use of non-renewable, limited resource
Primary conversion	Toxic materials, energy usage, HAPs, VOCs, wastes and wastewater
Processing	VOCs, HAPs, energy, hazardous materials, wastes and wastewater
Use	Out-gassing, unreacted monomer, release of residual solvents, plasticizer, etc., degradation and failure of the product, energy usage, interaction with environmental liquids, acids, foods, etc.
End-of-life	Solid hazard, litter, leaching, hazardous release during incineration, landfill shortage, unsustainable

A second important theme for polymers is energy usage. Polymer processing uses significant amounts of energy. For example, if the entire plastics industry experienced only a 1% improvement in process efficiency, enough energy would be saved to power over one million homes a year (Mattus 1997).

Finally, the common end-of-life scenarios for polymers are not sustainable. Of primary concern is the availability of petroleum feedstock, which is estimated to be at or near its historic peak and predicted to be in decline within the near future (Smil 1998). In addition, the current demands for energy resources and fresh water appear to be increasing at an unsustainable rate. Landfill space is also rapidly disappearing. In fact many countries, and some states in the United States, no longer have landfill as an option. While the immediate solution, particularly in the EU and Japan, is incineration, there are increasing efforts to identify more sustainable life-cycle scenarios for polymers. In response, governments and industry are exploring (a) reduction in use, (b) reuse, and (c) recycling of materials, as well as conservation of energy and energy production by non-carbon means.

Primary Polymer Conversion

Polymers are made up of long chain molecules with repeating units, mostly of hydrogen and carbon. Their production starts with small molecular units, monomers, which are usually gases or liquids derived from petroleum feedstocks, and catalysts, often metallic compounds, needed to initiate and control the reaction, as well as other ingredients. These reactions almost always require heating, cooling, striping, separation, and washing of the polymer product. The principal environmental impacts of this process are energy use, production of VOCs and HAPs, wastewater, and solid waste. For example, in the production of polystyrene by suspension polymerization, about 12.5 kg of wastewater is used for every kg of product (Nemerow 1995). The energy requirement to make polystyrene is on the order of 96 to 140 MJ/kg. For comparison purposes the energy requirement to make carbon steel is on the order of 50 to 60 MJ/kg, or only about one half. Note that on a per volume basis, however, the energy required for carbon steel is about four times that of polystyrene, due to the large difference in density between the two materials (Ashby 1992).

Most polymers are produced by a few very large companies in the chemical industry. The primary processing of polymers is usually carried out in large integrated facilities in order to capture by-products and to obtain economies of scale. The chemical industry produces on the order of 300 million tons of product, with sales of over $250 billion each year, therefore, it is a significant component of the U.S. economy and it has consistently contributed to U.S. exports. At the same time, however, it produces on the order of 1.5 billion tons of hazardous waste (leading all other manufacturing sectors) and 9 billion tons of non-hazardous waste each year. That is, it produces about 5 kg of hazardous waste for every kg of product, and it produces about 30 kg of non-hazardous waste for every kg of product. It leads all other manufacturing sectors in air emissions, and because it is also very energy intensive (using primarily fossil fuels) it is a major contributor to carbon emissions (Allen 1995). As a consequence, the chemical industry is subject to a range of environmental regulations, including the Clean Air Act (CAA), the Toxic Substance Control Act (TSCA), and the Resource Conservation and Recovery Act (RCRA), and has been the target of environmental groups. In fact, several of the companies in this industry may be best known to the public because of environmental disasters attached to their names.

In response to this situation, the chemical industry spends billions of dollars annually on pollution prevention and control, and has hundreds of billions of dollars invested in pollution control equipment. These measures have resulted in significant reduction in pollution and waste over the past decade. However, the utility of continuing this "end-of-pipe" treatment approach may now be reaching a point of diminishing returns. It appears that new approaches are necessary to address the staggering problem posed by the chemical industry. Recent studies have outlined new strategies based on "clean technologies" to improve the chemical industry (Allen 1995; Klee 1992). The basic clean technologies strategies to reduce wastes and usage of materials of concern include (1) waste recovery and materials exchanges, (2) waste reduction, including equipment redesign for more efficient processing, and (3) materials substitution.

Waste Recovery and Materials Exchanges

In many cases, the wastes and emissions from chemical and petroleum operations can be captured and sold or used as fuel. For example, in a recent vapor recovery project Conoco recovered $210,000/year worth of vent gas as on-site fuel and 3,633 barrels/year of saleable condensate resulting in less than a two-year payback for the initial investment. Furthermore, pollution reductions were significant: 884 tons/year of NOx, 2,366 tons/year of VOCs, and 495 tons/year of HAPs (Sharfman 1999). In another example of waste exchanges, DuPont found a market for hexamethyleneimine, a by-product of nylon manufacturing, that was previously a waste. The market for this new waste/product continued to grow and in 1989 demand exceeded supply (Allen 1995).

Waste Reduction

A recent comprehensive study by Amoco showed waste reduction at the source to be far superior to options like treatment and disposal ("end-of-pipe"). These cleaner technologies resulted in reducing the costs to handle pollutants by a factor of 5:1 (Klee 1992). These waste reducing, cleaner technologies are often built upon a better understanding of the underlying physical phenomena involved, which can then be translated into better process modeling, equipment design, and process control. Particular attention is focused on vessels, pumps, piping and valves, reactors, heat exchangers and separation technologies (Allen 1995; AIChE 1998).

Materials Substitution

In addition, much can be gained by materials substitution to alter feedstocks, reaction pathways, and by-products. One area where considerable leverage may be available is catalysis. Catalysts exert strong control over the quality and quantity of the polymer product and wastes. For example, early production of polypropylene always resulted in 7-10% of waste non-linear material (for example a total of 200×10^6 lbs. of waste in 1980). Process research led to a new catalyst that reduced this waste by 90% (DOE 1991). Furthermore, some catalysts that are left in the polymer can be potentially hazardous, especially at the end-of-life when they can leach out of landfills or contribute to toxicity if incinerated. Solutions for these problems require research into more benign catalysts.

Many other materials substitutions are also possible, including alternative solvents, new raw materials sources, and completely new reaction pathways. One area of particularly intense activity is in the production of polymers from biomass. This route could produce both sustainable and biodegradable materials (and because of its importance is addressed further later in this chapter). In general, both the biggest payoffs and the biggest risks lie in this area of new materials substitution. The risks are big because the implications are system wide, requiring reconsideration of many parts of the production process and, in some cases, the entire integrated plant and supply chain.

Polymer Processing

Polymer processing is concerned with the conversion of polymer resins into parts. Resins are generally classified as either thermoplastics or thermosets. In general, thermoplastics come as solid pellets or sheets and are softened or melted by heating during the process and solidified by cooling. These materials can be reheated and reformed and can be recycled by this means. Thermosetting materials, on the other hand, usually come in low molecular weight flowable material forms such as liquids or partially cured "pastes" and are solidified by a chemical reaction. Hence they cannot be remelted. The chemical reaction to form the thermosets is initiated by some external energy source, usually heat, or by mixing the reactants just prior to molding. Composites processing is an extension of polymer processing where the resins, usually thermosets, are mixed with fibers, such as carbon or glass, and molded and cured into final parts. The major environmental impacts associated with polymer processing fall into four categories: (1) energy usage, (2) waste, especially from thermosets, (3) wastewater, and (4) VOCs and HAPs from the polymers and/or from processing aids or additives such as solvents and blowing agents.

Examples of thermoplastics are PE and PET that are used extensively in automobile interiors, and ABS, PC and HIPS which are used in computer components such as housings. Examples of thermosetting polymers are polyurethanes and polyesters that are used in automobile exterior panels and glass/epoxy composites that are used for printed circuit boards.

An example of an important process that is used extensively for thermoplastics processing and in a modified form for thermoset processing is injection molding. A schematic of thermoplastic injection molding is shown in Figure 5.1. Solid pellets are loaded into the hopper and are melted as they move along the extrusion barrel. The melt is then forced into a closed cavity mold under high-pressure. For high-volume production the mold is likely to be water-cooled and to use a hot runner system.

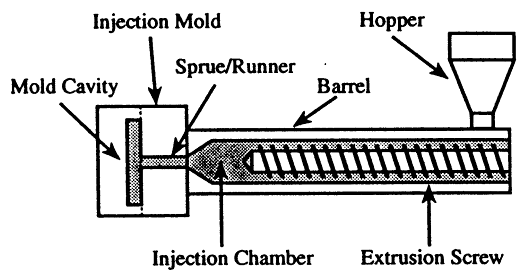

Fig. 5.1. Schematic of injection molding (Mattus 1997).

The injection-molded part then solidifies by cooling and is automatically ejected from the tool. Typical injection molding cycles are quite short, on the order of tens of seconds. Injection molding can produce pre-colored, highly complex parts to net-shape. In many cases there are no secondary operations required prior to use of the part. In other cases, cleaning, painting or coating and assembly with other components may be required before the product is ready.

The environmental impacts associated with injection molding are related to energy usage, which is primarily associated with melting, pumping and clamping, wastewater from cooling, and out-gassing of volatiles which for thermoplastics is usually small. In-process scrap is usually reground and recycled when a cold runner system is used. Hot runner systems reduce, and in many cases eliminate, the need to recycle the cold runner and save the energy associated with molding and then regrinding and recycling the cold runner. Secondary operation can lead to environmental impacts associated with cleaning and painting, but most parts are designed to eliminate secondary operations.

The processing of thermoset materials is similar to that of thermoplastics, but generally requires the handling of only partially reacted or unreacted polymeric materials at a very low molecular weight. Hence, the potential for out-gassing of unreacted monomer as well as residual solvents and other low molecular weight species during processing is very high. This leads to the escape of various volatile organic compounds (VOCs) or hazardous air pollutants (HAPs). For some industries, such as boat building, the management of vapors and fumes from the resin is a major environmental issue. In fact, recent interest in a variety of closed mold and enclosed molding techniques such as RTM (resin transfer molding), resin film infusion, SCRIMP (Seemann Composite Resin Infusion Molding Process) and VARTM (vacuum-assisted resin transfer molding) is due in large part because of their ability to manage fumes and out-gassing from thermoset processes. While thermoplastics can also out-gas, especially when subject to high temperatures, the amount of the VOCs released from thermoplastics tends to be significantly less compared to thermosets. Nevertheless, some of the thermoplastic materials do have the potential, particularly if subjected to thermal degradation during the processing, to release extremely harmful materials. A particular case in point is PVC, which can react at high temperatures with the atmosphere to produce hydrochloric acid (HCl).

Many of the environmental issues associated with polymer processing are related to the additives used to enhance processing characteristics or to improve the physical and chemical properties of the part, or both. Some of these are quite specific to a particular industry. For example the elimination of brominated flame retardants is a major issue in the electronics industry (see the electronics section of this chapter). Likewise, the transition from solvent based paints to water based paints is a major issue for the automotive industry (see the automotive section this chapter).

The entire range of additives, however, is enormous. The *Modern Plastics Encyclopedia* lists 13 different categories. These include; antiblocking agents, antimicrobials, antioxidants, antistats, blowing agents, carbon blacks and other fillers, colorants, flame retardants, heat stabilizers, light stabilizers, lubricants, organic peroxides, and plasticizers. Many of these can affect the environment by releasing undesirable by-products during processing, while the product is in use, or at the end of life. On the other hand, these additives can provide real benefits, too, even to the environment. For example, blowing agents allow us to foam plastic and thereby conserve material, reduce weight and improve insulation properties. All of these could improve the environment. However, in order to work properly during processing they also need to diffuse rapidly into the polymer and decompose during processing to allow the foaming action to occur. Unfortunately, many of the materials that do this also adversely affect the environment. For example, the original blowing agents used with polyurethanes used CFC-11, and while excellent blowing agents, they were chlorinated and as such contributed to ozone depletion. These have now been largely replaced by various alternatives, usually hydrocarbons—for example cyclopentane. While these are an improvement, the resulting foams are slightly denser and there are still environmental issues associated with the hydrocarbons and cyclopentanes—VOCs. Hence, continued work in this area is necessary to develop truly benign blowing agents. One interesting foaming alternative that can work with a variety of harmless gases is based on pre-saturation of the polymer prior to processing. Then, during processing, pressure can be released to allow the foaming action to occur. The resulting product is called “micocellular plastics” (Suh 2001).

Much attention to process innovation and new materials alternatives is focused on the elimination or reduction of solvent usage in polymer processing. For example, cleaning and painting operations can be big solvent users with many attendant environmental problems. Currently technology exists for rather effective solvent recapture (~ 90%), but in many cases it appears to be more effective to pursue alternative processing routes and alternative chemistries. Many advances have been made recently in both washing and painting technology. Completely satisfactory water based systems now exist to replace solvent washing and painting in many cases. Examples exist in both automotive painting (see Volvo and Ford site reports), and in electronics photo resists. Other interesting examples in this area include thermal vs. solvent based methods for wetting out fibers in the production of thermoplastic composites prepregs (Lutz 1999) and polymer coatings as a replacement for lubricants in steel can production (Toyo Seikan site visit).

New improvements to polymer processing technology require that attention be focused on a few key areas: (1) reduction of VOCs and HAPs, (2) improvements in energy efficiency, and (3) reduction in waste and wastewater. Significant environmental benefits for polymer processing may also be realized through improved process capability, which reduces scrap and waste. This can be achieved through process monitoring and control (including equipment and material-use sensors), process modeling, and equipment redesign for more energy efficient processing. Equipment redesign could include new heating and cooling techniques, new tool designs (including hot runner systems) and new ideas made possible by rapid tooling technologies, substitution of electric clamping for hydraulic clamping, and efficient sizing of equipment for a particular job.

Use Phase/Design

During product design, materials are chosen primarily based upon the requirements of the use phase and cost. While there are a number of potential environmental consequences of using polymers, as shown previously in Table 5.1, there is one recurring theme that presents a major challenge to the future development of polymers, composites and advanced materials of all types. This is the potential conflict between performance and the ability to either incorporate recycled content into the material and/or recycle the engineered material for use in high value applications at the end of the original product's life. Often, the very same feature that appears to be responsible for good performance, the use of multiple materials in a symbiotic way, may present an enormous challenge in both of these areas. First, engineered materials are typically complicated and use precise mixtures, making them intolerant to the variation that often comes with using recycled content. And secondly, because of their heterogeneous nature, these complex materials are either an enormous challenge to separate, or if not separated, they become a source of variation for most waste streams to which they could contribute in their end-of-life. Hence the significant benefits to using engineered polymers and polymer composites in the use phase are often counterbalanced by a significant end-of-life dilemma. Of considerable interest in this area are the new European directives for increased fuel economy and product take-back for automobiles. These dual directives are forcing this issue to be considered in depth by those who wish to compete in the European automobile market.

End-of-life Phase

One of the principal environmental dilemmas for a sustainable society is the end-of-life treatment for polymers. While polymer usage continues to grow, economic end-of-life treatments for polymers continue to be elusive. Nevertheless, the importance of the problem, particularly in societies that do not have additional landfill space, has created pressure to try a variety of creative solutions. In fact, most of the observations from the panel's site visits with a focus on polymers were in the area of end-of-life treatment, and in the area of "bio-materials" (covered in the next section) which are often developed precisely to solve end-of-life problems.

To organize this problem, end-of-life options can be categorized as shown in the first column of Table 5.2. Opposite each of these are technology issues that need to be solved in order to enable the option. Note that landfill is the least technologically intensive solution, while recycle and reuse are the most intensive.

Table 5.2
End-of-Life Options and Issues

End-of-Life Options	Sortation & Separation Technology	Infrastructure Requirement	Materials & Additives	Design
Recycling	X	X	X	X
Reuse	X	X	X	X
By-product synergy	X	X	X	
Incineration	X	X	X	
Landfill		X	X	

During our various site visits we found what appeared to be clear regional preferences for certain approaches. Many of the EU countries have, or are in the process of developing, extremely comprehensive collection schemes for recycling. However, the end-of-life treatment for plastics appears to be incineration after it has been separated from the more desirable metals and glass (MIREC site report). The panel also found that currently Japan also incinerates most of its plastics. In the U.S. most plastic waste is landfilled. However, in areas of very high population densities, e.g., some east coast states, plastics incineration is now increasing.

The burning of commodity plastics for energy can be a good use of these petroleum based products because of their inherently high heating values. However, incineration does lead to carbon emissions and can release toxic materials to the atmosphere. In fact, a major issue in the EU concerning the disposal of plastics from electronics is the potential toxicity of various flame retardants released during burning. For this reason chlorinated flame retardants, which can produce dioxins, have been banned for some time. And current efforts in the EU are focused on banning certain brominated flame retardants. Unfortunately, there is no current alternative to, nor method to detect, the brominated flame retardants which help companies meet the fire safety codes in the U.S.. As a result, companies must use different resins for different markets and cannot mix them. This issue, which has curtailed recycling of some materials, is discussed in more detail in the electronics section of this chapter.

In general, however, the panel did see some evidence of a move away from incineration and toward recycling in both Japan, due to the new recycling laws that were scheduled to take effect there in April 2000, and in the EU, where automobile recycling laws will limit the amount of incineration. Furthermore, in the U.S. many large urban areas already have well-developed collection programs intended for recycling. Yet the financial success of plastics recycling schemes to date has been very limited. The problem in most cases is related to infrastructure development and the reverse logistics process. In simple terms, it is very hard to get an adequate waste stream in terms of volume and purity that can supply the needed material for a viable product. At the heart of this issue are some of the very attributes that make polymers so successful in the first place—low weight and low cost. Low weight actually increases reverse logistics transportation costs per unit of plastics. And low cost means that transportation, cleaning and sorting must be very efficient in order to keep the costs below those for the virgin material. Hence, the chance for successful plastics recycling increases as the waste stream quality and quantity increase, and as the cost of the virgin material increases. Success stories to date are PET soda bottles and nylon carpet materials. Both are available in fairly large quantities that can be separated efficiently. Furthermore, both can be recycled back to their original monomer components in a recycling scheme akin to metal recycling back to basic metals. There is also significant interest in the development of recycling schemes for high-end engineering thermoplastics, which are typically used in automobiles and electronic equipment. These include ABS, HIPS, and PC. The Environmental Protection Agency and DOE are currently funding a "stakeholder dialogue" process at Tufts University to examine the barriers to this technology. And there have also been several pilot studies to look at infrastructure issues, including ones in San Jose, CA, Somerville, MA, and Binghamton, NY.

Clearly, new technology could turn around the plastics recycling problem, but the technology would have to address the fundamental systems issues. For example, one approach is to use shredding to densify the plastic for efficient transportation, and then technology to sort it. This is the approach that MBA Polymers has taken (see MBA site report). MBA has developed new proprietary technology to solve the key part of this scenario—the efficient sortation of mixed shredded plastics at high rates. Currently, MBA claims its technology can sort shredded plastics at the rate of 4 tons/hr. The panel also saw other sorting technology based upon infrared reflection, but this method still cannot handle black plastics (see MITI Japan site report). One new plastics identification technology that can deal with black plastic and even identify some fillers and additives is based upon Raman laser spectroscopy and developed by Spectra Code Inc. (*IndustryWeek.com* 1998). The technique offers increased accuracy, but at lower rates and higher investment costs compared to density sortation.

Yet another approach could be to reduce the transportation cost by the use of small scalable recycling units that could be operated locally, presumably near a suitable waste stream. Small melt processing units might work under this scenario, but various depolymerization technologies, such as those used with PET and nylon, generally require large investments and hence much larger processing volumes, making them hard to scale down.

While all of these schemes mentioned so far are for thermoplastics, work is being done on the recycling of thermosets, too. While at NIRE in Japan, the panel saw a project on the recovery of phenol from both phenolic and epoxy resins by liquid phase decomposition (see NIRE site report). This research is based on the use of a hydrogen donating solvent such as tetralin and moderate temperatures (400°C) to recover phenols from thermoset plastics. This route allows recovery of phenols at an efficiency of about 60 to 80% by weight directly from factory waste. This compares very favorably with current recovery scenarios based on pyrolysis and supercritical water, which can only give efficiencies of about 20% due to the recombination of radicals. Currently there is a small prototype facility built for this project that is being evaluated. Interest in this work has led to a joint research project with Sumitomo Bakelite, Hitachi Chemical, and JVC, which was scheduled to start in 2000. Work continues in the search for a tetralin substitute

In some cases, recycling infrastructures are set up to capture particular target materials because they are either valuable or troublesome. For example, among thermoplastics, PVC usually requires special handling because it can produce HCl during incineration, and it is a contaminant for some other plastics during recycling. While in Japan, the panel learned of a sophisticated infrastructure to collect and recycle PVC back into pipe, and in another application into window frames (see Japan PCIA report). The significant features of the Japanese infrastructure are: (1) careful collection and sortation of construction waste by a licensed technician on site (paid for by the site owner); (2) reprocessing of the PVC to established standards; (3) financial support in terms of a subsidy provided by the government to allow the recycled material to compete with the virgin material; and (4) careful development of the application. For example, in the case of the PVC window frame, processing involved the development of a sophisticated three-material co-extrusion process which could produce a frame cross section with a PMMA exterior, virgin PVC interior, and recycled PVC core. Furthermore, there is an excellent market for this window frame in the north of Japan where frames are predominantly aluminum.

Such infrastructure developments could pay off by cleaning up feed streams for other plastics and by preventing pollution from improper disposal of PVC. Furthermore, as volumes and efficiencies increase, these kinds of model efforts could become sustainable. Note that similar recycling schemes have been supported in the EU to make three–layer PVC pipe. An equivalent PVC pipe enterprise in the U.S. does not exist due to shortcomings in our infrastructure (ARC 1997).

One major challenge to the U.S. is the treatment of plastics used in automobiles. Currently, the U.S. recycles about 10 million cars a year primarily for the steel, aluminum and other metals. The plastics end up as a mixture, called ASR or “automobile shredder residue,” which currently goes to landfill. The opportunity to take advantage of this existing infrastructure appears to be significant, but to date no cost-effective solution for plastics has been demonstrated. Early attempts to disassemble large interior parts by plastic type from the automobile prior to shredding have been found too costly. This approach could have yielded relatively pure plastics waste streams, but disassembly proved too labor intensive. In an alternative scheme, ASR was flotation sorted to produce a power plant fuel source (Chaparral site report). However, this effort has been complicated by the presence of PCBs in the waste stream. Hence, even for incineration schemes, it is the development of a “clean” waste stream that is critically important for economic viability.

It appears that the key to success in this area is design for recycling. A first step would be to identify all materials in a product. And a second would be to design for their easy sortation. Clearly, the easiest products to recycle would be those made of a single material, or simply separated from other materials that require no secondary operations, like paint, label or surface coating removal and cleaning. Manufacturers are moving in this direction by redesigning products to facilitate take-back. There are several examples of this approach in the automobile industry. For example, both Ford and Toyota have designed new bumper systems from a single polymer. Furthermore there is much interest in driving toward new automobile interiors based upon a single polymer. Other examples come from the floor covering and carpeting industries. For example, new floor covering systems are now designed such that the variety and amount of materials are reduced, and the interfaces between layers are “zipable” to facilitate disassembly during recycle (see Interface site report).

Plastics can also be used in various by-product synergy schemes. For example, while in Japan the panel learned of projects to use plastics as a reducing agent in blast furnace steel production. In several pilot demonstrations, plastics have been used as a carbon source in steel production to reduce the oxygen content. Furthermore, because of the higher hydrogen content of plastics compared to the typical reducing agent (coke), the Japanese have argued that some hydrogen reducing will take place, thereby reducing the carbon emissions during steel making (see NSC site report). These Japanese firms are using this scheme to help meet their Kyoto Protocol targets. On the other hand, this argument has been dismissed by managers at the Dutch steel firm Hoogovens as marginal (see Hoogovens site report). Regardless, the use of plastics as a reducing agent provides an intriguing end-of-life scenario for plastics and is being actively pursued in Japan and Germany (Pipes and Fahrbach 1999). In addition, we also heard of other by-product synergies, such as the use of polymer composites in cement—both as filler and as fuel—and the use of glass fibers as a fluxing agent in the reclamation of metals from printed wire boards and after grinding a component of cement. Polymer and end-of-life treatments provide a rich opportunity for new technology and infrastructure development. Currently USCAR in cooperation with the APC is developing a “plastics in automobiles” roadmap (due out in the spring of 2000) which should provide additional guidance in this area.

Biomaterials

Many of the proposed solutions to a wide range of environmental issues for polymers involve the development of new materials. Certainly, one of the most intriguing areas of new materials development is in the area of biomaterials. In many cases the goal is to grow the feedstock for a new class of biodegradable polymers. For example, currently there are several commercial initiatives to develop biodegradable polymers from corn (*IndustryWeek.com* 2000). Two possible routes to do this include the processing of corn sugar to polylactide (PLA) and several routes to produce polyhydroxyalkanoate (PHA). In general, these products look promising but raise a host of life-cycle issues that require closer scrutiny. These include (1) potential land use conflicts, (2) net energy consumption, and (3) net greenhouse gas production (DuPont site report). For example, in a recent analysis it was found that the routes to PHA from corn generally require more energy than the conventional routes for equivalent polymers from petroleum (Gerngross and Slater 2000). On the other hand, PLA production appears to be energy competitive, but will lead to significant amounts of greenhouse gases. In any case one common element for all of these new materials scenarios is the need for major new infrastructure. For example, when referring to the production of PHA, Gerngross and Slater write, "This processing infrastructure rivaled existing petrochemical plastic factories in magnitude and exceeded the size of the original corn mill."

A related area is the growth of various fibrous plants such as sisal and flax to be used as reinforcements in polymer composites. For example, currently door panels for new Mercedes Benz automobiles are made by this route (see DaimlerChrysler-Stuttgart site report). For this project, DaimlerChrysler, with some (minor) support from the German government, developed the infrastructure to produce fibers of uniform properties in spite of variations in growing seasons. In this application, natural fibers would replace glass fibers that present particularly challenging end-of-life problems. Natural fiber composites, for example, could be easily incinerated for energy recovery, an option that is not currently available for glass fiber composites. Alternatively, they could be used with a biodegradable polymer matrix to make a biodegradable composite. The ultimate desirability of such an end-of-life scenario in countries with limited landfill space and for products that require durability requires further investigation.

Alternatively, synthesis with biodegradable linkages has also proven successful. For example, Fraunhofer IGB in Stuttgart is looking into the synthesis of "natural" polymers by the inclusion of amine and ester bonds to promote biodegradability (see Fraunhofer IGB site report). Along this line it has produced an alternative for cellulose called Ecoflex that shows good properties, but requires additional work to show economic feasibility and to develop processing techniques.

Many of these proposed new biomaterials are intended to be used in packaging applications—a significant source of polymer waste. One new packaging approach discovered by the panel comes from DuPont. Responding to the environmental concerns of customers, DuPont has developed new kinds of environmentally friendly containers that can be processed in the identical manner as the contents of the container. For example if the product is a compounding agent, after the entire contents are used, the remaining container can be crumpled up and put into the machine to be processed in an identical manner as the compounding agent. Or, for the case of agricultural products, the potentially hazardous box liner would be water soluble, just as the product, and could be deposited into the product applicator and sprayed onto the plants, just as the product was. This new kind of product container is called "Rotim," which stands for "return or throw in machine." Although not biodegradable, these materials are "process" degradable and may represent a new, very efficient recycling paradigm for some types of products.

Summary

Polymers compete against other materials by virtue of their light weight and low cost. This can make them desirable, and in fact environmentally friendly, during the "use phase" of the product. For example, the use of polymers and composites in automobiles has helped to lower weight and therefore lower fuel consumption. But these same attributes conspire to make recycling a difficult economic challenge. A lower material density actually increases transportation costs per kg of material, and the low cost of virgin materials makes recycling targets very difficult to meet. The primary problem is with the details of the reverse logistics stage, especially with streams that are extremely heterogeneous (mixed plastics) or dirty (contaminated with metal and paper). Major attention needs to be focused on the collection, transportation, cleaning and sorting of a sufficiently pure waste stream to make plastics recycling economically viable. To accelerate recycling, new technologies can help; for example, small scale recycling technologies would lessen transportation and infrastructure needs. New bulk-handling, cleaning and sorting techniques are also necessary.

And there is also the challenge of composites. These materials can provide enormous benefits at the use phase, but equally enormous challenges at the end-of-life phase. One possible route to recyclable composites could involve organic and/or biodegradable fibers, other strategies could be based upon new materials with designed in "disassembly" schemes. Polymers and polymer composites can also be used in various materials exchanges and as fuels. For example, there are pilot programs in Japan and Germany to use polymers as a reducing agent in steel making.

The processing challenges for polymers are in some ways quite similar to metals, in that many of the benefits should be self-motivating for the processors. However, there is a need for new technologies that concentrate on energy efficiency and the reduction in volatile organics. These can include new efficient heating and cooling methods, new tooling, closed-loop control, and new materials and additives to reduce solvents, residual organics and materials of concern.

One particularly interesting area is that of the biopolymers and biomaterials. There is significant activity worldwide in such areas as biodegradable polymers synthesized from petroleum, organic fibers and fillers, and biodegradable polymers derived from various crops and biomass. While this work looks very interesting, the overall effect of these materials on the environment is still not well known. For example, a recent analysis has shown that some new routes from crops to biopolymers are actually more energy intensive than the conventional routes from petroleum. Much new work is needed to follow through the entire life cycle for these materials.

Finally, the primary production of polymers from petroleum remains a serious challenge to the environment. These processes, contained in the petroleum and chemical industries, are subject to several initiatives to move from end-of-pipe treatments to proactive "clean technologies" approaches. Several studies sponsored by the EPA have shown the combined economic and environmental gains that can be obtained by these means.

ENVIRONMENTAL ISSUES OF THE AUTOMOTIVE INDUSTRY (J. SUTHERLAND)

Introduction

Automobile usage is increasing in the U.S. and elsewhere in the world. There were 700 million motorized vehicles registered in the world in 1999, with the U.S. itself contributing over 200 million passenger cars and light trucks (Alvord 2000). In the 1990s the number of cars worldwide grew three times faster than the human population (Pimental et al. 1998) and the number of U.S. cars increased six times faster than the population from 1969 to 1995 (Alvord 2000). The situation in Europe is also of concern. For example, the Copenhagen-based European Environment Agency (EEA) stated in its recent report on the "State of the European Environment" that transportation presents a huge threat to the environment as increases in freight and passenger vehicle use threaten climate change and air pollution goals. In fact, the EEA has stated that more efficient engines may not be enough to offset shifts towards larger cars, increases in car and air travel, and increases in distance driven per person (Burke 2000). While automobiles are presently too expensive for most people in developing nations, this situation may change with the increasing standard of living in such nations as India and China. All these facts point to the importance of environmental issues as they relate to the automotive industry.

The auto industry and its suppliers are aware of the ever increasing need to address environmental issues in their products and processes. Many of the companies within the industry are very large global corporations (GM, Ford, DaimlerChrysler, and Toyota) that are well informed about technological, sociological, and legal trends across the globe that are calling for improved environmental performance. As part of this WTEC study on environmentally benign manufacturing (EBM), all of these referenced organizations were visited, as well as several of their key Tier 1 suppliers and others in the vehicle industry. Every organization that was visited had some sort of environment-related company program/initiative, although these initiatives differed in their scope and focus. Differences were evident across countries as well as within the supply chain. In fact, one of the biggest differences evident from this study was not the company-to-company differences, but the differences in public attitudes toward the environment from country to country. Since the public makes up the work force of companies, the environmental awareness differs even within the same company as one moves from one country to another. Given this background, this section presents a number of the ongoing environmental improvement efforts that are being undertaken by companies within the automotive industry.

One way of organizing the environmental issues of the automotive industry is to employ the life-cycle stages of an automobile product. A typical life cycle is shown in Figure 5.2. In the figure, four principal stages are presented: (1) materials processing, (2) manufacturing, (3) use, and (4) post-use. The materials processing and manufacturing stages are largely concerned with creation of a finished product. The use stage considers the actual use of a product, in this case the operation of a vehicle. The post-use stage of the product includes both product recovery as well as its subsequent disposition via reuse, remanufacturing, recycling, or disposal.

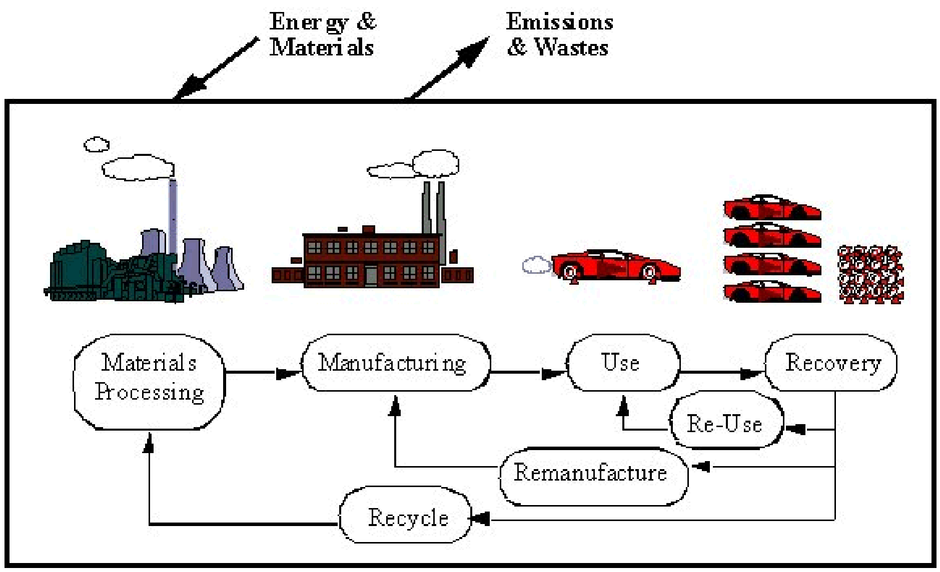

Fig. 5.2. Product life cycle.

Before examining the efforts around the globe that are directed at improving the environmental performance of automotive products and processes, it is useful to examine the current status of the industry. Under the umbrella of USCAR (United States Council for Automotive Research—a cooperative, pre-competitive organization formed in 1992 by General Motors, Ford, and Chrysler) the United States Automotive Materials Partnership Life-Cycle Assessment Special Topics Group (USAMP/LCA) recently completed an LCI (life-cycle inventory) of a generic mid-size vehicle. Sullivan et al. (1998) report that the LCI team also included representation from the AA (Aluminum Association), AISI (American Iron and Steel Institute), and the APC (American Plastics Council). The LCI was performed on a generic 1995 mid-size vehicle (Chevrolet Lumina, Dodge Intrepid, and Ford Taurus). For each part within the vehicle, the material type and mass were identified. The generic vehicle had a mass of 1532 kg, used gasoline as a fuel source, had a fuel efficiency of 23 mpg (city 20 and highway 29 mpg), and had a service life of 120,000 miles. For each stage in the life of the vehicle environmental data were collected—for example, energy usage, water consumption, air emissions, water emissions, solid wastes, and raw materials consumption. Key findings of the LCI include:

- The generic vehicle's "use" phase dominates the vehicle's energy consumption.
- The material production and manufacturing stages contribute 14 percent of the consumed energy, 65 percent of the particulate emissions, 67 percent of the solid waste, and 94 percent of the metal waste to water.
- The end-of-life phase contributes eight percent of the total life-cycle solid waste, primarily as automotive shredder residue (ASR).

While the WTEC EBM study is primarily concerned about the environmental issues surrounding manufacturing processes/systems, it is nearly impossible to address the environmental concerns of the automotive industry without at least a brief discussion of the product itself. As a result, each of the life-cycle stages will be addressed in the sections that follow. In addition, a section has been provided that addresses more system oriented issues, e.g., supply chain challenges. Findings from the technical literature will be reported, as will information extracted from site visits in Japan, Europe, and the U.S. The section will conclude by identifying industry-wide trends and need areas.

Material Issues

Previous sections/chapters have focused on the environmental challenges associated with the processing of aluminum, steel, polymer, and composite materials. This section concentrates on the role that material selection plays in the environmental performance of automotive products. An automobile is a complex product that consists of a number of systems and material types. As part of the USAMP LCI activity, Sullivan et al. (1998) tabulated the material composition of a generic mid-size U.S. automobile. Figure 5.3 displays the breakdown of the materials within the vehicle. As is evident, ferrous materials (cast iron and steel) make up nearly two-thirds of the total vehicle weight. However, this fraction has reduced significantly over the last several decades as lighter materials (aluminum and plastics) have begun to supplant the use of ferrous materials.

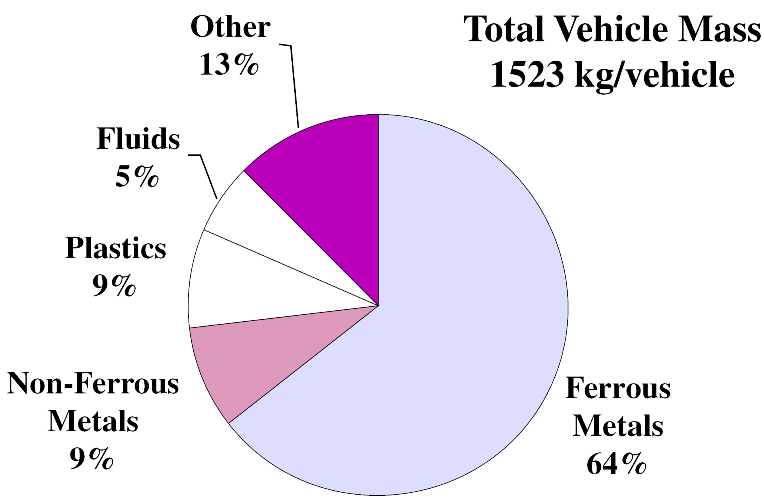

Fig. 5.3. Material composition of a generic mid-size U.S. automobile (Sullivan et al. 1998).

In considering the selection of materials, Graedel and Allenby (1998) advocate the use of the following guidelines for the design of industrial products:

- Select nontoxic and abundant materials
- Select natural materials (e.g., cellulose) rather than artificial substances (e.g., chlorinated aromatics)
- Select materials that are easy to recycle
- Minimize the variety of materials used in products and processes
- Acquire materials via a recycling stream

The automotive industry utilizes a tremendous amount of material resources; a summary of the amount of various types of materials within an automobile are given in Table 5.3. The first of the guidelines indicates that materials should be used that are abundant, and since iron and aluminum are plentiful in nature, they satisfy this criterion. Other listed metals are less common. Fluids (e.g., oil and transmission fluid) and rubber are petroleum derivatives and are therefore subject to the same scarcity as this limited natural resource. The table also lists the fraction of the total U.S. consumption that is used by the automotive industry. As is evident, the auto industry is the primary consumer of such materials as lead, platinum, and rubber.

Table 5.3
Amount of Various Material Types Used in an Automobile and their Usage as a Percent of the Total U.S. Consumption (adapted from Graedel and Allenby 1998)

Material	1950s Automobile (kg)	1990s Automobile (kg)	% of Total U.S. Consumption Used in 1990 Automobiles
Plastics	0	101	3.2
Aluminum	0	68	18.9
Copper	25	22	10.0
Lead	23	15	69.5
Zinc	25	10	23.0
Iron	220	207	34.5
Steel	1290	793	13.5
Platinum	—	0.002	41.4
Rubber	85	61	62.9
Glass	54	38	—
Fluids	96	81	—
Other	83	38	
Total	1901	1434	

Table 5.3 indicates that the relative use of ferrous materials has dropped significantly since the 1950s. The key to understanding the motivation for reducing the use of ferrous materials in an automobile is the fact that the replacement materials have a lower mass density, and mass reduction is a proven method for obtaining improved vehicle fuel economy. As an approximation, a 10 percent reduction in mass produces a 5 percent improvement in fuel economy. In the U.S. over the last 25 years, as the automakers have responded to government-mandated CAFE (corporate average fuel economy) requirements, they have turned to lighter materials such as aluminum and plastics. Magnesium, polymer composites, and ceramics are also being favorably viewed as automotive components. Graedel and Allenby (1998) suggest that the following material types are expected to play increasingly important roles in the vehicle of tomorrow:

- Engineered plastics: Lower costs and improved material performance will result from advances in processing technology. The total quantity of plastics in the vehicle may double—essentially eliminating non-plastics in vehicle interiors.
  - One of the organizations that was visited, Johnson Controls, is making effective use of recycled PET plastic in its headliner substrate.
- Composites: Organic and inorganic fibers that are woven together and impregnated with a plastic resin can be five times lighter than metals and provide competitive strength.
  - In partnership with the German government, DaimlerChrysler is working to use natural fibers (sisal and flax) instead of glass fibers in fiber-reinforced plastic vehicle components. The challenges of this effort include the lack of an existing transportation infrastructure and the variation in fiber quality introduced by weather conditions, processing, drying, etc.
- Ceramics: These materials can be light and retain their hardness at high temperatures. Advances in formulations and in processing techniques will allow these materials to find application as engine components.
  - As an example, DaimlerChrysler and its suppliers are working to develop a successful silicon nitride ceramic engine valve.

- Light metals: As noted, aluminum is already widely used in automotive applications. Magnesium usage is growing because its density is 25% of steel's and 67% of aluminum's. Factors limiting the widespread use of magnesium include its cost and availability, lack of suitable manufacturing technology or knowledge, and the susceptibility of the material to corrosion.
  - To support its growing need for magnesium, Ford is investing in Australia's magnesium mining industry.

Of course, material selection guidelines suggest that toxic/hazardous materials should be avoided in products and processes. Each U.S. automaker has developed a list of permissible materials that may be used by its vendors. These specifications are aimed at minimizing the introduction of hazardous materials that increase the regulatory burden of plants, result in the generation of hazardous waste requiring expensive management, or result in the release of chemicals that must be reported under the U.S. EPA's Toxics Release Inventory (TRI). European-based companies likewise have established "black-lists," materials that are to be avoided in their products and processes, and "gray-lists," materials that are to be avoided unless no viable substitutes are available. Japanese companies are also working with their suppliers to ensure that hazardous materials are avoided. Toyota's 1999 Environmental Report notes that environmental purchasing guidelines have been distributed to 450 parts and materials suppliers (in March 1999). These guidelines call for supplier ISO 14001 certification by 2003 and control of substances of environmental concern.

The ease with which a material can be recycled is another guideline that should be considered when making material selection decisions. Steel and aluminum may be recycled relatively easily, although it has been suggested that these materials may only undergo several recycling loops until contaminant levels are too high to produce acceptable microstructures without additional purification steps. The recycling loops associated with other metals, e.g., lead and copper, are also fairly well established. A by-product of the automotive metal recovery recycling process, ASR (automotive shredder residue), is largely composed of contaminated polymer materials. At present, ASR is often landfilled in the U.S.; there are several examples where ASR has been used as a fuel source. The bottom line, however, is that in the absence of regulatory intervention automotive plastics are not being recycled to a great extent. Since it is envisioned that efforts to further reduce vehicle weight will result in an increased fraction of plastic and composite components, this may hamper future recycling efforts. Reduced metal content may jeopardize the economic viability of the current vehicle recycling infrastructure, thus endangering recovery rates of material resources at vehicle end-of-life.

Manufacturing Issues

A key stage in the life cycle of an automobile is the creation of the vehicle itself from engineering materials. An automobile may be broken down into the following subsystems: powertrain, suspension, HVAC, electrical, body, and interior. The production of components for these systems involves a wide range of manufacturing processes (e.g., casting, compression molding, machining, forming, adhesive joining, welding, coating, painting, injection molding, fiber/textile manufacturing, glass production, cleaning, and assembly). To place the manufacturing stage in the context of the life cycle for the whole vehicle, Sullivan et al. (1998) report the following:

- The material production and manufacturing stage constitutes 14% (about 140 GJ) of the total vehicle life cycle energy demand of a generic vehicle. On its face, this suggests that manufacturing energy requirements constitute a minor portion of the overall energy demand compared to the use portion of the life cycle that consumes 84% of the energy. However, it must be noted that the energy consumed during vehicle use is distributed over a 10-15 year period, while the manufacturing energy demand (and concomitant CO_2 production) occurs over a much smaller time period.
- 65% of the airborne particulates and 94% of the water-borne metals are generated during the material production/manufacturing stage of the life cycle.
- 67% (about 2800 kg) of the solid waste is produced during the material production or manufacturing life-cycle stage. Figure 5.4 shows the distribution of solid waste across three stages of the life cycle.

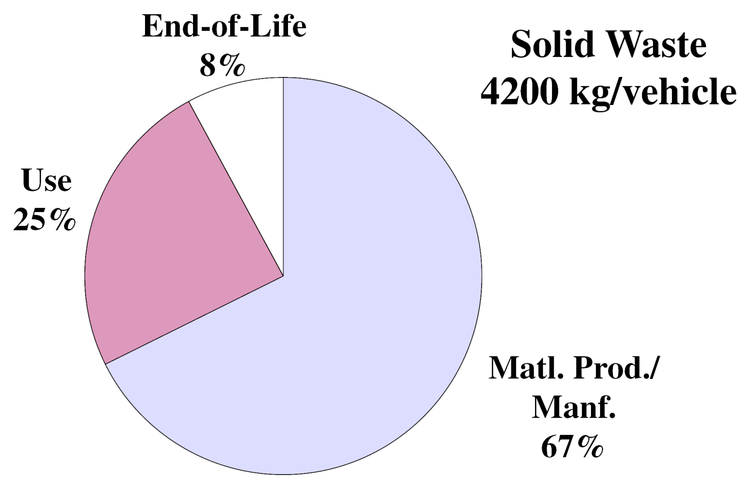

Fig. 5.4. Solid waste for three life-cycle stages for a generic mid-size U.S. automobile (Sullivan et al. 1998).

It should be reiterated that the energy/wastes associated with the manufacturing life-cycle stage tend to be more temporally and spatially concentrated than the energy/wastes associated with the use stage.

There are significant differences in the energy efficiency and the relative quantity of waste produced across the whole range of manufacturing processes. This EBM study revealed that there are also substantial differences in attitudes towards energy consumption and waste. These differing attitudes towards the environment were less a function of the company and more dependent on the sociopolitical climate of the sites that were visited:

- Industries in Japan are highly focused on the reduction of energy needs and CO_2 emissions. This attitude is perhaps motivated by the cost of meeting energy requirements through imports and the need to comply with the Kyoto Protocol. Solid waste reduction is also a priority. Again, this is principally motivated by specific Japanese factors: the small area of the country and thus rapidly diminishing space for landfills.
  - Japanese agricultural machinery manufacturer Kubota indicates that its ability to minimize waste and utilize energy efficiently is a key to the company’s long-term economic competitiveness.
- In Europe, industry is very concerned about end-of-life products. This concern is prompted by the lack of available landfill space and the prominence of environmental political movements. Leadership in terms of meeting ISO 14000 standards may also provide short term market protection for European industry.
- Attention by U.S. industry appears to be largely centered on compliance with government regulations that are principally directed at reducing/eliminating toxic discharges. The abundant supply of inexpensive energy and landfill space (in most of the U.S.) provides little economic incentive for pursuing non-regulatory driven environmental initiatives.
  - Several U.S. automakers have plants in Mexico that are zero wastewater producers. At these locations where the water supply is limited, there is economic incentive to minimize water usage, and thus water discharges are recovered and recycled.

Based upon all the site visits and a review of the technical literature, environmental concerns have been identified for the following manufacturing processes:

- Casting
- Sheet metal working
- Glass manufacturing
- Painting/coating
- Plating
- Machining

- Joining
- Plastics processing
- Part washing

A brief discussion of the environmental challenges associated with each of these processes is described below.

Casting

A previous section has addressed casting issues in greater detail, so this section is principally focused on casting as it relates to the automotive industry. Figure 5.4 indicates that about 2800 kg of solid waste is produced in the materials processing/manufacturing life-cycle stage for a generic vehicle. As part of another LCI study, Rogers (2000) partitions the purely manufacturing-related waste (totaling about 860 kg/vehicle) as shown in Figure 5.5. As is evident much of this waste may be termed “engineered scrap,” i.e., material built into a part that must subsequently be removed through processing. Examples of this type of scrap include the gates, risers, and sprues that are produced in casting processes. Casting sand represents another large solid waste contributor (about 120 kg/vehicle or 2 million tons/year for the U.S. automotive industry). Used foundry sands contain organic binders and heavy metals that could leach out upon disposal, and thus must be treated as hazardous waste. Casting processes also produce airborne emissions of environmental concern (NOx, VOCs, etc.). For non-ferrous metals, die casting is a widely utilized process, and the wastewater produced by die cooling represents an environmental improvement opportunity. Lost foam casting (expendable pattern casting) is another frequently employed operation, and the airborne emissions from the process are receiving increasing scrutiny.

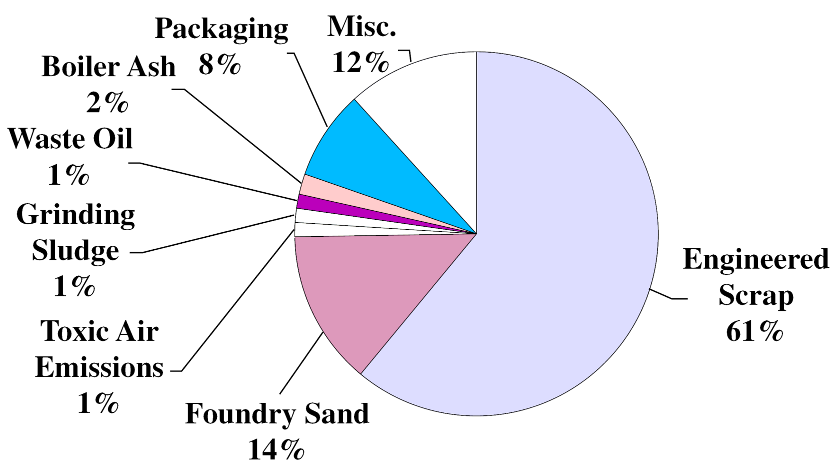

Fig. 5.5. Sources of manufacturing waste for a generic U.S. vehicle (Rogers 2000).

U.S. automakers (under the banner of USCAR) are collaborating with the U.S. Air Force, EPA, AFS (American Foundry Society), and the California EPA on the Casting Emissions Reduction Program (CERP). CERP’s mission is to improve/develop foundry materials and processes that enable the U.S. casting industry to be competitive and minimize environment impact. A current example of reducing casting process energy requirements is found at Kubota, where gas dryers were replaced with microwave dryers for drying core coatings.

To lower the environmental impact of casting processes, the quantity of parting and cooling agents should be curtailed. More benign expendable pattern materials should be investigated. Also of interest would be new uses for spent foundry sands and/or new casting methods that utilize different reusable or recyclable materials. Finally, and perhaps most importantly, there is a need to improve casting process accuracy/precision so that net-shape products can be produced, thus avoiding subsequent downstream processes.

Sheet Metal Working

Another source of the "engineered scrap" highlighted in Figure 5.5 are sheet metal working operations. For example, for stamping processes typically 40% of metal ends up as scrap. Research is needed into sheet metal forming processes that will reduce scrap production. To achieve higher vehicle energy efficiencies, lighter and thinner sheet materials will be employed. Since designers/manufacturers have less experience with these materials, research is needed to support their use in automotive applications. New processing technologies such as hydroforming and superplastic forming offer environmental advantages and merit continuing investigation, as does the processing of Tailor welded blanks.

Glass Manufacturing

Automotive glass manufacturing is the process with the largest energy consumption per kilogram of product (approximately 1 MJ/kg according to the DOE Glass Industry Roadmap). The production of virgin glass is more energy intensive than the production of recycled product. For both cases, glass production requires large amounts of energy (acquired via carbon-based fuel sources) and results in significant CO_2, NO_x, and SO_x emissions. Composition, coating, and tempering improvements, along with improved process control, can reduce the quantity of manufacturing pieces rejected and thus reduce overall energy consumption.

According to USCAR's Vehicle Recycling Partnership, while the technology exists to recycle automotive windshields, at present it is not economically feasible. It currently costs more to recover windshields for the recycling infrastructure than it does to send them to landfills. This may change as more plastic laminates—e.g., polyvinyl butyral (PVB)—are used in windshields. About 3% of ASR is associated with the windshield.

Painting/Coating

Historically, the set of processes (including coating and painting operations) used to produce an appealing finish for the vehicle body has resulted in the largest per vehicle emissions of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). These emissions are being reduced as automakers transition from oil-based paints to water-based paints. Research appears to be progressing on the development of powder or slurry paint applications, which are superior to oil- and water-based paints in terms of emissions. One of the principal challenges of powder paints is achieving an acceptable surface quality. It is estimated that the energy requirements for painting and its associated processes account for over 50% of the energy consumption in an assembly plant. Germany and the U.S. appear to be the leaders in the development of new paint technologies, with Japan placing less emphasis on airborne emissions. The range of paint technologies that are being used across the industry is very large, and the degree of control being exercised on airborne emissions is also highly variable from plant to plant. As with any new technology, much work remains to identify successful operating conditions—in this case, conditions that produce finishes attractive to the consumer.

GM researchers have identified steel pre-coating as one desirable solution to some of the painting-related concerns. Steel coils delivered in a coated/primed form may offer the following advantages: improved corrosion resistance, reduced environmental burden, reduced paint shop investment, lower losses to rust/stain, and reduction in stamping process lubricants. Of course, the use of pre-coated/primed steel sheet in lieu of painting has a number of technical challenges: development of appropriate coating formulation, suitability for welding and forming operations, corrosion protection, adhesion properties, color matching, and compatibility with existing systems.

Plating

Historically, heavy metals such as chromium and nickel have been used to prepare decorative coatings, e.g., chrome bumpers. These coatings are applied through a plating process in which the part is immersed in a series of baths. Metal plating facilities can release a variety of toxic compounds. Chlorinated hydrocarbons may be emitted during pre-cleaning (degreasing) of metal parts, and caustic mists, cyanides, and metals are released from the actual electroplating process. Hexavalent chromium, a carcinogen, is of particular concern for worker and public exposure. Development of better emission containment and recovery are priorities here for existing processes. Also, research needs to be completed into less hazardous coating materials.

Machining

Machining processes (e.g., milling, boring, grinding, and drilling) are inherently wasteful in that their purpose is to remove material from a component (engineered waste). However, at present, there are few alternatives to machining in terms of producing acceptable dimensional accuracy/precision and surface finish. Offal or chips produced by machining operations are routinely recycled, assuming they have not been contaminated with other materials or cutting fluids. (Contaminated chip disposal is an expense while uncontaminated chip recycling is a revenue.) Metalworking fluids are commonly used for lubrication, cooling, chip flushing, and part corrosion protection in machining operations. Metalworking fluid mists are a recognized occupational health hazard (Hands et al. 1996; Heitbrink et al. 2000). Dermal exposure to cutting fluids may cause a variety of skin ailments. These facts highlight the importance of mist control and industrial hygiene considerations. Research is needed on the advancement of improved mist collection/control/air handling strategies and worker protection systems, including the development of fluids that are less prone to aerosol formation (Marano et al. 1995) or that do not represent an inhalation hazard.

The disposal/treatment cost of used fluid is high, as are the other fluid-related costs (fluid recirculation, mist handling, maintenance, etc.). Recent European studies (Cselle and Baramani 1995) report that these costs may constitute 10-20% of the total costs in some production facilities. While these costs are somewhat less in the U.S., the costs and health-related liabilities do point out the growing importance of decisions regarding metalworking fluids. The degradation and therefore rate of disposal of metalworking fluids can be accelerated by improper fluid maintenance (failure to control bacteria growth, tramp oils, contaminants, etc.). Thus, work is needed to establish appropriate fluid system maintenance procedures and develop fluids that are robust to contaminants and slow to degrade. The development of better fluid recycling technologies is also a priority.

Another approach to reducing the environmental problems associated with cutting fluids is to stop using them, i.e., employ dry machining. Dry machining avoids many of the costs previously noted associated with the use of cutting fluids (and also has positive environmental and health effects). Several materials have been traditionally cut dry (e.g., cast iron), and research is underway on the development of technologies/strategies to achieve dry machining for more ductile materials such as aluminum. In the drilling and tapping of aluminum, cutting fluids provide lubrication that under dry conditions must be achieved by other means (new cutting tool coatings for example). While not completely dry, MQL (minimal quantity lubrication), i.e., the application of fluid at very low flow rates, is being pursued by both machine tool builders and end users. In the absence of a cutting fluid, issues such as heat transfer from the workpiece and chip flushing must be given special consideration.

Machine tool builder EX-CELL-O is developing new machine tool concepts where chips are allowed to fall through the center of the machine onto a chip conveyor (rather than off the front or rear of the machine). They are also working to standardize the heights of their machines to make them more interchangeable. EX-CELL-O is also a leader in the development of MQL technologies, where nearly dry machining is achieved by applying cutting fluid at rates on the order of ml/hour. Company representatives also indicated that for dry or nearly dry machining, the management of heat in and around the machine tool is absolutely essential to avoid workpiece thermal distortion problems.

At the 1999 NCMS (National Center for Manufacturing Sciences) Fall Workshop, several machine tool builders expressed concern over the long term reliability of machine tools in the absence of cutting fluids. It was indicated that the dust/chips produced under dry conditions could accelerate the wear rates of machine tool components.

Joining

Joining operations (including adhesive bonding and welding) produce a variety of wastes and can consume considerable amounts of energy. With adhesive bonding, epoxy resins may be used to join metallic or non-metallic materials to one another. Some of these adhesives generate VOCs and produce other airborne contaminants. Components that are to be joined via an adhesive bond often require some surface preparation (e.g., cleaning and degreasing) to ensure adequate/intimate contact between the adhesive material and the components—also having an environmental consequence. Another type of joining operation, soldering, is discussed in detail in the electronics section. Mechanical joining uses physical means to hold components together (e.g., screws and bolts). The environmental effects of such operations are largely associated with the energy required to perform the operation and the manufacture of the fasteners. It may be noted that, unlike many other joining methods, mechanical joining operations can often be reversed, which may offer some environmental advantage in terms of product recycling/remanufacture.

One of the most common types of joining operations are the welding processes, and in fact, resistance spot welding is the predominant means of joining sheet metal in auto body manufacturing. Welding operations can produce the following emissions: carbon monoxide, nitrogen oxides, ozone, dusts, and metallic fumes. The airborne particulate matter may include lead, cadmium, cobalt, copper, manganese, silica, and fluoride compounds. Additional wastes that may be generated include used filler rods and electrodes, heat, and electromagnetic radiation (possibly resulting in retinal damage). NIOSH (1988) has reported a number of health-related concerns associated with welding. Control of welding generated HAPs is clearly a priority, and the auto industry appears to be managing this concern effectively. Reducing the amount of welds (where possible) will reduce energy consumption and process wastes. Also desirable is research focused on improving welding technology for aluminum.

Plastics Processing

Many of the environmental challenges of plastics/polymer processing lie within the chemical industry rather than the automotive industry, and a previous section has addressed these challenges in detail. However, several points about plastics processing relative to the automotive industry deserve further comments here. Plastics processing (molding, extruding, etc.) generally requires large amounts of externally applied energy, though there are some recent innovations such as reaction injection molding, where heat is supplied by an exothermic reaction. The use of recycled plastics in automotive components is challenging due to the large number of polymer formulations and additives, and also because the polymer molecules degrade as they are reprocessed. Thermosets (commonly used in engineering applications and particularly in the electronics industry) present another problem in that they cannot be recycled. The use of polymer foams offers significant benefits in terms of weight reduction, although the blowing agent may represent an environmental concern. Polymer processing operations can produce contaminated wastewater, and under the high heat and pressure associated with molding processes, HAPs may be produced.

Part Washing

In the past solvents were often used to clean components, i.e., remove grease, dirt, and other foreign matter. To reduce HAPs (specifically VOCs), large manufacturers have moved to aqueous cleaning methods that are performed at elevated temperatures/pressures, often under acid or basic conditions. The wastewater produced during these cleaning operations represents an environmental concern and requires treatment. The energy consumed by the process is also an issue that has received little attention. Finally, the process is an aerosol source and little is known about the composition and therefore the health effects of the airborne particulate produced by such operations. Of course, actions should be pursued that can eliminate processes such as part washing that add no value to a part and generate environmental and worker health concerns.

In closing this section, it should be noted that automobile manufacturers are large, sophisticated global corporations. They follow one another very closely and quickly adopt new technologies if they offer economic/competitive advantages. However, the environmental landscape is changing quickly in the U.S. and abroad, and failure to achieve leadership or at least closely follow the environment-related manufacturing technology leaders may lead to loss of market share.

As stated by John Logan before the U.S. Senate Committee on Commerce, Science, and Transportation (Oct. 28, 1999), “Being second to market with innovation is not the way to maintain industrial leadership. That is not a situation in which we should want to place our key industrial sectors.”

Use Issues

The usage stage of the vehicle life cycle has large environmental impacts in terms of both resource consumption and the creation of wastes. It consumes 84% of the energy and produces 94% of the CO, 90%

of the NOx, 62% of the SO_x, and 91% of the non-methane hydrocarbon emissions (Sullivan et al. 1998). There are a number of excellent on-line references to the environmental activities underway related to the usage stage of automobiles. These include the Web sites of the automakers (GM 2000; Ford 2000; DaimlerChrysler 2000; Toyota 2000; Honda 2000) and other organizations (EPA 2000; DOE 2000; USCAR 2000).

Automakers based in the U.S., Japan, and Europe are all involved in activities directed at improving the fuel efficiency of their vehicles. In the U.S., under the aegis of USCAR, the Partnership for a New Generation of Vehicles (PNGV) has as one of its goals the production of an 80 mpg vehicle that meets the Tier II Clean Air Act Amendments gaseous emission standards and applicable ultra-low emission particulate standards. PNGV concept vehicles (utilizing compression-ignition direct-injection (CIDI) diesel engines) have recently been introduced according to the PNGV schedule by GM (Precept), Ford (Prodigy), and DaimlerChrysler (ESX3). Production models are scheduled to appear in 2004. In Europe efforts are also underway to develop high mileage vehicles. For example, DaimlerChrysler recently unveiled a “3 liter vehicle,” also a diesel, that uses 3.4 liters of fuel per 100 kilometers (68 miles per gallon) and that produces CO_2 emissions of less than 90 grams per kilometer. In Japan Toyota has produced the PRIUS hybrid vehicle that offers fuel economy near 60 mpg and emissions low enough to qualify the car as a Super Ultra Low Emissions Vehicle (SULEV). Honda’s Insight hybrid also meets California's Ultra-Low Emission Vehicle (ULEV) standard and has a fuel efficiency of approximately 65 mpg. The other automakers also will soon be introducing hybrids. Table 5.4 summarizes the differences between the various low emission vehicle types.

Table 5.4
California Low Emission Vehicle Classifications (emissions in g/mi)

Vehicle Type	Averaged over 50,000 mi			Averaged over 100,000 mi		
	NMOG*	CO	NOx	NMOG*	CO	NOx
LEV: Low Emission Vehicle	0.075	3.4	0.2	0.090	4.2	0.3
ULEV: Ultra Low Emission Vehicle	0.040	1.7	0.2	0.055	2.1	0.3
SULEV: Super Ultra Low Emission Vehicle	A category of vehicle with emissions less than ULEV.					
ZEV: Zero Emissions Vehicle	A category of vehicle defined that has no tailpipe emissions. At present, this applies only to electric vehicles.					

* Non-methane organic gases.

One of the principal challenges associated with achieving high mileage vehicles is to simultaneously meet the relevant emission standards. The U.S. (and more specifically, the State of California) has some of the world’s most stringent air quality standards. EPA’s Tier II tailpipe standards require nitrogen oxide emissions less than 0.07 g/mi and particulate matter (PM) emissions less than 0.01 g/mi for all classes of passenger vehicles beginning in 2004. Figure 5.6 illustrates the Tier II requirements relative to the Tier I standards. This includes all light-duty trucks, as well as the largest SUVs. Vehicles weighing less than 6000 pounds will be phased-in to this standard between 2004 and 2007. For the heaviest light-duty trucks, a three step approach to reducing emissions will be followed to achieve compliance by 2009 (EPA 2000a).

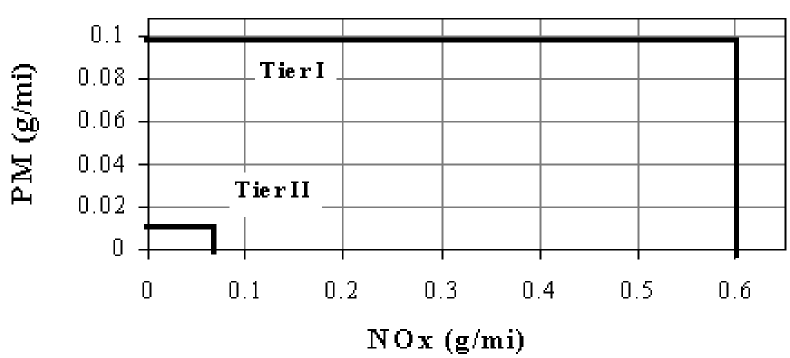

Fig. 5.6. Tier I and Tier II EPA air quality standards.

According to Zorpette (1999) the Tier II standards may present a problem for the PNGV, because the ULEV emission rates may be impossible to meet in a supercar that meets the other desired attributes. For a hybrid-electric car even to approach a fuel efficiency of 80 mpg would most likely require the use of a diesel engine, which produces more particle emissions than a traditional spark-combustion engine. A traditional spark-combustion engine, on the other hand, might satisfy particulate emission goals but would be unlikely to meet both the fuel-efficiency and the low-NOx requirements.

Kubota has adopted a strategy of developing/building engines that meet the world's tightest emission regulations (rather than having different engines for different markets). According to Kubota personnel, an audit of a group of engines indicated compliance with Tier I requirements and emissions just within the Tier II standards. However, at present, existing manufacturing and assembly processes are likely to produce a number of engines not capable of meeting design intent. Quality improvement activities are therefore needed to continue to improve the precision of Kubota's manufacturing and assembly processes.

A number of research activities and initiatives are underway that are directed at reducing the environmental impact resulting from automobile use. These initiatives include the reduction of vehicle weight, development of alternative fuels, and development of alternative power sources. The issue of vehicle weight reduction has been discussed previously in the context of material selection. A variety of alternative fuels for vehicles are being investigated: compressed natural gas, methanol, ethanol (unlike methanol, ethanol is non-poisonous and non-corrosive), diesel, etc. Research into cleaner burning diesel fuels may enable the development of a hybrid vehicle that achieves the emission and fuel economy goals associated with the PNGV initiative. MacLean and Lave (2000) have studied the environmental implications of alternative-fueled automobiles in regards to air quality and greenhouse gas trade-offs. They concluded that compressed natural gas vehicles have the best exhaust emission performance while direct injected diesels had the worst. However, greenhouse gases can be reduced with direct injected diesels and direct injected compressed natural gas relative to a conventional fueled automobile.

Of course, much research is underway on the development of alternative power sources (engines) for automobiles. Figure 5.7 shows estimated fuel economies for a variety of these power sources. This includes work on CIDI (compression ignition-direct injection) diesel engines, electric or battery power, hybrid vehicles (engine and battery power), and fuel cell technology. The challenges and advantages of diesels have been addressed previously, and certainly diesel technology does not eliminate dependence on carbon-based fuels. Electric vehicles are currently being produced, but at present, high cost and marginal performance limits their broad consumer acceptance. Battery technology is a limiting factor, and unless a breakthrough is achieved, electric vehicles seem to represent a transition technology. Hybrid vehicles counter some of the performance concerns of purely electric vehicles; however, cost is still a concern. Hybrids appear to be an effective near term answer to transportation needs, but it seems unlikely that a vehicle with two power sources is an efficient long-term solution.

Hydrogen as a fuel source seems to be the most promising long-term solution. It is envisioned that fuel cell technology can then be employed to combine hydrogen with oxygen to create energy and produce water vapor as waste. The energy is then used to power a traction motor that drives the wheels. On-board storage of uncompressed hydrogen gas occupies about 3,000 times more space than gasoline under ambient conditions and must therefore be pressurized and liquefied, or stored as a slurry or solid (e.g., metal hydride and carbon adsorption). On-board storage of hydrogen or a hydrogen impregnated carrier may initially be met with resistance by consumers and significant infrastructure changes will be required (transportation via pipelines, H_2 stations, etc.). The required hydrogen can also be extracted (or reformed) from a conventional fuel (e.g., gasoline). This appears to be an effective transitional approach, especially in light of the challenges associated with accomplishing the required infrastructure changes for on-board hydrogen storage. The long term role of on-board reforming is unlikely since it does produce emissions and does not eliminate reliance on carbon-based fuels. On-board storage of hydrogen presents a number of significant technical challenges including embrittlement and leak issues. Then, there is the issue of where the energy comes from to generate the hydrogen (from water). The use of carbon-based fuels is not the preferred solution to this problem—cleaner solutions are solar/wind power (i.e., renewable energy sources). However, it may be that only nuclear power can produce hydrogen in sufficient quantities for use as an automotive fuel.

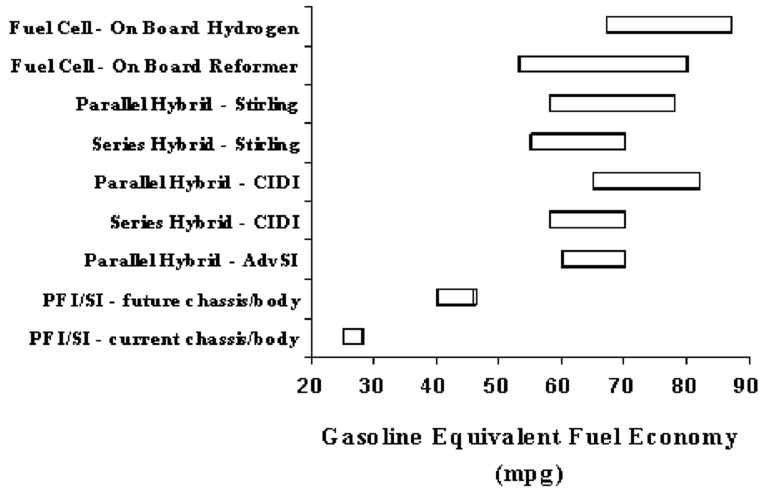

Fig. 5.7. Fuel economy estimates for various vehicle configurations. Except for "current," configuration chassis/body is PNGV-class. PFI/SI: port fuel injection/spark ignition. CIDI: compression ignition/direct injection. AdvSI: advanced spark ignition (NRC 1998).

As stated previously, this WTEC study is primarily concerned with environmental issues surrounding manufacturing processes/systems. This brief overview of some of the environmental issues surrounding the automotive product only begins to address this complex issue. The next ten to twenty years will likely see a number of technology changes, both planned and unanticipated, and a wide range of vehicle and fuel types. The broad acceptance of any of these products is very dependent on the ability of the automakers to produce it cost-effectively. Thus, the economic success associated with these vehicles of the future is dependent on the manufacturing processes/systems of the future.

Post-use Issues

The automobile is one of the most highly recycled consumer products. About 95% of retired cars enter the recycling system, and approximately 75% of each car in the system is recycled (Cobas-Flores et al. 1998). In spite of these seemingly large rates, the post-use stage of the vehicle life cycle still generates a significant amount of solid waste (roughly 300 kg/vehicle) (Sullivan et al. 1998). When a car is viewed as no longer having any useful life, it is transferred to a dismantler. The dismantler removes components that may be resold for their material content (e.g., battery and catalytic converter) or as spare parts (body panels, wheels/tires, alternators, etc.). The remaining vehicle then passes to a shredding facility where large machines (shredders) cut the hulk into small pieces (6-10 cm in size). The pieces are then sorted into three streams: ferrous metals, non-ferrous metals, and automotive shredder residue (ASR). The sorted metals are sold to scrap metal dealers who serve as suppliers to primary metal processors (for example, steel mills). In other countries the energy content of ASR is recovered through incineration. In the U.S. the ASR (largely metal and fluid contaminated polymers) is generally landfilled. However, with landfills closing in New Jersey and elsewhere on the East Coast, incineration is becoming more common. A high proportion of vehicles is recycled because market-based incentives exist that promote the activity; virtually every material transfer involves some cash flow.

Graedel and Allenby (1998) make several key points with respect to the automobile recycling system that exists today. Just because a product is physically capable of being recycled does not mean the technology and economics support recycling. The automobile recycling system can be derailed at any step if the technology or costs are unfavorable. For example, prior to the wide use of vehicle shredding in the 1960s metal recovery from vehicles was difficult. In the 1970s as steelmakers switched from open hearth to basic oxygen furnaces the amount of scrap steel that could be accommodated was significantly lowered, again hampering recycling efforts. These "lessons learned" should be kept in mind as we contemplate legislative initiatives, new materials, new vehicle concepts, etc. It must also be remembered that the decisions made today may not see their real impact for decades, i.e., the lifetime of a car.

It appears that the end-of-life handling of vehicles, such as described above, may soon change. Motivated by the diminishing availability of landfill space in Europe and Japan (and for that matter in large U.S. metropolitan areas), take-back regulations are being established that mandate vehicle return at the end-of-life and call for higher recovery rates for automobile recycling. Generalizing, it appears that by about 2005 an 85% recycling recovery rate and by 2015 a 95% rate will be required. These rates both include a small percentage of energy recovery associated with the incineration/pyrolysis of ASR. As might be expected, automakers are concerned about these targets and the take-back requirement. As challenging as these percentages appear, they will be even more challenging in the future as the ferrous metal content in the vehicle is reduced in favor of lighter metals and plastics to achieve higher fuel efficiencies.

A recent European Union directive calls for the re-use and recycling (recovery) of end-of-life vehicles and their components, with a view to reducing waste disposal. No later than January 2006, the re-use and recycling of end-of-life vehicles are to be increased to a minimum of 80%. No later than January 2015, re-use and recycling are to be increased to a minimum of 85%.

In October 1996, Japan's Ministry of International Trade and Industry proposed a recycling target of 85% by 2002, and a target of 95% by 2015.

In November 1998, the government of Belgium's Flanders region introduced a take-back obligation that requires the last owner to hand in end-of-life vehicles to licensed recovery centers (or to car dealers if they buy a new car). Disposing of a vehicle in this way carries no charge. By 2005, 85% of each vehicle is to be recovered (up to 5% energy recovery allowed), and by 2015 the recovery rate must reach 95% (up to 10% energy recovery).

Given the need to increase recycling rates from their current level of about 75%, a principal challenge is to attack the remaining 25% that is associated with ASR. Altschuller (1997) provides an excellent discussion of the challenges associated with addressing the ASR associated with vehicle end-of-life. There are three principal strategies for enhancing the amount of the vehicle that is recycled or re-used:

- Expanded application of ASR pyrolysis and incineration
- Heightened use of ASR or ASR derived materials in products
- Increased utility of vehicle dismantling and component re-use approaches

Of course, it is unclear what effect any of these three strategies (or even the regulations being established in Europe and Japan) will have on the stability of the present vehicle recycling infrastructure. And, if the present recycling infrastructure is displaced with a more dismantling-oriented system, little thought has been given to the transition between the two systems.

One approach for dealing with ASR is pyrolysis. By heating the largely organic materials that constitute ASR in the absence of oxygen, it is possible to generate low grade petrochemicals, along with ash and heat. If the petrochemicals produced from pyrolysis are unable to serve as feedstock for manufacturing processes, then incineration is a better alternative for the recovery of ASR energy content. While pyrolysis is technologically feasible, its implementation is inhibited by the present economics of automobile recycling. The potential profit from the sale of the petrochemicals (pyro-gas and pyro-oil) does not offset the combined costs of acquiring the technology and procuring the ASR feedstock. The principal advantage of both pyrolysis and incineration appears to be in keeping material out of landfills rather than profit. The economics of both are dependent upon the process efficiencies and whether the ASR feedstock must be purchased (will shredders pay to dispose of their ASR waste?). Both pyrolysis and incineration are potential pollution sources, although new technology appears to control airborne emissions fairly well. In fact, one German Web site reports that a modern waste incineration plant has less emissions than the trucks delivering the waste input. The issue of hazardous waste also represents an issue of concern (e.g., dioxins and chlorine).

According to one German consulting company, GUA (Gesellschaft für umfassende Analysen), recent European legislation (issued in Germany, Austria, Switzerland, Scandinavia and the Benelux countries) stipulates that virtually no organic carbon shall be disposed in landfills. A typical regulation is to restrict the content of total organic carbon in all landfill materials to 5% by weight. This goal can only be reached through significant waste incineration. The majority of the population now accepts the fact that waste incineration is less harmful to the environment than landfilling.

Certainly, seeking another use for the materials within the ASR is preferable to incineration. Much research has been performed and continues on this issue. Researchers at Argonne National Laboratory have developed an ASR separation technique that separates the ASR into three categories: polyurethane foam (15-20% of ASR by weight), particulate iron "fines" (30-40%), and plastics (about 50%). Materials in the first two categories have market value. The foam can be used again (e.g., carpet padding or automotive applications). The iron fines are contaminated with other light metals, but can be used as feedstock for other products. Research is still needed to address the plastics-dominated balance of the ASR (Altschuller 1997). Toyota (Kajiwara 2000) has established an ASR recovery plant that can process 100 tons of ASR per day and is able to increase the vehicle recovery rate to 87%. The processes used in the plant are performed dry, and markets for the streams emanating from the facility have been established (bricks, sound absorption materials, etc.). The facility operates as a subsidiary to Toyota.

The two approaches (incineration/pyrolysis and separation) that are focused on the processing of ASR essentially seek to work within the existing vehicle recycling infrastructure. This infrastructure relies heavily on shredding processes and is focused on material recovery rather than the recovery of individual components. Some researchers envision that it will require a sea change in the vehicle recycling system to achieve the high recycling rates referred to earlier. This view calls for the dismantling of vehicles, reuse of components where possible, and the recycling of the remaining materials. This comprehensive dismantling process differs substantially from the process being undertaken at present. As has been stated previously, currently only those components that can be readily removed and easily marketed are addressed. A comprehensive vehicle dismantling process involves taking apart the car piece by piece: fluids, engine, body, interior, etc. This more thorough dismantling/disassembly process would greatly reduce the amount of material that is shredded and therefore reduce the quantity of ASR. In part enabled by higher levels of unemployment, nascent dismantling activities are underway in Europe (including those by U.S.-based automakers), but more research is needed in this area. Attention must also be devoted to designing automobiles that are compatible with such dismantling activities. In the U.S., one company (Comprehensive Automotive Reclamation Services (CARS) of Maryland) is engaged in the total dismantling concept using technology from the Netherlands. The Netherlands is a leader in state-of-the-art dismantling systems because its National Environmental Policy Plan finances environmentally sound automobile recycling (Johnson 1995).

Robert M. Day (World Resources Institute) notes that “proactive companies take a leadership position that allows them some influence over the form of future constraints. A good example is BMW’s leadership on the issue of product take-back in Germany. By taking a visible leadership position on the issue, BMW anticipated, and even promoted, new regulatory take-back requirements which, because it held a strong market position in automobile disassembly, not only helped reduce waste but also provided it with a market advantage.”

An overview of the challenges associated with vehicle end-of-life has been provided. Motivated by their limited landfill space, regulations have been established in Europe that call for very high vehicle recycling rates. Similar regulations are being established in Japan. Given the existing recycling infrastructure, ASR incineration and pyrolysis (to recover energy content) are the easiest techniques to reduce the amount of material going to landfills. Other strategies seek to recover the original materials from the ASR (Argonne method). Europe is pioneering the use of vehicle dismantling techniques that could dramatically change the vehicle recycling infrastructure. Take-back regulations do not exist in the U.S., and given the relative abundance of landfill space, there is little economic incentive domestically to address the ASR problem. However, automakers based in the U.S. must abide with the regulations of Europe and Japan for the vehicles that are sold there. As a consequence, they are closely following developments overseas.

System-level Issues

Previous sections have addressed environmental issues for various stages of the vehicle life cycle: materials, manufacturing, use, and post-use. There are several topics related to the automotive industry that could not be accommodated as part of this classification scheme. These subjects include inter-company relationship challenges, industry-government concerns, standards, the role of e-commerce, and philosophical changes in how a company views its business. A brief discussion of several of these issues is provided below.

The future of transportation (including the effects of such topics as e-commerce) is addressed by Graedel and Allenby (1998). They conclude that cultural trends will not greatly impact the short-term increase in the size of the automobile sector and that the impact of e-commerce will not reduce the size of the automobile sector nor reduce the number of miles traveled by society. The number of automobiles will increase in the future. Research is needed on a variety of topics to support this growth in an environmentally sound manner. These topics include the development of new energy sources, more efficient energy storage systems, and advanced materials. In addition, research is needed that is directed at the development and maintenance of the complete transportation system to reduce its energy intensity and rate of resource consumption.

One of the disturbing trends that surfaced during the course of the site visits conducted during this study concerned a significant difference between the U.S. companies and those in Europe and Japan. Individuals from U.S.-based plants frequently commented that existing regulations tend to inhibit technology changes that could result in positive environmental effects. It seems that once a given process technology has been formally approved, as new (better) technologies are developed the burden to pursue the formal approval of these new technologies is often so large that the technology changes are not pursued. This appears to be in sharp contrast to industry-government interactions abroad where there is a common vision regarding technological innovations directed at environmental improvement and economic development.

All of the automakers and suppliers that were visited, as well as those identified via the Internet and the technical literature, are pursuing or have achieved some level of ISO 14000 certification. While the European-based organizations appear to view this pursuit as completely consonant with their overall environmental strategy, attitudes in Japan and the U.S. seem to be more focused on certification as a hurdle to achieve market entry. Automakers in the U.S., Japan, and Europe all have well documented environmental strategies. In the U.S. the Tier 1 suppliers are also literate with regard to environmental issues, although there was some variability evident in the commitment level of the suppliers to environmental issues. All automakers are asking their suppliers to become ISO 14000 certified, and again, there was variability in where the suppliers stand in this certification process. The expectation is that this ISO certification requirement will be passed through the supply chain.

GM and Ford suppliers have notified their Tier 1 suppliers that they need to be ISO 14001 certified by the end of 2002.

The management and synthesis of information across the automotive supply chain is an issue that extends well beyond the topic of environmentally benign manufacturing. There are a number of open issues about how to propagate environmental measures across the supply chain. For example, as the automakers track their energy usage from year to year, how can the energy usage of the suppliers be properly incorporated? Supplier data on emissions, wastes, and resource consumption are also needed, and techniques for combining all this information are needed. It is clear that much work will be required before some of the ISO 14000 standards will be met (e.g., ISO 14020 series on eco-labelling).

Several representatives of the automakers were queried about corporate trends in selling “product use” rather than the product itself. Under such a scenario, the manufacturer (or its agent) would retain ownership of the product and consumers would pay to use the product. While they were aware of this concept, there does not appear to be any concerted effort to move the industry in that direction. On the other hand, the auto industry does distribute approximately 30% of its vehicles through lease programs, and one could argue that this is in fact “selling use.” There did not appear to be any significant differences in attitudes to this idea across the sites that were visited.

Building upon the thought of the previous paragraph, the notions of product stewardship, extended producer responsibility, and vehicle take-back represent considerable challenges to the auto industry. This is especially true in light of the trend in the U.S. for automakers to delegate more and more of their manufacturing tasks to their suppliers. It is unclear who will be responsible for end-of-life vehicles. Certainly, communication with suppliers indicated that most do not believe they have any extended responsibility for a product after it has been sold to their customer. Given the previous comments about the post-use stage of the vehicle's life cycle, it is likely that these issues will first be addressed in Europe.

In closing this section, one of the principal differences that was evident between the U.S. and Japan/Europe was the attitude of consumers toward vehicles. While consumers in the U.S. have recently complained about the high cost of gasoline, the prices are still well below the prices abroad. The high cost of driving and maintaining a vehicle in Europe/Japan has, in part, created consumer habits/attitudes that differ remarkably from those practiced by individuals in the U.S. It is hard to imagine wide consumer acceptance in Japan/Europe of SUVs that are presently so popular in the U.S. A large gap exists between the environmental awareness of consumers in the U.S. and those in Europe and Japan. Clearly, efforts must be undertaken to better educate the U.S. public on matters related to the environment and resource conservation.

Summary

The automotive industry is one of the largest and most important industries in the world. As part of this study, sites were visited in Japan, Europe, and the U.S. The following general observations about the emphases each country places on the environment are described below:

- In Japan the focus is on reduction of solid waste and energy usage/CO_2 emissions.
- In Europe attention is directed at reducing solid waste and achieving ISO 14000 certification.
- In the U.S. emphasis is directed at compliance with government regulations and promoting worker safety.

In terms of public recognition of environmental issues, Europe appears to be the leader closely followed by Japan, with the U.S. being a distant third. European governments are rapidly establishing a number of environment-related regulations, and Japanese industry closely tracks activities in Europe. With a few notable exceptions (e.g., the DOE Office of Industrial Technologies), the U.S. government is largely focused on penalizing non-compliance with regulations rather than promoting environmental improvements. (In their defense, many of these organizations were created for the purpose of enforcement.) Company-to-company differences in terms of the environment are far less than those from country to country.

Environmental issues surround each stage of the vehicle life cycle (materials, manufacturing, use, and post-use) and there are a number of system oriented issues as well. Research on the following topics is needed to address challenges associated with each life-cycle stage:

- Materials: development of technologies to support the use of light weight materials
- Manufacturing: reduced waste and improved energy efficiency of processes, including casting, sheet metal working, glass manufacturing, painting/coating/plating, machining, joining, plastics processing, and part washing
- Use: advancement in alternative fuel/engine/power plant technology to achieve higher fuel economies and lower emissions
- Post-use: improved recovery rates of ASR and increased attention to disassembly and dismantling; assessment of the economics/stability of the vehicle end-of-life system
- System: role of suppliers and the management of information in the supply chain, and product stewardship

It would also seem prudent to re-examine company-government interactions and the role of regulations in promoting environmental improvements. Do the existing relationships and regulations simply require compliance or do they promote never-ending improvement? Lastly, and perhaps most important, the U.S. public lags far behind other nations in environmental awareness—strategies should be undertaken to close this gap.

ELECTRONICS (C.F. MURPHY)

Summary

The dual trends of growing consumption and decreasing product life spans presents a serious end-of-life issue for electronic products. For example, PCs (personal computers) are expected to see a six-fold increase in the obsolescence rate over a six year span, reaching about 65 million PCs per year in 2003. Furthermore, as the PC has evolved, there is a tendency toward material compositions that are less economical to recycle. The volume of precious and base metals used on integrated circuits and printed wiring boards has decreased, and the housings are more commonly made of engineering thermoplastics rather than steel. In addition to the end-of-life issues surrounding electronics, there are significant environmental impacts associated with electronics manufacturing, particularly from wafer fabrication processes. These processes, which are characterized by gaseous deposition, ultra-clean manufacturing environments, and in some cases low yields, result in high amounts of waste and wastewater, high usage of energy, and the emission of materials of concern, including perfluoro compounds. Because of their importance, these issues have received research support through a variety of programs sponsored by SEMATECH, the National Science Foundation and the Environmental Protection Agency. Strategies to address issues at the wafer fab level have been outlined in the SIA (Semiconductor Industry Association) roadmap. A separate set of environmental issues is encountered at the printed wiring board and board level assembly steps. These include laminate manufacture and processing, cleaning, plating, etching, and various through-hole-plating and interconnect technologies. However, the current major focus is on lead-free solders. Driven primarily, if not exclusively, by the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive, there has been a strong incentive for electronics companies worldwide to develop alternatives to tin-lead (Sn-Pb) solder. (For further information on the WEEE Directive, see Committee on the Environment…2000.) Lastly there is a move toward the elimination of brominated flame retardants (BFRs), driven by the WEEE Directive, but also by the general tendency (outside the U.S.) to incinerate plastics and concern over potential liability associated with incineration at temperatures that are below optimum levels.

Introduction

The last decade of the 20th century has seen two defining trends: the explosive growth of electronic and information technology and the pervasive concern for environmental protection. These two trends are tightly interwoven by technical opportunities (increased function combined with decreased resource utilization), systems approaches to maximize yield and thus minimize waste, and a high-profile industry that has made environmental stewardship a priority. While the electronics industry is not a highly toxic one—with only 1.6% of the Toxic Release Inventory (TRI) emissions (MCC 1994)—the processes used to manufacture the components can be extremely wasteful. According to a study sponsored by the Department of Energy (MCC 1993), fabrication of the silicon chips used in a workstation (with a total weight of less than an ounce) requires 31 pounds of liquid chemicals and 9 pounds of sodium hydroxide for wastewater neutralization. The printed wiring board manufacturing process produces 46 pounds of material waste for a total of 4 pounds of finished product.

In response to these concerns and opportunities, the electronics industry has been one of the worldwide leaders in the area of environmentally benign manufacturing. In particular, electronic product and component manufacturers have been proactive in the areas of life-cycle assessment (LCA), design for environment (DFE), and end-of-life management (ELM). The general industry culture of minimization, cost-reduction, and increased efficiency are all compatible with EBM. There are rapid changes in technology that result in average product life spans of 18 to 48 months. In addition, design changes often require process changes, which in turn may result in complete turnovers in capital equipment every 5-10 years. Consequently, design and process changes that benefit the environment may also be incorporated more rapidly and at less marginal cost than might be true in other manufacturing areas. Lastly, as a legacy of the quality movement and because of the complexity of the processes, the electronics industry is expert at managing and analyzing large amounts of data. This is key in the implementation, documentation, and management of environmentally benign manufacturing activities.

Focus areas within the electronics industry have been (1) materials of concern, including elimination and substitutions, (2) reduction in resource consumption, including product volume reduction, (3) design for disassembly and reuse, (4) board-level assembly technology and materials, (5) reduction in number of materials used, (6) emissions reductions, and (7) end-of-life disposition.

Electronics Manufacturing Overview

Electronics manufacturing can be divided into several sub-industries. These are wafer fabrication and chip-level packaging, printed wiring board (PWB) manufacture and board-level assembly, display manufacturing, and final assembly. Each of these has specific material sets and EBM issues.

Wafer Fabrication and Chip-level Assembly

Integrated circuits are manufactured on silicon wafers, with each wafer containing hundreds to thousands of individual integrated circuits. The wafer fabrication industry is represented by large, highly capital intensive manufacturers. The largest companies (by sales) are in the U.S., followed by Japan, and Europe. However, there are a number of emerging companies in Taiwan and Korea.

Wafers (and the resulting integrated circuits) are composed of elemental silicon with thin layers of silicon dioxide (SiO_2), aluminum, and in some cases copper. The manufacturing process consists of deposition of very thin layers and etching of patterns into sub-micron features. This involves energy intensive, gaseous processes that result in emissions of concern, especially PFCs (perfluoro compounds). In addition, functionality of the circuits is dependent upon ultra-clean surfaces, which in turn requires the use of significant amounts of water. The SIA roadmap (SIA 1999) identified several key concerns for environmentally benign manufacturing. These are qualification of new materials, reduction in PFC emissions, and reduction in energy and water usage. SEMATECH, a research consortium of which all of the major U.S. wafer fabricators are or have been members, has a major thrust area in environmental health and safety. The key project areas are closely aligned to the SIA roadmap. The NSF also has an ERC (Engineering Research Center) at the University of Arizona focused on environmentally benign manufacture of integrated circuits. This center has been focusing on water usage and chemical mechanical polishing (CMP), a process that uses large amounts of water and produces significant amounts of solid waste. NSF and EPA are also funding a project at the University of Texas (with Motorola and SEMATECH) to develop generic life-cycle inventory modules for wafer fabrication.

Processes in wafer fabrication are equipment driven; consequently, the relationship between equipment suppliers and the wafer fabrication companies is critical. This is true in the area of EBM as well. The panel conducted a site visit at Applied Materials (see Appendix E). It was apparent from the information provided by Applied Materials that it is working very closely with customers to improve the overall environment footprint for wafer fabrication.

After wafer fabrication, the individual integrated circuits (chips) are singulated, bonded onto metal alloy lead-frames (Ni, Cu, ± Au), and assembled into ceramic or plastic (thermo-set) packages. This process is typically done by the wafer fabrication companies. In relation to other electronics processes, the EBM issues are relatively minor for this process. The processes do require heat (energy) and produce material waste and metal-bearing liquid waste.

Individual components are then assembled onto printed wiring boards, as shown in Figure 5.8.

Printed Wiring Board Fabrication and Board-level Assembly

The printed wiring board (PWB) industry consists of many manufacturers of varying size. Most are independent but some are captive (i.e., a division within an original equipment manufacturer, or OEM). While moderate capital investments are involved, this industry is more material-driven than equipment-driven in comparison to the wafer fabrication industry. Relatively small feature sizes (as fine as 3 to 4 mm) require a relatively clean environment, but much less so than for integrated circuits.

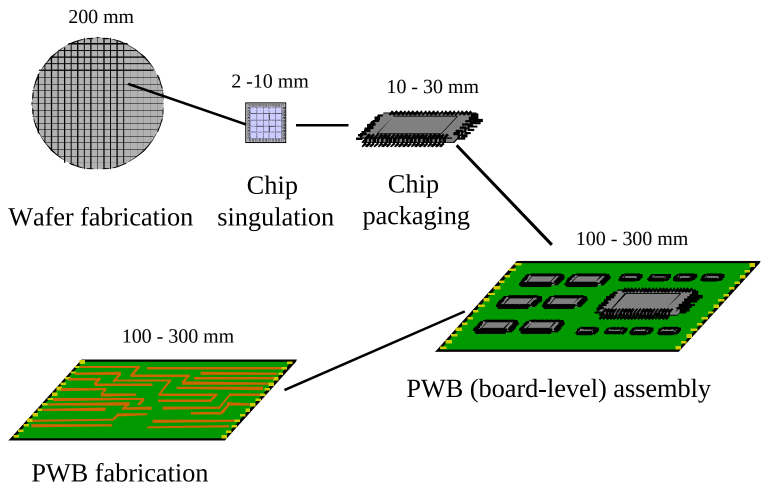

Fig. 5.8. Individual integrated circuits are fabricated on silicon wafers, singulated, packaged and assembled onto printed wiring boards.

The majority of PWBs fabricated today are multi-layer (four or more layers) and are commonly constructed using polymer composites and copper. The composites, typically epoxy-glass, provide structural integrity and electrical insulation and typically have glass transition temperatures (T_gs) of 140° to 160°C. T_gs in this range are compatible with current assembly processes that use lead (Pb) solder; however, with the move toward Pb-free solders, which require higher process temperatures, it may be necessary for PWB manufacturers to look at alternative materials for substrates (Miric and Heraeus 2000; Grossman 2000). (See site reports for Hitachi and Siemens, Appendices C and D.)

Copper, either plated or etched, provides electrical circuitry. Etched copper lines (within the plane of the boards) are typically passivated using an oxidation process that is water, energy, and chemical intensive. Connectivity between layers for the majority of boards is provided by plated through holes (PTHs) (Figure 5.9). Plating baths, used for PTHs and for surface metallization, use large amounts of water and complex chemistries (organic and inorganic compounds). The U.S. EPA Design for Environment (DFE) project identified "making holes conductive" as one of the key issues in its initial report (EPA 1995). Subsequent work explored the environmental impacts and costs of various options (EPA 1997). Another area of environmental concern is lamination of the layers, which uses large presses that are very energy intensive. Solid waste from the drilling process and from excise and trim can also be significant (as much as 50% of the total material budget) (Sandborn and McFall 1996).

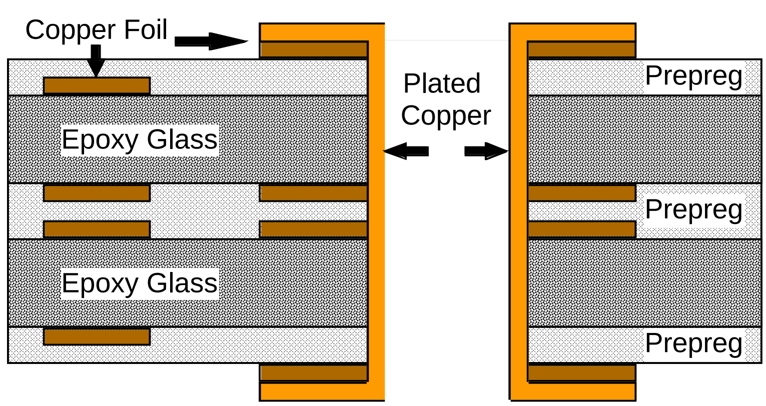

Fig. 5.9. PWBs are typically constructed with epoxy-glass and copper; connectivity between layers is most commonly provided by plated through holes (PTHs).

In addition to EPA's DFE project, the U.S. Defense Advanced Research Projects Agency (DARPA) Environmentally Conscious Manufacturing Program funded a number of industry projects in the mid 1990s that focused on PWBs (DARPA 1996). This resulted in several technical successes. IBM developed a laminate material derived from renewable resources (lignin derived from pine trees). DuPont commercially introduced a permanent resist that eliminates the need for the copper passivation (oxidation) process. DuPont, Shipley, and Ormet developed several fully additive processes that use microvia technologies in conjunction with photoimagable dielectric (Figure 5.10) (Lott, Quindlen and Vaughan 1997; Lott, Kraus, and Murphy 1997; Sandborn and Murphy 1998; Murphy et al. 1997). These technologies use significantly less water and produce less waste than conventional PTH constructions.

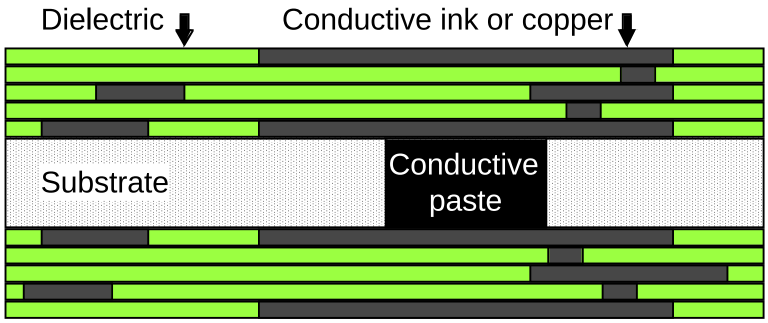

Fig. 5.10. Microvia technologies typically use less water and produce less waste than conventional plated through holes.

There are a number of emerging microvia technologies (Rasul, Bratschun, and McGowen 1997; Holden 1996). Sony (see Appendix D) and a number of other companies are beginning to incorporate these into their products. While the motivation is typically performance driven, these approaches should all be inherently more environmentally friendly. They require fewer layers and smaller areas for the equivalent amount of wiring, thus reducing the amount of resource consumption for the same function. There is less solid waste because the drilling operation is minimized or eliminated. In addition, smaller geometries require greater precision in order to maintain yields. This is making it more attractive for companies to invest in the capital equipment that will allow them to move from mechanical alignment to vision alignment. This in turn results in a drastic decrease in the amount of trim waste.

In the area of EBM, one of the biggest challenges for PWB manufacturers in the near future is the use of brominated flame retardants (BFRs). This is in large part due to the WEEE Directive, which was approved by the European Commission on June 13, 2000 (but which must still be formally adopted by the European Parliament prior to being officially implemented). This directive, which bans the use of many substances, including some BFRs, will be discussed in more detail in a subsequent section.

Completed PWBs are prepared for board-level assembly using Sn-Pb solder. The boards are heated to the melting point of the solder and packaged ICs are placed on the boards, typically using pick-and-place mechanical systems. The use of Pb solder dominates the environmental concerns for this process and is a key area of concern for electronics end-of-life.

Displays

Computer displays are predominately cathode ray tubes (CRTs); however, an increasing number of displays are flat panel displays (FPDs) that are used either in laptop computers or as stand-alone desktop units. Most small- to medium-sized CRTs are manufactured in Japan. Large displays for the U.S. market are made in the U.S., as these units are quite heavy and therefore costly to transport significant distances. During the manufacture of CRTs, the environmental issue is energy consumption due to the extreme temperatures used to form the glass. The biggest concern surrounding CRTs, however, is the lead that is contained in the funnel glass and in some panel glass and its potential effect on groundwater supplies if placed in landfill. Massachusetts has banned landfilling of CRTs, and at least one large international waste-disposal company has considered banning them from all of their landfills as well.

Envirocycle (http://www.enviroinc.com), located in Hallstead, Pennsylvania, has an effective glass-to-glass recycling program. In a combination manual and automatic process, leaded funnel glass, leaded panel glass, and unleaded panel glass is sorted. The resultant separated glass is then sold to major CRT glass manufacturers, principally Techneglas and Corning. These CRT manufacturers are able to incorporate this sorted glass cullet back into new monitors. At the Hallstead site, Envirocycle currently processes 600 tons of glass per week. However, most monitors in the U.S., Europe, and Japan are recycled by including them in smelting processes.

Flat panel displays are expected to introduce a new set of environmental issues. However, because most are manufactured overseas using proprietary processes, the exact nature of these problems has not yet been defined. EPA's DFE program is currently looking at FPDs to try to characterize their material content (EPA 1998b). MIREC (see Appendix C) shreds laptop computers as a single unit in order to avoid having to worry about whether there might be hazardous materials associated with the FPDs. (As a product, rather than a set of materials, hazardous substances are not controlled.)

Other Components

Nickel/cadmium batteries are a problem due to the cadmium. The EC WEEE Directive includes a ban on cadmium in electronic products. However, with the shift to lithium batteries, this will primarily be a problem with older products at end-of-life. Storage media, specifically hard drives, have been manufactured using processes similar to wafer and PWB fabrication and have similar problems with water consumption and plating bath solutions. During the site visit to IBM, San Jose (see Appendix E), it was explained that IBM had manufactured the disks using nickel and magnesium plated over aluminum. The aluminum in these disks could not be recycled due to the nickel. Recently, however, IBM switched to glass substrates for performance reasons (tighter dimensional control). The glass does not require a nickel adhesion layer, which simplified the process and consequently has reduced the environmental impact of the manufacturing process. In addition, the glass disks can be recycled by a local glass recycling company. One of the more striking aspects of this success story was that IBM personnel noted and publicized the positive environmental impact of a technology improvement where the primary focus was not EBM.

Final Assembly

The individual components of a computer and other electronic products are typically housed in a case made of engineering thermoplastic. It is estimated that more than 3 billion pounds of plastics were consumed by the U.S. electric and electronic products industry in 1996 (SPI 1997). The Microelectronics and Computer Technology Corporation determined that almost 23% (by weight) of a typical desktop computer consists of engineered thermoplastics (MCC 1996). Since the current trend is to minimize both cost and weight of electronics devices, it is expected that the amount of plastic used in these products will only increase. Plastics that dominate the market share in computers, business machines, and other electronic products are high impact polystyrene (HIPS), 22.7%; acrylonitrile butadiene styrene (ABS), 20.5%; polycarbonate (PC), 19.2%; PC/ABS blends, 11.7%; and polyphenylene oxide blends (PPO), 6.5%; the remaining 19.4% consists of a variety of other plastic blends (Arola, Allen, and Biddle 1999).

There are some issues with material waste and energy use during the manufacture (extrusion and molding) of plastic parts for use in electronic products (see polymer section of this chapter). However, the chief environmental concerns for thermoplastics occur at end-of-life. In both Japan and Europe, landfill of solid waste is being significantly reduced or eliminated and being replaced by recycling and/or incineration. Both of these options pose challenges for the plastics used in electronic products.

Recycling of many plastic products (such as bottles and film) has been quite successful. However, these are typically made of a single plastic and do not have other (non-plastic) materials affixed to them. The components of a single electronic product, however, may use 10 different types of plastics, some of which may be painted or coated, and all of which are attached to other parts that are made of plastic (probably of a different composition), glass, or metal. This contamination with non-plastic materials and by commingling of different types of plastics makes recycling technically difficult and therefore economically problematic.

Incineration of the plastics used in electronic products is an issue when brominated flame retardants (BFRs) are used (most commonly in ABS). This is due to the concern that BFRs could be precursors for the formation of carcinogenic dioxins if incinerated at less than optimum temperatures.

End-of-life Management

Electronic products and/or components have been recycled for decades. Historically this has been driven by the use of significant amounts of precious and base metals (e.g., gold, palladium, copper, and lead) on the chips and boards. Housings were typically constructed of steel, which is also a relatively cost-effective material to recycle. In addition, many of the components were very costly and had lifetime utilities that made recovery profitable. In recent years, however, recycling of electronic products has become increasingly less economically viable. Silicon chips are no longer gold-backed, the volume of precious and base metals used on PWBs has decreased (in part because the boards themselves are smaller), housings are more commonly made of engineering thermoplastics than steel, and components are less costly and have much shorter lifetimes.

At the same time that recycling of electronic materials and components is becoming less economically attractive, there is growing pressure to recycle. First, the volume of electronic products being manufactured is growing at an unprecedented rate and product lifetimes are being shortened, thus accelerating rates of obsolescence. The National Safety Council issued a report (NSC 1999) that presents data for personal computers showing estimated number of computers shipped, average lifetimes, and rates of obsolescence for the years 1992-2007. This information is shown graphically in Figures 5.11–5.13. Second, in Europe and Japan there is pending legislation that requires electronic equipment to be recycled. The Netherlands has already enacted such legislation and has made the producer of the equipment responsible for the cost of recycling. MIREC (Appendix C) handles 95% of all end-of-life electronic products. Third, in the U.S., Massachusetts has banned landfilling of CRT displays because of the lead they contain. Several states, including Minnesota and Florida, are discussing similar actions, and it is anticipated that other states may follow. Lastly, the Department of Defense (DOD) and the Department of Energy (DOE) have an interest in properly handling their end-of-life electronic products either because of sensitive technology and/or information or due the hazardous materials that they may contain. In response to this, both agencies have multi-million dollar projects to develop electronics recycling technologies and establish disposition centers.

While some equipment may be cascaded (high performance equipment sold or transferred by original owners/users to second owners/users with lower performance demands), the ability to do this is limited. It has been found that for a three-year-old personal computer, recovery costs equal the value of the system, and at five years, the system has virtually no value (even with zero recovery costs) (Grenchus, Keene, and Nobs 2000). For this reason, there is increasing interest in materials recycling of electronic products.

Recycling of the metals contained within electronic equipment, as stated earlier, is well established. Most electronic product recyclers focus on this material recovery operation. Micro Metallics (Appendix E), which is jointly operated by Noranda and Hewlett-Packard in Roseville, California, is an excellent example of this type of approach. Material scrap is shredded and separated into steel, plastics, precious metals, and base metals plus glass. Precious metals and the base metals plus glass mixture are sent to Noranda's smelter in Canada. Steel and plastics are shipped to other companies that can make use of these materials. Of most concern to recyclers, whose profits depend upon the metal content of electronic products, is the decreasing amount of all metals, and precious metals in particular, in electronic products.

Glass recycling is currently not a well-established technology, primarily because of the lead content in the CRT glass. Envirocycle in Pennsylvania has a glass-to-glass recycling operation (CRT glass is re-used as CRT glass) and the DOD's DEER2 project in Florida has an outlet for leaded glass in glass bricks and ceramic tiles for use in X-ray laboratories. However, both of these are somewhat limited markets and the economics of these technologies is still being optimized. Most CRT glass is currently sent to smelters, where it is used as flux, and some is sent overseas where control of lead content is less stringent.

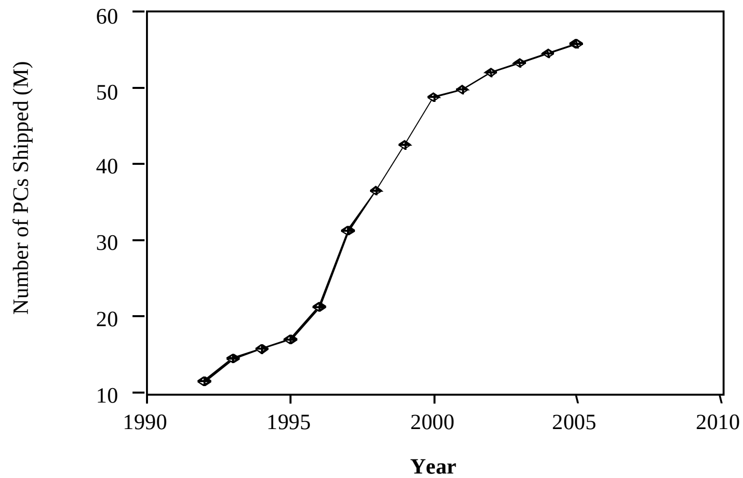

Fig. 5.11. In the U.S., the number of PCs shipped in 1992 was 11.5 million. In 2005, the number is projected to be 55.8 million. Data from National Safety Council 1999.

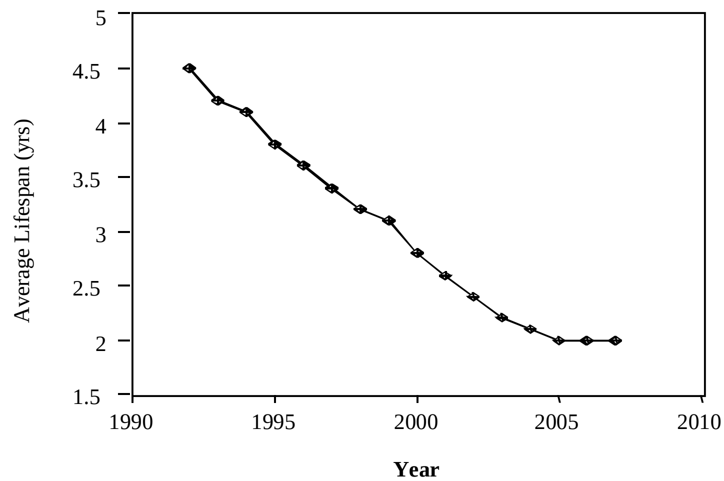

Fig. 5.12. The average lifetime of a PC in 1992 was 4.5 years. By 2005, the average age is projected to be two years. Data from National Safety Council 1999.

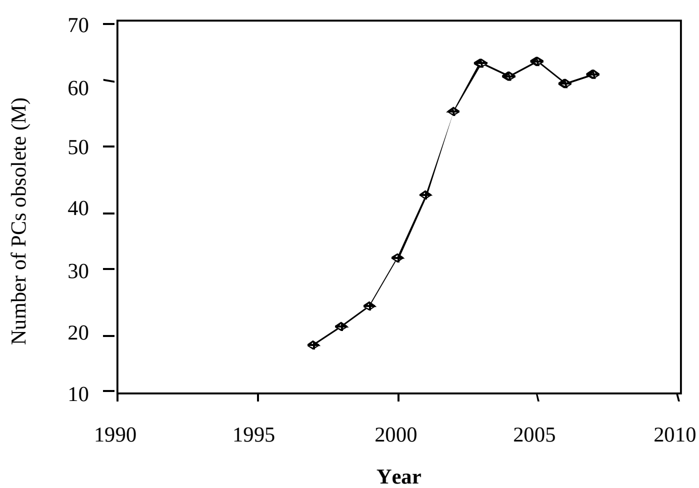

Fig. 5.13. The number of PCs that became obsolete in 1997 was 17.5 million. By 2007, the number is projected to reach 61.3 million. Data from National Safety Council 1999.

The barriers to recycling of engineering thermoplastics have been the subject of ongoing "stakeholder dialogues" at Tufts University. The Massachusetts Chelsea Center for Recycling and Economic Development provided funding for the first two dialogues in May and June of 1999. The U.S. Environmental Protection Agency Office of Solid Waste provided funding for two additional meetings in December 1999 and April 2000. The Department of Energy plans to continue funding this effort beginning in September 2000. A number of excellent background reports on the challenges to engineering thermoplastics recycling have been issued by The Gordon Institute (TGI) at Tufts University (Dillon 1999a; Dillon and Aqua 2000). The Stakeholder Group is now working to develop collaborative industry solutions (Dillon 1999b; Dillon 2000). These reports are available on the TGI Web site (www.gordoninstitute.com).

One of the biggest problems with recycling plastics used in electronic products is the presence of flame retardants. In Japan and Europe, plastics are incinerated rather than recycled, and the presence of brominated flame retardants (BFRs) raises the concern of dioxin formation during the burning process. As currently written, the WEEE Directive in Europe bans the use of plastics containing selected BFRs. Unfortunately, BFRs are very difficult to detect economically in a recycling process. Since most products sold in the U.S. contain these substances, and plastics cannot effectively be sorted by whether they contain BFRs, it is assumed that most recycled plastic from electronic products, particularly ABS, contains flame retardants. Consequently, many OEMs are reluctant to include recycled plastics in new products that may be sold in Europe.

Regional Trends

Both Japanese and U.S. companies are highly responsive to activities in Europe, particularly the WEEE Directive, with the primary focus being elimination of halogenated flame retardants (typically BFRs) and lead-containing solder. ISO 14000 certification is a key concern for Japanese companies; in Europe there is a moderate effort to complete certification; and in the U.S., it is primarily the international companies that are actively pursuing ISO 14000 activities. While the U.S. leads in developing alternative PWB technologies (such as microvias), the Japanese are most aggressively pursuing these alternatives in commercial products. The motivation is typically reduced size and increased performance for portable consumer products; however, the processes used to manufacture these boards typically use less water, energy, and material resources. Hitachi, Sony, NEC (Appendix D), and many other companies (IBM, Motorola, etc.) are all using this approach in some of their products.

Europe has several countries with take-back legislation in place, but The Netherlands appears to be the only country to date with a well-developed infrastructure for collecting and recycling computers. It is expected that other members of the EU will follow suit within the next few years. The industry representatives the WTEC team visited indicated that there is a strong push to be able to document EBM practices in both their own manufacturing processes as well as from suppliers. Both Philips and Lucent are especially active in this area (see site report for TU Delft in Appendix C). Companies such as Siemens (Appendix C) offer "green" products in parallel with conventional, but with a price differential.

U.S. electronics companies are responding to activities in Europe by investigating alternatives to lead solder and BFRs. However, these activities are moving more slowly and with more reluctance than in Japan. The general feeling is that the benefits of the materials far outweigh the environmental risks. There is more interest in disassembly technologies and design for disassembly. There is also a strong emphasis on metrics and supply chain management. Most recycling activities in the U.S. are occurring (or have occurred) as partnerships with OEMs. Examples of this are Micro Metallics (Noranda and Hewlett-Packard, see Appendix E), Dell Computer and Resource Concepts Inc. in Dallas, AT&T/Lucent and Butler-MacDonald in Indianapolis, and IBM's Aurora project in central New York state.

Pb-free Solder

Driven primarily, if not exclusively, by the European Union's WEEE Directive, there has been a strong incentive for electronic companies worldwide to develop alternatives to tin-lead (Sn-Pb) solder. This material has been the primary means of attaching electronic components and connectors to PWBs. Sn-Pb solder is easy to work with, as it is a simple system that has a well-defined eutectic (melting point) at a relatively low temperature. If manufacturing processes are well controlled and products are recycled, there is little environmental risk to using Sn-Pb solder, as it is easily recovered. However, the concern is that if control of Pb-containing products is inadequate, these products may end up in landfills and ultimately contaminate groundwater.

There is, however, resistance to converting to Pb-free solders. Sn-Pb solders have extremely high reliability through thermal excursions. Most military and automotive applications require components to be able to survive 1000 cycles between +125°C and –65°C. One of the challenges with Pb-free solders is difficulty in achieving this performance. Several companies have released products using Pb-free solders. In at least one instance, however, the product was pulled from the market due to failures associated with thermal fatigue. Hitachi, Sony, and Siemens were all quite open in discussing these issues with the panel.

A second problem with Pb-free solders is that they typically have higher melting temperatures and therefore require increased process temperatures. Since this is one of the final processes seen by the PWB, all the materials and components on the board must be able to withstand the increased thermal exposure. Most of the laminates currently used to construct PWBs have relatively low glass transition temperatures. This means that alternative, and probably more expensive, substrates will need to be used. The industry also needs capacitors and resistors that can withstand increased temperatures. The Pb-free solder processes are also more energy intensive.

Sn-Pb solder has only two components and the composition (and therefore eutectic) are easy to control. Most of the Pb-free solders have at least three components and some have as many six. This makes it more difficult to maintain a uniform composition, thus making process control much more critical and increasing the likelihood of process scrap. Many of the Pb-free alternatives are difficult to rework (leading to additional scrap) or disassemble. Some contain elements that are incompatible with recycling processes.

Finally, if a full life-cycle analysis is done, it is unclear that Pb-free solders are actually more environmentally friendly (Turbini et al. 2000). If material availability, impacts of extraction, increased processing difficulties, and end-of-life issues are accounted for, Sn-Pb solder may actually be a better choice. Ultimately the best solution may be completely new attachment technologies that do not use solder, such as adhesive flip chip.

Flame Retardants

The use of flame retardants may be one of the most unclear and confounding environmental concerns affecting electronic products. Since many polymers are highly flammable and their presence in electronics provides a ready source of heat and/or energy, there is a very real concern that flame retardants of some type be incorporated into the housings (thermoplastics) and printed wiring boards (thermo-sets) used in electronic equipment. According to one source, flame retardants saved over 900 lives in 1991 (Squires 2000). Historically, electronic components have used halogenated flame retardants, organic compounds containing chlorine or bromine. Chlorinated flame retardants are well known to have detrimental effects on both health and the environment. While these compounds have been replaced with brominated flame retardants (BFRs), which are believed to be much safer, the legacy of halogenated flame retardants in general continues to linger. Even if the focus is limited to BFRs, there is confusion as to whether all BFRs or only certain ones (many of which are no longer used in electronics) should be considered. There are numerous commercial BFRs, each with unique chemical, physical, and toxicological properties.

The European WEEE Directive addresses several concerns with the use of flame retardants. The primary ones are (1) formation of dioxins and furans during incineration or recycling, and (2) persistence and bioaccumulation. According to the WEEE draft from June 13, 2000, copper (which is used to form the electrical interconnects in PWBs) "works like a catalyst, thereby increasing the risk of formation of dioxins when flame retardants are incinerated. This is of particular concern as the incineration of brominated flame retardants at a low temperature (600-800°C) may lead to the generation of extremely toxic polybrominated disbenso dioxins (PBDDs) and polybrominated disbenso furans (PBDFs)." Representatives within the electronics industry, however, believe that this is misleading, in that when properly maintained and operated, incinerators are never used at such low temperatures. The draft directive also expresses concern that dioxins and furans may form during recycling (smelting) of metals and extrusion of recovered plastics associated with waste electronics. In addition to questions regarding actual temperatures of operation, it is unclear whether or not the BFRs currently in use in electronic products exhibit these particular phenomena.

The WEEE Directive calls for two specific BFRs, polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs), to be phased out by January 1, 2008. Most of the evidence cited within the directive as to the environmental and health issues associated with BFRs address only these two substances. However, these compounds are rarely if ever used and most are no longer manufactured. Even within the directive it is noted that PBBs and PBDEs account for only 1% and 9%, respectively, of the flame retardants found in waste electronics (presumably in older equipment).

There are two primary families of BFRs currently in use. The first is polybrominated diphenyl oxides (PBDPO), which include DBDPO (decabromodiphenyl oxide), OBDPO (octabromodiphenyl oxide), and PeBDPO (pentabromodiphenyl oxide). In the electronics industry, DBDPO is the dominant PBDPO BFR and is used primarily in computer housings. The second family of BFRs is the phenolics, which includes TBBPA (tetrabromo-bisphenol A). TBBPA (also referred to as TBBA) is used primarily for printed wiring boards. There continues to be debate as to whether these compounds are actually an environmental problem. Initial studies suggest that they do not have any negative persistence or bioaccumulation characteristics (Hardy 2000; Hedemalm et al. 2000). In addition, substitutes or alternatively complete elimination of flame retardants altogether may not actually be beneficial to the environment (Simonson and Stripple 2000; Segerberg et al. 2000).

Despite the debate about whether or not there are sufficient data to support the environmental and health concerns surrounding use of the BFRs currently in use, there is a significant effort within the electronics community to find substitutes, particularly in Japan and Europe. Sony is investigating phosphate esters and nitrite flame deterrents and plans to begin mass production of halogen-free double-sided CEM3, double-sided FR4, 4-layer epoxy-glass plated-through-hole (PTH), and 8-layer blind-via (BVH) boards. In contrast, the U.S. based trade association, IPC, which represents manufacturers of printed wiring boards (PWBs), has a task force on flame retardants. The task force takes the position that there are no obvious alternative flame retardants for BFRs used with the epoxy-based resins (thermo-sets) from which PWBs are constructed. However, members of this task force are beginning to investigate possible solutions with a focus on technical performance and cost. One approach is to use large organic aromatic molecules or nitrogen containing compounds that do not burn well. According to one of the task force members, who works for DuPont's iTechnologies (Appendix E), these technologies can be applied to polyimides (a very small portion of the PWB market), but not all other laminate materials. Another option for eliminating BFRs is to design PWBs such that they do not require any flame retardants (Bergendahl 2000). This includes using materials with low rates of combustion and high glass transition temperatures. In addition, fuses that minimize operating temperatures and use of materials that conduct heat well may also reduce the need for flame retardants.

The exterior cases for electronic products are constructed of thermoplastics. The most common of these are PC/ABS and ABS, which are extremely flammable. ABS is commonly used because of low cost and good performance (mechanical properties); however, it is one of the most flammable of the engineering thermoplastics. There are alternatives to BFRs for thermoplastics, including the choice of the specific plastic used. Among the flame retardants being explored for thermoplastics are inorganic fillers such as MgO and nanocomposites (extremely fine alumino-silicate clay). However, these inorganic fillers may require very high loadings that can have significant consequences on mechanical strength and electrical properties and therefore cannot be used in all applications. Another alternative is red phosphorus, but it is not clear that this is a more environmentally friendly solution.

Conclusions

The electronics industry is a complex one, with many different "sub-industries" that contribute the components that make up a final electronic product. There have been significant efforts in the area of environmentally benign manufacturing, especially for wafer and printed wiring board fabrication, but due to the ever-changing nature of the industry and its immense complexity, it continues to have environmental issues associated with it. It is also highly competitive and regionally segmented, making it at times difficult to differentiate between environmental and market share initiatives. The current areas of greatest concern are product take-back and recycling, Pb-free solders, and flame retardants (see the DuPont-RTP site report).

ENERGY (T. PIWONKA)

Summary

The primary source of energy for most of the world today is the energy released when carbon is combined with oxygen. This reaction produces carbon dioxide (CO_2) that is usually vented to the atmosphere, a condition that has been linked to global warming. In addition, carbon combustion releases organic decomposition products formed from the presence of other elements, such as sulfur, nitrogen and chlorine in carbon-containing fuels; many of these have been shown to be hazardous to biosystems. This discussion will focus on the methods being explored to reduce the production of carbon dioxide and the current status of alternative energy sources.

Introduction

Manufacturing requires energy. And, since some forms of energy production generate pollutants and greenhouse gases, especially carbon dioxide, the choice of energy source has important implications in designing an environmentally benign manufacturing process.

The ideal energy source should be safe, non-polluting, portable, reliably available in all climates and locations, inexpensive and of high quality. Safe means that opportunities to release the energy uncontrollably, as in an unwanted explosion, are nearly non-existent. Non-polluting means that greenhouse gases, pollutants and radioactivity should not be released as a by-product of energy generation. Portable means that the source can power transportation equipment, such as motor vehicles aircraft and ships, without regard to their position relative to a primary power generation source. Reliably available means that it must not be interrupted by changes in the weather, or require that people live in an unattractive part of the world to use it. High quality means that variations in power output are minimized. And it should be sufficiently inexpensive that it is within the economic reach of all.

Unfortunately, no energy source meets all of these criteria; all have some drawbacks. To a large extent, the question of producing environmentally benign products in an environmentally benign way depends on the choice of energy source used by the products and in their manufacture. Note, however, that many products, such as automobiles and aircraft, consume far more energy in use than in their manufacture.

Global Warming

Global warming is a problem of increasing concern worldwide. Mean temperatures have been rising at a slow but steady rate in the ocean and in the atmosphere since the middle of the last century (Dunn 2000). The rise in global temperatures tracks the increase in the amount of fossil fuels burned by humankind over the last 150 years very closely, leading to the conclusion that global warming is very probably caused by human activities. While the increase in global temperatures is not debatable, it is not established beyond all doubt that people are the cause of global warming, as the earth has gone through heating and cooling cycles in the past before humankind could influence these cycles. Nevertheless, the parallel increase in combustion of carbon-based fuels and global warming in the last 150 years is highly suggestive of a cause and effect relationship, certainly to the extent that a prudent engineer could assume that a direct relationship is probable.

Since global warming can be traced to the amount of carbon dioxide in the upper atmosphere, and carbon dioxide is formed from the combustion of organic matter which is burned in increasingly large amounts to heat and move people and to process materials, the implications could be serious. As the atmosphere warms, polar ice caps and glaciers melt, increasing the volume of water in the oceans. In turn, the ocean level rises, flooding low-lying coastal areas. Temperate growing areas shift towards the poles and away from the equator, disrupting civilization patterns that have endured for centuries. Precipitation patterns change, and the effect on ocean currents such as the Gulf Stream are not clear. In addition, there is concern about the possibility of a “runaway greenhouse effect” (Benarde 1992) in which the temperature of the earth increases very quickly and cannot be reversed, leading to conditions similar to those on Venus.

In addition to carbon dioxide, other gases, such as methane, also are greenhouse gases. Moreover, other hydrocarbon gases produced when organic matter such as petroleum products, wood, or coal is burned have been shown to cause disease and degrade the environment.

It has been argued that if the only effect of global warming is to move temperate zones closer to the poles, and perhaps inundate some low-lying coastal areas, the consequences are not really that serious. It is assumed that the consequences of global warming events would take an economic toll on society, in the form of migrations of people from seacoasts and areas of the world that become less desirable than they are today because of warming climates, or changes in precipitation. It is not known, however, what the long-term effect of global warming will actually be (Kerr 2000), or how adaptable people might be in re-locating from affected areas of the planet.

The concern over global warming varies by country. Japan takes the threat very seriously, and Japanese ads on television and in subways sell the environmental advantages of one product over another. One Japanese company, Horiba, is a world leader in the development of analyzers that track the generation of greenhouse gases and other air pollutants. In Kyoto a sign in a large public square announces the hourly concentration of carbon dioxide in the local atmosphere. Toyota includes in its annual environmental report the number of tons of CO_2 its engineering and operations have saved annually; one example is controlling the just-in-time truck shipments of parts from its suppliers to its assembly plants and shipments of finished products and parts to its dealers (Toyota 1999). (Though note that “just-in-time” delivery of parts from suppliers to assembly plants actually *increases* CO_2 by requiring many small truckloads of parts hourly, instead of a few large trainloads of parts weekly.)

European automobile companies are careful to publicize their efforts to reduce greenhouse gas emissions to an extent rare in the United States (though recent statements by the management of Ford Motor Company are changing this). Scandinavian Airlines System recently spent two pages in its in-flight magazine to detail what it is doing to use less fuel.

The Carbon Economy

The basic source of energy for human civilization has been the combustion of carbon in organic materials such as wood or fossil fuels. Archeologists report that ancient cities moved when local sources of wood were depleted. Less than 300 years ago, the production of cast iron nearly denuded England of its forests; only when coke (coke is coal that has been heated to drive off volatile constituents, thus increasing its carbon content) was developed as an alternate metallurgical fuel did the industrial revolution really mature.

The carbon economy has advantages. Carbon is easily portable. In solid form, coal has been used to power steam engines in ships and locomotives since the invention of the steam engine. Refined into liquid fuels, the thermal energy of the fuel is increased, and the fuel is easily dispensed and carried in transportation equipment and used for space heating.

But the carbon economy also has drawbacks. The supplies of carbon in forms that can be converted to energy are limited, and not necessarily located near users. Combustion of carbon fuels produces by-products that are not necessarily benign to life. More efficient methods of converting carbon to energy depend on refinements in component manufacturing techniques, as Kubota representatives pointed out in a discussion of new environmental requirements for diesel engines. Conversion efficiencies improve with increasing combustion temperatures, and therefore are limited by the properties (melting point and softening temperatures) of the materials used to confine the combustion reaction. As an example, the temperature of the combustion gases entering the turbine section of current gas turbine engines is above the melting point of the alloys used in the turbine section—only sophisticated cooling schemes allow the engine to operate without melting. And, even the most efficient combustion of carbon produces carbon dioxide, the major greenhouse gas.

There have been examples of highly efficient use of the energy generated from fossil fuels to minimize emissions. Recovery of waste heat from industrial processes is widespread. In Japan there are serious attempts to recover waste heat from air and water that is close to ambient temperatures. Combined cycle gas turbines are increasing as a source of commercial electric power. Such installations achieve energy efficiencies of better than 50%. It is fairly common for large industrial installations, such as steel plants, to generate their own energy on-site and make the excess available to a nearby power grid, as Corus Holland does. Eco-industrial parks such as Kalundborg in Denmark have provided a model for future industrial parks. However, these efforts merely dent the overall impact of the carbon economy on the environment.

Nevertheless, the carbon economy is thoroughly entrenched in society, for historical as well as technological reasons. An extensive commercial economy is based on it, and converting it to one based on another energy source would be difficult and expensive. The question of whether—or when—such a conversion will be made depends on how serious the disruption of society by global warming will be, a question that cannot be answered today.

Alternatives to the Carbon Economy

Because of concern about emissions from carbon-based fuels, a number of alternatives have been proposed for industrial systems and their products to minimize the generation of carbon dioxide, or avoid it altogether. Some of these ideas are new, some are not, but all are under active consideration today.

Hybrid and All-Electric Engines

In hybrid vehicle engines, fossil fuels provide the driving power during acceleration. Excess power is delivered to a secondary source, such as a battery or a flywheel. Braking energy is also delivered to a battery or flywheel. The secondary energy source is then used when the vehicle is in motion. Gasoline mileage ranges from 45 to 70 miles per gallon. Honda and Toyota now offer small cars with this engine system in Japan and the United States. Both Ford and General Motors have promised hybrid vehicles (including sport utility vehicles) by the 2005 model year. Buyer acceptance has not yet been assessed, but there is hope that these vehicles will sell satisfactorily, especially in cities.

All electric vehicles (or “zero-emission” vehicles) have been offered for sale or lease in California for a number of years. Their acceptance by consumers has been disappointing. Despite a state mandate that 5% of cars sold in California are to be zero-emission vehicles, California drivers have shown little interest in them. Their performance is poorer than gasoline and diesel-powered cars, recharging batteries is inconvenient, and their range between recharges is believed to be insufficient by most drivers. (Some environmentalists consider these arguments to be excuses by automobile companies to postpone eliminating greenhouse gas generation from their products.) There is also the question of whether zero-emission vehicles actually reduce global warming, since the electricity that powers them must be generated, and then transmitted from the generating plant to the recharging station, which involves transmission losses. Clearly, if the electrical energy is generated by a fossil fuel-burning power station, substantial amounts of greenhouse gases will be generated; if it is generated by solar or wind energy, electric vehicles will actually be pollution-free.

Alternative Fuel Sources and Fuel Cells

Liquid Natural Gas. One suggestion has been to use liquid natural gas (LNG) instead of gasoline or diesel fuel for internal combustion or gas turbine engines. LNG yields only carbon dioxide on combustion (no NOx or SO_x), and has a greater energy content per pound than diesel fuel. A number of commercial fleets of cars and small trucks have been successfully converted to natural gas, and some municipal transit systems have also been converted. LNG occupies more space for the same amount of energy than liquid fossil fuels, thus limiting its use where large amounts of fuel must be carried in limited space, as on ships or in aircraft. Although there is an infrastructure for the nationwide distribution of LNG, consumers have shown little interest in LNG automobiles. Nevertheless, because LNG has a lower proportion of carbon to hydrogen (compared with other fossil fuels), its use in transportation systems can reduce the production of greenhouse gases; and it is receiving attention from owners of barges, buses, and light truck fleets as a way of reducing greenhouse gases.

Biomass and “Decarbonized” Fossil Fuel. Biomass conversion has been proposed as a way to ease dependence on fossil fuels. However, growing biomass requires land that might otherwise be used for food. It has been proposed that various biofuels could be grown on otherwise non-productive ground. Whether this would be the best use of steadily diminishing water resources and natural ecosystems is questionable, especially as increasing world population will require that increasing amounts of land be used for food crops.

Biomass needs to be processed and the product distilled. While the distilled product adds less to global warming, it does not eliminate it during combustion or use in a fuel cell.

“Decarbonized” fossil fuels are treated so that the carbon dioxide created on combustion is sequestered by injecting it into the ocean or reacting with materials to create stable carbonates (primarily calcium carbonate). Experimental development of this technique is still in its early stages, and it is premature to predict the impact of this technology.

Fuel Cells. Fuel cells, which make use of the energy released when hydrogen and oxygen combine, are under intense study all over the world. If pure hydrogen is used as a fuel, these engines release only water as a combustion product, so do not contribute to global warming. All major automobile companies are developing fuel cells. General Motors reports that its seventh generation fuel cell produces 75 hp, and comes rapidly to full power in cold weather. More generations of fuel cells are under development, with the major focus being to reduce acquisition costs. For maximum efficiency, automotive fuel cells run on pure liquid hydrogen; Ford and Toyota have addressed the problem of liquid hydrogen supply infrastructure by developing prototype hydrogen-dispensing “gas” stations.

Because hydrogen is not widely available as a fuel, most fuel cells today use a small chemical converter to extract hydrogen from conventional fossil fuels or methane, thus limiting their efficiency and forming at least some carbon dioxide. Pure hydrogen would be an ideal fuel, but the most common method of obtaining pure hydrogen, electrolysis of water, uses large quantities of energy, which, if the energy is produced using conventional fossil fuels, might defeat the purpose of the technology. In addition, keeping hydrogen liquid during transportation and storage requires energy for refrigeration. There is also a popular impression that hydrogen is inherently unsafe and liable to explode (as in the Hindenburg disaster), although it is actually safer than gasoline. However, hydrogen can present unique storage and transport problems due to the extremely small size of H_2 molecules: H_2 tends to leak out of conventional metal pipelines and storage tanks. Hydride or carbon nanotube storage may provide solutions.

Fuel cells can be designed to operate at high or low temperature. The high temperature fuel cells (solid oxide fuel cells), though more powerful, have up to now required heat resistant alloys, and, when operated on fossil fuels such as natural gas, tended to foul from carbon build-up at the electrodes. However, new developments during the last six months (Service 2000) suggest that these more powerful fuel cells, running on fossil fuels, are capable of being made at costs that make them attractive to consumers. In one estimate, fuel cells that could provide power for a small manufacturing plant could be available commercially within a decade. Such cells would be desirable, since the development of a national infrastructure to provide hydrogen for fuel cells is not currently considered to be likely within the decade.

Much fuel cell development today is focused on power plants for transportation, such as cars, small trucks, or busses. All of the automotive companies visited mentioned having a fuel cell project, though none was anxious to share its findings with us. More powerful cells serve as power sources for industrial plants, and for homes, eliminating transmission losses and the service interruptions that can occur when storms knock down power lines, and it is this application that is expected to reach commercialization first. Note that the use of fuel cells instead of internal combustion engines would significantly impact manufacturing, since much foundry and machining output today is centered on producing components for internal combustion engines. The impact of removing a major market for metal manufacturing would be expected to reduce emissions that result from these processes.

Water, Solar and Wind Power

Solar power, wind power and water power are potential “free” energy sources. Water power has fallen from favor recently as it is found that dams constructed to produce power interfere with fish reproduction in some species (notably salmon), and disrupt local populations and ecosystems (and occasionally archeological sites, such as in Turkey) when lakes are formed behind the dams. In addition, many sources of water power are far from population centers, requiring transmission lines with their attendant transmission losses. The outlook for water power is that it will decrease over time as a percentage of total power generated worldwide.

Solar power continues to receive attention as the cost of solar cells continues to decline (Flavin 2000a). Solar powered automobiles have successfully crossed the country, and solar power is used in sunny climates as an auxiliary power source for both private homes and commercial buildings. Solar powered road signs are used in many countries. DaimlerChrysler has installed solar panels in two of its plants in Germany, and currently generates electricity for its own usage. Another installation in Europe is an office building that uses solar power transmitted by fiber optics to light individual offices.

Production of photovoltaic (PV) cells for solar power generation has grown substantially in the last ten years. Japan currently leads the rest of the world in PV cell production, helped by the Japanese government's subsidy of solar power heating systems for residences. Some European governments are also encouraging their producers by making it easy for homeowners to install solar power in their homes. The cost of solar power modules continues to decrease (currently about $3500/kW), but is not yet sufficiently low to make this form of energy competitive in most applications where power is available from a conventional power grid. A carpet plant in the United States has installed a solar powered loom to demonstrate the feasibility of using solar power in industrial production; it has a 65 year pay-back period.

Solar power as an industrial or domestic power source has not had the acceptance in the United States that was initially hoped for. Often the best locations for solar power generation (deserts) are unattractive to people as a location for homes and businesses. Solar power also requires a method to store the power for use at night or during inclement weather. It is expected to play an increasing role as an auxiliary source of power.

Technology for wind power has improved dramatically in the last two decades; indeed, it is today the world's fastest-growing source of power (Flavin 2000b). Over $3 billion worth of wind generation equipment was installed in 1999, and the cost of wind power is nearing the cost of that generated by new fossil fuel plants. As in the case of solar power, however, wind power is generated only in certain geographical areas. Ways must be found to store it when the wind does not blow, and often it must be transmitted over substantial distances (with attendant losses) to customers. Wind power, like solar power, is an important adjunct to other power generation methods, and a strong case can be made for continued development of this technology.

Nuclear Power

Nuclear power offers abundant clean energy. Unfortunately, it is currently a forbidden solution to the energy problem. Memories of Three Mile Island, Chernobyl, and, in Japan the release of nuclear material shortly before the WTEC panel visited Japan, color any discussion of nuclear power as a viable method of obtaining energy. This is in spite of the record of France, which generates 85% of its power from nuclear sources, and of the United States, which generates nearly 20% of its power in nuclear plants and has had no recurrence of the Three Mile Island incident. (As for Chernobyl, its reactor design was unacceptable anywhere except in the Soviet Union. However, since the Russian Republic has more such reactors operating, there remains the chance that another incident could occur.)

As well as generating electricity, nuclear power could produce large quantities of liquid hydrogen for fuel cells without forming greenhouse gases. Used as a power supply for ships, it could permit high speed ocean transport of industrial goods and components for assembly, needed for just-in-time manufacturing, since the volume of space occupied by the fuel supply is small in comparison to that required for liquid petroleum fuel. (Note, however, that many countries will not allow nuclear-powered ships in their waters.) A recent study (Sailor et al. 2000) strongly suggests that nuclear power should be reassessed in view of the threat of global warming and advances in nuclear power technology.

Even though total installed nuclear generating capability increased during the last year (Lenssen 2000), the future of nuclear power in Europe and the United States is not bright. Although there have been significant improvements in the design, control and operation of nuclear power plants in the last 30 years, the public is convinced that they are more hazardous than conventional power plants. There is controversy over the sequestering and storage of spent nuclear fuel, much of it focused on the lack of trust of those who would have responsibility for it. It seems probable that it will take a major ecological or economic dislocation resulting from the use of fossil fuels to persuade the public to reexamine nuclear power.

Other Approaches

Deregulation. The United States is currently in the process of deregulating the electric power industry. What we used to think of as monolithic power companies that generated, distributed, and then sold power at wholesale rates (to industry) or retail rates (to small shop owners and homeowners), is in the process of breaking up into companies that will specialize in generation, transmission, or sales of power.

The consequences of this have yet to be worked out. Some retail sales companies offer their customers the choice of conventionally generated power, or, at a somewhat higher rate, "green" power. Given choices between differing sources of power, customers are able to choose among competing methods, weighing cost, reliability and environmental load. However, the high temperatures experienced in southern California (one of the first states to deregulate power) during the summer of 2000 caused increases in the price of electric power that infuriated citizens and led some people to question the wisdom of deregulation. Rolling blackouts in the winter of 2000-2001 further underscored these concerns.

"Micropower" Plants. One possibility is for customers to generate their own power, using small power plants sited at the point of use (Dunn and Flavin 2000). A number of firms now offer small power plants (up to 10 megawatts) that can be installed without using step-up and step-down high voltage transformers in commercial or residential complexes for the use of only those connected to it. Such installations could also provide power for factories. For individual homeowners, fuel cells running on LNG or natural gas would be able to provide the power needed, without involving a conventional power company. These small power sources typically produce fewer emissions than large power plants, because they can be sized for the most efficient operation and tuned to their expected load. Transmission losses are eliminated, downed power lines in storms are no longer a problem, and reliability and quality of power are increased. Reliability and power quality are of increasing importance in the era of computers, where an interruption or power spike can cause a system to crash. A number of companies are looking very closely at the potential for these "micropower" plants, which may assume a greater role as energy sources in the future.

Move Manufacturing Offshore. A scenario often suggested is that of moving all manufacturing offshore to countries with emerging economies. Indeed, many of these countries actively court such moves, including the pollution they bring, as they provide jobs, promote increased foreign trade, and boost economic development of these countries. However, exporting manufacturing operations does not reduce their global environmental impact, and thus does not provide a fundamental solution to the problem of decreasing the generation of greenhouse gases.

Energy Conservation. Energy conservation is an ongoing effort around the world, and was not specifically studied by the panel. Conservation efforts increase when the price of energy increases, and often stagnate when energy costs are decreasing or stable. There are different levels of energy conservation in different parts of the world. For instance, the roofs of the Daimler headquarters in Stuttgart have been planted with grass, which serves as an insulator, though the roof of the Chrysler headquarters has not.

At a number of the foreign sites visited, WTEC panel members heard criticism of the American use of energy, which some foreign company representatives considered to be wasteful, especially in regard to our automobiles. However, it is necessary to acknowledge—as DaimlerChrysler's chief environmental officer Dr. Werner Pollmann has done (Pollman 1999)—that differences in automobile fuel consumption between the United States and Europe/Japan are to a large extent the result of the vast distances that many Americans travel each day. Even so, it is worth noting that during the oil crisis of the 1970s, Americans substantially reduced their need for oil through conservation methods, not technology.

Hydrogen Economy

One possibility—that some people have argued should be pursued vigorously—is the conversion of our carbon economy to a hydrogen economy. The opportunities to eliminate greenhouse gases through the use of fuel cells in cars and in micropower systems is simply too great to ignore. This requires that a source of liquid hydrogen be found. Hydrogen can be produced by electrolysis of water, a process that requires substantial quantities of electric power. Obviously, obtaining that power from fossil fuels defeats the purpose of converting to a hydrogen economy. Alternative power sources, if sufficient, would have to be used instead.

One alternative that has been suggested is obtaining hydrogen as a result of chemical reactions, or by biosynthesis. The biosynthesis route needs to be encouraged, and research into this process supported. However, even with a mature, economical, environmentally benign method for producing hydrogen, a barrier will exist in establishing the distribution infrastructure around the world. This is a matter for consideration by energy companies and governments. Note that some governments, particularly those of oil and natural gas-producing countries, can be expected to be less than enthusiastic about the development of hydrogen as a substitute fuel.

Summary

The choices facing society regarding energy sources for the future are not reassuring. Continued use of the traditional source of energy, carbon, may cause severe societal dislocations in the next century as a result of global warming. Various forms of "free" energy are not distributed equally to all in the world. It is clear that more education is required on the consequences of our attitudes toward energy sources—especially nuclear power—and on the consequences of our choices.

If it is accepted by society that burning carbon contributes significantly to global warming, and that the societal dislocations implied in global warming are unacceptable, then conversion from a carbon energy economy to a non-carbon energy economy is required. Given the appetite for energy in the world (including emerging economies), it seems naive to believe that wind, water and solar power alone will be able to satisfy the world's energy needs. The contribution of nuclear power to the energy requirements of the world needs to be reassessed, and steps taken to educate the public on the issues and facts about modern forms of nuclear power.

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CHAPTER 6

CROSS-CUTTING TECHNOLOGIES AND APPLICATIONS

Diana Bauer and Paul Sheng

INTRODUCTION

The major focus of pollution prevention work to-date has been on development of critical technologies for material processing and design tools and guidelines. While these are the key first steps towards societal adoption of environmentally benign practices, they are often not sufficient conditions for successful deployment. Consistency of motivation, coordination of activities, and communication between stakeholders are also important. An industrial decision-maker has a confusing array of sometimes conflicting motivating factors, ranging from economics to regulations to customer requirements. For a new technology to have the greatest chance to move beyond the laboratory, the motivations to use it should be clear and consistent. Another critical factor is that the coordination of interdisciplinary groups and processes required to deploy technology, while not a unique need for environmental projects, is especially important given the wide scope and breadth of knowledge required. Finally, means to effectively communicate requirements and measured performance among the relevant organizations and groups is important. This chapter strives to highlight some of these key factors for success. The factors become particularly acute when we place them in the lens of regional or cross-border distinctions for Japan, Europe and the U.S. In general, the major dimensions needed to enable successful deployment are:

- Clear alignment of external mandates for improvement, such as regulation or certification
- Cascading communication and specification of the environmental mandate throughout the supply chain of a product
- Consistent management and interpretation of environmental information within and across multiple organizations and stakeholders
- Explicit and/or implicit economic incentivization to scale environmental technology to a level at which it can be sustained

This study presented us with a unique opportunity to examine environmental technology deployment through case studies across Japan, Europe, and the U.S. The data and information collected enabled us, first, to gain insight into similarities and differences in how entities coordinate in bringing key technologies to scale, and second, to reflect on challenges for corporations and other organizations in developing global environmental strategies sensitive to local needs. The initial framework for examining these factors will be an industrial supply chain, since key process and product engineering decisions are made in this context. However, the web of influence actually reaches well beyond the supply chain to (among others) economic incentives, consumer perceptions, and governmental regulations. These aspects will be addressed later in the chapter.

COMMUNICATING REQUIREMENTS IN THE SUPPLY CHAIN

A starting framework for discussion is the supply chain, comprised of a set of geographically dispersed organizations connected by material and information flows (Figure 6.1). Generally the flows of materials and components in this context are unidirectional, dedicated, and relatively controllable, although with the use of remanufactured and recycled content, there is now material feedback in some instances. The various organizations in the supply chain are also connected by a cascading set of requirements, originating from customers and/or government regulators. These requirements in turn engender a set of motivating factors.

First, region-dependent customer requirements, such as material bans or recycling requirements, are important particularly for original equipment manufacturers (OEMs): these often have impacts on engineering decisions even outside of the region. For example, the restriction on brominated flame retardants and heavy metals in electronic products was generated for the European consumer market, but has spurred significant R&D activity at Sony in Japan. The scale of the European market forces many manufacturers to face a critical decision: apply environmental technologies to comply with regional requirements or face consumer-based restrictions on market access.

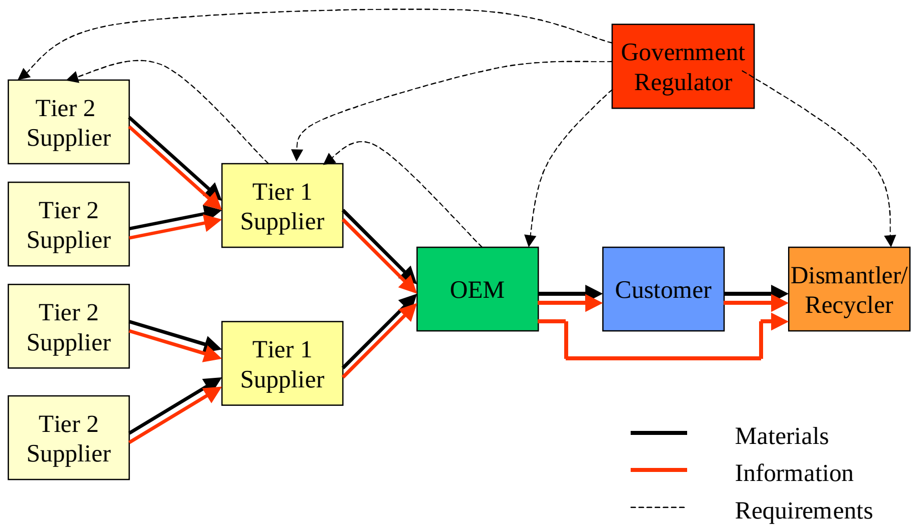

Fig. 6.1. Material and information flow in the supply chain.

Second, motivation at the supplier level may be derived from the requirements of the supplier's corporate customers, such as through ISO 14000 certification or eco-labeling requirements. A corporation's motivations to apply these pressures are mixed, ranging from genuine environmental benevolence, to a desire to limit environmental liability risk, to a desire to improve corporate environmental image. For example, Ford is now requiring its suppliers to be ISO 14000 certified. It is also in the process of developing a uniform set of metrics through the supply chain, such as for VOC emissions and total waste, to enable corporate quarterly environmental performance reporting.

Third, environmental regulations and requirements are imposed directly by governmental agencies and also passed down the supply chain. For example, there are limits for copper content in effluent. In such a case, an OEM may give manufacturing equipment suppliers process specifications, such as for copper chemical mechanical polishing (CMP) in the semiconductor industry. Additionally, there may be disposal regulations, such as regarding lead content in CRT computer monitors, which affect consumer purchase behavior.

To effectively communicate these requirements down the supply chain, the environmental specifications must be integrated with non-environmental specifications regarding product performance, manufacturability, quality, etc. There are two aspects of this type of information dissemination that require particular attention. First, the requirements must be presented at a level of resolution consistent with other requirements (such as dimensions, tolerances, and functional performance specification) through a simple interface; inundating a supplier with requirement information is counterproductive. Additionally, the efficient transmittal of this information must leverage the existing supply chain management groups within OEMs and suppliers, which in most systems is a proven link between organizations.

In addition to communication between organizations, communication between functions is also important. Within each supplier and OEM organization there are multiple departments with potentially competing roles. In order for environmental management to be effective both within and outside of the organization, environmental activities must be integrated appropriately into these individual functions. Roles that are important for specifying, transmitting, and meeting environmental performance objectives range from supplier production planning and environmental health and safety to OEM procurement and product design to consumer purchasing and recycler processing. Each of these roles has its own set of drivers and motivating factors ranging from regulatory compliance to cost minimization to minimization of liability risk (Figure 6.2). Coordination of these activities to achieve optimal environmental performance requires clear leadership from a group with clear visibility across organizational boundaries (e.g., OEM leadership, governmental regulators, etc.).

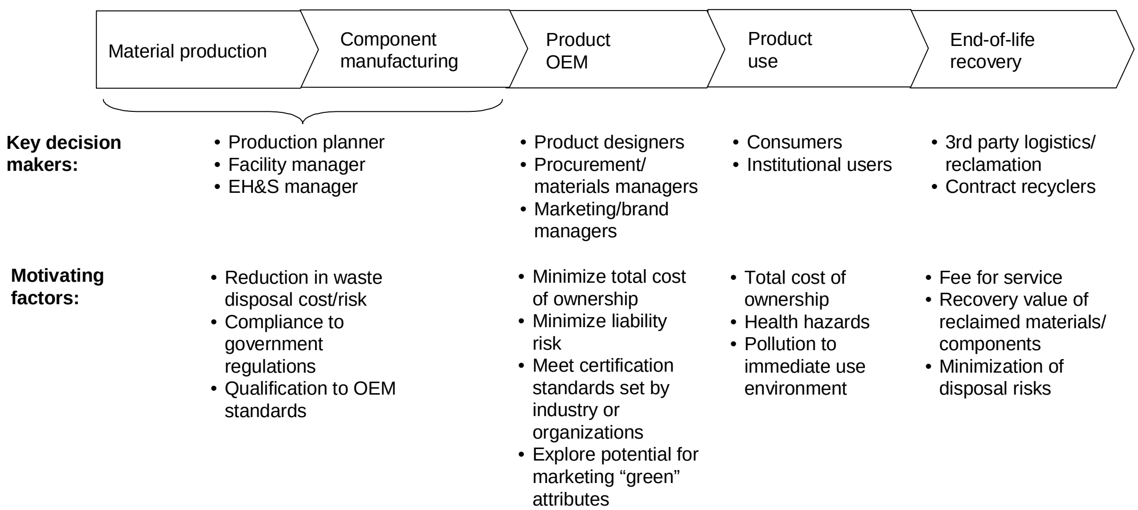

Fig. 6.2. Supply chain decision-makers and their motivating factors.

DATA, INFORMATION, AND KNOWLEDGE MANAGEMENT

One way that such a group can demonstrate clear leadership is through standardization of data, information, and knowledge management. A major challenge for information flow within a company or organization is transmission across interfaces between functions, as shown in Figure 6.3. In this view, the corporate leadership sets targets that can be in areas such as energy consumption, waste minimization, and restricted substances. These targets are then conveyed to the product designer, which in the case of banned substances is straightforward but in the case of continuous targets such as energy efficiency and waste minimization requires a strategic apportioning of effort among products. The designer in turn interprets the targets through material, process, and design specifications to the production planner and facilities manager. Metrics and performance measures applying to the continuous targets, such as hazardous substance emissions, local health hazards, waste disposal, and energy consumption are then fed back up the hierarchy at an appropriate level of resolution.

In our contact with companies, cross industry sectors and geographies, we have come across a uniform need to better support cross-functional and multi-layered transfer of environmental information and decision-making, including:

- A formalism for aggregating measures at different layers while preserving the value of information
- Linkage of specifications and targets with actual measures and benchmarks
- Trajectory of continuous improvement against targets
- Consistent prioritization among objectives
- Linkage to economic and engineering performance

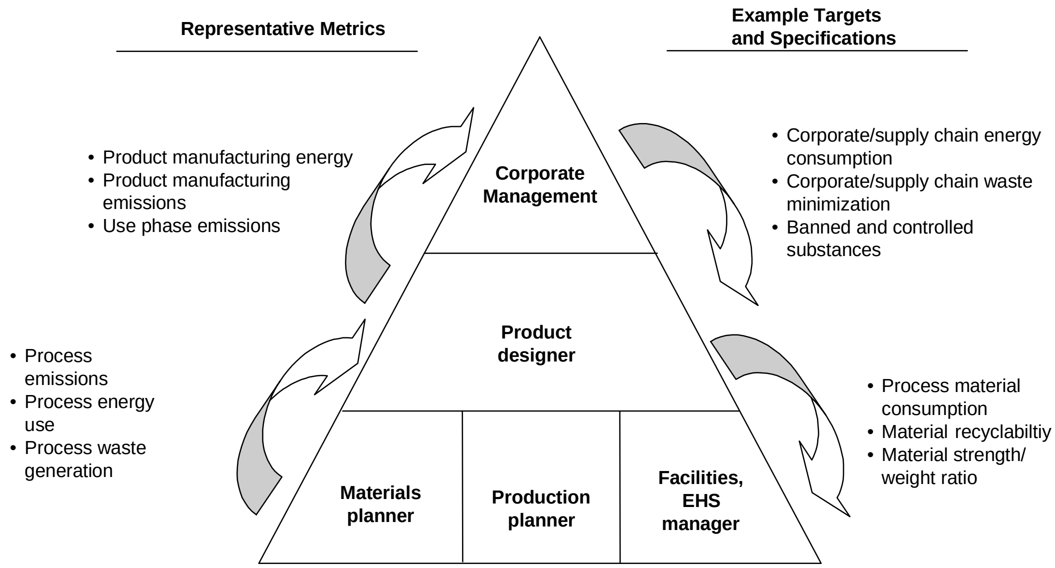

Fig. 6.3. Organizational levels of aggregation for actuation and assessment of environmental activities.

Some of the companies the WTEC panel visited are starting to address these areas. Figure 6.4 illustrates coordinated levels of activities and metrics at Chaparral Steel. At the corporate level, opportunities for process synergies between steel and cement operations were identified. Energy use and air pollution reduction targets were set. Automotive steel was targeted as a key source of scrap to drive the recycling process. These corporate level directives led to actions both internally and within the supply chain, including setting up a material exchange infrastructure enabling steel slag to be used as cement kiln feed. This served corporate level goals, as the corporate level raw material cost is linked to the supply chain level consumption of gypsum or anhydrite. At the facility level, energy use and air pollution reduction levels relating to the corporate targets were set. And technologies that met these performance targets were acquired and/or developed. These included dry cement manufacturing operations and flotation separation of non-ferrous metals and halogenated plastics.

	Actions	Metrics
Corporate leadership	• Identified opportunity for process synergies between steel and cement • Set directives for energy use and air pollution reduction • Developed efficient source of scrap metal recovery to feed steel processing	• Raw material cost • Utility cost • Residual value of recovered materials • Air quality compliance
Supply chain	• Set up a material exchange infrastructure between steel and cement production • Used steel slag as cement kiln feed • Calcium sulfate recovered from scrubbers	• Energy consumption for cement production • Air pollutant levels (CO2) • Consumption of gypsum or anhydrite
Facility	• Reduced nitrogen oxides using CO emissions from cement production • Converted cement operations from wet to dry • Separated by floatation non-ferrous metals and halogenated plastics	• Energy consumption for cement production • Air pollutant levels • Amount of materials recovered • Presence of trace contaminants (e.g., PCBs)

Fig. 6.4. Hierarchical decision-making at Chaparral Steel.

Coordination of activities beyond a single company is important. For example, an OEM may choose to transfer high-impact processes to its supplier. In this instance, while the measures for the OEM improves dramatically, the environmental impact over the entire supply chain has not changed. In the worst case, overall performance may decline, since smaller organizations often have neither the clear environmental mandate nor the resources of the OEM. A case like this illustrates that managing the information flows through the supply chain system is critical because consistent and appropriate information flow provides the means to assess overall system performance.

Transferring measures, targets and decisions across organizations brings additional layers of complexity beyond that within an organization and requires greater structure and formalism. Supply chain management activities directed at purchased components generally fall into four categories (Table 6.1). First, *operational requirements* imply an adherence to local laws (relating to process emissions, disposal and material content) or to environmental management systems, resulting in minimal data flow.

Second, environmental *guidelines* can be applied to purchased components, supplier-sited manufacturing processes, and manufacturing equipment. These guidelines fall short of clear mandates but represent commonly accepted best practices across a supply chain or industry sector. Guidelines address aspects of materials, products, and equipment such as material use and content, energy efficiency, ease of repair, and ease of recycling. For example IBM has enacted a corporate standard for "environmentally conscious design" (IBM Corporate Environmental Standards, IBM Site Report, Gabriel et al. 2000) that requires materials of concern, such as cadmium, to be identified in a required environmental profile if they are contained in products. Additional guidelines also address design for reuse and recyclability. Both operational requirements and guidelines are primarily means for transmitting directives from an OEM, rather than for evaluating or monitoring actual supplier performance.

A third category of supply chain information is used to fulfill *data reporting and tracking* needs. This type of information often is used to monitor supplier performance, such as in waste stream discharge or material handling. A more complicated and challenging application is aggregation of data from many suppliers to characterize the overall environmental performance of a product or OEM. An example of data reporting is of energy consumption so that performance against targets set in response to the Kyoto accords can be tracked. Ford and Toyota have such programs. Also, at Ford and Toyota, there are programs to track use of hazardous or frequently used substances. Toyota additionally has a program in place to track frequently used and hazardous substances such as mercury, lead, and CFCs through the supply chain. Wide-scale data tracking introduces challenges similar to those found in assembling life cycle inventory data; in order for data aggregation from multiple organizations to be meaningful, data collection and reporting practices must be standardized and validated across the supply chain. Also, strategies for improvement are difficult to develop when the performance data are not linked to process parameters through mechanistic models or other means.

The first three categories of supply chain management shown in Table 6.1 are focused on evaluation and incremental improvement and are consistent with the common definition found in green procurement, rather than environmental supply chain management (Nagels 2000b). In the fourth category, more dramatic changes can in theory be facilitated by cooperating with suppliers and investing in development of new materials and processes through *knowledge exchange*. However, though some companies such as Ford have supplier classes in ISO 14000, little technical collaboration between OEMs and suppliers to stimulate environmental innovation was reported at the sites visited. This is an important area for focus of effort in the future.

While the above four categories of information flow imply unidirectional reporting from the supply base to the OEM (and for some types, ultimately government), the supply chain relationship and related information flow in practice is bi-directional. In many cases, forward-thinking suppliers anticipate the needs of customers in addition to abiding by current requirements (Table 6.2). Materials producers, such as Nippon Steel and Hoogovens, are increasingly working with customers to devise solutions to environmental challenges. For example, with the recycling requirements initiated by the European and Japanese product take-back laws, enhancing recyclability for materials, such as coated automotive steel, has become a priority. Another challenge is to develop new alloys with higher performance-to-weight ratios based on energy consumption reduction goals in the automotive industry.

Table 6.1
Levels of Supply Chain Management Requirements Focusing on Components and Processes

Operational Requirements	Legal Agreements	Required to obey local environmental laws
	Environmental Management Requirements	Adoption of environmental management systems (such as ISO 14000) Implementation of product assessment Activities related to the recovery/recycling of used products Activities relating to preserving the ozone layer/preventing global warming
Guidelines	Product Design	Environmental purchase guidelines: banned substances, substances to avoid, substances requiring control Energy efficiency Ease of repair Use of reusable materials Ease of recycling
	Process Requirements	Production guidelines: banned substances, substances to avoid, substances requiring control
Data Reporting and Tracking	Required provision of process emissions data, energy use data, material use data	
Knowledge and Information Exchange	Supplier liaison environmental action committees Technology transfer Joint technology development	

Source: Compiled from IBM, NEC, Toyota Corporate Environmental Reports

Table 6.2
Typical Environmental Needs of Customers

Materials	High performance/weight ratio easily recyclable
Equipment	Controlled water use Consistent power draw Reusable/reconfigurable Nonhazardous consumables

Additionally, there are supply chain information management activities particularly important at product end-of-life. For the capturing of residual value of components, one particular challenge for recycling is the transfer of relevant information (such as material content, remaining component life, component value) forward in time to a known or unknown recycling organization. This can be done simply through code labeling of polymer parts, or more complexly through embedded sensors which track product use and/or monitor or measure degradation, such as caused by fatigue or other sources of degradation. Component use patterns and projected failure rates can also be linked through statistical estimation. For example, Fuji Xerox determines which parts are reusable by tracking the copy count history for individual parts in its copying machines. The projected remaining life for each component is then estimated using Weibell analysis. Component value can also be tracked in an external database, such as at the Noranda recycling facility. At Noranda, current market prices are tracked for different possible (dis)aggregations of varying grades of components and materials, and the prices compared against the projected costs of handling and disassembling the incoming product streams.

One class of companies requiring especially keen insights into anticipated environmental needs is production equipment manufacturers such as semiconductor equipment manufacturer Applied Materials (Figure 6.5).

Applied Materials is challenged by an array of location-dependent requirements, such as for electricity consumption and water use, that may not be clearly expressed up front because the main customer base (semiconductor manufacturers) generally focus on more traditional performance metrics such as production rate and yield when arriving at equipment specifications. In cases where environmental concerns have become a priority, semiconductor manufacturers generally address these issues at a facility, rather than an equipment level, which implies a post-process remediation, rather than a process-intrinsic prevention emphasis. The OEM has one further level of segregation from key decisions that drive semiconductor manufacturing environmental performance. The situation is further complicated by communications challenges, such as:

- Loss of insight on systems performance as data (such as water use, global warming potential emissions) rather than predictive models or analyses are transferred from organization to organization
- Difficulty in apportioning low level requirements (such as supplier specifications) from high level guidelines (such as facilities water usage limits)
- Lack of interface between functions (e.g., supplier EHS to semiconductor manufacturer process engineering, supplier process engineering to semiconductor manufacturer EHS, supplier process engineering/marketing to OEM design groups)

The challenge for an equipment supplier is to work with customers to enable facilities-level environmental management through development of equipment level design specifications and assessment metrics. Figure 6.5 illustrates the chain of specifications and array of motivating factors facing Applied Materials and its customers. One approach taken by Applied has been to focus on the development of embedded treatment systems (e.g., water recycling) without sacrificing process integrity, cost effectiveness and technological advantage.

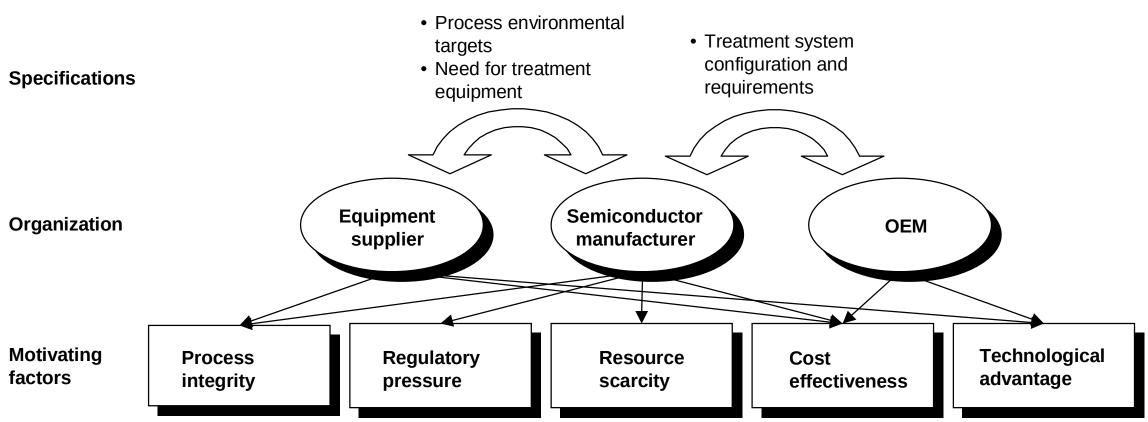

Fig. 6.5. Design for environment in the CMP process.

After organizational communications, a second significant challenge is the characterization of data—potentially including the mechanistic link to process parameters and performance—appropriate to the range of environmental objectives held by the various decision-makers in the various relevant organizations. Linked to data requirements is the development of metrics for performance measurement and assessment.

One of the challenges for information management is that environmental data cannot necessarily be compared and evaluated in its collected form. For this, benchmarking and metric characterization and standardization is required. For example, emission and energy data aggregated at the facility level may be readily obtained, but true insight into environmental impact from an OEM perspective (particularly for an evaluation of global and regional scale effects) may best be gained through a comparison at the component level. However, metrics that are both realistic for data gathering and appropriate for comparison can be challenging to develop. Furthermore, while there may be a desire to completely track a product's environmental performance, the value of this analysis does not always justify the effort due to the following factors:

- Difficulty in attributing facility-level environmental performance (e.g., resource use, energy consumption) to individual manufactured components
- Problems with collapsing multiple dimensions of environmental performance down to a single or small set of metrics
- Missing link between effort spent on environmental performance characterization and environmental performance improvement

There were different approaches to metric development seen at the sites visited by the WTEC team. A summary of these is shown in Table 6.3. As can be seen from the table, one common corporate approach is to track and aggregate one or several dimensions of environmental performance, such as energy use or solid waste generation. The advantage here is that these are (relatively) easy to measure and track at different scales. Energy use, for example, can be evaluated at levels ranging from that of a single process up to an entire corporation. It can be normalized by many factors, such as by dollar, by product, or by facility. The disadvantage is that the environmental effects considered are limited. The quantity of environmental effects considered could be increased by creating additional categories, such as lead, chlorinated solvents, NOx, etc., but soon the ability to evaluate at multiple levels and discern overall environmental improvements is diluted by the multitude of effects considered.

Table 6.3
Metric Types

Type of Metric	Sites Used	Advantages/ Disadvantages
Aggregation of Single Measure		Relatively easy to normalize, optimize and track at different scales But, doesn't address multiple effects
Energy	Ford, Toyota, NEC	
Solid Waste	Toyota	
Material Usage	Lucent	
Aggregation of Different Effects		Includes multiple effects But isn't transparent, and goal setting less straightforward
EcoIndicator	Lucent	

A second type of approach used that addresses this disadvantage is to apply scaled weightings. One method is based on anticipated ecological, health, and/or resource impacts, such as through the EcoIndicator, which is used by Lucent. The EcoIndicator considers the following effects: greenhouse gas, ozone depletion, acidification, eutrophication, metals, carcinogenesis, summer smog, and winter smog (Pre 1999). This approach does allow for comparison across more potential effects, but it may not consider all dimensions of environmental performance that are important. For example, the EcoIndicator does not consider water use. Also, the method is not as transparent and not as tangible as aggregations based on a single measure, and therefore it is difficult to set meaningful targets at the corporate level. In fact, though Lucent used the EcoIndicator to evaluate product design alternatives, none of the sites visited reported setting corporate level targets using an EcoIndicator or similar method.

Table 6.4 shows the observed priorities for environmental management in the regions studied. The localized environmental and health hazard focus of environmental priorities in the U.S. makes it challenging to develop metrics that can be scaled up and managed globally within a corporation. This is not to say that the European or Japanese environmental priorities can be measured and managed perfectly through metrics. But, in any event, coordinated supply chain efforts are more difficult in cases where the metrics are less clear. Management of corporate environmental performance across regional boundaries is further complicated by differences in the priorities themselves.

Regional differences in objectives, in some cases, can even lead to a difference in environmental approach within the same organization. For instance, the main environmental focus for DaimlerChrysler (Germany) is on design for recyclability, while the focus for DaimlerChrysler (U.S.) is towards minimizing process emissions (see discussion later in this section). Can a corporation consistently meet the most stringent global environmental requirements along all dimensions? In some instances it is unclear whether it is best for a transnational corporation to integrate environmental best practices across borders or to maintain separate operations.

Table 6.4
Observed Environmental Priorities and Corresponding Metrics

Region	Priority	Suitable Metrics for Aggregation
Japan	Production: energy use and waste minimization	Aggregation of single measure
Europe	Product design	EcoIndicator
	Recyclability	Unknown
U.S.	Localized health and environmental hazards	Unknown

Once the current local or global environmental objectives have been specified and linked to data requirements, gathered data must be standardized, validated, and maintained at multiple levels of resolution. Managing and manipulating such large quantities of data in many cases necessitates development of a database. This raises additional issues, such as structure, location, access, and protocol. Modes of data transmission, aggregation, and delivery must be developed. There is the additional challenge of maintaining transparency while abiding by proprietary requirements. In order for the flow of data and information to be effective, data management should be cost-effective, and generation and use of the data must be integrated into existing and evolving practice within the relevant organizations.

ALIGNMENT OF TECHNOLOGY, REGULATION, AND ECONOMIC DRIVERS

Enhanced flow of data and information can enable and highlight potential improvements and stimulate relevant technology development, given existing cost and regulatory drivers. However, this is not sufficient to achieve some environmental performance attributes. For example, if the cost of the environmental impact of process emissions is not fully internalized and such emissions are not regulated, there is little incentive to effect environmental improvement. In these cases, enhancement of regulations, incentives, and/or economic drivers is required. Most effective activities, both from an industrial and from an environmental policy perspective, require alignment of technology (such as pollution prevention and environmentally benign materials), cost (such as for resource acquisition and disposal), and regulatory drivers (such as limitations on air, water, and solid waste emissions) (Figure 6.6). Each of these areas has its own modes for information transmission, as well.

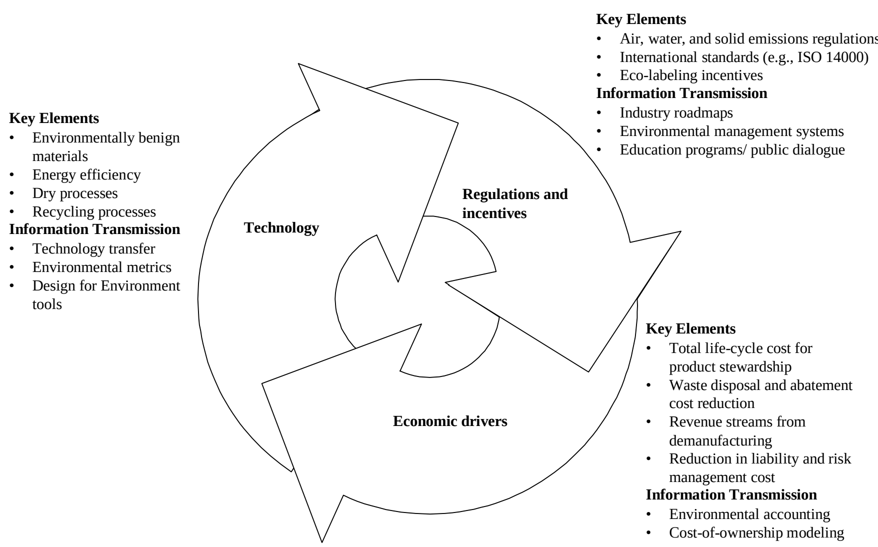

Fig. 6.6. Technology, incentives, and cost drivers combine to strengthen environmental activities.

In cases where environmental benefit relates to efficiency—such as for materials, energy, water, and landfill space—environmental cost can usually be internalized and a culture of continuous improvement created. In this scenario, environmental performance can be sustained without an external driver or stimulus. However, for cases where cost advantage is not aligned with environmentally favorable behavior, there may be a lack of incentive to exceed a compliance level in environmental performance (and therefore, to develop and deploy critical technologies), unless components and products with enhanced environmental performance can be sold at a higher price (Figure 6.7). In these cases, an external market stimulus such as a government or OEM-led subsidy must be put in place to foster sustainability, at least until broad-level behavioral changes occur. Environmental policy which best integrates into this vision is flexible and developed collaboratively with industry and other stakeholders, rather than the traditional command and control approach.

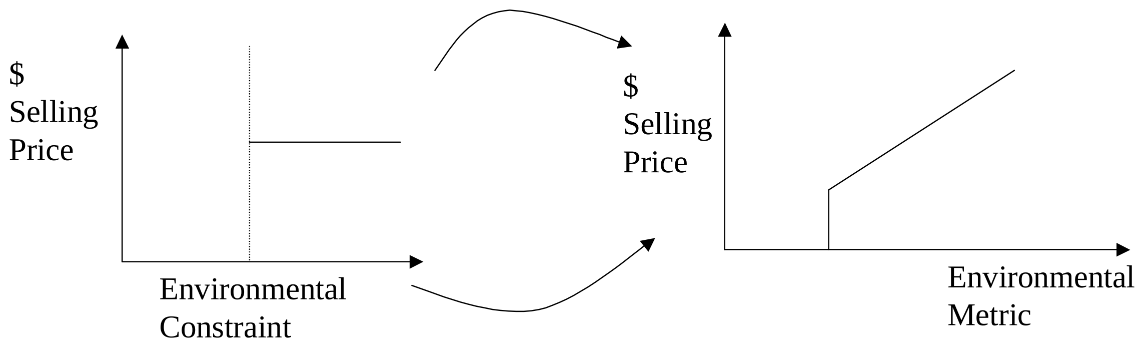

Fig. 6.7. Moving from compliance to continuous improvement.

An example illustrating government-initiated improved alignment of technology, incentives, and economic drivers in the Japanese PVC industry is shown in Figure 6.8. Key technology developed was a three-layer co-extrusion process for composite recycled/virgin sash with adequate aesthetic and structural properties. However, this technology was not sufficient on its own to stimulate wide-scale adoption because it involved higher logistic costs and a lower level of performance than virgin PVC. Part of the reason for the cost discrepancy is that the end-of-life disposal cost for the PVC was not originally internalized into the PVC industry costs. To counter this lack of internalization, the Japanese government imposed a construction site disposal fee that was then applied to subsidize the logistics of collection, sortation, and recycling. This enabled recycled PVC producers to sell at prices comparable to virgin sash. The Japanese government also developed an educational program to encourage a select group of construction industry buyers to select recycled PVC. The alignment of all of these factors led to a general transition from the use of virgin to the use of recycled PVC sash in northern Japan.

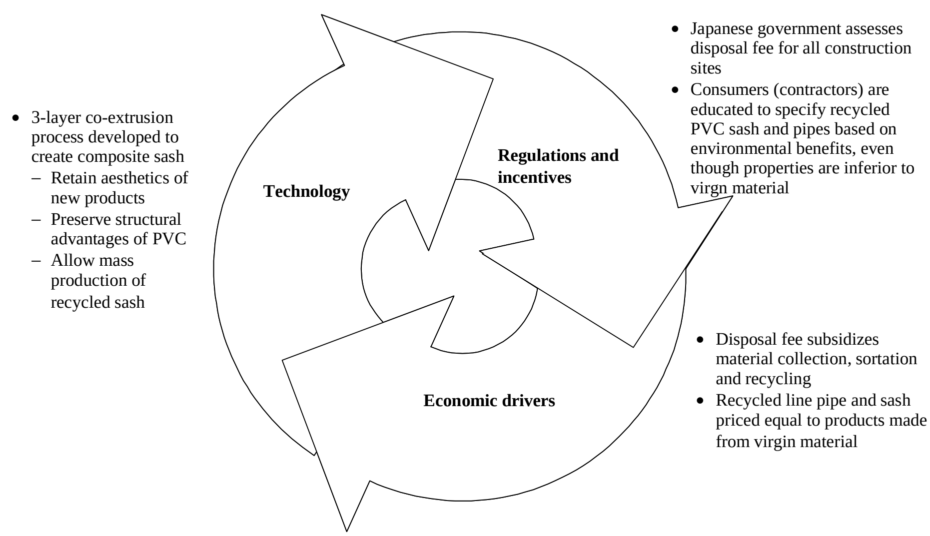

Fig. 6.8. Cross-cutting drivers for PVC recycling.

A more general, widespread use of regulation to expand the region of internalized costs is the ongoing development of product take-back laws in Europe and Japan (Figure 6.9). Under the traditional mode of product development, manufacturers are not responsible for the recycling or disposal of their products. In this case, a manufacturer derives no financial benefit from investment in designs and technologies that facilitate product end-of-life management, since another party must pay the costs associated with disposal. The new laws have spurred emerging R&D activities in an array of technologies ranging from automated disassembly to natural fiber components.

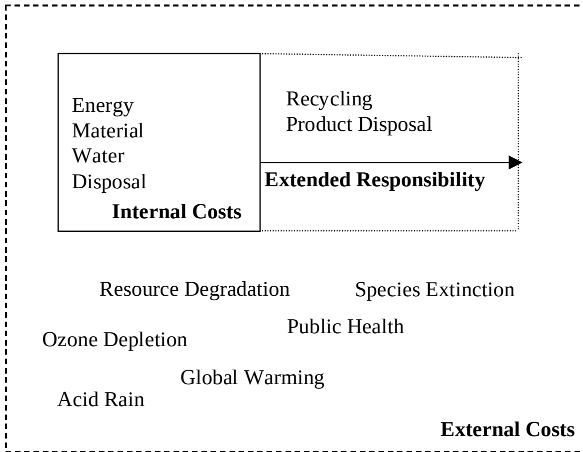

Fig. 6.9. Expanding the region of internal costs through extended producer responsibility.

It should be pointed out that recycling is not necessarily the most economical or even the most environmental strategy at the end of a product life. However, internalizing the environmental costs associated with product end-of-life stimulates a producer to select the preferred option and to devise system-level strategies, including those that reduce costs and potential environmental impacts associated with logistics and transport. Relevant strategies range from reducing volume by grinding polymers prior to transport (so that fewer trucks can be used) to leveraging existing supply channels for product take-back (through leasing or servicing agreements) to decentralizing recycling facilities.

Economic incentives can further stimulate relevant technological development, as illustrated by the following example of activities at DaimlerChrysler (Figure 6.10). Government subsidies for development of environmentally benign materials align with end-of-life vehicle take-back and recycled content legislation to encourage new materials development in Europe. The recycled content and fuel economy requirements combine to pose dramatic technical challenges. Supplier ISO 14000 subsidies lead to increases in the level of ISO 14000 compliance. Though there is an alignment of factors leading to product end-of-life activities in Europe, it has been challenging to develop a coordinated corporate approach in the U.S., since the vehicle end-of-life costs are not internalized in this country. A key corporate decision in this case is on deployment: roll out the critical technology within a single region or deploy globally. So far in the case of DaimlerChrysler, products are deployed with regional content and specifications, limiting the spread of key technologies in areas such as fuel efficiency and recyclability; however, there would be clear global environmental benefit if these technologies were to be more uniformly deployed. Ford is taking a different approach to deployment and is developing global vehicle design for recyclability guidelines, based on European recyclablility requirements.

VISION FOR THE FUTURE

The integration and coordination of environmental activities within and across organizations is a key challenge for environmentally benign manufacturing practitioners and policymakers. Both enhanced information flow and better mechanisms for multiple levels of technological and motivational alignment are important for effective cross-cutting activities.

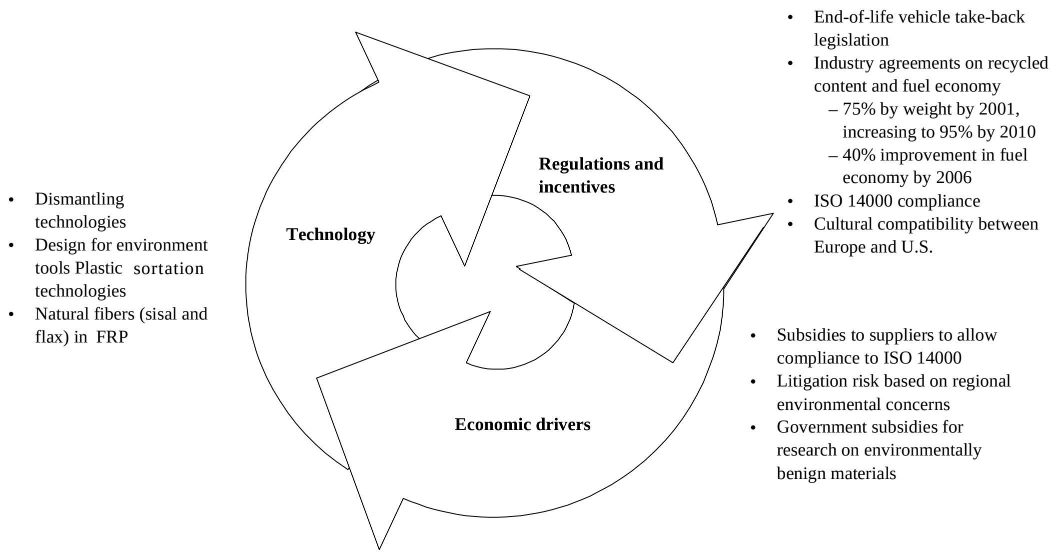

Fig. 6.10. Cross-cutting drivers for vehicle recycling—DaimlerChrysler.

Figure 6.11 illustrates important key enablers for fostering the growth of environmental activities in the long, medium, and short term. First, a collaborative identification of needs among industry, government, non-governmental organizations (NGOs), and academic organizations is key to setting a long-range R&D agenda. This agenda must also encompass a clear program for public environmental education. Seed funding in technologies, environmental metrics, and infrastructure and logistics can be initiated at this stage.

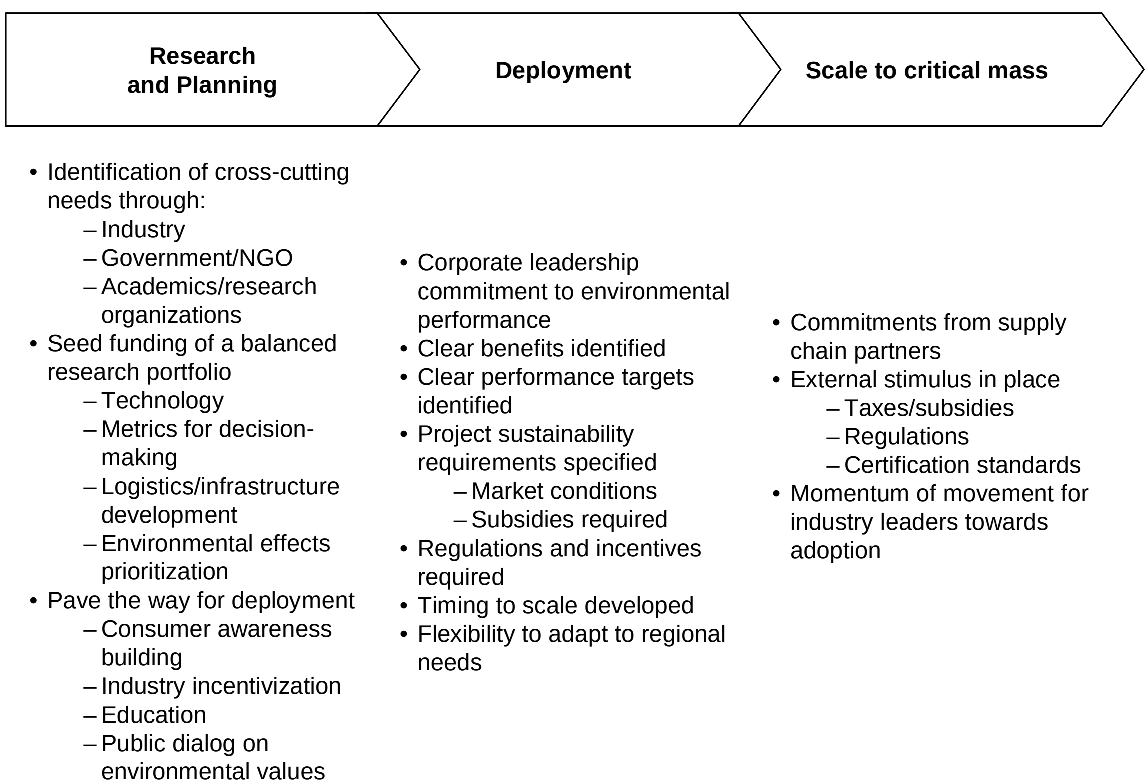

Fig. 6.11. Important long, medium, and short range activities.

The medium term set of enablers revolves around initial deployment, which requires commitment by corporate leadership through agenda setting. For some technologies, regulatory and economic stimuli may need to be initiated through environmental policymaking to position for scale-up. For others, cost benefits need to be highlighted through corporate education, or environmental benefits may need to be highlighted through public education. Needs for regional flexibility based on localized public values and resource scarcity are identified.

At the scale-up phase, commitment from supply chain partners is required. The incentives are in place, and early adoption by industry leaders encourages others to participate. Clearly this scale of coordinated effort requires multiple levels of communication, cooperation, and understanding—between industry and regulators, OEMs and suppliers, different regions, and all public stakeholders.

Table 6.5 summaries key roles in this effort for the different entities. Roles range from the most strategic research planning (NSF/DOE) to environmental leadership at OEMs to facilitating dialogue at NGOs. To address cross-cutting priorities, needed at the various levels are projects and visions that integrate different subsets of technology, environment, economics, and policy. One of the greatest challenges for these activities is that, to be most effective, the different entities must act in a coordinated fashion.

None of the regions visited were fully successful at integrating all of these roles into planning, research, deployment, and scale-up activities. Notable areas of strong effort are shown in Table 6.5. Japan was strong on leadership from OEMs and supplier-OEM relationships. Some of the countries in Europe, particularly the Netherlands, were developing innovative strategies for incentivization in policy.

Cross-cutting activities are particularly difficult, not for scientific or technical reasons, but rather because they require collaboration and coordination among organizations and groups which are not accustomed to communicating, much less cooperating. Lessons can be learned from successful approaches in other companies and countries. But key is strong strategic technology research and environmental policy leadership that applies a broad systems view to prioritize and guide efforts in academics and industry.

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Table 6.5
Key Tasks By Organization For Cross Cutting Activities

Organization Type	Key Tasks	Region of Strength
Research Agency (NSF/DOE)	Identify and fund key technology areas	
	Develop strategies for cross-cutting research	EU strength
	Develop environmental data/ information management schemes (such as LCA) with potential long term benefit to support industrial optimization and decision-making	
Environmental Agency (EPA)	Identify environmental problem areas	
	Identify national performance targets	
	Develop policy approaches which move towards internalizing society's environmental costs	EU strength
	Develop policy approaches which integrate economics and technology	
	Develop strategies for cross-cutting research	
	Develop environmental data/ information management schemes/ metrics (such as those in LCA) with long term benefit to support environmental policy decision-making	
Academy	Interdisciplinary research integrating technology, economic factors and environmental policy	
	Educate engineering students to consider environmental factors	
	Research on environmental data and information management systems	
OEMs	Demonstrate leadership and commitment to environmental performance	Japan strength
	Identify performance targets	Japan strength
	Respond to policy directives	
	Integrate environmental requirements into supplier specifications	
	Collaborate with suppliers on development of new technologies	
Supplier Industry	Anticipate and respond to OEM environmental needs	
Public	Voice environmental priorities	
	Match behavior to environmental priorities	
NGOs	Identify environmental problem areas	
	Facilitate public, government, industry dialogue	
	Help develop and assure certification standards	EU strength

CHAPTER 7

RESEARCH STRUCTURE TO DEVELOP EBM TECHNOLOGIES

Egon Wolff

SUMMARY

A review of research activities observed during the WTEC panel's visits and an overview of governmental policies, processes, and methods used to address knowledge deficiencies is provided. In general, the panel witnessed a collaborative and less confrontational research environment between industry and government in both Japan and Europe to solve environmentally benign manufacturing (EBM) issues. It is hoped that recommended future R&D work in the United States would also benefit from a greatly enhanced collaborative process.

INTRODUCTION

Today, in the United States, we are in the midst of a long economic boom stimulated by a rapid rate of innovation in both physical products and conceptual ideas. At the center of this process is a continual push to create new technologies and eliminate old ones, a process described by Joseph Schumpeter (1950) in his concept of "Creative Destruction." Simply, firms that can sustain the pace of innovation dictated by the global economy will succeed, while the others will fail. In the European Union (EU) and Japan, the pace of innovation is rapidly approaching that of the U.S. and in some cases exceeding it. Economic growth will follow successful innovation.

The innovation "environment" in the United States encompasses a complex mix of institutions and policies that are often disconnected. The institutions include universities performing research and education, corporate research laboratories, supplier research laboratories, not-for-profit research laboratories, national laboratories (e.g., those funded by the Department of Energy), National Science Foundation (NSF) funded activities, and National Institute of Standards and Technology (NIST) funded activities. Here, cooperation among the publicly and privately funded research entities is limited by legal and intellectual property constraints. In contrast, in the EU and Japan the panel saw more cooperation at the institutional level. For example, in Europe there have been efforts to pool resources to create a critical mass of shared expertise, the most notable being the inter-company and industry/academia/governmental alliances. In Japan, MITI is well known for its coordination of national research and development. As pointed out by Landau, Taylor and Wright (1996), governmental, institutional and social policies and cooperation can determine levels of comparative advantages in innovation (see Table 7.1).

Even from a static perspective, the process of innovation has an added non-quantifiable dimension of complexity—people. The most significant information cannot produce economic value without human creativity and intellect. Moreover, the knowledge required to innovate is not just the codified knowledge found in books and taught in universities, but also the tacit knowledge rooted in individual experience, beliefs, perspectives and values. Being a successful innovator is not sufficient; one must innovate at a pace that exceeds the competition, and it is the characteristics of the people that largely determine this speed of innovation.

Table 7.1
Levels of Comparative Advantage

National governance	
Socio-political climate	
Macro policies	Fiscal Monetary Trade Tax
Institutional setting	Financial Legal (including torts, antitrust, and intellectual property)
Corporate governance	Professional bodies
Intermediating institutions	
Structural and supportive policies	Education (including university-industry relations) Labor Tax Science and technology (including role of engineers and scientists) Regulatory and environmental
The industry collectively	
Companies within the industry	

An example of the process of innovation is the current interest in EBM. Each region that we visited—the U.S., the European Union (EU), and Japan—has a different approach to developing an environmentally benign manufacturing strategy. Each region also has different drivers. In the U.S., the drivers are the correlation between cost savings and the environmental benefit, given the vast space available for landfills. In the EU, the high population density, a recycle mindset, and take-back provisions drive environmental policy (see also Chapter 2). In Japan, the environmental policy drivers are the export economy, high population density and ISO 14000.

For American firms with a majority of sales abroad, such as Boeing, IBM, and Caterpillar, responding to the U.S. drivers alone is not sufficient. A broader vision that includes design for environment issues is necessary as an integral part of their future. For many of these companies, EBM is now a major component of responsible economic growth. A key conclusion of this panel is that there are substantial benefits to promoting proactive environmental management rather than reactive end-of-pipe behaviors among manufacturers and R&D for manufacturing. In many instances, this proactive behavior can be very cost effective. This requires that environmental considerations be included as part of the entire system from both a business and an engineering viewpoint.

POLICIES

Environmentally benign manufacturing is a broad concept involving many aspects of society and how they interact. Figure 4.1 in Chapter 4, contributed by Bert Bras, shows this idea graphically. Many of the issues addressed by EBM must be solved at the largest scale, including all of society, as shown in the figure. A good example of this complexity is the issue of energy policy. Currently, carbon based fuels provide more than 75 percent of the world’s energy supply. The support structure that enables this usage is pervasive throughout society, and includes exploration, extraction, refining and processing, distribution and the development of compatible heating, transportation and power applications. During the next century, the development of economically competitive renewable energy sources will require extensive collaborative development. Attention will have to be focused, not only on the individual components of the problem, but also on their interconnection. For example, a new energy source cannot be viable until the complete system of delivery is realized in a mode that is compatible with society’s values for safety, economy, environmental protection and equality. Similar collaborative development activities will be required to implement almost all aspects of an environmentally benign manufacturing strategy.

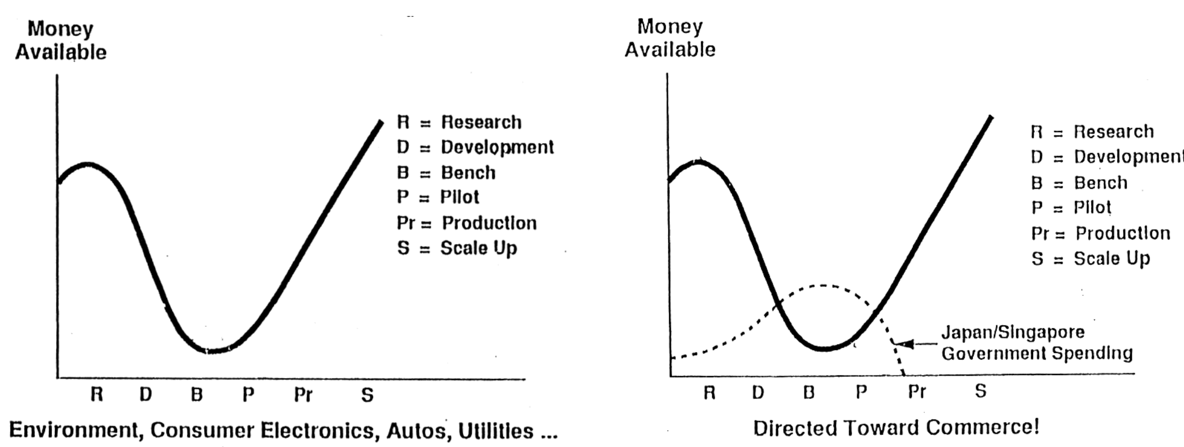
The development of a workable proactive policy to foster EBM behaviors is a major challenge to society. The solution requires shared information and unified goals for the many players involved. The panel found no shortage of examples of failed policies when the inputs of various parties were ignored. In particular, end-of-pipe solutions appear to be of this type, mandating results without sufficient concern for the means. For example, there are a number of instances where well-intended policies and initiatives have unintended consequences because the underlying manufacturing processes were not well understood by those stipulating the end-of-pipe regulations. Examples of this include the initial German take-back initiative (which failed due to an immature infrastructure), PCB contamination in some plastics (which makes it impractical to recycle despite careful separation), and the questionable environmental merits of alternative technologies such as Pb-free solder and water-based paints.

However, the new EU initiatives on automotive product take-back, and those of Japan on consumer and electronic goods, have relied on substantial public and private sector feedback and cooperative decision making. This has helped with the development of targets, metrics, and tools to manage product take-back and the development of infrastructures and policies to support them. Currently, under the European Council of Ministers direction, the following actions at the EU level are included in national programs:

- Agreement in 1998 with the automobile industry to improve fuel efficiency
- Legislation on waste (the landfill directive)
- The Strategy and Action Plan on Renewables (Altener program)

Funding Strategies

In contrast to the United States, research funding in Japan and the EU enjoys relatively coordinated support over the entire range of activities required to bring a new technology to market. In comparison, U.S. funding is episodic with a strong emphasis on the early phase (fundamental research) and the last phase (scale-up), with relatively lower levels of funding for the entire intermediate phase. This issue was addressed by MIT's John Preston in his 1993 congressional testimony (Preston 1993) which describes the different funding mechanisms for creating new knowledge in environment, consumer electronics, autos, and utilities between the United States and Japan. U.S. funding strongly supports the research phase but ignores intermediate work in the pilot and bench phases (and which may include technology transfer). The Preston report shows that Japan funds less fundamental research and concentrates on the development, bench and pilot areas. Preston concludes that this has been Japan's mechanism for gaining global predominance in the above-referenced fields (see Figures 7.1a and 7.1b).



(a) (b)

Fig. 7.1. (a) U.S. R&D spending; (b) Pacific Rim R&D spending relative to U.S. (J. Preston, MIT).

While the European Commission's "collaboration in technology" development is of more recent vintage, the institutional process for collaboration and funding support throughout the technology development cycle has been extensively practiced in most Scandinavian countries, the Netherlands and Germany. Examples for these are the laboratories operated by the Netherlands Organization for Applied Scientific Research (TNO) and the Fraunhofer Gesellschaft (FhG) in Germany. The largest of these, the Fraunhofer group, consists of more than 45 institutes located at all major German universities. TNO and FhG are managed semi-autonomously, incorporate university and industrial staff, and provide fundamental understanding, prototype development, and technology transfer functions. Base funding from governments (30%) gives a continuous enabling support; prototype development combines governmental and private sector resources (30%); and the technology transfer activities (40%) are the sole responsibility of the private sector. Additional funding for science and technology research is provided to all public universities and some private institutions. Hence, EU funding shows a strong commitment throughout the technology development cycle. Particular target areas for the EU have been: communications, transportation, environmental remediation, machine tools and the materials manufacturing industries. The EU has emerged as a strong, and in some cases a leading, technology provider in these fields. From the author's perspective and in collaboration with several faculty at Bradley University, Figure 7.2 represents the situation in Germany, the Netherlands and Scandinavia.

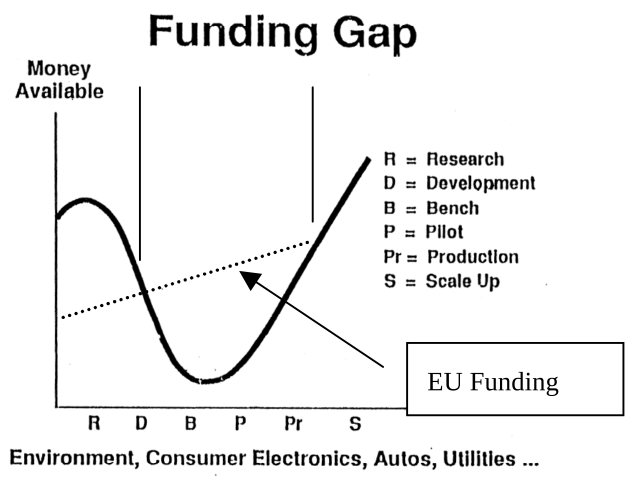


Fig. 7.2. EU research funding.

As can be seen in the representations of the Japanese and EU funding models, the proof that scientific and engineering concepts work at bench, pilot, and production levels is viewed as an important research outcome. This optimizes the speed of implementation of the innovations. The U.S. model, which leaves this up to an eventual private sector activity, does not consider validation and proof as an integral part of the research enterprise. Hence, in the U.S. more resources need to be allocated to the intermediate steps of the innovation process to be globally competitive.

Thus, the private sector in the EU and Japan is more fully integrated into publicly funded research programs than is the case in the United States. Additionally, the EU and Japan have elevated research and development to ministerial status with an objective to complement the education, knowledge, and job-creating infrastructure. While the merits for permanent R&D tax credits have been subject to annual debates in the United States, Japan and Europe have long recognized these R&D benefits to society and economies and have established permanent R&D incentives and tax credits (Jernigan 1998).

While total U.S. governmental and private sector R&D funding exceeds that for the EU and Japan, the almost exclusively market focus, the lack of complete funding for the entire innovation process, and, in some cases, the limited relevance to societal needs, has made some of this U.S. work less noticeable. On the other hand, the focused EU and Japan effort, especially towards environmental objectives, has shown significant results.

EUROPEAN UNION AND JAPAN OVERVIEW

European Union

It is useful to examine the collaborative approaches utilized in the EU and Japan for transforming scientific and engineering knowledge into economic value. A review of different styles of interaction among the private sector, research entities and government is insightful and provides a basis for comparison.

An example of the education-research-innovation model that is more competitive is the "thematic networks" activity of the European Commission's Industrial and Materials Technologies Program. Using education and research to stimulate innovation through thematic networks is seen as critical to the European Community, because it creates the critical mass of scientific and engineering personnel necessary to optimize the pace of innovation. The 100 networks operate in three general areas: production technologies, materials and technology for product innovation, and transportation technologies (see also chapter 3 of this report).

Examples of thematic networks at work were evident at the Technical University of Berlin, Technical University-Aachen, and University of Stuttgart. There, faculty and researchers have teamed with engineers of the Fraunhofer Institutes, which are also managed by university faculty and private sector entities, to concurrently address scale-up, technology transfer and demonstration issues.

According to Edith Cresson of the European Commission for Research, Innovation, Education, Training and Youth, "The overall aim of this initiative is to strengthen Europe's R&D infrastructure. It has been achieved by the transfer of technology and know-how and by ensuring the needs of industry are widely understood and met." In addition, she noted, "From 1999, technical areas of Industrial and Materials Technologies program will be absorbed into the thematic program: "competitive and sustainable growth." This will support research activities contributing to competitiveness and sustainability; its strategic approach will be based upon the development of critical technologies and targeted platforms where project clustering will play an important role."

As explained in the European Commission Report *A Road to European Cooperation, Industry and Materials Technology Program,* "Industry will not only have to identify areas for collaboration but also bring together and integrate activities—especially cross-sectoral projects along the value chain. The intention is to ensure more efficient technology uptake and innovation across Europe. Coordination and pooling of resources will be promoted between universities, research centers and companies with particular emphasis on small and medium size enterprises. The aim is to achieve synergy and wider benefits around the objectives of the key actions and generic technologies."

Japan

The evolution of science and technology toward greater complexity, coupled with the fact that around the world science and technology are now seen as tools for economic competition, has required that Japan's researchers focus on original research rather than translating the results from overseas research.

Beginning with the basic plan for science and technology in 1996 and the merger of the Ministry of Education with the Science and Technology Agency, Japan's universities are expected to play the central role in the new system of academic research and technology development. Note that most of the Japanese research universities are public. For example, while most of the top 20 recipients of U.S. federal grants are private institutions, Keio University is the only non-public school in the top 20 recipients of science research grants from the Japanese Ministry of Education.

Where Japanese masters degree programs, as well as doctoral programs, were once organized mainly to train academic researchers, new institutes have in recent years been promoted with more practical goals. These are institutions in a different sense in that they include programs with courses aimed at supporting industry and technology (e.g., the University of Tsukuba and the University of the Air). At the Shonan Fujisawa Campus of Keio University, a department for comprehensive policy and environment information has been established. Recent academic attention is given to improving graduate opportunities to fulfill the demand for people with highly specialized knowledge and skills. In its 1991 report, the University Council recommended that the number of graduate schools be at least doubled by the year 2000.

OBSERVED AREAS OF EBM RESEARCH IN JAPAN AND THE EU

The following represent selected areas for EBM R&D that were seen and discussed by WTEC panel members:

- Soft materials, soft processing: University of Tokyo, IKP at University of Stuttgart, Dresden University, Hitachi PERL, Sony
- Non-traditional materials forming: IBF at University of Technology-Aachen, MITI (MEL), Toyo Seikan, Dresden University, Polyvinyl Chloride Industrial Association (Japan)
- Material removal: MITI, EX-CELL-O, IBF at University of Technology-Aachen, Nagoya Institute of Technology, Nagoya University, Fraunhofer IPT (Aachen), Toyota
- Design for product disassembly, inverted manufacturing: MITI (MEL), Fraunhofer IZM (Berlin), University of Tokyo, Hitachi PERL
- Life-cycle analysis: MITI (NIRE), NEC, IKP at University of Stuttgart, Fraunhofer IZM (Berlin), Fraunhofer IPT (Aachen), University of Tokyo, Hitachi PERL

The site reports in appendixes C and D provide additional details. Note that research in Japan on inverted manufacturing (University of Tokyo) and in Germany on life-cycle analysis (University of Stuttgart and Fraunhofer IGB in Stuttgart) has revealed the challenges posed by complexity of environmental trade-offs. Consequently, significant efforts are underway to develop decision tools that include databases and new technologies (alternatives) for existing processes. (The author has also visited Dresden University, and has included Dresden in the above list, where appropriate.)

In comparison, the Department of Energy's industrial road maps provide a good basis for a U.S. EBM R&D effort and, in some cases, a basis for international collaboration. While this effort accepts a business consideration for the development of alternative processes, it fails to stress the development of life-cycle analysis (LCA) tools for EBM for the entire product development chain.

Discussions with European and Japanese government leaders, university faculty, developmental laboratory staff and private sector managers all concluded that without pooling and integrating the resources of the universities, research centers, government and private sector companies, results for society and sustainability will fall short of intended goals.

FINDINGS

Having compared the EBM research strategies of the European community, Japan and United States, the differences may be described as well-coordinated and focused within the EU and Japan, and seemingly ad hoc in the United States. That is, in terms of solving the larger problems of society—in this case environmental problems—the almost exclusive market orientation of U.S. activities makes them appear disorganized and unfocused.

The EU and Japanese efforts contain directions, scope and goals involving all segments of society to achieve the EBM objectives; collaboration and consensus is the *predominant enabler* in these countries. United States EBM research efforts, on the other hand, are disconnected and rarely involve all parties. Furthermore, when described by some companies, it is difficult to do research in the current regulatory environment due to concerns about liability.

While U.S. EBM efforts are mainly initiated for global competitiveness by international corporations, the university segment remains a distant player and lacks the governmental funding support so prevalent in the EU and Japan. Meeting global environmental challenges will require new modes of diplomacy, new ways to stimulate technological innovation, and the inclusion of new participants at all levels in the decision-making processes (ACP 2000).

The United States can learn from Europe and Japan if it wants to be a relevant participant, contributor, and beneficiary from global environmental remediation. Efforts by National Science Foundation and Department of Energy program directors to develop a focused U.S. EBM research platform involving university and private sector are significant steps. The Department of Energy roadmaps involving primary manufacturing of materials commodities need to be expanded to involve materials transformation, joining, and re-manufacturing, in the broad areas listed below:

- Materials processing (metals/polymer)
- Thermal processes (heat treat/stress relief/curing)
- Joining (welding/bonding)
- Machining
- Remanufacturing processes
- Cleaning
- Dismantling
- Remaining life determination
- Reconditioning
- Surface engineering for enhanced durability
- Surface protection, i.e., coatings, paints, etc.
- Wear and tribology knowledge
- Life-cycle analysis with business/value attributes
- In-process sensor capability to modify/correct process deficiencies
- Foundry emission reduction (sand and binder waste)
- Methods of removing contaminants and trace elements from recycled alloys
- Methods of economically recovering and reprocessing composite materials
- Development of true net-shape metal casting and forging methods
- Methods of recycling and recovering alloys in engineered materials
- Evaluation of recyclability of materials and new materials systems

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APPENDICES

APPENDIX A. BIOGRAPHIES OF PANEL MEMBERS

Name: Dr. Timothy G. Gutowski (Panel Chair)

Address: Professor of Mechanical Engineering
Director, Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
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Dr. Timothy G. Gutowski is a Professor of Mechanical Engineering and Director of the Laboratory for Manufacturing and Productivity (LMP) at the Massachusetts Institute of Technology. The LMP is responsible for manufacturing development, including manufacturing process and system design, control, analysis and optimization. He has also been Director of the MIT-Industry Composites and Polymer Processing Program, 1984-93, and is currently the Co-Lead of Factory Operations for the MIT Lean Aircraft Initiative.

Dr. Gutowski has over 100 technical publications, including seven patents, in such areas as advanced composites processing, polymer processing, new process development, design for manufacturing, cost estimating, physical chemistry, and acoustics and vibration. He and his students have developed several new processes for the forming of advanced composites for aerospace applications. He has also developed new theories for the consolidation of composites and the mapping of fiber assemblies onto complex shapes. His most recent book, *Advanced Composites Manufacturing*, was published by John Wiley in 1997. Dr. Gutowski is the North American Editor for the international journal *Composites, Part A Applied Science and Manufacturing,* and he is an Associate Editor for the *Journal of Manufacturing Systems*.

He held the Alcoa Professorship at MIT from 1985 to 1992, and in 1989 was named an MIT Leader for Manufacturing Professor.

Name: Cynthia F. Murphy (Panel Co-chair)

Address: Research Scientist, Center for Energy and Environmental Resources
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Ms. Murphy is currently a research scientist at the Center for Energy and Environmental Resources, University of Texas at Austin. She has been the Principal Investigator for two projects attempting to advance electronic products recycling in the context of an eco-industrial park. The focus of both projects is to evaluate material streams associated with these products, including metals, thermoplastics, and leaded glass. This is being done through the development of activity-based process and logistics models that address cost, quality, and environmental metrics. She is also the Principal Investigator for an NSF/EPA project in cooperation with Motorola and SEMATECH to develop generic LCI modules for the semiconductor industry.

Prior to joining the University of Texas, Ms. Murphy was a Senior Member of Technical Staff and Project Leader in Environmental Programs at the Microelectronics and Computer Technology Corp. (MCC) in Austin, TX. She was the project manager and/or technical lead on numerous projects at MCC, including “Making Design for Environment and Life-cycle Assessment Work,” and “Revolutionary Environmental Manufacture of Printed Wiring Boards,” a $7.3 million project involving six industry partners. In addition, she contributed to the Electronic Products Environmental Roadmap (1996). Ms. Murphy has 10 years of experience in the area of cost-modeling, process-modeling, and materials inventory modeling for the purpose of performing tradeoff analyses and optimization for various sectors of the electronics industry. Her background includes manufacture and test of semiconductors and printed wiring boards, and advanced electronic packaging and assembly technologies.

Ms. Murphy's research interests include design for environment, life-cycle assessment, environmentally conscious manufacturing, process modeling of manufacturing processes, and economic and environmental tradeoff analyses. She has numerous publications.

Name: Dr. David T. Allen

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Dr. David Allen is Beckman Professor of Chemical Engineering and Director of the Center for Energy and Environmental Resources at the University of Texas at Austin. Prior to joining the faculty at the University of Texas, Dr. Allen was Professor and Chairman of the Chemical Engineering Department at the University of California, Los Angeles. His research interests lie in environmental reaction engineering, particularly issues related to air quality and pollution prevention. He is the author of three books and over 100 papers in these areas, and the quality of his research has been recognized by the National Science Foundation through the Presidential Young Investigator Award and the AT&T Foundation through an award in Industrial Ecology. Dr. Allen is also active in developing pollution prevention education materials for engineering curricula, and his teaching has been recognized through UCLA's Excellence in Engineering Teaching Award.

Dr. Allen received his BS degree in Chemical Engineering, with distinction, from Cornell University in 1979. His MS and PhD degrees in Chemical Engineering were awarded by the California Institute of Technology in 1981 and 1983. He has held visiting faculty appointments at the California Institute of Technology and the Department of Energy.

Name: Dr. Diana J. Bauer

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Dr. Diana Bauer is currently serving as a AAAS Fellow at the Environmental Projection Agency in Washington, DC. She received her PhD in mechanical engineering with a specialization in environmentally conscious design and manufacturing from UC Berkeley in 1999. Before returning to graduate school she spent several years in industry, first developing computer models in the Systems and Design Integration Group at Foster Miller, Inc., and later conceptualizing new CAD product ideas in the Product Planning Group at Parametric Technology Corporation. She has also lived and traveled extensively in Asia, including two months in 1998 based at MEL in Tsukuba researching Japanese industry and the environment. Her research interests include process-level environmental evaluation of manufacturing, tools to support environmental decision making in design and manufacturing, and international comparisons of environmentally conscious design and manufacturing activities and motivations.

Name: Dr. Bert Bras

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Dr. Bert Bras has been Associate Professor at the George W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology since September 1992. His research focus is on environmentally conscious design and manufacturing, design for de- and remanufacture, activity-based life-cycle assessments, and industrial ecology. His primary research interest is how to reduce the environmental impact of companies while increasing their competitiveness, i.e., how to promote sustainable development. He has received funding and donations from the National Science Foundation, the Georgia Research Alliance, the Center for Sustainable Technology, AT&T, Motorola, Ford Electronics, the Army Environmental Policy Institute, and DaimlerChrysler for his research. He has authored and co-authored over 60 publications. He has developed and taught an undergraduate course on Environmentally Conscious Design & Manufacturing since 1993 and has developed a curriculum in Sustainable Development with colleagues from other engineering schools and public policy. He also taught segments of a National Center for Advanced Technologies (NCAT) short course on Integrated Product and Process Development for the Army and for the U.S. Navy. He has won Georgia Tech's 1995 Amoco and Center for Enhancement of Teaching and Learning Young Faculty Teaching Award, was named the 1996 Engineer of the Year in Education by the Georgia Society of Professional Engineers, and received a NSF Young Faculty Career Award in 1996, and a Society of Automotive Engineers Ralph R. Teetor Award in 1999.

Dr. Bras obtained his Master of Science ("Ingenieur") degree in Mechanical Engineering from the University of Twente, The Netherlands, in August 1987. After completion of his MS thesis he was hired as a full time research associate at the Maritime Research Institute Netherlands' (MARIN) Design Research Department and sponsored by MARIN to complete PhD study in the U.S. He obtained his Doctor of Philosophy degree in Operations Research from the University of Houston in May 1992. Upon completion of his PhD, he received a Post-Doctoral grant from the Institute of Space Systems and Operations at the University of Houston.

Name: Dr. Thomas S. Piwonka

Address: Director, Metal Casting Technology Center
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Dr. Piwonka is Director of the Metal Casting Technology Center and Acting Director of the Marine Transportation Center at the University of Alabama in Tuscaloosa, AL. Prior to joining the university, Dr. Piwonka spent 25 years in the metalcasting industry, at the General Motors Corporation, Kelsey-Hayes Corp, and TRW Inc. He has held a variety of positions in the cast metals industry, ranging from production engineer to research director. He is a graduate of Case-Western Reserve University, and received his advanced degrees from the Massachusetts Institute of Technology.

Dr. Piwonka is a member of the American Foundrymen's Society, The Minerals, Metals and Materials Society, ASM International, and the Investment Casting Institute. He is a member of the Advisory Technical Awareness Council of ASM International, is on the Editorial Board of the *International Journal of Cast Metals Research*, and was on the editorial board of *Metals Handbook, Desk Edition–Second Edition*. He has authored more than 80 technical papers on foundry technology and has seven patents in the field of metal casting. He is a member of the Process Design & Modeling, Aerospace Structural Casting, Aluminum Gating and Risering, Mold-Metal Interface and Green Sand Committees, and the Steel Division at AFS, and is Program Manager for the Thin Wall Iron Casting Program at AFS, and the Maritime Administration's High Speed Sealift Program.

Dr. Piwonka's research interests include alloy solidification, non-ferrous foundry processes, manufacturing processing of superalloys, mold making science and technology and manufacturing systems. He teaches courses in non-ferrous metalcasting, high temperature alloys, materials processing and powder metallurgy.

Name: **Dr. Paul Sheng**

Address: Associate Principal
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Dr. Paul Sheng has recently moved to a position with McKinsey & Company, from his previous post at UC Berkeley. His research interests are in environmentally conscious processing and planning, particularly in machining and electronics manufacturing. He has co-authored over 90 journal and conference publications on environment and manufacturing topics. Dr. Sheng is the recipient of the Office of Naval Research Young Investigator Award, Society of Manufacturing Engineering Young Engineer Award, NAMRI Outstanding Paper Award, Japan-USA Flexible Automation Young Investigator Award, and the Lucent Technology Industrial Ecology Faculty Fellowship. He is currently a corresponding member of the CIRP.

Dr. Sheng received his SB, SM and PhD degrees in mechanical engineering from MIT. Prior to joining the faculty at Berkeley, he served as Sr. Project Engineer on the Advanced Manufacturing Staff of General Motors Corporation.

Name: **Dr. John W. Sutherland**

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Dr. John W. Sutherland is presently Professor and Associate Chair in the Dept. of ME-EM at Michigan Technological University. He received his BS, MS, and PhD degrees from the University of Illinois at Urbana-Champaign. Previously, he held an adjunct faculty position at the University of Illinois and served as a manufacturing consultant. He has published over 100 technical papers in various journals and conference proceedings. He is a member of the Board of Directors and the Scientific Committee of the North American Manufacturing Research Institution of SME, and serves on the Executive Committee of ASME's Manufacturing Engineering Division. Professor Sutherland has received numerous teaching awards, SME's Outstanding Young Manufacturing Engineer Award (1992), Presidential Early Career Award for Scientists and Engineering (1996), and SAE's Ralph R. Teetor Award (1999).

Name: **Dr. Deborah L. Thurston**

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Dr. Deborah L. Thurston is Director of the Decision Systems Laboratory at the University of Illinois at Urbana-Champaign, where she conducts research in multiobjective engineering design decision making. She is a Professor of General Engineering, and also holds appointments in the Civil and Environmental Engineering Department, and in the Mechanical and Industrial Engineering Department.

The focus of her research is on developing new methods for integrating environmental impacts, production costs, product performance and quality into concurrent design and manufacturing analysis. She has published over 70 technical papers. Her research has been funded by the National Science Foundation, Chrysler, General Motors, Ford, Motorola, Hayes-Lemmerz, Hewlett-Packard, Sun, Armstrong World Industries, Prefinish Metals, Nestle, Illinois Department of Natural Resources, and EPRI.

She received the prestigious Presidential Young Investigator Award from the National Science Foundation in 1989, the Xerox Award for excellence in engineering research in 1992 and 1995, three awards for excellence in undergraduate advising, and a 1994 Best Paper of the Year Award for *The Engineering Economist*. Professor Thurston currently serves as an Area Editor for *The Engineering Economist*, and as past Associate Technical Editor in Design Theory and Methodology for the Transactions of the American Society of Mechanical Engineers: *Journal of Mechanical Design*. She is a registered professional engineer and a member of ASEE, ASME, IEEE and IIE.

She earned the MS and PhD degrees from the Massachusetts Institute of Technology (MIT) in 1984 and 1987, respectively. After obtaining the BS degree in Civil Engineering from the University of Minnesota in 1978, she worked for the Minnesota Pollution Control Agency for four years.

Name: Egon E. Wolff

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Egon Wolff's career at Caterpillar started in 1967 as a Project Engineer for large off-highway vehicles. He served as a Technical Resources and Development Manager in the United States and Brazil before taking the position as Director, International Materials and Component Research.

His work focuses on developing and acquiring emerging technologies from universities and institutions, research funded by agencies of government, and through the creation of technology ventures. He has formed partnerships with more than 20 international institutions and specifically focused on technology transfer as a means to improve the discovery process for increased implementation. He earned degrees in Materials Science and Engineering in Germany and is a Professor for Engineering and Technology at Bradley University.

APPENDIX B. BIOGRAPHIES OF OTHER TEAM MEMBERS

Name: Delcie R. Durham, Ph.D., PE

Address: Program Director, Design and Manufacturing Research Group
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Dr. Durham is Program Director for the Materials Processing and Manufacturing Program in the Engineering Directorate at the National Science Foundation. This program sponsors research in novel materials processing, including nanotechnologies, microfabrication, and plasma deposition processes. The program also funds research in modeling and simulation of netshape processes such as casting, forming, polymer composites and thin films for predictability and improved productivity. Many of the awards are directed towards environmentally conscious manufacturing. Dr. Durham was previously at the University of Vermont, where she was Associate Professor of Mechanical Engineering and Materials Science, and also served as Dean of the Graduate College. Dr. Durham has served on the Board of the North American Manufacturing Research Institute of the Society of Manufacturing Engineers, including President in 1995. She is a member of the American Society of Mechanical Engineers, and is currently a member of the Executive Committee of the Manufacturing Engineering Division. Dr. Durham is a registered Professional Engineer in the State of Vermont and has worked as a consultant for numerous industries.

Name: Mr. Hiroshi Morishita

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Hiroshi Morishita, President, HMI Corporation, specializes in ultra-micro manipulation technology for MEMS (microelectromechanical systems). He founded HMI Corporation in 1991 to commercialize his ultra-micro manipulator system. He extended his interest and business to the field of archaeological excavating and to the new robot manipulator system to help bed-ridden persons. In 1994, he became a consultant to WTEC for study tours in Japan. He graduated from the University of Tokyo (BA, MA, mechanical engineering), and is in the final stage of preparing his doctoral thesis. He was a visiting researcher in the University of Tokyo's Mechanical Engineering Department in 1992-93 and at RCAST (the Research Center for Advanced Science and Technology) at the University of Tokyo in 1994-95.

Name: Dr. K.P. Rajurkar

Address: Program Director, Manufacturing Machines & Equipment Group
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Dr. K.P. Rajurkar is Program Director for the Manufacturing Machines & Equipment Program in the Engineering Directorate at the National Science Foundation. He received his BS degree with honors from Jabalpur University, India. He received his MS and PhD degrees from Michigan Technological University in 1978 and 1982, respectively.

Dr. Rajurkar is the founder of the Center for Nontraditional Manufacturing Research of the College of Engineering and Technology, University of Nebraska-Lincoln. In the past he has worked as Associate Professor at the University of Nebraska-Lincoln and as Assistant Professor at Michigan Technological University. Dr. Rajurkar is a member of ASME, SME and a corresponding member of CIRP. Dr. Rajurkar serves as a reviewer for several professional journals including *Trans. ASME, Journal of Manufacturing*

Science and Engineering; *Trans. ASME, Journal of Engineering Materials and Technology*; the *ASM Journal of Shaping Technology*; *International Journal of Electro-Machining*; *Wear*; and others. Dr. Rajurkar served as an Associate Editor of the *ASME Journal of Engineering for Industry* and Chairman of the Scientific Committee of the NAMRI/SME. He is the President-Elect of the North American Manufacturing Research Institute of SME.

Dr. Rajurkar has more than 90 refereed publications and nearly 100 technically edited papers which were published in conference proceedings. He has authored many technical reports and has made several unpublished presentations. Dr. Rajurkar has participated in numerous seminars, workshops, and curricular/lab development activities. He has been successful in attracting research grants from NSF, NIST/ATP, DOD, GEAE, Extrude Hone, Brush Wellman, Cummins Engines, NCMS, Mitsubishi Electric Corporation (Japan), Trans Tec Inc. (England), State of Nebraska, and other sponsors. He has received College of Engineering and Technology Awards for research and teaching. He also has received the ASME Blackall Machine Tool and Gage Award for a paper on Pulse Electrochemical Machining. Recently his patent on cryogenically cooled tool machining has been approved.

His areas of teaching experience include undergraduate and graduate courses in manufacturing methods and processes, metal cutting theory and practice, nontraditional manufacturing methods, computer aided manufacturing, numerical control and automation, robotics, applied operation research, production planning, statics, dynamics, strength of materials, statistical experimental design, and modeling of manufacturing processes and systems.

Name: **Dr. A. Frederick Thompson, PE**

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Dr. Fred Thompson joined the National Science Foundation in 1997 after 28 years in the environmental consulting and construction industry. He has broad experience in all phases of environmental engineering and management, and his activities have included all media, including air, water, wastewater, and solid and hazardous wastes. He has been a consultant to industry and to municipal, state and federal government agencies as they solved existing environmental problems or established programs and plans to avoid future pollution. His experience includes a three-year assignment in Milan, Italy, where he served industrial clients throughout Europe. Dr. Thompson earned his BS in Engineering Science from the Pennsylvania State University (1963) and his MS (1965) and PhD (1968) in Environmental Health Engineering from the California Institute of Technology. He is a registered professional engineer in Pennsylvania, Maryland and Virginia.

At NSF, he directs the Environmental Technology element of the Environmental/Ocean Systems Program in the Division of Bioengineering and Environmental Systems. This program element focuses on technologies to prevent the formation and discharge of pollutants and to avoid environmental harm.

APPENDIX C. SITE REPORTS—EUROPE

Site:	**DaimlerChrysler AG** **Epplestrasse 225** **Stuttgart-Möhringen** **Germany**
Date:	April 6, 2000
WTEC Attendees:	T. Piwonka (report author), B. Bras, D. Durham, T. Gutowski, R. Horning, C. Murphy, D. Thurston
Hosts:	Dr. Eberhard Bessey Dr. Franz-Josef Ecker Mr. Joachim Diener

INTRODUCTION

DaimlerChrysler personnel reviewed the company's efforts in the environmental area. The company issues an annual environmental report, which now includes all of the corporation's operations, e.g., Mercedes-Benz, Chrysler, Dasa, debis, and the rest. After the merger with Chrysler, they had to integrate the two differing environmental policies. The Board of Directors has issued a six-point series of objectives. All operations are now implementing these objectives.

EBM ACTIVITIES

Two years ago Daimler toured the world benchmarking the best environmental management practices. A long-time goal of DaimlerChrysler is zero waste. Today, 97% of their waste can be recycled by means of either material or thermal recycling; only 3% must be landfilled. The amount of non-recyclable waste produced per Mercedes-Benz car is 21 kg. They have put their automotive designers under pressure to produce an environmentally acceptable car. This is in addition to the other pressures on the designers, such as the European take-back laws now in effect. These require that 75% of each car (by weight) must be recyclable for 2001 cars (increasing to 95% in ten years), and fuel economy must increase by 40% by 2006. (They believe that the technology exists to accomplish these goals but that it is not currently commercial.) In addition, the development time of new Mercedes-Benz models has been decreased substantially, to 36 months.

To respond to these pressures they have established dismantling centers in Germany for rebuilding components for the used car and warranty markets. Their international engine recycling center is in Berlin. They noted that, without end-of-life take-back laws, recycling would be profitable only for high value parts, such as engines and electric generators. There have also been setbacks: companies that invested in the recycling of electronic components before take-back laws existed went bankrupt (except in Holland, which already had those laws).

DaimlerChrysler is currently in the process of integrating the environmental policies of Daimler and Chrysler into one corporate approach. However, they acknowledge that the two political approaches to environmental issues are different. In Germany there is great concern over fuel economy and greenhouse gases, while in the U.S. there is more concern about emissions and soil pollution. They note that their German practice of actively helping their suppliers to become leaders in environmentally benign manufacturing practices would not work in the United States because of the possibility of litigation if the practices did not work as planned. Although they do not currently require their suppliers to be ISO 14000 compliant, they are discussing the possibility of so doing, and, in Germany, will help the supplier achieve that goal.

They recognize the financial burden of ISO certification to small and medium size enterprises, such as their suppliers, and mentioned that ISO 18000, on worker safety, is likely to come next. They would prefer to see one overall certification, covering ISO 9000, 14000 and 18000, instead of three different ones. They expect their Tier 1 suppliers to be pushing ISO 14000 compliance down to *their* suppliers.

In Europe, their plants are EMAS and ISO 14000 compliant, and the plants are expected to work actively on environmental issues. They emphasized that the effectiveness of ISO 14000 depends on the people in the plants. The ISO 14000 plans drawn up for each plant are the responsibility of that plant. Corporate headquarters reviews each plant's performance each year. This is not just an assessment of the technical data in each plant, but also of the management of each plant.

In product design, they have had for some time a team assigned to each product. Each member of the design team is responsible for incorporation of design for the environment (DFE) principles. Each design modification must go through "gates" (cost, performance, etc.) to make it to the next level successfully, and DFE considerations must also make it through the gates. They are in the process of integrating DFE procedures between U.S. and European operations. Additionally there are so-called "black" and "gray" lists of materials, indicating substances not tolerated in manufacture, or tolerated in restricted use only until there is an environmentally benign substitute.

They are trying to reduce the number of different materials used in their products, and the number of different manufacturing operations used. Thus, they view net-shape casting as a manufacturing method of the future, because it cuts down on the number of components. They have a methodology for DFE that includes LCA and design for cost. One measure is the use of "Ecopoint" lists. Among their goals are: reduce number of components, reduce number of materials, use compatible plastics, use snap locks instead of screws, etc.

They have developed a method of dry machining and have reduced the use of coolant from 3000 l/hr to 20 ml/hr. This depends on tool material and geometry. Chip removal was a problem, as was built-up edge. They noted that any environmental advance must also be able to produce the same quality product at the same or lower cost.

DaimlerChrysler has had an extensive program to develop natural fibers for use in fiber-reinforced plastic components in their vehicles. In this process they use, among other things, sisal and flax instead of glass fibers, which reduces vehicle weight and increases recyclability of the composites. They discovered that it is very important to analyze the complete process chain from the field (crops) to the final automobile part. They had to learn about the effect of weather conditions, post-harvest processing, drying conditions, etc., on the properties of the fibers. They also had to establish an infrastructure to move the fibers from the farm to the composite manufacturing plant, and to guarantee consistency in fiber performance. This included helping their suppliers design processing parameters and equipment. The project resulted in cost reductions of up to 30% in some components, and weight reductions of up to 30%. No carbon dioxide emissions are involved.

Research and development departments have to transfer technology they develop to business divisions. Research has the responsibility of developing processes for competitiveness and sustainability.

DaimlerChrysler has considered what an ideal product mix would be. They also have considered being a supplier of mobility, i.e., owning the vehicles they produce and leasing them to customers (30% of their cars and 70% of their SMART vehicle, a two seater car marketed only in Europe, are leased today). They have used LCA as a decision support tool in discussing environmental regulations with legislators. An example cited was the use of solvent-based paints, vs. solvent-based paints with air cleaners, vs. water-based paints for their vehicles. In this case none of the choices was optimum. They therefore initiated the development of an entirely new powder/slurry technique.

They did note that currently no car can be imported into certain European countries if it is more than five years old. Before this law was enacted, a lot of their vehicles were ending up there in response to the need for reliable used personal transportation.

One other item of note: the roofs of the buildings at DaimlerChrysler headquarters are planted with grass. The grass and soil act as insulation during the year, decreasing heating and cooling costs and the energy they require.

Site: **Delft University of Technology (TU Delft)**
Jaffalaan 9
2628 BX Delft
The Netherlands

Date visited: April 3, 2000

WTEC attendees: B. Bras (report author), R. Horning, C. Murphy, D. Thurston

Hosts Prof. Ab Stevels (part-time faculty as well as Senior Advisor, Environmental Engineering, Philips)
Dr. Henk Strietman (Coordinator, Sustainable Product Development, Ministry of Housing, Spatial Planning and the Environment)
Dr. Harry te Riele, MSc (STORRM C.S.)
Dr. Ir. Menno Nagel (Lucent Technologies)
Catherine Ross, Casper Boks, Jeroen Rombouts, Piet Huizinga (PhD students)

DESIGN FOR SUSTAINABILITY PROGRAM AT TU DELFT

Dr. Stevels provided a presentation about the history of the Delft University of Technology, as well as current environmental activities. Delft University of Technology was founded in 1842, contains seven faculties with 15 programs, and has 14,000 students. The major programs are Architecture, Industrial Design Engineering, Mechanical Engineering and Aerospace Engineering. There are also large faculties in Engineering Physics, Chemistry, Electrotechnical Engineering, and Technical Management.

Design for Sustainability activities are in two areas:

- Design for Sustainability (DFS) program of the faculty of Design, Construction, and Production ("OCP") focusing on eco-design methodology and management, as well as Design for Sustainable Services-Product Combination.
- Smart Product Design, an interdisciplinary effort with cooperation of faculties of Earth Sciences, Industrial Design, Aerospace Design. The design of an electric/hybrid vehicle is a focus project.

The DFS program has been active since the late eighties and early nineties. It currently has three full professors, five assistant professors and 15 PhD students. One of its first accomplishments was the Promise eco-design cases and UNEP manual on eco-design developed under the guidance of Prof. Han Brezet in 1992. Now, about 130 graduation projects have been done in industry worldwide. Examples of collaboration with industrial partners include Philips (Chair on Environmental Aspects of Electronics), Unilever (packaging design), Shell (new services, scenarios), Atag (energy intelligent kitchen), Ahrend-KPN consortium (sustainable workplace), DAF Trucks (eco-design intranet tool, POEMS). The annual budget for the DFS program is about two million Dutch Guilders (almost one million U.S. dollars) of which 70% comes from internal university funding.

Stevels started the discussion by providing what he called provocative statements from personal observations and experience:

- Eco-design needs tailor-made solutions (nothing is generic).
- Eco-design has to be put into perspective. Its success or failure depends on other issues, such as internal circumstances (organizational culture), how the business is doing, external pressure (government pressure is not really an issue for a multi-national), and product and process characteristics.
- Design for "X" is crap, especially design for disassembly.

- Idea generation is more important than validation (e.g., by life-cycle analysis).
- Eco-labels are counter-productive. (This sparked a discussion among the Dutch delegates. Strietman stated that although the eco-label itself may not be good, the process behind obtaining an eco-label is definitely very worthwhile. Stevels suggested that eco-labels should be transformed into an environmental care system where the processes around eco-design are managed. The Dutch eco-label is called "milieukeur" which stands for environmental certificate.)

CONSUMER BEHAVIOR, NEW TAX LAW, DRIVERS

The behavior of consumers was also a topic of discussion. Stevels suggested that Europeans have the same buying behavior as in the U.S.: about 25% are environmentally concerned, 50% are neutral, and 25% are negative towards the environment in terms of behavior. Te Riele felt that much of this depends on the network and public awareness as well as shock effect of environmental issues. He added that in the Netherlands, consumers can choose to buy "Green Energy," that is, energy generated from alternative sources (wind, solar, etc.). Even though the energy costs per kWh are higher for consumers, the demand for this type of energy is going up. A fundamental question for Te Riele is when a system (in this case consumer behavior) starts to move. Te Riele suggested that sometimes a nucleus can cause a complete societal change. A significant problem currently is the enormous economic wealth in the Netherlands and other Western countries. The rebound of the economy has resulted in the fact that there is too much money to spend. This results in more environmental impact.

The Dutch government has made a very significant move to influence consumer behavior by adopting a new tax system. In the new system, taxes on labor, income, etc., will be reduced. However, the tax on material based systems will be raised. The intent is to have tax system that will reward low (natural) resource consumption. This new system will go into effect January 1, 2001. This change of the tax system had wide-ranging support in the Dutch Parliament, from both government and opposition parties.

When asked about the drivers for these far-reaching environmental efforts in the Netherlands, Strietman explained that many were historical. In the 1960-1970s the Dutch had severe air, water, and waste pollution problems. Furthermore, the Netherlands has historically had a lot of environmental pressure groups. Strietman also pointed out that the Dutch have a lot of positive notions about the environment. Part of the motivation also stems from religious notions that humans are supposed to be good caretakers of God's creation.

INDUSTRY-GOVERNMENT COLLABORATION

Strietman explained that in 1989 a shift occurred in the approach taken by the Dutch Ministry of Environment (the equivalent of the U.S. EPA), to an industry-sector-based approach rather than a media (air, water, land) based approach. Furthermore, the Ministry of Economic Affairs started to cooperate directly with the Ministry of Environment. The result is that in governmental policy making the correlation between economic and environmental issues is much better understood and managed. The collaboration between the Dutch Ministries is referred to as the "polder model." The name signifies that 50% of the Netherlands lies below sea level, and if the Dutch do not collaborate, the consequences of environmental problems are significant. This strong collaboration between government and industry is rather unique. Asked about inspection, Strietman said that the Ministry of Environment does have an inspection department. However, he added, companies are doing a lot of self-policing because a case of bad publicity related to one company can quickly affect the whole industry group. Also, the environmental inspections are not geared towards fining a company, but rather are goal oriented and focused on the question "What are you going to improve?" In this way, a positive atmosphere of collaboration between government and industry has been created. (See *Silent Revolution…* for more details on this approach.)

Given the high level of environmental awareness, the issue of how foreign companies and imports are handled was raised. According to the Dutch, imports are an issue. Stevels argued that the GATT agreements should have a minimum of environmental agreements included. He is also very fed up with the attitudes of some foreign companies (especially U.S. companies) towards environmental issues. Philips has the same environmental standards worldwide. Related to exports, Te Riele pointed out that Third World countries will not necessarily go through similar environmental problems as the developed countries because the Third World can buy much better equipment and catch-up much faster.

LUCENT ON SUPPLIER CERTIFICATION

Mr. Nagels provided an overview of the supplier certification system that he employs within Lucent Technologies in the Netherlands.

If you ask structural questions, then the supplier responds very conscientiously and will provide accurate data. Lucent is very open about why and how it is using the surveys. Lucent also handles all data confidentially.

The surveys are used in price negotiations. Initially, this was a surprise for U.S. colleagues of Mr. Nagels. They thought that it was “merely” an environmental survey to satisfy some customer request.

Nagel advises that you should organize your process well and do it from a strategic viewpoint. He strongly discourages the practice of sending lists of regulated substances around which he feels are too much action driven. In his opinion, when environment is not integrated into the business, it will not work. Environmental issues should be made practical and measurable.

The trend is “outsource what you can outsource,” but Nagel believes that the pendulum may swing back on this. A negative aspect of outsourcing is that it increases ones supply chain and decreases the (internal) knowledge base.

Lucent uses two approaches in its supplier certifications:

- A relative-zero approach
- An absolute approach

The relative-zero approach is basically a benchmarking approach and focuses on the efficiency of converting raw materials into products. Efficiency is measured per kilogram product. This approach basically asks the suppliers to set up a mass and energy balance of their operations. It considers base materials, auxiliary (process) materials, water, energy, and packaging as inputs, and emission (air, water, waste) and products as outputs of a manufacturing operation. The goal is to minimize all inputs and emissions, while maximizing the amount of product.

The absolute approach uses the Eco-Indicator metric to obtain a single number for environmental impact. Lucent provides suppliers guidance on necessary level of detail.

Both approaches are performed simultaneously and result in a numeric score that can be used to differentiate supplier performance. Based on the suppliers’ reported value(s), Lucent ranks the suppliers into categories.

FUTURE ISSUES

When asked about future issues, Te Riele and Strietman observed that in the Netherlands the “disturbing thought” and realization has occurred that life-cycle analysis is not enough for a strategic way of thinking. Life-cycle analysis has long been perceived as the tool that would give definite answers to what products are good or bad for the environment. However, LCA has been geared towards looking at the environmental load per functional unit. Now, in the Netherlands, the thinking is moving towards looking at the value of a product instead of the function of a product, and here LCA falls short. Te Riele suggested that value and load have to be separated better. Stevels pointed out that there is a difference between scientific green, governmental green, and perceived green.

Te Riele sees three major areas as gaining importance:

- Redesign of system concept—i.e., the sale of services rather than products (see also *Product Service Systems, Ecological and Economic Basics*)
- Influencing of system behavior—i.e., "get out of the box"
- Changing of accounting basics—i.e., to better reflect environmental impact (see change in Dutch tax system)

The Dutch government has connected the economic and environmental aspects (see collaboration between Ministries of Environment and Economic Affairs) and is now working on bringing in the social aspects. Currently, the fourth national policy act ("NMP4") is being worked on by the government.

It is noteworthy that a distinction is made between population growth and household growth. Although the population in the Netherlands is still growing (current population is 15 million), the number of households grows faster. This causes even more strain on housing and land. It was stated that the environmental load is caused evenly by three groups: industry, mobility, and household. The mobility sector includes industrial traffic, so roughly 50% of the environmental load comes from industry and the other half from the private sector. When asked about tele-commuting, Strietman mentioned that the Ministry of Traffic had done a study and one of the findings was that people who tele-commuted traveled more that those who worked in offices because they still liked to get out of the house and even more on holidays in weekends.

Stevels suggest that there is still a lot of work to be done on the "classical" environmental issues: energy and toxic substances. Also, supplier system needs work. Emphasizing the new tax system, it was stated that the tax should be on consumption, not on income.

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Site: **The European Commission Directorate for Science, Research and Development**
The Environment Directorate-General
200 rue de la Loi/Wetstraat 200
B-1049 Brussels
Belgium

Date: April 3, 2000

WTEC Attendees: D. Allen (report author), D. Bauer, D. Durham, T. Gutowski, K. Rajurkar, E. Wolff

EC Attendees: H. Pero
M. Douka
G. Katalagarianakis
S. Cervera-March
M. Gislev

INTRODUCTION

Two distinct groups were represented at the meeting. Attendees from the European Commission Directorate for Science, Research and Development, who described their research portfolios, and a representative from the Environment Directorate-General, who described the European Union's Integrated Pollution Prevention and Control Directive.

DIRECTORATE FOR SCIENCE, RESEARCH AND TECHNOLOGY

Herve Pero, Head of the EC Research and Technology Development (RTD) Programme on "Competitive and Sustainable Growth," gave an overview of the RTD program (described in detail at www.cordis.lu/growth/src/cwp_en). The program has four pillars:

- Quality of life and living resources (with an annual budget of 2.4 billion Euro)
- Creating a user friendly information society (3.6 billion Euro)
- Promoting competitive and sustainable growth (2.7 billion Euro)
- Energy, environment, and sustainable development (1.1 billion Euro)

As is evident from their titles, most of the pillars incorporate environmental issues to some degree, but the main focus of activities in environmentally benign manufacturing is the Thematic Programme on Competitive and Sustainable Growth. The thematic program has a set of key actions that concentrate research and technology development on clearly defined social and economic challenges. The four key actions are:

- Efficient production, including design, manufacturing and control
- Intelligent production
- Eco-efficient processes and design
- Organisation of production and work

The projects address these key areas and fall into the categories of:

- Products of the future
- Advanced functional materials
- New generation of machines
- The extended enterprise
- The modern factory

Infrastructures

It was beyond the scope of the meeting to discuss individual projects. However, there was substantial discussion of mechanisms for setting strategic directions for research. The EC Directorate uses a number of tools to set strategic direction. To provide an overview of research needs, the Directorate funds "virtual research institutes" that suggest strategic directions for research. These are complemented by a number of industrial/academic networks that provide more technical insight and direction on research needs. Approximately 100 of these networks exist; many are Web based; many of the Web sites are cited at the Directorate home page. Finally, most research is funded in the form of consortia, which generally contain industrial partners who help fund the research (approximately 50% in a typical consortium) and set research direction.

A typical consortium is funded at the level of approximately 1 million Euro per year for a period of three to four years. Consortia are evaluated based on five criteria:

- Science and technology excellence
- Community added value
- Social needs
- Economic development
- Partnership and management

The focus is on matching the scientific base within the university systems with industry needs, particularly those that will contribute to product quality, employment, or social needs.

After Herve Pero's presentation, individual program managers described programs.

Maria Douka described a cluster of approximately 35 consortia in new processing technologies, environmentally benign materials and chemistries (new solvents, new catalysts, membrane separations, processing under supercritical materials), and process integration tools.

George Katalagarianakis described a program on new generation machines, which are described at www.tra-fect.com and www.euspen.com. The program focuses on issues such as efficient equipment design and manufacture, rehabilitation and decommissioning.

Dr. Salvador Cervera-March described advanced materials and transformation technologies, including sustainable technology, steel and other programs.

Finally, there was some discussion of programs jointly funded by the European Commission and the National Science Foundation. An initial, joint program in materials is in the advanced planning stages.

ENVIRONMENT DIRECTORATE-GENERAL

Magnus Gislev represented Herbert Aichinger, from the European Commission Environment Directorate. Mr. Gislev's specific responsibility is the Integrated Pollution Prevention and Control (IPPC) Directive. This directive establishes best available techniques for environmental management in manufacturing processes (see http://europe.eu.int/comm/environment/ippc/index.htm).

The IPPC Directive is of use in assessing the state of environmentally benign manufacturing because it provides information on both current and emerging technologies. (These prospective technologies, as well as the reference documents, are described at the site http://eippcb.jrc.es.)

In addition to describing the IPPC, Mr. Gislev addressed a wide range of questions both in the group discussion and in smaller, ad-hoc discussions. Of particular interest to the panel were a variety of product initiatives underway at the Environment Directorate-General. Product take-back legislation is seen as an important driver for environmental innovation in the automotive and electronics sector. Mr. Gislev reported that in the automotive sector, original manufacturers of new cars will be responsible for taking back and recycling vehicles. Cars manufactured in 2001 need to meet a fixed recycling rate and this rate will be gradually increased over time. In parallel, fuel economy increases will be required. Similar initiatives are planned for the electronics sector.

Site: **EX-CELL-O GmbH**
Salacher Straße 93
D – 73054 Eislingen/Fils
Germany

Date: April 4, 2000

WTEC Attendees: D. Bauer (report author), D. Allen, T. Gutowski, K. Rajurkar, E. Wolff

Hosts: Dr.-Ing. Lothar Ophey, General Manager
Dipl.-Ing. Bert Lubner, Sales Manager

BACKGROUND

EX-CELL-O is one of several sister companies under IWKA. Machine tool products include transfer lines, high speed machining centers, special machine tools, test and assembly stations. The main customers are the auto industry and its suppliers, who use the machines to make cylinder blocks, cylinder heads, crankshafts and connecting rods, gear boxes, coupling housing, etc.

CURRENT TECHNOLOGY DEVELOPMENT TRENDS/INDUSTRY GOALS

High Speed Machining

EX-CELL-O is producing machines which operate at high speeds (accel ~ 1.2 g and speed ~ 120 m/sec). There is also current research into higher speeds and accelerations, but this requires a design shift, as the behavior of secondary components (cabling sheet metal covers, splash guards, doors, etc.) under such dynamic conditions becomes important. Current research in linear drives also supports the development of higher speed machines.

Dry Machining

With the high (and increasing) cost of cutting fluid management (fluid management is about 17% of manufacturing costs), there is significant development work in dry and minimal quantity lubricant (MQL) processing. This is the main environmentally related research effort at EX-CELL-O. Aerosol formation/aerosol management is of secondary concern, mainly for U.S. customers such as Ford.

There are several factors that become more important for dry and MQL machining. First, thermal management becomes key. Much of the process heat is transferred to the chips, and hot chips need to be isolated from work piece and machine surfaces. The EX-CELL-O approach is to isolate chips onto a chip conveyor running under the center of each machine. The elevated temperature in the work piece itself leads to different process planning paradigms, such as instances where some finishing passes are completed before some bulk removal (usually milling) passes to minimize dimensional inaccuracies caused by work piece thermal deformation. Second, chip removal also becomes challenging in dry machining. Gravity is used where possible. Finally, MQL requires that cutting fluid be brought to the cutting surface as efficiently as possible. This generally means mixing air and fluid shortly before coming to the cutting edge.

Dry machining of cast iron is fairly common, but otherwise, there has not yet been wide-scale manufacturing line implementation. First in-plant tests have been made to evaluate the quality and reliability of dry machining on aluminum parts.

Transfer Line Systems

Customers are increasingly interested in purchasing integrated transfer line systems. EX-CELL-O is applying modular design principles to simplify design of such systems. First, each machine is made up of defined modules, such as sub-bases, ball screw spindles, doors, etc. Second there is a standardization of physical and informational interfaces, such as the machining table, chip conveyor, control algorithms, etc. Third, there is the definition of design rules, such as the consistent placement of secondary systems such as hydraulics, no hinged doors, and decentralised controls. Standardization between machine tool manufacturers is difficult because it conflicts with the need to differentiate from competitors.

With general trends towards take-back laws, and trends in production philosophy towards agility and reconfigurability, EX-CELL-O is beginning to think about strategies for reconfiguring machines for reuse.

Additional Technologies

There are several other research areas. First hard machining is being developed to replace grinding. There is some work on parallel kinematics (hexipod). There is some research on linear drives to enable increased machining speeds. Finally there is some research in laser machining. A more long range research effort with environmental implications is taking a systems approach to reducing the quantity and intensity of process steps (melting→forming→cutting).

Site: **Fraunhofer IGB (Institut Grenzflächen- und Bioverfahrenstechnik)**
Nobelstrasse 12
D-70569 Stuttgart
Germany

Date: Apri 6, 2000

WTEC Attendees: T. Gutowski (report author), B. Bras, D. Durham, R. Horning, C. Murphy, T. Piwonka

Hosts: Prof. Dr. Herwig Brunner
Dr. Christian Oehr
Dr. Norbert Stroh
Dr. Iris Trick
Prof. Dr. Hans Knackmuss
Dr. Dieter Bryniok

INTRODUCTION

Professor Dr. Herwig Brunner provided us with an introduction and overview of the activities of the Fraunhofer IGB. This institute employs 161 people with an annual budget of 17.7 million DM in 1999. Research is focused in three different areas: (1) Membrane and Interfacial Engineering, (2) Biotechnology and Cell Engineering, and (3) Environmental Biotechnology. After a brief introduction by Dr. Brunner, we then explained the mission and purpose of the WTEC panel. This was followed by five presentations by our hosts, summarized below.

R&D ACTIVITIES

Interfacial Engineering and Plasma Technology for Clean Production (Dr. Christian Oehr)

Dr. Oehr described the importance of interfacial engineering for the recycling of plastics. An emphasis on plastics recycling and reuse leads designers to use fewer materials, which in turn creates a need to alter surface properties for different applications. Surface treatment can affect a variety of important properties including appearance and wettability as well as adhesion to other materials or coatings. The IGB is equipped to modify surfaces with various plasma surface treatments, including plasma cleaning, etching, sterilization, surface modification and plasma polymerization. For evaluation of surface treatment procedures a wide variety of techniques for surface characterization are available. Applications to textiles and biomaterials were mentioned. Dr. Oehr also mentioned that they have used a surface tension measurement apparatus to monitor the environmental quality of water.

Membrane Technology and Environmentally Benign Production (Dr. Norbert Stroh)

IGB produces a variety of membranes including both polymers and ceramics in a array of geometries. One interesting project described by Norbert Stroh was online measurement of cutting fluid and liquids. Cutting fluids are routinely used in machining to cool and lubricate and generally improve the material removal process. Under the conventional situation, cutting fluids are monitored infrequently by laboratory techniques. As a consequence most adjustments to the composition are based on experience rather than data. Hence, renewal tends to be conservative and very likely wasteful of cutting fluids. The purpose of this project was to develop an online cutting fluid quality monitoring system to be used in a feedback control loop for fluid renewal. In this scheme, six parameters were measured directly or inferred from other measurements: temperature, concentration of the tramp oil, pH, conductivity, and concentration of the aerobic micro-organisms. The concentration of micro-organisms is actually measured indirectly by measuring the concentration of O_2. This new technology makes possible reduction in the amount of cutting fluids and additives used and can significantly extend the life of cutting fluid. These developments are particularly important because in Germany cutting fluids are treated as toxic waste and require special handling procedures. Furthermore, this will have a positive impact on worker health by reducing micro-organisms, which are harmful to people.

Sustainable Biotechnology (Dr. Iris Trick)

In this area Dr. Trick provided reviews on two important project areas: (1) a new approach using integrated bioprocesses for the production of lactic acid and other products from whey, and (2) waste treatment for solids including the precipitation of metals.

The integrated bioprocess for the recovery of products from whey has the potential for a significant positive environmental effect because it not only captures useful products from whey, but it also helps solve a significant waste fluid problem. Waste fluids from milk products manufacturing constitute an increasingly expensive disposal problem due to the high chemical oxygen demand (COD) and high amounts of whey produced. The proposed process reduces the COD of wastewater by 93%.

In the second area, Dr. Trick described a variety of projects for the treatment of various solid wastes. These included: (1) the anaerobic treatment of organic waste, (2) the anaerobic treatment of sewage sludge, and (3) an integrated purification process for municipal sewage, which included modern membrane techniques, anaerobic and aerobic processes.

From Benign Production to Benign Products (Prof. Dr. Hans Knackmuss)

Here we learned about the synthesis of new natural polymers with amine and ester bonds to promote biodegradability. Dr. Knackmuss mentioned to us that they had tried to apply genetic engineered microorganisms for biodegradation of xenobiotics in complex systems without success. He showed us the production of a new degradable type of cellulose called Ecoflex. Because of the designed weaker bonds, these new compounds are biodegradable. This new material has good properties, but there is a small cost premium to produce it now. Furthermore, some new developments in process technology will also be needed. Hence, some appropriate economic driver would be quite helpful for the development of these new types of materials.

Fraunhofer Office for Energy and Environment (Dr. Dieter Bryniok)

Dr. Bryniok talked about the planned establishment of the Fraunhofer Center for Energy and Environment to be opened at the University of Pittsburgh in the USA to promote technology transfer. The center will focus on chemical technology, membrane technology, biotechnology, combustion technology and safety engineering for energy and environmental technology. A preliminary office for the preparation of the center has been working since August 1999. This new Fraunhofer adds to a list of others in the United States, including one at Boston University in Massachusetts. Apparently, these Fraunhofers answer a need in the United States that is not met by the current university research system.

Site: **Fraunhofer IPT (Institut Produktionstechnologie)**
Steinbachstrasse 17
D-52074 Aachen
Germany

Date: April 7, 2000

WTEC Visitors: J. Sutherland (report author), D. Allen, D. Bauer, K. Rajurkar, E. Wolff

Hosts: Michael Leiters, Chief Engineer, Planning and Organization Department
Frank Dopper
Dirk Untiedt

INTRODUCTION

Fraunhofer IPT is affiliated with the University of Technology-Aachen (Rheinisch-Westfalische Technische Hochschule Aachen) and is largely focused on machining processes and machine tools. The head of the institute is Prof. F. Klocke. For 1999, Fraunhofer IPT had a workforce of approximately 900 people (250 academic staff, 200 non-academic staff, and 450 students). Financial support may be broken down into institute funding ($12 million), research funding ($10 million), federation support ($8 million), and industry funding ($7 million). The departments of the institute are: (i) Process Technology (led by Prof. Klocke), (ii) Production Machines (Prof. Weck), (iii) Metrology and Quality Management (Prof. Pfeifer), (iv) Planning and Organization (Prof. Eversheim), and (v) Center for Manufacturing Innovation-Boston (Prof. Sharon). These departments are working together on issues related to environmental engineering and management.

R&D ACTIVITIES

Efforts at IPT related to environmental oriented production can be broken down into five areas:

- Planning and introduction of environmental management systems
- Computer aided life-cycle analysis (CALA)
- Resource-oriented production optimization
- Measurement and reduction of particle emissions during materials processing
- Realization of model scale systems and plants

CALA (computer aided life-cycle analysis) is a software program that has been developed at the institute for the process-oriented analysis and evaluation of products and enterprises. The purpose of the software is to lower the energy and material demand over the whole product life cycle and to identify improvement opportunities in terms of resource consumption or waste reduction. Software functions include the capturing of data (i.e., the storage of process-specific energy, material, and waste data), balancing (internal aggregation of data), economical and ecological evaluation, and utilization (results presentation). The software considers a given reference product (quantity, unit, etc.) and then the input resources and outputs to the ecosystem are defined for each subsystem (process). CALA provides information on both the econosphere and the ecosphere. The effect of changes in subsystem ordering may be evaluated in terms of such measures as resource depletion, global warming, and toxic emissions. A variety of graphical displays are possible with CALA and both absolute and relative comparisons may be made. When CALA has been applied to specific projects, both top-down and bottom-up analyses have been undertaken.

One effort was discussed in which picture tube and glass manufacturing is being analyzed by Philips in cooperation with the institute. A number of initiatives are underway, including an environmental comparison of glass bath lines, exploration of rinse water circulation methods, evaluation of alternatives for rinse water circulation, and glass sorting/recycling. One of the key lessons learned is the importance of inter-company cooperation—matching up of one organization’s “wastes” to another’s material demands.

In 1998 Fraunhofer IPT completed a survey of 1000 companies regarding sustainable production issues. Companies identified the following topics as being important in the future: (a) low emission processes (45%), (b) environmentally friendly auxiliary materials (58%), (c) environmentally friendly raw materials (41%), (d) resource efficient technologies (54%), (e) internal recycling (26%), and (f) external recycling (26%). A similar survey of consultants produced the following: (a) low emission processes (26%), (b) environmentally friendly auxiliary materials (8%), (c) environmentally friendly raw materials (10%), (d) resource efficient technologies (23%), (e) internal recycling (15%), and (f) external recycling (10%).

An activity is also underway to characterize the airborne emissions associated with machining processes and, in particular, operations performed without cutting fluid. Experiments are being performed for a range of tool materials, tool geometries, cutting conditions, enclosure systems, and exhaust/filtering systems. Information on particulate concentrations and particle size distributions are being collected in the experiments. Work materials of interest include brittle materials and fiber reinforced plastics. Some concern exists about the effect of brittle dust particles on the wear of the machine tool in the absence of a cutting fluid.

Site: **Fraunhofer IZM (Institut Zuverlassigkeit und Mikrointegration)**
Gustave-Meyer-Allee 25
Gebaude 17
D-13355 Berlin
Germany

Date: April 6, 2000

WTEC Visitors: J. Sutherland (report author), D. Allen, D. Bauer, K. Rajurkar, E. Wolff

Hosts: Dr. Lars Heinze
Dr. Jutta Muller

INTRODUCTION

The Fraunhofer IZM researches, develops, and verifies methods and technologies for mounting and connecting microelectronic components and systems (electronic packaging). The institute has the following departments: (i) Chip Interconnection Technologies, (ii) Mechanical Reliability and Micro Materials, (iii) High Density Interconnect and Waferlevel Packaging, (iv) Advanced System Engineering, (v) Board Interconnection Technologies, (vi) Polymeric Materials and Composites, (vii) Micro Devices and Equipment, and (viii) Environmental Engineering. The IZM is affiliated with the Technical University of Berlin (the Research Center for Microperipheric Technologies). The director of both institutes is Dr. Reichl. For 1998 Fraunhofer IZM had a workforce of approximately 250 employees (150 staff and 100 students). The financial expenditures of IZM for 1998 were approximately $30 million.

Dr. Heinze gave a brief overview of Fraunhofer IZM, which has a center of competence in packaging, quality, and reliability that maintains a 800 square meter clean room facility. The IZM has three main areas of activity: material development and simulation (micro devices, equipment, materials, and reliability); packaging technology (chip integration including flip chip, high density, and board interconnections); and system integration (pervasive computing systems, environmental engineering, and advanced systems engineering). Most institute projects are focused on interconnection technology.

R&D ACTIVITIES

The main areas of emphasis for the environmental engineering department include: environmentally compatible product design, material analysis for ecological assessment, environmental and economic analysis of processes, and material and product recycling. The department is working on the development of a Toxic Potential Indicator (TPI) based on product material composition. Factors such as water pollution, hazardous substances, and industrial hygiene (workplace concentrations) are being used to form the TPI. Software and data are being established to support the effort, and a logarithmic aggregation approach is being used to combine the environmental information for multi-component products. One of the motivations for the software development is to provide a framework for managing environmental information for products obtained through the supply chain.

One example of an environmental review of a semiconductor company with a product based on SMT (surface mount technology) revealed the following impacts (expressed as a percentage of the total Eco-Indicator points):

- Wafer Processing 40%
- Chip Assembly and packaging 40%
- Transport to final tests 11%
- Business Travel 6%
- Others 3%

Some discussion followed relating to the need to compile environmental data (MSDS sheets, TPI evaluations, etc.) from suppliers and maintain the database.

In another project a CMOS process in semiconductor manufacturing was analyzed for its environmental impact. Most of the impact was attributed to energy usage, with 50% of the total energy associated with conditioning the clean room air. Strategies for reducing water usage in processing are being investigated. A variety of alternatives to lead-based solders are being investigated in terms of their technological and environmental impacts. Work is underway to eliminate the use of cyanide in plating operations.

The use of Eco-Toolbox (software) as part of the integrated, computer-aided design of electronic packages was then described. The software relies on a database of environmental characteristics for each component. The thinking is that environmental and economic information can be combined and provided to the designer as a “cost of ownership.” There is growing interest in the use of Eco-Toolbox, and designers are beginning to adopt its use as more attention is being paid to the environment.

Activities related to the remanufacturing of electronic products include: the automatic disassembly of PCBs, optical scanning of the board to identify valuable components, and desoldering the components via controlled heating that does not damage components. The establishment of a network structure for electronic products was also noted (consisting of producers, scrap merchants, recyclers, disposal specialists, and second-hand dealers).

The visitors asked Drs. Heinze and Muller about their involvement in education-related activities. The department has offered lectures and practical training to engineering students on the subject (design of environmentally friendly products) for three years. It was indicated that the student interest level is small but growing quickly.

Discussion concluded with the identification of high priority issues for the future:

- Lead-free, halogen-free PCBs
- Energy issues in microfabrication
- Life-cycle inventories and information management in the supply chain
- Quality management for reuse and repair, including remaining lifetime assessment
- Environmental impact of mobile products

Site: **Hoogovens Steel**
P.O. Box 10.000
1970 CA IJmuiden
The Netherlands

Date: April 4, 2000

WTEC Attendees: T. Piwonka (report author), D. Durham, R. Horning

Hosts: Willem Kat
Dr. Raads Welvaadt

INTRODUCTION

Hoogovens is a major producer of steel and aluminum, located in the Netherlands. Its steel plant at IJmuiden occupies 800 hectares on the North Sea, and is the only integrated steel plant in the Netherlands. Hoogovens merged last year with British Steel Corp. to form the new company Corus, which is headquartered in Great Britain. Hoogoven's major products are used in the transportation, packaging, and construction industries. Forty-five people are employed in the environmental department at the IJmuiden site.

In the Netherlands the environmental system is one of covenants between industry and the government. Industry associations meet with the government and negotiate four-year goals for the introduction of environmentally beneficial manufacturing technology. A year-by-year plan is established for the construction and installation of the new technology. When the goals are reached, the new technology becomes part of the operating permit for the plant. If the goal is not reached, meetings are held, and the reasons why the goal could not be reached are discussed. New goals are established with new time-tables. An advantage of this system is that companies can plan their capital investments in the environmental area four years at a time. Goals are set within the larger framework of national and EU goals.

Hoogovens is a “two metal” company, producing both steel and aluminum. They are dependent on their customers' specifications. As an example, they pointed out that Volkswagen is a major customer, and that Volkswagen is facing take-back laws. Therefore their alloy development is focused on developing alloys that can perform well and still be easy to recycle.

It was pointed out that at the current time the national goals for NOx emissions do not appear to be reachable, even though Hoogovens has installed a state-of-the-art deNOx plant in IJmuiden. NOx is apparently a greater problem to the Dutch government than to other governments in Europe.

Hoogovens publishes an annual environmental report. Dutch law requires that all companies report their discharges; this report is on file as a matter of public record. (The Dutch do not, however, publish an annual list of the top ten polluters in the country as do the British.)

EBM ACTIVITIES

The company recycles and reuses all but about 1% of the residual substances (other than shipped steel) in the plant. Blast furnace slag is used in the construction industry, tar from the coke ovens is used in the chemical industry, ammonium sulfate and sulfuric acid are used to make fertilizer. Even the excess blast furnace and coke oven gas that is not used on-site is piped to a nearby electrical generation plant. Solid waste disposal is not permitted in Holland. One of the problems they have had is Zn-containing blast furnace dust. They have found a way to use it in cupolas in foundries producing low-strength cast iron. They also have a problem with radioactive elements in their blast furnace dust; the dust is stored on-site until the radioactivity decreases to an acceptable level.

A major key to their success in recycling is the operation of a sintering plant (they noted that Sweden had ordered all sintering plants closed for fear of environmental damage). All solid wastes from the plant are combined with iron ore and sintered to make a feed for the blast furnaces. This allows them to concentrate their air and water treatment efforts on the effluent from the sintering plant, and substantially decreases environmental waste. The flue gas cleaning system has a two-stage scrubber that removes SO_2, HCl, and HF, as well as much of the dust that contains heavy metals and dioxins.

They are concerned with global warming, but concede that at this time there is no practical substitute for carbon in reducing iron ore. They have considered burning plastic as a source of carbon and hydrogen, but an LCA showed that hydrogen contributed very little to the reduction of carbon dioxide. They are capable of performing LCAs, and use them in their long-range planning. They will provide their customers with data for use in LCAs that involve their products, but in general are not enthusiastic about them, as steel often suffers in comparison to other materials when an LCA is invoked.

They are concerned with recycling pressures. Coated steels are a particular worry, and they are working with their automotive customers to solve the problems. In Holland, household waste is not separated at home. This causes losses in beverage cans, 98% of which are made of steel.

They are now focusing on meeting European environmental rules in their operations. BAT ("best available technology") will be the standard across Europe. Because they have developed a de-NOx process they believe they will have a competitive advantage (apparently their competitors were not thrilled when Hoogovens managed to establish this technology to mitigate the NOx problem). By the end of 2000 all Hoogovens plants were expected to be ISO 14000 compliant. This is as much to satisfy their workers as to satisfy their customers (they have had a similar internal system for 14 years).

They noted that odor control is a problem in some of their operations, and that they had concerns over projected $PM_{2.5}$ regulations.

In determining how to assess environmental investments, they go through a three-step process:

- How big is the problem?
- What will it cost to fix it?
- Will the proposed fix really work?

As an example, they cited a new direct reduction process that was not installed, even though it had clear environmental advantages, because their current steelmaking process was far less costly.

The environmental advantages of the merger between British Steel and Hoogovens are still being worked out. It was not clear what priorities, British or Dutch, would be used in setting the company's environmental agenda for the next few years. However, the Hoogovens people were looking forward to acquiring British Steel technology, such as the use of expert systems to control metallurgical processes.

Site: **Institute for Communication and Analysis of Science and Technology (ICAST)**
28, rue de l'Athenee
1205 Geneve
Switzerland

Date Visited: April 5, 2000

WTEC Attendees: D. Allen (report author), D. Bauer, K. Rajurkar, J. Sutherland

Hosts: Suren Erkman, Director, ICAST
Claude Gentaz, Director, Transtec S.A.

INTRODUCTION

The Institute for Communication and Analysis of Science and Technology (ICAST) is a non-profit research institution specializing in analyzing and communicating scientific and technical issues with significant public policy implications. The director of ICAST, Suren Erkman, is recognized internationally for his work in industrial ecology, an emerging discipline that examines the flows of materials and energy in anthropogenic systems. Studies in industrial ecology are useful in examining a number of strategies for environmentally benign manufacturing, including the use of eco-industrial parks, and byproduct synergy (using wastes from one process as raw materials for another). Attending the meeting from ICAST were Suren Erkman, and Claude Gentaz, an associate of Mr. Erkman, specializing in flows of metals.

R&D ACTIVITIES

The ICAST group described a number of projects that they are conducting or planning. Dr. Gentaz described an initiative that will link zinc battery recycling, zinc refining, and steel making in an industrial ecosystem. Dr. Gentaz described the technological, social, and political hurdles that need to be overcome in establishing such networks. He also described the factors that can inhibit the implementation of profitable industrial networks (these included reluctance to rely on additional industrial partners and unwillingness to explore projects outside of core competency areas).

Suren Erkman described some of his experiences in developing industrial networks in India and China. He stressed the strong interest of India and China in this area, but pointed out that the models of industrial parks that are effective in western Europe (e.g., Kalundborg) may be ineffective in developing countries because of differences in the sizes of enterprises and differences in the transportation infrastucture. He also pointed out that in these countries, the main focus is on developing industrial networks to enhance profitability, rather than to meet environmental goals. Regardless of the motivation, these industrial networks promote the efficient use of resources and reduce the generation of wastes.

Suren Erkman also identified the need for data on material flows. Unfortunately, the extensive data sets developed for life-cycle assessments are of limited use in the design of industrial networks. This is because data for industrial network design require information on the location of the material flows and LCA data sources are not, in general, spatially resolved. So, once again, data availability is a key issue in implementing this component of environmentally benign manufacturing.

Finally, Suren Erkman briefly discussed two sets of policy drivers for his work. The first set of drivers is associated with the liberalization of energy markets in Europe that is scheduled for July, 2000. While the uncertainty surrounding this liberalization is delaying some capital investments, it was also promoting interest in innovative industrial networks. The second set of drivers dealt with the unique position of Switzerland in European markets. While not a member of the EU, Switzerland is home to many large firms with extensive dealings throughout Europe. The complex policies created by Switzerland's position can either inhibit or promote novel solutions to environmental challenges.

Site:	**IVF– Institutet för Verkstadsteknisk Forskning** **(Swedish Institute of Production Engineering Research)** **Argongatan 30, SE-431 53 Mölndal** **Sweden**
Date:	April 5, 2000
WTEC attendees:	B. Bras (report author), D. Durham, R. Horning, D. Thurston
Hosts:	Mr. Richard Berglund, Division Manager, Industrial Environment Division. Presentations by Göran Brohammer, Hans-Lennart Norblom, Lars Österberg, Per Lindahl, and Carl Gunnar Bergendahl

BACKGROUND

IVF is the biggest industrial institute in Sweden with 230 employees. It is comparable in mission to the German Fraunhofer and Dutch TNO institutes, although not as large. IVF's focus is on manufacturing and electronics industry. Its financing is as follows: 42% from companies, 31% from NUTEK, 9% from the Swedish Council for Work Life Research, 6% from IRECO R&D grants, and 12% from European Union projects (see also ref. IVF 1998). IVF does applied R&D (with industry partners), business development (information activities), and technical development and implementation (focused on products).

A noteworthy issue is that in Sweden, 90% of the companies have 50 or fewer employees. Recent mergers have caused some change in this number, but not significantly. Sweden also has very few global companies.

With respect to environmental issues, IVF staff believes that good, effective technological solutions lie at the union of economy, quality, and environment. Some of IVF's findings are that the direct contribution of the manufacturing industry to environmental problems is very low in terms of energy consumption, electricity, CO_2, NO_x, VOC, etc. The only exception is the direct impact related to metals. However, the product impact (i.e., the *indirect* impact) is very high, followed by the impact caused by suppliers. Environmental issues are still not a driving force. However, the thinking is very much focused on life-cycle analyses and the consequences of a change.

After the background presentation by Mr. Berglund, several presentations related to environmentally benign manufacturing were given.

R&D ACTIVITIES

Joining Processes (Per Lindahl)

Mr. Lindahl provided an overview of some of the joining and forming work at IVF. IVF has 20 persons working mostly on welding; a few work on adhesives. Seven persons work on laser welding, with some working on associated simulation and robotics.

Mr. Lindahl explained IVF's efforts in friction stir welding where a tool-bit is used to generate heat from friction that is used to weld. The efforts are focused on aluminum welding. Motivation comes from several areas—e.g., Volvo would like to weld aluminum alloys. Friction stir welding is also deemed better for recycling because no welding filler material is introduced. Hence, the material is purer. Lindahl cites a number of friction stir welding successes. However, the primary project described was on the straightening of truck chassis and motorcycle frames. IVF worked with a small company that used the change in color of soap (white to brown) as an indicator for the amount of heat brought into a truck frame for straightening. However, the soap changes color at 400°C whereas aluminum needs to remain below 250°C in order to retain its performance properties. Lindahl stated that thermocouples are now used instead of soap.

Lindahl also provided some information on adhesives and their environmental issues that basically deal with the generally known problem of toxicity versus performance. Swedish regulations are much stricter than U.S. regulations.

With respect to laser welding, Lindahl stated that although this is more precise than "regular" welding, efficiency is a problem. YAG laser welding equipment is big and has a 4% efficiency. Diode lasers are going to be better, but are not yet at the required performance level. Lindahl is investigating the use of lasers for welding aluminum.

All these joining technologies promote aluminum as a material of choice, in case weight is an important issue (e.g., in the transport industry). IVF thinks that aluminum is a good choice.

Surface Engineering (Lars Österberg)

In Sweden, there is little development of new processes. Many new processes come from abroad. In Sweden, there are many job-shops (fewer than 20 employees) that avoid new coating processes out of fear for the risk. IVF's work mode in introducing new process technology is to

- seek cooperation with the process developer
- do a vertical project with suppliers, coaters, and end-users
- bring in new processes and scale up new technology

New areas for EBM processes are powder painting and chromium-6 (hexavalent) free surface treatment.

Powder painting is deemed to be a good process and has long been used for metal painting. Now, new uses for powder painting are being explored:

- Wood. The problem is that wood is very heat sensitive. IVF's goal is to set up a complete test-bed for wood powder painting.
- Aircraft components. Powder painting currently is not done for these components—again because of the heat brought in, as well as the conservative risk-averse nature of the industry.
- Plastic materials. Although the non-conductivity problem has been overcome, heat again can be an issue. The recyclability of coated plastics is also reduced.

With respect to chromium-6 free surface treatments, IVF has worked on replacing hard chromium coating with chromium-3 coatings, but Österberg stated that no known process with chromium-3 exists. Currently IVF is working on chromate free coatings for the building industry and aircraft industry. It was stated that although chromium coatings are perceived as environmentally harmful, they actually result in a longer product life and from a life-cycle perspective actually cause a lower environmental impact than, say, repetitive painting. An example of a kitchen water faucet was shown. Its life with chromium coating was 15+ years, whereas its life with powder coating was only 9 years.

Electronic Production (Carl Gunnar Bergendahl)

The main focus of IVF's work in electronics production is on product realization, specifically reliability, environmental compatibility, and high yield manufacturability. The environmental compatibility aspect became more important in the beginning of the 1990s. The Nordic countries produce about 500,000 tons of electronic and electrical scrap per year. IVF's group focuses on how to reduce the environmental impact throughout the product life cycle by design, in contrast to Germany where the focus is more on the take-back and recycling, according to Bergendahl.

Mentioned is the proposal for an EU directive for waste from electrical and electronic equipment (July 1999) which calls upon member states to reduce lead, mercury, cadmium, hexavalent chromium, PBB and PBDE. These substances are to be phased out by January 1, 2004. Components with halogenated flame retardants also are to be removed.

The TCO labeling of computers also had a big effect on manufacturers. The TCO requirements have been adopted by over 100 manufacturers, worldwide. IVF is certified by TCO to handle applications and testing.

Bergendahl discussed some examples of IVF projects. One project dealt with CFC phase-out in cleaning operations. Twenty Nordic companies participated in the study. The outcomes were as follows:

- CFC free cleaning was possible with equal or less cost
- 50% of the companies ended up not having to clean at all, the rest could use water and/or alcohol
- a 2-3 years headstart was gained in knowledge
- a complete phase-out of CFC for cleaning electronics was achieved in Sweden

A key issue was a shift from thinking about cleaning to thinking about *cleanliness*.

Another study cited was an international project (with 12 international companies) on flame retardants in electronics. Swedish studies found evidence of bromium flame retardants in breast milk and in recycling facility workers. According to Bergendahl, in Europe, the drivers for reducing flame retardants are environment and health. In Japan, the drivers are dioxine problems during incineration and European market requirements. In the U.S., the drivers are purely business; there is no purely environmental concern at all, according to Bergendahl. Similar to the cleanliness vs. cleaning thinking, the IVF idea is to move away from flame retardancy by thinking about fire safety and increasing fire safety by design. It was stated that U.S. fire marshals are interested in the labeling of products meeting fire safety requirements.

A third sample project mentioned was related to the use of anaesotropic adhesives for replacing lead solder. A cellular phone example was shown where this technology was used. This technology is commercially used today. (For the latest information about electronics and the environment at IVF, see http://extra.ivf.se/dfee.)

Eco-design with SMEs (Hans-Lennart Norblom)

IVF has worked on introducing eco-design in small and medium sized enterprises (SMEs). This was an international project together with Norwegian and Finnish institutes. The technology and approach used was obtained from Syntens in the Netherlands where a similar project was performed in the early nineties. In essence, the IVF project attempts a technology transfer of the Syntens' approach, tools, and findings.

The IVF project has a budget of SEK 2,500,000 (about $300,000). IVF is working with 14 companies ranging in size from 10 to 200 employees. The eco-design tools used for this project are the MET-matrix, environmental Failure Mode and Effect Analysis (FMEA), environmental Quality Function Deployment (QFD), Eco-Indicator 95 manual (now Eco-Indicator 99), EcoScan, SimaPro, and the Eco-strategy Wheel.

Almost all of these tools came from the Netherlands (developed by Delft University of Technology, PreConsultants) where they were used in the Dutch Syntens project.

A surprise finding for IVF was that many of the participating companies did not even use "regular" FMEA and QFD. Normally, one would expect familiarity with these approaches.

Conclusions of the project were that

- The above mentioned tools were good enough for the SMEs, although SimaPro was too difficult for SMEs.
- The SMEs do not put enough effort into eco-design. They are too busy and do not know whether it will pay off.

IVF believes that "environmental should be part of design, not part of environmentalist." It was stated that many environmentalists consider the above tools to be incomplete, but the findings indicate that they are already good enough for a designer to work with.

Life-Cycle Assessment (Göran Brohammer)

Mr. Brohammer provided details on the current state of life-cycle assessment (LCA). According to him, the use of LCA in a company evolves according to a natural progression. First, the focus is on individual case studies. This phase lasts for about 1-3 years. Second, one starts to aggregate data and build (company) databases. This phase also lasts for about 1-3 years. The third phase is that the gained skills are adopted for product and process design. This is a continuous process and is currently state-of-the-art thinking in LCA. Brohammer foresees that the fourth phase might be to adopt LCA within management systems, but this is still an open issue.

A critical problem is that LCAs are done when the data are available, but this generally is too late in the design process to change the design. Moving the LCA earlier in the design process is therefore necessary. It was also emphasized that the ISO 14042/43 LCA standard does not allow a single index/metric (such as, e.g., the Eco-Indicator 95) for product promotion. A single index is only allowed for internal evaluation purposes, not for external marketing.

Background on Type III eco-labeling (ISO Technical Report 14025) was also given. Sweden, Canada, Korea and Japan are looking at Type III eco-labels. The Swedish system has existed since 1997. An international trial with Ricoh has been underway since the end of 1999. For type III eco-labels, the ISO 14042/43 LCA standard is augmented with Product Specific Requirements (PSR) which includes specifications for the product groups (e.g., copy machines) and specific rules for the LCA. The result is a statement of resources use, emissions, and the translation to environmental effects (use of a single index is not allowed). This forms the input to the Environmental Product Declaration (EPD). (Detailed information can be found at www.environmarket.com/epd/.)

Brohammer considers LCA more as a learning and attention-directing tool. The main conclusion after performing an LCA is often that the product should be improved. This becomes a driver for gaining market share through better products. As an example, he cited Electrolux's "green" refrigerator. This refrigerator costs a bit more for the consumer but consumes less energy than the "regular" refrigerator. Demand for the green refrigerator is very high and has boosted Electrolux's market share.

Brohammer thinks that in the future there will be more screening type LCAs, whereas detailed studies will be limited to only certain key aspects.

REFERENCES

Institutet för Verkstadsteknisk Forskning (IVF). 1998. *IVF Annual Report 1998.* Institutet för Verkstadsteknisk Forskning - Swedish Institute of Production Engineering Research. Mölndal, Sweden.

Site: **MIREC B.V.**
Dillenburgstraat 4
Postbus 80015
5600 JZ Eindhoven
The Netherlands

Date: April 4, 2000

WTEC Attendees: C. Murphy (report author), B. Bras, D. Thurston

Hosts: Paul Verhappen, Projecten & Processen
Johan Zwart, International Account Manager

BACKGROUND

MIREC was established in response to a metal shortage after World War II as an internal department of Philips. In the early 1960s, a second plant was started to handle hazardous waste. A production outlet for product dismantling (overstocks and quality related returns) was established in the late 1970s. End-of-life management was begun in the late 1980s. MIREC became a separate organization in the early 1990s. The logistics and hazardous waste portion of the operation was sold to a sister company last year. MIREC was owned briefly by a British company, Cleanaway, before they were sold to Watco N.V., a Belgian company. Watco N.V. is owned by Fabricom, which is owned by Tractebel (an energy company), which in turn is owned by Suez-Lyonnaise des Eaux, a French corporation that also owns SITA, another waste company, which just bought BFI Europe. In addition to the site in Eindhoven, MIREC has a separate plant in Holland for glass (lamps and CRTs), several plants in Belgium, and one in Germany that is a trade organization. They are currently buying an electronics recycling company in Germany. Their main focus is now electronics and some industrial scrap metals.

LEGISLATION

The EU has ruled that each member country must have its own take-back legislation by 2001 or else must adopt the general European version. It is expected that existing legislation, such as that present in the Netherlands, will provide the model for the EU. The Netherlands is the first country in Europe that has adopted and fully implemented take-back legislation. More information on the Dutch laws can be found on the Web site of the Dutch Ministry of Spatial Ordering and Environment (www.vrom.nl). Belgium also has a law, but it is not currently being enforced. Germany is in the process of refining its legislation.

MIREC operations are mostly driven by legislation. The take-back legislation currently in effect in Holland includes medical equipment, and other items that might be very difficult to collect. In addition, it covers historical not just current products. However, this applies only if the company is still in business and making that type of product. For example, a company that used to make computers, but now makes only software, will not be responsible for computer take-back. The take-back law covers two categories: ICT (information communication technology products) and NVMP (Nederlandse Vereniging voor Metaal- en Electro-Producenten, or the Dutch Association for Metal and Electro-Producers), which include toys, tools, and refrigerators.

ICT products, which include computer CPUs, monitors, telephones, and printers, are collected by contractors (including MIREC). As it is brought into the disposition center, each item is invoiced by the name of the producer and its weight. MIREC measures the total weight received, and each producer pays a percentage share based on the amount attributed to its company. This approach provides OEMs with an incentive to reduce both product mass and obsolescence rates. All Dutch OEMs are required to participate in this program. Companies are exempted if they can demonstrate a collection system that is effective, but if their products start showing up at general collection points, this will be seen as evidence that their system is not working. While foreign companies are not required to participate, many, such as Dell, participate voluntarily.

Last year more than 50% of the incoming items appeared to be orphan products. This situation arises when (1) the company is no longer a producer, (2) a foreign company chooses not to participate, (3) a Dutch company is illegally not participating, or (4) brand of products is not recognized by the system as belonging to a participating producer. It is estimated that 25 to 30% of orphan products are due to non-compliance by Dutch companies, who will consequently be fined. The difficulties in correlating brand names with producer were credited as being the primary reason for the high volume of orphan products in 1999. This problem is being resolved by defining better links within the system to correctly identify producers by brand name. However, there still are and will continue to be a significant volume of orphan products. In order to cover the cost of handling these materials, each participating producer is proportionally responsible based on the percentage of their identifiable contribution to the waste stream.

In contrast to the ICT system, NVMP products have a recycling “fee” that is paid at the point of purchase. This fee ranges from F2.5 for toys to F40 for refrigerators, and goes to an organization that manages the fund. Last year one million new TVs were sold in the Netherlands, but only 250,000 were recycled. This lag has allowed the managing organization to build up its fund and provide reserves for future periods of declining sales. There is some concern that the fixed fee, point-of-purchase approach lends itself to price fixing; consequently, the ICT system is being considered as an alternative. Both systems are intended not only to fund recycling, but also to provide incentives to producers to design for recycling. In the NVMP product model, this would occur by allowing the fixed fee to be reduced. In the ICT model, the producers would be charged a lower fee per unit of weight. However, the ICT approach is thought to have a tighter feedback loop in addressing this issue.

LOGISTICS

In the Netherlands, the consumer has three choices. The first is to return the product directly to the producer. Some producers will come and pick up items, others will not accept returns at all. The second is to return items to a retail outlet or repair shop. The third is to take the product to one of 340 municipal collection points. Municipalities and repair shops send the products to one of 60 regional collection stations (“ROS” = “Regionaal Overslag Station”). This number was selected in order to provide one ROS for every 300,000 inhabitants. An additional goal was to place a ROS within 10-15 kilometers and/or a 20-minute driving distance of each municipal collection point. Municipalities receive a fee per kilogram and are responsible for transporting material to the ROS. Transportation is done by road (25-ton trucks, max). Repair shops and stores may also take items to the ROS. ICT and NVMP collect from each ROS and send the collected materials to one of five licensed recyclers. The distance between recyclers and the nearest ROS is 30 to 60 minutes. Transportation costs are covered by ICT. NVMP uses the same logistics system. (In the 1990s refrigerators using CFCs were being sent to Africa and Asia. It is now illegal, per Dutch legislation, to export CFC or products that are known as waste unless it can be proven that the receiving country is better equipped to handle the waste. This is based on technology, not volume and cost considerations.)

MIREC OPERATIONS

MIREC handles 90 to 95% of all returned ICT products in the Netherlands, which amounted to 3500 metric tons in 1999 (the first year the law was in effect) and which is projected to reach 8000 metric tons in 2000. The expected steady state is 10,000 to 12,000 metric tons/year. MIREC also handles 40% of all TV’s (an NVMP product). The other four licensed recyclers are: (1) CRS (Computer Recycling Service), which handles only very small volumes; (2) Coolrec, which handles 60% of TVs, all refrigerators, and 50% of small appliances; (3) Recydur, which handles 50% of small appliances; and (4) HKS, a car shredder that works for Coolrec and which shreds washing machines and refrigerators. MIREC handles TVs as well as information technology equipment. All of the glass and metals (75% by weight) are recycled; plastics and wood are incinerated. 30% of all CRT recycling is glass-to-glass; 70% is glass-to-ceramic.

Material vs. Product Recycling

The focus of MIREC operations is materials recycling. After any CRTs are removed, iron and aluminum are separated out, resulting in a mixture of plastics, metals, and glass, which is then shredded and sent to a smelter. MIREC operates by having direct contracts with producers buying commodities, rather than putting materials on a commodity market. This is important to OEMs such as IBM who want to know where the material is going. MIREC will manage an amount for reuse and refurbishment, but only if requested by, and paid for by, the particular customer. The ICT contract prohibits resale. MIREC is interested in developing a small-scale re-manufacturing outfit, but will do so only if asked. Many OEMs are concerned that resale will create competition with new products. Many computer and peripheral companies are exploring leasing options, but question whether it is a good economic model because of rapid obsolescence. Copier OEMs, such as OCE, have made leasing pay by salvaging parts and upgrading only what is necessary.

Labor and Inventory

The MIREC site uses 100 regular employees and 40 contract employees as direct labor (two shifts a day, five days a week). Hiring also includes a program for at-risk youth. Turn-over is about one week using a FIFO (first in first out) system. Glass and metals are sent off immediately. Specialty materials are collected until a specified amount is accumulated (e.g., aluminum is held until there is a total of 25 tons). The site has 20,000 square meters of storage.

QUESTIONS

Displays

When asked about flat panel displays, our hosts explained that they avoid having to handle these as hazardous waste by not dismantling them. The unit is recycled whole. If it were necessary to dismantle laptops, it would be very expensive to do so. We also asked about alternative markets for CRT glass (other than glass-to-glass and glass-to-ceramic) and were told that because of the Ba, Sr, and Pb content, the glass was of very high quality and therefore not suitable for secondary recycling.

DFD and “Green” TVs

IBM, Lucent, Ericsson, Philips and many others are all working on “green” products despite the general belief that it will be too expensive. There are also efforts in the area of design for disassembly (DFD) and recycling, but specifications are a challenge. Currently, because all products of a given type are lumped together, it is difficult to create a price structure that would benefit a company for doing design for recycling. However, by 2005 when there are producer oriented streams, it may be possible to do this.

Other

The glass from scanners is glued in place so these must go to mixed waste, which is incinerated. Plastics recycling has been successful only when developed for a particular customer with a particular content and volume (pull rather than push system). Low oil prices in recent years and mislabeling of plastics have also hurt recycling efforts in this area. Although flame retardants are a concern, most plastics in Europe are incinerated.

TOUR

In addition to MIREC’s contract with ICT, it also contracts with individual companies. IBM is an individual client. MIREC receives one trailer per day of IBM products. IBM pays extra for this service. All IBM material is run in batches separate from other incoming product. When material arrives at MIREC, it has already been at another (IBM) site for component salvage. Hazardous waste is handled by a sister company. IBM keeps detailed track of its product EOL by waste stream. Hard disks are treated by physically damaging them with a hammer.

The ICT material received by MIREC includes equipment plus wires, toner cartridges, and packaging material. Each individual product is weighed and accounted for by manufacturer and product type. MIREC’s contract with ICT requires that they receive complete products in order to prevent scavenging of high value components upstream. If an incomplete product is received, it is accepted but noted in the computer tracking system. The computerized tracking system accounts for five product types: CPUs, monitors, keyboards, telephones, and printers.

In the CRT dismantling operation, sorting is done by hand. There are 12 working stations on the second floor. As materials are sorted they are dropped into bins on the first floor. There are three material streams: wood and plastic, glass, and electronics. At the time of our visit there were nine men disassembling monitors. The operations model assumes a dismantling rate of 25 per hour. One reason for performing this step is to remove glass from the rest of the material stream, as glass in the shredder quickly dulls the blades. From the disassembly line, materials are sent to the machine line. At the time of our visit, the line was being rebuilt in order to improve the capacity.

Prior to shredding, toner and paper must be removed in order to reduce fire hazards. In the machine line, Al, steel, and plastics are separated. Plastics are separated using forced air. The line includes ferro-magnetic belts and two in-line eddy current separators to remove non-ferrous metals. The dry separation techniques used are pretty standard for Holland. There is no waste water, but there is a bag-house dust evacuation system. Three to four people are required to operate the line. The staging area is roughly equal to the area taken up by equipment. Metal assays are done in a lab on-site prior to being sent off to a smelter. ICP is used to perform the assays. MIREC believes its analysis is superior to others because the solution includes the matrix (all metals not just precious metals). This method is more difficult because of the resulting spectral interference, but it gives more accurate results.

The perimeter of the operation is surrounded by an earthen wall. This provides a sound barrier to the close-by residential areas. MIREC operates 12.5 hours per day using two shifts.

ISSUES AND CONCERNS

Plastics recycling is an economic challenge. Prices are hurt not only by depressed oil prices but also by overproduction of plastic pellets and rapid changes in formulations and technology. These materials, while obsolete for their intended uses, can be used for lower end applications. Sorting at end-of-life is also a significant problem. Current legislation calls for labeling on plastic pieces greater than 50 grams. However, the recommendation was made that a good area for research would be internal marking systems (a plastic "DNA structure") that would facilitate development of automatic detection systems.

Site:	**Siemens AG** **Corporate Technology** **ZT D2P** **D-81730 Munich** **Germany** **URL: http://www.siemens.com**
Date:	April 7, 2000
WTEC Attendees:	C. Murphy (report author), B. Bras, T. Gutowski, D. Thurston
Hosts:	Gerd Kohler, Project Manager, Manufacturing Bernhard Brabetz, Project Manager, Design to Prototype Martin Schaefer, Project Engineer, Materials Application Center Ferdinand Quella, Product Related Environmental Protection

BACKGROUND

Siemens is a 150-year old company with more than 400,000 employees worldwide. It is the third largest electronics producer after GE and IBM (Hitachi is fourth). If, as planned, Siemens buys ATECS, an automotive supplier, it is likely to become the second largest. More than half of Siemens's sales are within Germany and Europe, approximately one-fourth are to North America, and less than one-tenth are to Japan. The company is divided into six business units: Energy, Industry, Information and Communications, Transportation, Health Care, and Lighting. The Components Group was spun off in 1999 and is now known as Infineon (see http://www.infineon.com). Our host was the Corporate Technology Group under which environmental development falls and which also includes Materials and Manufacturing with electronic packaging as its major focus. There are 19 people working in the environmental group, including Martin Schaefer who flew in from Berlin to meet with us. A subsection of Corporate Technology, called "Corporate Functions," handles worldwide coordination of certain environmental issues, including radiation and fire protection. Dr. Quella heads one function: product-related environmental protection. In addition, groups and factories have their own organizations which cooperate within a so-called "three-level tier" with corporate environmental efforts.

According to their 1998 environmental report, Siemens has the philosophy that, "If we let coherent ecological analysis inform the way we think and act, this almost inevitably produces economic benefit." In brief, their five environmental objectives are:

- Establish environmental management systems in all plants
- Set up an internal reporting system
- Intensify environmentally compatible product design and extend the integrated approach to environmental protection to every area
- Favor suppliers who have an environmental management system
- Optimize transportation and logistics for worldwide distribution of goods

Rather than have a large environmental department, Siemens integrates product-related environmental protection into their design activities and into other organizational levels, including having someone on the board (three-level model).

CURRENT ACTIVITIES

Materials and Manufacturing

This group is divided into nine subgroups:

- Ceramic Components and Reliability
- Plastics and Functional Materials
- Magneto- and Polymer-Electronics
- Micromechanics and Coating Technologies
- Packaging and Assembly
- Joining Technologies and Laser Processing
- Application Center Materials
- Analytics
- Design to Prototype (D2P)

The major focus of the Materials and Manufacturing Group is electronic packaging, or more generally, the bridge between silicon and the system. Mainstream interests include thin film technology, direct chip attach (DCA), and high density interconnect (HDI) substrates. For DCA, Siemens is looking at bumping, flip chip (conductive adhesives and compressed bumps with underfill), and high pin count mounting.

Lead-free and Halogen-free Products

One of the current concerns is elimination of lead (Pb) and halogens (Br) in printed wiring boards (PWBs). This is being driven largely by the WEEE directive, which at the time of our visit was slated to take effect in 2004 (now extended to 2008). Siemens's analysis of the lead-free and halogen-free movement is that once a few companies (largely Japanese) followed the "discussion" about directives and made a change (e.g., to halogen free housings), then it became a competitive issue, and others were almost obliged to follow even though no formal legislation had been passed.

Lead-free connective technologies are of particular interest to the Design for Prototyping group. Most U.S. and European companies (including Siemens) believe that no lead-free solder can yet directly replace tin-lead. This is primarily due to the higher temperature requirements of the solder and consequently all related components (chips, substrates, etc.).

A supply chain questionnaire of the German telecom industry indicated that they are very interested in halogen-free products. However, most of the products currently available are in consumer electronics. The primary competition is coming from Japan. PIAD, Hitachi, Isola (AlliedSignal), Nelco, Mitsubishi, Matsushita, MC-Electronic, Sumitomo, and Toshiba all offer halogen-free products. Siemens believes that available substitutes for composite (thermosets) and functional materials are too expensive and may have been introduced too early (with not enough information available).

Design for Environment

DFE is purely coupled with and considered equal to cost reduction. Siemens standard SN36350 for "Environmentally Compatible Products" (used since 1993) contains design guidelines, a list of substances of concern (only those which are legally controlled), and recommendations for plastic and metal selection. Among the guidelines listed under the section on procurement and manufacturing aspects are:

- Minimize the amount of materials used
- Minimize production waste by means of appropriate design
- Minimize product weight
- Minimize the variety of materials used
- Minimize the number and variety of components
- Employ recycled plastics where possible
- Minimize energy consumption in manufacturing
- Minimize amount of packaging

Guidelines under product usage aspects include:

- Design products to have a long useful life
- Design products to be easy to repair and upgrade
- Minimize energy consumption during idle status and during operation

Included in the disassembly and disposal guidelines are:

- Minimize the number and variety of connections
- Minimize the number of steps required for disassembly
- Use a small number of standard tools that require few changes in position
- Mark all plastic components suitable for recycling
- Avoid non-recyclable composites and coatings

Electronics End-of-Life

Germany has a controlled landfill price that is currently set at 1,500 DM per ton, so there are financial incentives to reuse and recycle end-of-life products. Computers that are less than two years old are donated to schools (not always free of charge). Older units are recycled at a facility in Paderborn. At least 200 tons per year are required to make recycling economic; the volume in Paderborn is about 6,000 t/a. Most of the revenue is from copper recovery. In addition, approximately 12 to 15 tons are resold. Computers that are five to six years old or older are disassembled. Components are harvested and resold at spot market prices. The remainder is shredded by a third party. The light fraction (plastics) is landfilled rather than incinerated, in part due to concerns over dioxins and furans that may be generated when halogenated materials are improperly burned. The need to establish an automatic identification method for halogen-free materials was expressed, as labels are not reliable. CRTs are recycled using a glass-to-glass process; leaded glass factions are separated from the lead-free panels by cutting the tubes with a hot wire.

Take-back is done using a variety of organizational systems. Under the WEEE directive, manufacturers are being asked to take back product, but logistics will be expensive and may end up being done by communities. Computers and medical supplies are handled by Siemens directly. Other end-of-life products are managed in cooperation with other companies or else outsourced. There is concern about southern EU nations because there is no local collection and recovery infrastructure. The EU wants companies to be responsible for their own waste to help overcome this problem. Germany would like to see local municipalities, rather than individual companies, handle collection, dismantling, and separation, in part as a means to creating low-skill jobs.

ISO 14001 and Supply Chain Issues

Siemens's goal is to structure their environmental management systems to be compatible with ISO 14001. Each plant is expected to have an environmental management plan and must survive audits (or make changes if out of compliance). Siemens does not have a specific policy on ISO 14001 and they pursue formal certification only if the customer requires it. Siemens suppliers are given guidelines, including a list of substances to be avoided. They are considering moving towards a survey system.

The strict demands made by the automotive industry provide strong motivational drivers. Software used by car manufacturing plants requires that suppliers provide a materials list for all materials up to 0.1%, plus an eight page list of specific materials, which is available on the internet. Suppliers may also be asked about specific materials used in manufacturing processes, which can be difficult to obtain. For example, in considering the precursor to ABS the exact percentage of acrylonitrile may not be known.

Siemens has many group-specific programs for logistics based on customer modifications; they are therefore different, and data transfer is sometimes not compatible. In addition, it is very expensive to get product or materials data, but Siemens plans to change this. Car manufacturers have material databases where suppliers enter information, but data consistency is a big problem.

Life-Cycle Assessment

Life-cycle assessment within Siemens includes a focus on metrology, life-cycle management, and life-cycle costing. It is currently done on a limited basis within certain factories. Companies or departments within the company may ask for an LCA, but paying for it can be an issue. Siemens typically uses in-house software (that has already been paid for), but sometimes may use commercial software that has a low-cost site license. Siemens is looking at system-wide mass balance systems. Most commonly, they do simple input-output analyses, i.e., inputs over outputs produced.

One of the biggest challenges for Siemens, as for others attempting to do meaningful LCAs, is how to prioritize impacts. In general there are two positions on this within the European community. The EcoPoint system, which is used in the Netherlands and by Philips in particular, is widely recognized because of its relative simplicity. It is an additive method that results in a single number, where the best solution is the one with the lowest number of points. Siemens believes that EcoPoints (or Eco-indicators from which EcoPoints are derived) are not scientific, in part because impacts can not be assumed to be additive. They prefer instead to use an expert decision method. The German government, which initially wanted to adopt the EcoPoint system as a standard, agreed on an alternative code of conduct. This includes (1) a critical review (i.e., an audit) and (2) a clear process with targets and expected results for a given product decided upon up front. This methodology follows the rules of ISO 14040, which does not include EcoPoints. There was significant effort by a number of companies to keep EcoPoints out of ISO 14040. However, it should be acknowledged that some companies do like the EcoPoint system, largely because it is quick and inexpensive. And in fact, it can be useful for simple screening.

FUTURE ISSUES

Siemens sees the next big issues as systems related. For example, one study suggests that the energy demand/consumption by information technologies will see exponential growth in the very near future.

Another point that was brought up was the observation that software upgrades can produce premature hardware obsolescence. It was suggested that if new software had greater compatibility with older systems, the rate at which computers reached their useful end-of-life could be significantly reduced.

Lastly, the point was made that gradual technological evolutions do not continue indefinitely. There are always technology jumps (such as CO_2 cleans) or complete paradigm shifts that typically cannot be predicted. But by such planned innovation jumps, the environmental improvement needed worldwide to achieve global reduction targets could be accelerated.

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Site: **Technical University of Berlin**
Institute for Machine Tools and Factory Management
PTZ 2
Pascalstrasse 8-9
D-10587 Berlin
Germany

Date: April 6, 2000

WTEC Attendees: E. Wolff (report author), D. Allen, D. Bauer, K. Rajurkar, J. Sutherland

Hosts: Univ.-Prof. Dr.-Ing. Gunther Seliger, Director, IWF
Dipl.-Ing.Waldemar Grudzien, Chief Engineer

INTRODUCTION

This institute also maintains a formal relationship with the Fraunhofer Institute; Professor Seliger maintains control over both organizations. The combined staff level is at approximately 120; students provide valuable resources while at the same time gaining practical experiences in engineering fields.

Education and work at these institutes comprise the fields of mechanical engineering, electronics, information technology, and business management; environmental topics are an extension of these areas.

EBM ACTIVITIES

Rapid population growth is viewed as the source for the environmental challenges confronting this and future generations. Professor Seliger sees an increase in the standard of living as a mechanism to reduce population growth; increased standards of living have resulted in substantial population declines in highly developed nations. The challenge is to additionally introduce environmentally benign levels of consumption.

“Selling use instead of products” could contribute to higher utilization rates in transportation and manufacturing areas, thereby reducing the consumption of energy and materials resources. This would also reduce the number of transport vehicles and the resulting emissions.

Additionally, effective and efficient technical capabilities for recycling need to be developed. The institute has engaged in a number of research projects for industrial clients in consumer electronics and appliances, and heads the efforts on behalf of DaimlerChrysler to disassemble automotive engines. Demonstration projects were presented to panel members involving research to clean and remove product contamination, develop vision recognition of fasteners (type and location, for robotic disassembly), mechanical and laser trimming and removal of appliance sheet metal, and sensor capabilities to determine remaining service life in a number of mechanical and electronic components.

The life-cycle working group headed by Dipl. Ing. Grudzien have recognized that without the full knowledge of market forces involving business cases and competitiveness, sustainable manufacturing will be difficult to achieve. Thus, work to develop educational and design tools for EBM emphasizes the need for a business case and value.

Other observations and comments from our hosts pointed to their belief that take-back requirements at times have been counterproductive, e.g., automotive brake re-conditioning. The brake rebuilding process had been facilitated by an organization that had no connection to the automotive OEM’s. Since take-back regulations require the return of the automotive parts to the OEMs, the current re-conditioners have been sidelined. Thus, more careful analysis should be made before regulations are implemented.

Furthermore, Professor Seliger believes that the EBM challenges require better understanding of the global supply chain, scientific and economic issues. Global collaboration would improve the chances for successful implementation and avoid missing out on the full environmental benefits.

Trends in science and engineering education are not promising. In 1990 more than 60,000 first semester engineering students continued their science and engineering education. By 1998 the number of those continuing on had dropped to only 45,000; and market surveys for Germany indicated a shortage of 66,750 engineers and 75,000 IT experts. With more than 230,000 students enrolled in Berlin schools, a considerable opportunity exists for increasing the enrollment into science and engineering fields.

The IWF Institute, under the direction of Professor Seliger, initiated a project (Theo Prax) wherein high school students learn with university students and faculty in solving real industry problems. Industry submits a problem to the university, which in turn contracts with a local high school to solve the problem. Projects last from two to five months and range in cost from $1,000 to $5,000 per project. The State of Berlin contributes a similar amount, or more, depending upon the project. The university may elect to engage more than one project team in providing multiple choices for solving industry's problems. Current industries listed as using the Theo Prax program include BMW, Krone, Siemens, DaimlerChrysler, and Naiss GmbH, among others.

Site: **Technical University of Denmark**
Department of Manufacturing Engineering
DK 2800 Lyngby
Denmark

Date: April 3, 2000

WTEC Attendees: T. Piwonka (report author), K. Rajurkar, J. Sutherland

Hosts: Prof. Leo Alting
Prof. Michael Hauschild
Prof. Torben Lenau
Niki Bey (graduate student)

INTRODUCTION

Prof. Alting is one of the pioneers in the use of life-cycle assessment. He is currently head of the Department of Manufacturing Engineering at Technical University of Denmark (DTU). This department currently has about 150 students and researchers, of whom 27 are professors. They have extensive manufacturing laboratories, very well equipped, in machining, powder metallurgy, metalworking, welding and casting.

EBM ACTIVITIES

Prof. Alting and his group emphasize *sustainability* in manufacturing. In addition to their work in LCA, they also emphasize micro-technological production (very small components), near net shape processing, and intelligent production systems. The Life-Cycle Center has been in existence for 15 years. It started as a result of analyzing the problems in wastewater from plating systems.

They are well-connected internationally and collaborate, or have collaborated, with Prof. Kimura at the University of Tokyo, Technical University of Berlin, and Cambridge University; and they are active in CIRP, especially the Life-Cycle Working Group. In addition, they have taken advantage of the Institute for Product Development (IPU) at DTU, which was founded in 1956. IPU is administratively and financially independent from DTU; it acts as a commercial arm, providing consultants and doing tasks for industry. They have expertise in "Process and Production Systematics, Recycling Technologies and Cleaner Production Systems." Note that they use the term "cleaner" rather than "clean" to avoid implying that current industrial production is not as clean as it might be. IPU's support is primarily from industry; any funds left over when projects are completed are transferred to the Department of Manufacturing Engineering.

Legislation is now the main driving force for environmentally benign manufacturing in Europe. In the past, the focus was on point sources of pollution; today it is shifting to diffuse sources. They believe that a promising way to control diffuse sources is to control each product. This leads naturally to life-cycle assessment.

They have developed a concept called "Environmental Design of Industrial Products" (EDIP). It includes methodology, guidelines, PC software, and implementation help. They have written two books: *Environmental Assessment of Products, Volume 1: Methodology, Tools, Techniques and Case Studies*, and *Volume II: Scientific Background* (ISBN 0 412 80800 5 and ISBN 0412 80810 2). Both have been translated into English and are now being translated into Japanese. This methodology emphasizes normalization of the environmental load related to a product against what an average person uses or loads the environment. The original "person" was an average Dane, but at present the average person is being converted into the average European.

The EDIP program allows a designer to model the product life cycle as a decision support aid. The software is designed to permit the choice of which potential solution is best, a comparison of how much better it is than other solutions.

As this model may take some time to run, and is limited by lack of data (much of the data needed for the model is proprietary to companies), a simplified version of the program is available for rapid assessment of areas where the more detailed model may be useful. This model is known as "MECO" for the matrix it uses. This is shown below:

Table C.1

Causes of Environmental Impact	**Life-cycle Stage**			
	Extraction of Raw Materials	**Manufacturing Stage**	**Use Stage**	**Disposal Stage**
Materials				
Energy				
Chemicals				
Other				

They made the point that the greatest potential for influencing the environmental performance of a product is at the beginning of the design stage, when knowledge about the product is at its least. They also pointed out that their model does not include ethical or societal concerns. The EDIP method does, however, assess working environment. The importance of considering the environmental impact of a product is increased in Europe by the EU initiative of "Integrated Product Policy" that includes eco-labeling, government purchasing guidelines and consumer education. LCA is used in implementing this policy, with the government paying for the LCAs.

DTU currently offers a course in LCA. The course carries 10 credits with an expected workload of 16 hours per week during the semester, and includes working out a case study in industry.

Professor Lenau gave a number of examples. He noted that, in Denmark, plastic beverage containers are made of heavier gauge plastic than in the U.S., and re-used up to 20-30 times. He also commented on the life-cycle costs of wool, cotton and polyester. He noted that process energy was lost when plastics were incinerated, and spoke of reading about a building where fiber optics are used to transmit sunlight throughout the building instead of using electric lights (at night a plasma light source is used). He also commented on the potential to use human power through piezoelectric devices in low power-consuming products such as remote keyless entry systems in cars, and emphasized that one must know the alternatives in preparing an LCA.

DTU has established a Web site (www.designinsite.dk) that helps designers learn about new materials or manufacturing processes. They also offer an annual course in integration of design in engineering and business. The course is limited to 30 students, ten each from design, business and engineering.

One more concept that is being developed is that of the "oil-point" (OP). This is a method of normalizing energy usage in terms of the amount of energy contained in one kg of crude oil (45 MJ). Toxicological effects are omitted, and care is needed in treating energy data (efficiency factors must be included). Some examples include the following:

- PET resin (resource and processing) = 1.7 OP
- Steel (processing) = 0.7 OP
- Injection molding (energy consumption) = 0.4 OP
- Electricity (European average) = 0.3 OP

One detailed study of using wood window frames or steel reinforced PVC window frames yielded the result that the wood had a score of 4.5 OP, while the PVC score was 14.3 OP.

They concluded with indicating that they believed that current important challenges to EBM in Europe today include the problems of recyclability of products, reduction of energy consumption, increasing product complication, and the lack of adequate databases for accurate LCAs.

Site: **University of Stuttgart**
Institute for Polymer Testing and Polymer Science (IKP)
Pfaffenwaldring 32
D-70569 Stuttgart-Vaihingen
Germany

Date Visited: April 4, 2000

WTEC Attendees: D. Bauer (report author), D. Allen, T. Gutowski, K. Rajurkar, J. Sutherland, E. Wolff

Hosts: Prof. Dr.-Ing. Peter Eyerer
Dipl.-Ing. Martin Baitz
Dipl.-Ing. Johannes Kreissig

BACKGROUND

Professor Eyerer is the Chair for Material Science at IKP and also the Director of the Fraunhofer Institute for Chemical Technology (ICT) in Pfinztal. Together, the two institutes have a wide-ranging scope of polymer-related research, from renewable resources to polymer processing to life-cycle engineering. IKP has about 95 researchers and DM7 million annual budget. ICT has 335 researchers and a DM40 million annual budget. The main international LCA research collaboration is between ICT, IKP, ETH (Switzerland), and MIT.

LCA SOFTWARE DEVELOPMENT AND PROCESS DATA COLLECTION

IKP has developed an LCA software package, GABi3 (we received demo samples of this). The vision for GaBi3 software is to support engineering decisions. Process data are aggregated over a global network of data sources. These data sources were found mostly by tracing back European products through their supply chains. Material and energy flows, as well as time and costs, are traceable through the product manufacture process chain. Some emissions data are available, though the user generally has to supply the cost structure. Attributing the cost of emissions was acknowledged to be a challenge. There is also work within the group on developing an environmental assessment, which translates impact categories (GWP, POCP, AP, EP, Ecotoxicity, Human Toxicity, etc.) into three safeguard subject categories (human health, ecological health, and resource depletion).

Data management is challenging. Rapidly changing areas, such as polymer production, are on their third set of data, whereas cement is still on its first data set. Data are generally averaged across an industry. Some process information is kept opaque for company proprietary reasons.

LCA is encouraging different types of system analysis and improvement, such as tradeoffs between local emissions reductions and increases in energy use. The tool is used both to recommend areas for government-sponsored research, and for industrial decision-making. Companies considering using LCA are most convincible when there is an economic argument.

BEST AVAILBLE POLYMER TECHNOLOGIES

PVC

Because of the chlorine content, it is problematic to incinerate PVC. Thus, there is focus on achieving closed loop recycling. There is a project to recycle PVC window frames. The company (Veka) is producing new window frames with mixed content (20-25% recycled). Used windows are taken to one of several locations where they are shredded, separated, and recycled. They are also working on a window frame eco-labeling program.

Polyethylene/Polypropylene, Nylon

In both cases, the strategy was to optimize a process sequence for energy and waste through introduction of catalysts and additives.

MOTIVATIONS FOR ENVIRONMENTAL WORK WITHIN INDUSTRY

Cost is a key motivator, but sometimes costs do not drive decisions in environmentally preferable directions.

Though the environmental gut feeling is that recycling is good, recycling is not always environmentally preferred, as benefits may be offset by energy-related impacts, particularly from transportation. The opinion expressed is that in Germany the price of energy is not high enough (by a factor of 3) to internalize the environmental implications of energy. Another important recycling, processing, and transportation decision is when to separate and when to shred. If materials for recycling are shipped prior to shredding, then they occupy a large volume-unit mass, so shredding earlier may be better, but this requires distributed processing. Also there is the question of whether/how to sort prior to shredding.

Construction material recycling is currently difficult because landfill disposal of these materials is currently relatively cheap (because in 2005 disposal of construction materials in landfills will no longer be allowed, and thus there is a current excess landfill capacity).

In the automotive industry, there are competing objectives of 90-95% recyclability and dramatic increases in fuel efficiency. This makes development of new automotive materials, such as lightweight composites, particularly challenging

CURRENT AND FUTURE RESEARCH EFFORTS

There is some current work integrating process model-based LCA with economic environmental input/output analyses.

A major current and future application of polymers is fuel cells.

EDUCATION

Environmental issues are intensely integrated into the curriculum in Germany, particularly in elementary school. The integration there may not be balanced enough. In the universities and technical schools there is a more realistic balance, with some environmental course sequences required and also integration of environmental factors into established courses. For example Peter Eyerer’s course is now 25% environmental.

Site: **University of Technology–Aachen**
Institute of Metal Forming
Intzestrasse 10
52072 Aachen
Germany

Date: April 10, 2000

WTEC Attendees: E. Wolff (report author), D. Allen, D. Bauer, K. Rajurkar, J. Sutherland

Hosts: Professor Dr.-Ing. R. Kopp, Director, Institute of Metal Forming
Dipl.-Ing. A. Ebert, Sheet Metal Forming
Dipl.-Ing. T. Möller, Thixo Forming
Dipl.-Ing. K. Kober, Surface Technology
Dipl.-Ing. F. Hageman, Casting/Forming
Dipl.-Ing. T. Hülshorst, Ring Rolling

INTRODUCTION

Professor Kopp described the institute's facilities and departmental organization. Six research groups are focused as follows:

- Casting/forming (twin roll casting)
- Hot forming (open die forging, incremental forging, thixo forging, ring rolling, longitudinal rolling, extrusion)
- Cold forming (drawing, material cycles, lead optimization, composite structures, shot peen forming, forming by load heading)
- Computer applications (CAD/CAE/CAM, FEM simulation)
- Optimization lab (physical simulation and FEM simulations for process optimization, computer-aided optimization)
- Material data (stress strain curves, thermal properties, models for material specification, microstructure simulation and process layout)

RESEARCH AREAS

The principal research thrust is minimization of energy and materials consumption via process shortening, thermo-mechanical treatment, re-use, net shape, lightweight construction, simulation and optimization. The team visited the facilities for thin strip casting now utilized by Thyssen Krupp Stahl AG, where we observed:

- the flexible sheet rolling process that offers load-optimized sheet material for structural automotive application
- Thixo-forging of aluminum components
- incremental forging of structural aircraft aluminum parts
- shot peen forming of large conical sections
- surface quality determination of automotive coiled sheets
- optimization of hot formed rolled rings
- materials data generation for high speed, high temperature forming processes

Several of these processes were in prototype stages and already involved in technology transfer with industrial partners. Comparison between former processes and processes that had eliminated certain operations showed substantial energy and cost savings—e.g., fivefold reduction in thin-strip casting vs. slab casting and hot rolling, 48% reduction in materials consumption through incremental forging, 25% passenger car cross member weight reduction from flexible rolling.

Other industrial projects had explored high strength laminated sheet incorporating steel wire and plastic mesh for weight reduction; reclaiming of recycled automotive body parts; and extending Thixo forging into steel materials.

Professor Kopp has been a principal collaborator in international efforts to develop EBM methodologies and establish environmental initiatives on the campus of UT Aachen with more than 60 institutes and faculty collaborating. Professor Kopp shared his views and offered recommendations in the following areas:

- Exploring higher speeds and pressures in forming operations
- Combining lasers with forming
- Microstructures and chemistries that offer improved forming processes
- Additionally, more accurate formability measurements involving temperatures, speed, and pressure, and simulation tools that can predict forming at a micro structure scale

Site: **AB Volvo**
Dept. 870 VHK
SE-405 08 Goteborg
Sweden

Date: April 5, 2000

WTEC Attendees: D. Thurston (report author), B. Bras, D. Durham, T. Gutowski, R. Horning, C. Murphy, T. Piwonka

Hosts: Dr. Lena Gevert, Director, Environmental Affairs
Dr. Tomas Rydberg

BACKGROUND

Professor Tim Gutowski first delivered an introductory talk describing WTEC and our mission. Dr. Gevert then distributed copies of the Volvo Annual Report (which includes some environmental program information), a more detailed Volvo Environmental Report, and another environmental report. Dr. Gevert then delivered a comprehensive and well-organized overview of Volvo's environmental program.

Since the divestiture of their automotive line to Ford, Volvo has been focusing on its commercial product lines. At present, the main product lines are trucks and buses, which account for 57% of total sales. Aerospace engine services are a growing portion of their business. Each of these product areas serves industrial-based customers, rather than consumer-based.

Volvo views itself as having evolved from a Swedish company into a global corporation based in Sweden. They do business in different ways in different parts of the world, but still maintain their "three core values of Quality, Safety and the Environment." Safety is their main core value, while quality and the environment are viewed as extensions of the core value of safety. Company culture is top-down, with strong guidance from top executives, who are also concerned with empowering local plants. Corporate culture emphasizes environmentalism.

ENVIRONMENTAL PROGRAM

Before its divestiture, the environmental program centered on the automotive company, which was the environmental "driver" for the other Volvo companies. Since the media pays much less attention to the environmental impacts of commercial products than to automobiles, it is unclear precisely how Volvo's commitment to the environment will evolve. Volvo views itself as the environmental leader in the transportation industry. The Volvo Environmental Prize is given to scientists, and is likened to a Nobel Prize for the environment. They expect that their commitment to the environment will give them a competitive edge by following four strategies: (1) a holistic approach which analyzes a complete global value chain, (2) continuous quality improvement, (3) technological development, and (4) resource efficiency.

Volvo considers global warming to be a significant concern, perhaps the most important environmental impact facing society today. A valuable lesson was learned after Volvo spent significant funds to build "the world's cleanest paint shop" in 1995. The water-based paint system decreased emissions, but increased energy requirements, energy costs, and also increased environmental impacts from energy production. Their focus has thus shifted from manufacturing plant emissions to product emissions. There are three main thrusts to their efforts: (1) decrease CO_2 emissions by decreasing fuel consumption, (2) decrease CO_2 emissions by developing alternative fuels, and (3) decrease exhaust emissions.

Fuel consumption

Decrease in fuel consumption is the primary focus of Volvo's effort to decrease CO_2 emissions. The three approaches taken are load optimization, engine and transmission design, and traffic planning/information systems.

Alternative fuels

Volvo is the largest producer of natural gas buses in Europe. They commented that they have not yet seen a fully satisfactory solution to the problem of alternative fuels or power sources for their products. The best bet so far is methane. They would like to use fuel cells, but do not believe that any current designs are satisfactory for their products. They are concerned that the infrastructure for alternative fuel supply is not established. Hybrid power plants are acceptable, but not ideal. Volvo has developed demonstration vehicles that use hybrid and fuel cell technologies.

Decrease exhaust emissions

Buses are the biggest problem in regards to emissions, especially city buses. Trucks are the next biggest. The main effort is in design of engines and engine control equipment. Fuels which reduce sulfur, lead and aromatic emissions are also being explored. The different legal requirements for emissions testing present difficulties. Although the regulations tend to catch up with one another by leap-frogging between Europe and the U.S. approximately every four years, one standard regulatory system would be preferred. Although Volvo remanufactures engines, it does so only to the original specifications, not current specifications.

The following topics were also discussed:

Recycling

There is some discussion about instituting take-back and recycling requirements for trucks and buses, similar to those for automobiles.

Vendors

Vendors are viewed as part of the complete value chain. All Volvo suppliers must be ISO 9000 compliant, as well as ISO 14000 compliant (or develop an action plan for compliance). This is part of encouraging lean manufacturing. Volvo views itself as a world leader in design and manufacturing technology, and they expect their Tier 1 suppliers to be world leaders also. For this reason, they have a small, but high quality supplier base, and emphasize teaming with suppliers in design and manufacturing development.

Manufacturing

As mentioned above, the corporate focus has shifted from manufacturing plant emissions to product emissions since global warming is such a key issue. Manufacturing emissions are viewed as a local issue. A corporate environmental auditor ensures compliance with local standards. In some arenas, though, there is a more stringent corporate "decency limit," and a "black list" of chemicals that plants are not allowed to use, even though they may be legal locally, as well as a "gray list" of materials that should be phased out. The goal is to be the best plant locally.

Life-cycle Analysis

Volvo was an initiator of the LCA concept, ahead of the ISO process. They have developed EP (environmental priority system) an in-house LCA tool. Tradeoff analysis is the most difficult problem, particularly tradeoffs between economic and environmental impacts. Currently, these tradeoffs are achieved through discussion and compromise, rather than analysis. In Sweden, a consequence analysis for products must be performed. This is a more balanced approach than the U.S. waste-stream specific focus.

TOUR OF TRUCK ASSEMBLY PLANT

The tour of the truck assembly plant was very interesting. They have converted all drilling operations in the frame to punching and laser cutting, thereby allowing recovery of the material removed. Their frame bending operation is done cold, on a series of roll formers. One observation was that all of the shaping, punching and laser cutting equipment was encased in cubicles that were designed to minimize plant noise. Assembly is done by teams. There are two different assembly practices. For the smaller trucks that are made in larger quantities, a modified assembly line is used. For larger trucks, usually ordered in much smaller quantities, assembly "docks" are used, with each team turning out three trucks a day. Virtually all trucks are custom ordered.

Site:	**Fuji Xerox (Ebina plant)** **2274 Hongo, Ebina** **Kanagawa, 243-0494** **Japan**
Date:	October 19, 1999
WTEC Attendees:	B. Bras (report author), H. Morishita, F. Thompson, D. Thurston, E. Wolff
Hosts:	Dr. Takashi Nakagami, Asset Recovery Management Department Takako Hamashima, Asset Recovery Management Department

BACKGROUND

Mr. Nakagami provided a presentation on asset recovery in Fuji Xerox, including a video, as well as a plant tour.

Until around 1965, Fuji Xerox's environmental focus was on pollution at a specific area. A major shift came with the energy crises, and the focus shifted towards energy saving. Now, the focus is on global environmental issues. The basic motivators for Fuji Xerox asset recovery in Japan are that Japan has no room for landfills and that recycling is a necessity. In the past, the focus was on a "one way economy" but now an expansion to a "re-circulating economic system" has been introduced.

EBM ACTIVITIES

A key strategy is to promote reuse of resources to reduce landfill close to zero. To do that, the following two items are pursued:

- Recirculatory recycling system
- Part reuse system that enables the same quality assurance as with newly built parts

Dr. Nakagami explained Fuji Xerox's process. Notable is that all parts are checked, repaired if needed, etc., and fed back to an integrated production line.

Key steps to achieve this are:

- Structure the recycle loop, i.e., establish the infrastructure and ensure that a basic recycling loop is established.
- Increase the recycling rate, i.e., strive for shorter paths through the recycling loop. This implies that product recycling is better than material recycling.
- Speed up the loop, i.e., make it all go faster.

Answering a question on how this is achieved, Dr. Nakagami explained that Fuji Xerox has design guidelines for longer life, disassembly, etc., so a designer focuses on recycling as part of the other requirements. Fuji Xerox exploits the longer life that printed circuit boards now have, compared to the past.

Warranty and Service

To ensure the quality assurance of recycled parts, the status of usage at the user is evaluated by means of the copy counter. Furthermore, the remaining life of parts is estimated for parts with a life longer than a single usage life. These two indicators are combined into a system to assure part quality. Parts from the asset recovery line are placed next to the supplier's new parts and are treated as equal.

Warranty and service costs have not changed due to part reuse, but are a very important issue. Reliability is tracked carefully. Data from the field is fed back by maintenance and service personnel directly through central databases. These data allow Fuji Xerox to employ Weibull analysis, i.e., statistical life estimation. Visual quality inspections are also made in the plant itself. Regarding life times, typical use time for a 35 page per minute (ppm) copier is three years, and 115 ppm copiers typically stay around eight years at a single customer.

Design Guidelines

In 1995, a Xerox worldwide Design for Recycling Guideline I was established, which focused on material recycling. An improved version (DFR Guideline II) will focus on designing for longer life, common design, DFD, use of reusable material, separation/modularization of contamination and/or failing parts. Trade-offs exist between design and production, and are also a big issue in Fuji Xerox. Segmentation is made between fast and slowly changing technology when parts are designed. Decisions are made about which customer requirements will remain stable and which will not. In the past, design goals were focused on quality, cost, and delivery; now environment has been added.

Fuji Xerox also pursues so-called product plan for the life cycle (PFL). Currently the goal is to (1) recycle to the same product and (2) recycle to the same series, but there is no real PFL (yet). PFL includes simulation of hulk collection, concept of three product generations, modular design concept.

Collection and Reuse Ratios

Fuji Xerox's collection ratio through direct channels is 96%. Collection through indirect channels (retailers, etc.) is 60% and needs improvement. Efforts are focused on increased volume of used machine collection, reduction of logistics costs by improved loading efficiency and reduced warehouse costs, and more efficient hulk using an information system for hulk use (this already exists for direct channels, but not for the indirect channels).

There are recycled parts in 27 products. The part reuse ratio is about 40%. Short-term improvements are focused on making the line more flexible and improved quality assurance. Long-term efforts will be focusing on automatic cleaning systems, design for disassembly and detachment, design for repair, and design for automatic inspection.

In 1998, 18.5% of products incorporated recycled parts. The goal is to boost this to 25% in the year 2000. The part reuse ratio is planned to increase from 40% (1998) to 50% in 2000. Landfill (from the direct channels) will be reduced from 14.9% to zero in 2000. The zero target is technically no problem, but operationally it is very difficult and partnerships are needed.

De-manufacturing Operation

Fuji Xerox (Japan), Xerox Limited (Europe) and Xerox (United States) all have their own asset recovery lines. Representatives meet about twice a year to consult each other. In Japan, all recovered machines are brought to the Fuji Xerox Ebina plant, which has an integrated de-manufacture-manufacture production line. The Ebina de-manufacturing line is for recycling/reuse of parts and subassemblies. An important function of the line is to sort the parts. Products are split into three groups according to the copy volume. A truck comes about five times daily from a warehouse depending on the plant needs. Machines are boxed to avoid transportation damage. Autonomous Guided Vehicles (AGVs) are used for in-plant transportation of material.

The main stages of the de-manufacture process are as follows:

- Each machine is unboxed and checked for basic operation by plugging it in and making a test copy.
- Covers are removed.
- Non-reusable parts are sorted and packed for material recycling. These are taken away by material recyclers, with the exception of ABS plastics which are recycled directly for Fuji Xerox by a company for new outer covers.

- Each mechanism is cleaned from dust and toner using an automatic (robotic) dry-ice blast cleaning set-up.
- The machines arrive at the disassembly line where non-reusable and reusable parts are manually disassembled (using pneumatic tools) and sorted. Sorting relies on a worker's understanding. Each disassembly station has a manual with information for the worker regarding the products, parts, and actions to be taken. Panelists observed that most workers were relatively young and, according to our hosts, from a temp agency.
- After (partial) disassembly, further cleaning is undertaken at an air cleaning station, a wet cleaning station (detergent & hot water), and another robotic dry-ice blasting station. The robot reads a bar code on the subassembly to be cleaned and automatically starts the programmed cleaning path.
- Re-assembly is done to the sub-unit level using the same process as the original supplier uses. Small parts are checked at different areas.
- Quality checks are performed.
- Re-assembled units are staged for shipping to the assembly plant. The entire inventory is shipped every day to the assembly area.

In the assembly area (which is housed in a different, but connected building), rebuilt and new parts/units are all staged together and treated the same. The assembly lines use a lean production paradigm. The low volume line only has four basic products, but many varieties exist for the different markets. Workers know that a different product is being assembled from the previous one by a simple flag raised on the product tray. The speed of the kitting AGVs is controlled to match the speed of the assembly. The final inspection is computer assisted. Adjustments are made to set printing properties, etc., and safety checks are done using high voltage testing.

Profitability and Competition

Currently, there is still a loss in the recycling business, but it is expected that it will become profitable when the volume increases. The customers, however, like what Fuji Xerox has done and the Green Purchasing Network program requires recycling. According to our hosts, the first motivation came from the United States where Xerox started reuse. Secondly, Fuji Xerox used to be a rental business so take-back and reuse was a natural extension of their business. Thirdly, the landfill problem provides motivation.

Down the road, Fuji Xerox sees the need to increase the life at the customer by increased reliability and also to make upgrades by changing parts at the customer rather than in-plant upgrades.

Fuji Xerox is currently the benchmark with regards to collection volume, not only from rental customers but also non-rental, and with regards to the production volume of copiers including recycled parts compared to other companies. But it was stated that Canon has a good toner cartridge recycling program, and Ricoh is also very open with respect to environmental issues to the customer.

Fuji Xerox applied for ISO 14000 certification two years ago. Its current ISO 14000 focus is on including suppliers.

REFERENCES

"Recycling of Fuji Xerox Products," Fuji Xerox, brochure no. ARM-003

Site: **Hitachi Production Engineering Research Laboratory (PERL)**
292 Yoshido-cho, Totsuka, Yokohama
Kanagawa, 244-0817
Japan

Date: October 21, 1999

WTEC attendees: D. Thurston (report author), D. Bauer, B. Bras, T. Gutowski, H. Morishita, C. Murphy, T. Piwonka, P. Sheng, J. Sutherland, F. Thompson, E. Wolff

Hosts: Dr. M. Takahashi
Dr. T. Kamei
Dr. H. Yamaguchi
Mr. T. Ohashi
Mr. K. Serizawa
Mr. M. Uno
Ms. H. Shimokawa

INTRODUCTION

Dr. Takahashi provided a welcome and introduction, and described their programs. PERL is one of seven Hitachi corporate laboratories. Their mission is development of new production processes, facilities and systems, and productivity improvement. Environmental projects are one of four areas PERL pursues in its mission of total cost minimization. The other three are in the areas of engineering, production, and logistics. Hitachi's environmental policy includes ISO 14001 certification for all Hitachi sites and affiliates by the end of 1999. Other goals are a 20% reduction in energy consumption (compared with 1990 values) and a 90% reduction in waste by 2010 (compared with 1991). Also, product assessments include consideration of increased use of recycled materials, reduction in disassembly time, and achieving 100% lead-free soldering for new products by 2002.

MAJOR PROJECTS

Lead-free Soldering

A national project in Japan concerning the lead-free soldering development effort at Hitachi began in January, 1999 and is expected to continue through March, 2000. It was initially funded through MITI and then NEDO (New Energy and Industrial Technology Development Organization) for 340M yen. A number of companies and organizations are involved in this effort. It includes JEIDA's project, which equipment suppliers mostly join, working on application technologies, Japan Welding Association's project, addressing standardization of lead-free solder, and EIAJ's project (which mostly parts suppliers join) evaluating plating technologies and heat resistance. Hitachi joined all three projects. In the case of JEIDA's project, several different Pb-free solders were discussed, including silver-containing solder (Sn/Ag/Cu) for reflow or wave-solder applications, tin-copper binary solder (Sn/Cu) for wave-solder, bismuth-containing solders (Sn/Ag/Bi/Cu, Sn/Ag/Bi/Cu/Ge, and Sn/Ag/Bi) for reflow applications, and low-temperature solder (Sn/Bi/Ag) for reflow or wave-solder.

The issues surrounding lead-free solder include composition and technology, life-estimates of the joints (thermal fatigue), and solder process construction. All solders undergo reliability testing. Temperature cycling condition is from –55 to +125°C (equivalent to MIL STD Condition B). The thermal fatigue life of lead-free solders was compared with standard Sn-Pb solder for some packages. In the case of 50-pin TSOP, standard Sn-Pb solder survived around 750 cycles, but the high temperature lead-free solder failed around 800 cycles; the mid-temperature lead-free solder failed around 500 cycles; and the low-temperature solder failed around 200 cycles. 20-pin SOPs and 208-pin QFPs were also tested.

Lead reduction targets are 50% by March of 2000 and 100% by March of 2002 for new models.

Recyclability Evaluation Method (REM)

The quantitative attributes of REM are recycle expense index, estimated value, estimated recyclability rate, and a recyclability/disassemblability evaluation score, etc. The goal is to provide designers with a tool to compare recyclability of various design options. The user inputs part name, material, and mass, and symbols which indicate the required disassembly operation. There are approximately 20 types of disassembly operation elements, categorized by movement, tool operations, etc. Examples include upward movement, screw rotation and cutting. Model output includes estimated disassembly time and total recycling expense. REM is offered to contracted users through the internet (http://ecoassist.omika.hitachi.co.jp).

Inverse Manufacturing Forum and Information Exchange System

The Inverse Manufacturing Forum was established in December 1996. Priorities are IT and system engineering for circulating society, towards evolution to a post mass-production paradigm. The process is viewed as, ideally, a horizontal loop, or at worst a cascading loop, where waste material from one manufacturing process or product (at the end of its useful life) is used as a part of the same product or at least a raw material for another product or process. A number of companies are working toward this goal—for example, Toyota in its 5R program (Refine, Reduce, Reuse, Recycle and Retrieve Energy) and Ricoh in its Comet Circle, which connects life-cycle phases. The forum plans strategies, reviews research themes, and arranges projects. The forum has many goals, including quantitative analysis of the performance of inverse manufacturing efforts.

In the Information Exchange System, a systems approach is taken to develop a method for organizing and communicating information that enable to circulation of various phases of products (new, grade-up, and recycled ones) among manufacturers, users and recyclers, etc. This is one of Hitachi's most active projects, and is sponsored by MITI through MSTC (Manufacturing Science Technology Center). A prototype system is posted on a Web site (http://ecoassist.omika.hitachi.co.jp. or http://www.mstc.or.jp/m-1db/). Early stage models for major home appliances and PCs were developed to test the concept. This prototype system is structured to include product, process and recycling data between manufacturers and recyclers. Hitachi is currently working on the next phase, an extension of this system which provides data with respect to users' needs, maintenance parts, recycled parts, recycling process, etc., throughout each phase of the life cycle, from manufacturing through delivery, use, maintenance, collection and end-processing. The concept of product "circulation or re-use" during its useful life is again employed. One major task remaining is to develop a standardized format for information input and output.

One problem area is the market economics of recycled materials (recycled materials are often more expensive than new materials). Mr. Ohashi offered his personal opinion that an even more drastic systems engineering, feed-forward approach needs to be taken. This might include governmental policy aimed at increasing the "value" of materials and energy, and encouraging the circulation of used parts and materials (perhaps through policy or taxation programs) in order to redress the value balance between too cheap materials/energy (and labor and information) and more expensive recycled materials. He also feels that although technology is vital in order to raise the quality of the solution, technology can play only a partner role (together with legal, economic, social policies, etc.) in an effort to increase society's and individuals' sense of responsibility toward the environment. Such comprehensive activities alone enable feed-forward social movement that can force a drastic change.

SUMMARY

Hitachi is working in several different areas of environmentally benign manufacturing, including lead-free soldering, evaluation methods for recycling, inverse manufacturing, and recycling information exchange systems. They have clearly articulated a policy to pursue environmentally conscious design and manufacturing in a variety of areas, and quantified specific goals and target dates. More detail can be found in the references listed below.

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Ohashi, T., T. Ishida, Y. Hiroshige, T. Urakami, T. Midorikawa, and M. Uno. 1999. Ecological Information System – Data Exchange System Between Manufacturers and Recyclers. *IEEE*, pp. 143-147*

Nishi, T., T. Ohashi, Y. Hiroshige, M. Hirano, and K. Ueno. 1999. Study on TV Recyclability. *IEEE*, pp. 278-280 *

For Planet Earth: Hitachi's Approach to Environmental Issues. (Hitachi brochure).

Site: **Horiba, Ltd.**
2, Miyanohigashi-cho, Kisshoin, Minami-ku
Kyoto, 601-8510
Japan

Date: October 21, 1999

WTEC Attendees: T. Piwonka (report author), H. Morishita, J. Sutherland

Hosts: Keiichi Handa, Planning and Development Department, Analytical Equipment & Systems Division
Katsumi Nagasawa, Senior Manager, Analytical Equipment & Systems Division
Hajime Mikasa, Certified Environment Assessor, Manager, Technical Information Office

BACKGROUND

Horiba is a manufacturer of analytical equipment used to monitor automobile emissions, smoke stack emissions, and air and water quality, located in Kyoto. It also makes medical products and semiconductor inspection systems. The company was founded in 1945 and incorporated in 1953. The company started as a result of the development of a portable pH meter by its founder, Dr. Masao Horiba. He continues to be chairman of the board; his son is president of the company. Horiba products are sold internationally, and the company had annual consolidated sales of $575 million for the year ending March, 1999. About 5% of its revenues are plowed back into the company for product research. One company slogan is to be the “ultra quick supplier” of instruments to customers.

Their instruments are based primarily on pH, infrared and X-ray analysis. A specialty is integrated emission test systems for automotive (gasoline and diesel) engines. These total engine performance systems are sold to automotive companies (Kubota indicated that they use them), where they are used in the development of clean engines. They have an emission test “cell” installed in Ann Arbor, MI for use by U.S. automotive customers.

EBM ACTIVITIES

Horiba makes a variety of air pollution monitoring systems for installation in stacks and to measure ambient air conditions. Their analyzers are mostly compound-specific, measuring CO_2, oxygen, etc. At the present time they are working on developing instruments to detect volatile organic compounds, notably aromatic hydrocarbons (benzene, toluene and xylene), aldehydes, and chlorinated hydrocarbons in air and soil. They anticipate that regulations on odor pollution may appear in Japan at some time in the intermediate future, and are working to identify specific compounds that may be regulated.

In water quality, they offer a checker that measures 13 items, including pH, conductivity, turbidity and temperature, and is equipped with a global positioning system for three dimensional mapping of lakes and rivers, as well as an oil content analyzer for waterways. Their instruments monitor the effect of acid rain in hundreds of locations in Japan; they consider that the network thus set up is an “honest” system of keeping track of the effects of acid rain. They have other checkers for water quality and continue to develop new instruments in anticipation of more stringent environmental regulations on water quality.

They also manufacture analyzers to measure particulate matter and, in some cases, the chemical make-up of particulate emissions, using an infrared spectrophotometer database.

They supply analytical services on a spot basis for companies as a sales service, to encourage customers to buy their equipment. They also supply calibration services for those customers that have purchased their equipment; some of the calibration is provided automatically by data loggers and a wide area network with their customers. They have branches worldwide that monitor the performance of the instruments they sell in those countries. They offer upgrade kits for some of their instruments to accommodate more stringent regulations that may come along. They will beta-test their new instruments at selected customers.

As increasingly restrictive pollution regulations mean more business for them, they are enthusiastic about them. However, they are concerned that some regulations may lead to requirements for analytical precision that are very difficult to meet. They donated an air monitoring system to the city of Kyoto that displays airborne SOx, NOx, and CO_2 contents of the air in the city; it displays its readings in a public square.

Specific concerns for the future include development of better methods for measuring hydrocarbon emissions, lower concentrations of regulated substances, and small air-quality devices for application to real-time control of auto emissions. Other substances that they believe they will be asked to measure include organic chromates, PFCs, noxious odors (ammonia, hydrogen sulfide) and those compounds that affect interior air quality.

They publish (in Japanese with English abstracts, sometimes extended) a periodic review of technical reports. In addition, information about their products is available at their Web site (www.horiba.co.jp, in Japanese or English).

Site: **Kubota Corporation**
1-12-47 Shikidu-Higashi, Naniwa-ku
Osaka, 556-8601
Japan

Date: October 21, 1999

WTEC Attendees: J. Sutherland (author), H. Morishita, T. Piwonka

Hosts: Hiroyuki Kisaka, Executive Managing Director
Yasunori Shiraishi, General Manager, Engine Engineering Department
Yoshikazu Yamada, General Manager, Environmental Protection Dept.
Takeo Morimoto, Senior Associate Engineer, Environmental Protection Dept.
Kazuyuki Sunabe, Deputy Mgr., Environmental Protection Dept., Section Mgr.

INTRODUCTION

Several brochures were distributed and a videotape describing Kubota's activities was shown. Kubota's business interests include: farm and industrial machinery; pipe and fluid systems engineering; environmental control plants; housing materials and utilities; materials; and air conditioning equipment. According to the hosts, all Kubota plants will be ISO 14001 certified by the end of 2000.

EBM ACTIVITIES

Kubota has established five thrust areas as part of its "Environment-Friendly Corporate Activities":

- Environment friendly products—directed at product and technology development
- Zero emission—directed at product development and manufacturing
- Energy and resources conservation—directed at product development and manufacturing
- Local environmental conservation and comfortable work shop—for regional and working environments
- Efficient environmental management system—for business processes

Kubota has $8 billion in sales per year, and about 0.5% of this amount ($40 million) is associated with the management of environmental issues. The breakdown for this is as follows: personnel, $9 million; solid waste management, $10 million; investment in new equipment/facilities, $16 million; other, $4 million. As a comparison, the research and development budget is $400 million. It was noted that the term "environmental accounting" has begun to be used, but is far from being fully implemented. They view environmental regulations not as something to be fought; rather, environmental costs are viewed as taxes. Kubota is working to make their plants in Japan as green as possible, and are compliant with customs/regulations in other countries. The energy costs for Kubota are approximately 2% of their sales.

Yasunori Shiraishi then spoke for some time on their engine development activities. Of the diesel engines they produce, approximately 28% go into their own equipment, with the balance largely exported. Kubota is the dominant player in the Japanese market. As engine developers, Kubota is keenly aware of the worldwide regulations relating to NOx, HC, CO, and PM. They have adopted a strategy that, while seeming to focus on developing/building engines, simultaneously meets the union of all the tightest regulations. Discussion ensued on the independence of the quality audit process to R&D and manufacturing. A graph was shown displaying the audited performance of most of their engines relative to the California/EPA standards for PM and NOx+HC. The engines complied with the Tier I requirements as well as with the Tier II standards. The Kubota personnel did indicate that for the case of high volume production, stringent adherence to manufacturing tolerances would be required to meet design intent.

An analogy was made between competitiveness and power density. Under such an analogy, noise, vibration, exhaust gases, and waste heat are indicators of inefficiency and endanger competitiveness. This philosophy provides some feeling for Kubota's desire to obtain larger engine displacements on essentially the same basic platform. To illustrate this point, Mr. Shiraishi discussed the conversion of their 2.2 liter engine to 2.4 liters. Increasing the bore diameter on the 2.2 liter engine would normally result in thin 8 mm wall sections between the bores leading to excessively high temperatures. In order to reduce the temperature, a water passage has been introduced between the bores, producing wall thicknesses in several locations of 3 mm. A stainless steel insert is being used for support of the water jacket core.

Mr. Morimoto described Kubota's environment improvement efforts related to casting. Specifically he cited two changes that were implemented two years ago when an old cylinder block and head casting line was remodeled. One of the changes was to replace gas dryers with microwave dryers in drying core coatings. Not only did this change reduce the cycle time (to 6.5 minutes) by a significant amount, but it also cost two-thirds as much and dramatically lowered CO_2 production. A self-annealing process was also discussed, where the heat in the casting immediately after shakeout is used for self-annealing as opposed to allowing the casting to cool and subsequently heat-treat it. For self-annealing, several hot castings are placed into an insulated box for approximately 8 hours. The self-annealing process resulted in a significant cycle time reduction (from about 72 hours to 8 hours), less plant space taken, and a tremendous drop in energy usage. The total cycle time for the new environmentally friendly casting line is 17.7 hours as compared to the old time of 132 hours.

Site: **Mechanical Engineering Laboratory (MEL)**
Ministry of International Trade and Industry (MITI)
1-2 Namiki, Tsukuba
Ibaraki, 305-8564
Japan
URL: http://www.mel.go.jp

Date: October 18, 1999

WTEC Attendees: C. Murphy (report author), D. Bauer, B. Bras, T. Gutowski, R. Horning, T. Piwonka, P. Sheng, J. Sutherland, F. Thompson, D. Thurston, E. Wolff

Hosts:
Naotake Ooyama, Director-General
Takayoshi Ohmi, International Research Cooperation Officer
Keijiro Masui, Manufacturing Machinery Division
Mitsuro Hattori, Director, Machining Process Division, Manufacturing Systems Department
Toshio Sano, Director, Manufacturing System Department
Satoshi Imamura, Director, Computational Engineering Division, Department of Applied Physics
Kazuo Mori, Director, Manufacturing Information Division, Manufacturing Systems Department
Nozomu Mishima, Senior Researcher, Manufacturing Machinery Division
Kohmei Halada, Team Leader, Ecomaterials Research Team, National Research Institute for Metals
Kazutoshi Tanabe, Chief Senior Researcher, National Institute of Materials and Chemical Research
Osamu Kitao, National Institute of Materials and Chemical Research
Atsushi Inaba, National Institute for Resources and Environment
Norihiro Itsubo, LCA Development Division, Japan Environmental Management Association for Industry (http://www.jemai.or.jp)
Toshijiro Ohashi, Chief Researcher, Production Engineering Research Laboratory, Hitachi, Ltd.

BACKGROUND

The Mechanical Engineering Laboratory (MEL), originally known as the Government Mechanical Laboratory, was founded in 1937. Its original aim was to reduce Japanese dependency on foreign technology. Current research at MEL covers seven main areas: materials science and technology; bioengineering; information and systems science; advanced machine technology; energy technology; manufacturing technology; and robotics. MEL and associated government agencies have a number of projects related to environmentally benign manufacturing, most notably in the areas of machining, material selection and processing, and LCA software development.

LAB TOURS

Satoshi Imamura

Design for Product Evolution/ Product (Dis)assembly Optimization

Mr. Imamura discussed the software being developed by his group. The purpose of the software is to allow designers to account for product evolution and evolving products for environmental changes. Target products are plant equipment, big machines, manufacturing systems, boilers, elevators, etc. The issues that the design tool is meant to address are deterioration and failures and mismatches between product functions and requirements. The idea is to develop concepts for system design that are easy to service and that are upgradable as performance requirements change and overall component technology improves.

Assembly/disassembly software generates 2- and 3-dimensional assembly/disassembly sequencing for initial assembly, component service, and end-of-life disassembly. There are three approaches: (1) to reconfigure for fixed structured systems; (2) to reconfigure for unfixed structured systems; and (3) to use CAD for product evolution through component reuse. Fixed structured systems are optimized for decreased number of part exchanges and decreased costs (parts and engineering). Unfixed structured systems are optimized using general algorithms and a design language with dynamic data structure modification. CAD optimization is done using a database containing historical design and reliability (reverse engineering) data for existing products. A brief demonstration of software was given.

Kazuo Mori

Tool Wear Monitoring Using Integrated Sensors

The goal is develop more effective in-process monitoring techniques for tooling processes by using knowledge-based control and a real-time expert system. Sensor technology is key to achieving this. In one method, a simple laser displacement sensor is used to monitor tool wear by detecting wear on the bit. Although compressed air is used to remove fluid, which might obstruct measurements, there is still enough detritus and lubricant to disturb the laser. Since the disturbance is random, it can be factored out using a series of histograms to represent the distance from the laser corresponding to points along the tool. A second method uses an electronic sensor made using a simple resistor of CVD TiN on ceramic. The resistors open through the same wear mechanism as the tool. This resistor is calibrated (by controlling the metal film thickness to about 20 µm) to open at the point when the maximum desired amount of wear on the tool has occurred.

Nozomu Mishima

Micro-Factory

This project is investigating reduction in the size of machine tools. The “micro-factory” includes a lathe, a machine mill, a manipulator, etc. The goal appears to be reduction in factory size in order to reduce the environmental load related to factory facilitization (e.g., construction, heating and cooling, etc.). It was unclear whether the relative amount of energy use by these micro-machines was actually less than traditional systems.

WORKSHOP PRESENTATIONS

The workshop was designed to bring together representatives from MEL and other government and industry research organizations. The NSF/WTEC panelists each gave brief presentations of their research interests. This was followed by presentations from invited researchers. These are described below.

Toshio Sano

International Committee on Environment and Manufacturing (ICEM)

A brief overview of the International Committee on Environment and Manufacturing (ICEM) was presented and two handouts were distributed: “ICEM in Retrospect” and “Ideas for the Development of the ICEM.” This non-profit organization was formed in 1993. They have held annual workshops with participation by MITI and universities from nine countries including Japan, Germany, and the Netherlands. Their Web site is http://www.mel.go.jp/soshiki/seisan/bucyo/icemwebsite.

A brief technical presentation was made on the ecological benefits of magnesium and its alloys. Among the benefits mentioned were the ability to form lightweight structural materials, ease of recycling, high thermal conductivity, good EM shielding, and high stiffness. The lowest eco-indicators and energy consumption are for machining and atomizing (vs. casting).

Mitsuro Hattori

Emission-Free Manufacturing

The environmental burden of the manufacturing process is a critical portion in the life cycle of a product. The long-term goal of this project is to identify technologies for emission-free manufacturing. One means of achieving this is by reducing the amount of oil-based lubricants in the machining process with a move to water-based lubricants and eventually to dry machining. Downsizing of products is seen as another means to minimizing oil usage. A third technique for decreasing emissions related to oil (or other lubricants) is near-net-shape and net-shape forging. By forming the product very close to its final shape (vs. the conventional technique of pre-forming, rough machining, and final machining) the total amount of machining required is significantly reduced along with the amount of lubricant used. In addition, material waste volumes and total energy consumption (including that used for air conditioning the production area) are also diminished.

Kohmei Halada

Recent Development of Ecomaterials in Japan

A presentation on the merits of "ecomaterials" was given. Two publications were handed out: "Progress of Ecomaterials Research towards Sustainable Society" and "Barrier-Free Processing to Improve Resource-Efficiency through Life Cycle of Material." In addition, a copy of the presentation and a brochure for The Fourth International Conference on Ecomaterials were provided.

Ecomaterials

One of the key tenets of ecomaterials is to control material properties by structure rather than by elemental additives (e.g., Cu, Ni, etc., in steel), because in the recycling process these additives become impurities. In addition, at the final disposal step, additives and impurities may create a hazardous waste problem. "Ecomaterials" is a subject of VAMAS (Versailles Project on Advanced Materials and Standards) as an inter-government pre-standardization collaboration.

In general, three categories of materials were addressed, each with different issues.

- Diffusive materials are materials of mass consumption and wide distribution. Areas where substitute materials are being investigated include Pb-based solder, asbestos, PVC, and fire retardant systems for plastics.
- Bulky materials are materials for structural use with mass-production. There are two major thrust areas under this category. The first are materials that improve the environmental profiles during processing. These include materials from nature (e.g., wood- or soil-based ceramics), from waste (e.g., cement from municipal waste or ash), those with multiple-potential, and materials processed with low emissions and energy consumption materials. The second group of materials are those which are selected for their improved recycling potential such as alloys (e.g., steels with fewer elements) and plastics/composites that are designed to be recycled.
- Energy-transmission materials are materials for power generation and transmission. Ecomaterials in this category include those with higher performance and/or longer life in the use stage (e.g., greater strength and heat resistance), and those which reduce the amount of energy required such as light-weight alloys for vehicles.

Barrier-Free Processing of Materials

The primary goal of this area of research is to keep materials in use for as long as possible before ultimate disposal. Three themes are focused upon:

- Material selection (use recycled materials and materials that can be easily recycled)
- Design for X (include environmental factors in determining function and process parameters)
- Materials efficiency accounting (measure and model effects of material selection on environmental factors)

STA (Science Technology Agency, Japan Government) has launched a five-year research project on "Barrier-free Processing" with funding of about Yen 300 million per year, beginning in 1999, following the research project on "Ecomaterials" from 1993 to 1997.

Kazutoshi Tanabe

Discrimination of Plastics Wastes by Combining Near-Infrared Spectra Measurement and Neural Network Analysis

A method for rapid discrimination of plastic wastes for recycling was presented. A portable spectrophotometer weighing less than 2 Kg was used to measure 300 samples of 51 different kinds of plastics. Normalized, second-derivative, near-infrared spectral data in the 1.3 to 2.3 μm wavelength region were trained in a three-layer (input, intermediate, and output) perceptron-type neural network. The average discrimination ("hit-rate") was 77%. The method performed best on low-end plastics such as PET. Engineered plastics had the poorest discrimination rates (38% for ABS and 60% for PC/ABS). The method does not work on densely colored or black plastics.

Osamu Kitao

Materials Engineering towards Green Chemistry

The background of the U.S. EPA's Green Chemistry program was reviewed. This was followed by a timeline showing the history of similar programs supported by the Japanese government. A reference list was also provided.

Atsushi Inaba

Current Activities of Energy Analysis Division, NIRE

NIRE's LCA software package was described. This software is distributed free of charge to both industry and universities with approximately 250 received by the former and 40 by the latter. The software was used to evaluate CO_2 emissions for three different power station construction options and the results were presented.

A general discussion of LCA followed with the suggestion that three key areas of analyses were needed in order to make LCA a truly valuable tool. These were cost, social (industry commitments), and time functions.

Norihiro Itsubo

Development of Assessment Technology of Life-Cycle Environmental Impacts of Products

The project was started in 1998, is scheduled to last five years, and has an overall budget of ¥850 million (~$8.5M). The project is designed to develop a highly reliable LCA database and LCA methodology and consists of three committees covering inventory, database, and impact assessment. The results of the project are intended to be applied to:

- Popularization of eco-design and construction of eco-processes within industry
- Approval of eco-labeling
- Establishment of environmental specifications
- Green purchasing

- Dealing with COP3 Protocol (see http://www.cop3.de/)
- Textbooks for education and reliable LCA software
- Training of LCA experts

One of the most significant challenges will be to develop a usable material database. Twenty-three industry associations are participating in the Inventory Study Committee with representatives from seven stages along the life cycle (resources and energy, materials, parts, products, uses, recycling, and waste). Both real material flow data and statistically derived data will be included, and the data format will be in accordance with ISO 14040 and 14041.

The primary goal of the Impact Assessment Study Committee will be to establish damage functions, which link environmental impacts to specific damages. Damage is categorized by whether the impact is on Human Health, Ecosystems, or Resource Depletion. These are then weighted to give a final single indicator or index. There was significant discussion between the panelists and Dr. Itsubo regarding the use of a single index.

FINAL DISCUSSION

Key Contributors

Halada, Ohashi, Kitao, Inaba, Itsubo

Background

Industrial environmental activities have greatly increased in the last three years. This is evidenced by the increase in environmental reports generated by companies, by widespread ISO 14000 certification, and an intensive national effort to increase the use of LCA. The general trend in government is towards smaller, leaner groups. This has an impact on the ability of agencies such as MEL to pursue environmental investigations at an optimal level. The consensus seemed to be that there was still a significant amount of work to be done, especially in the area of public education, and that the effort would require international leadership.

Industrial Perspective

Environmental evaluation priorities from an industrial perspective are two-fold. The first is characterization of environmental impact; the second is integration of economic and environmental factors. In order to meet both of these objectives, the primary need is the development of methodologies for measurement, documentation, and prioritization among environmental and other goals. It was noted that companies often do not see material and energy savings as cost savings, and cost is the key driving factor for industrial decisions.

Technical Perspective

There was a discussion regarding the effectiveness of technology transfer between MITI and industry. It was felt by some of the representatives that it was working well in the area of LCA (see notes from presentations by Inaba and Itsubo above). Development of environmental evaluation tools to support conceptual (early stage) design of products and materials is seen as the critical area for technological advancement. The two areas for which the most technical information and methodologies have been developed appear to be energy consumption and CO_2 emissions. This is in large part due to direct economic benefits and ease of measurement and accounting for these factors.

LCA Challenges

The consensus was that LCA is not currently being used as a viable, technical, decision-making tool but rather as a marketing tool or as propaganda (by both government and industry). There was strong agreement that the most difficult challenge in implementing LCA impact assessment will be integration of the scientific method with judgmental decisions. There was a significant amount of discussion surrounding what dimensionality of indices is appropriate (i.e., single vs. multiple) and who can and/or should make the value judgements.

National Leadership Challenges

The researchers felt that it was important for the Japanese government to continue its support of industry in meeting environmental goals. Some concern was expressed, however, that the level of government investment in this research area is diminishing. There was a feeling that international leadership would be required in order to help establish environmental priorities. Japan operates in a much more global environment than the United States and must respond to these types of leadership initiatives. There are also strong economic incentives to do so. Both within Japan and internationally, there is a tendency for industry to benchmark against neighbors (close competitors). This will facilitate the effectiveness of goals set by both national and international leaders.

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Site: **Nagoya University**
Department of Mechanical Engineering
Furo-cho, Chikusa-ku,
Nagoya, 464-8603
Japan

Date: October 22, 1999

WTEC Attendees: P. Sheng (report author), D. Bauer, B. Bras, T. Gutowski, C. Murphy, T. Piwonka, J. Sutherland, F. Thompson, D. Thurston, E. Wolff

Hosts: Katsumi Yamaguchi, Nagoya University
Tomio Matsubara, Nagoya Institute of Technology
Hideo Sekiguchi, Nara National College of Technology

BACKGROUND

Environmentally benign manufacturing research is a relatively new area of focus for Kansai area universities. However, some initial steps have been taken in terms of creating a network of interested researchers and possible research directions.

Organizationally, the International Committee on Manufacturing for the Japan Society for Technology of Plasticity (JSTP) has recently formed a working group focused on environmental issues. The Japan Society for Precision Engineering (JSPE) has formed a committee to study EBM applications in metal cutting. Finally, the International Committee on Environment and Manufacturing (ICEM) has had strong Japanese participation through its past and present directorship (Prof. Kimura of the University of Tokyo and Dr. Sano of MITI, respectively).

MICROFABRICATION RESEARCH AT NAGOYA UNIVERSITY

Prof. Yamaguchi has a main research focus in the area of microfabrication. The general linkage with environment is a reduction in energy and material consumption through miniaturization and elimination of chemical agents. In particular, three research projects were described:

- 3-D rapid prototyping through microjet metal deposition. Solder droplets are ejected through a piezo-electric nozzle to solidify on a target surface. By repeated scanning of the nozzle over the surface, a 3-D structure can be built up in layers. Prototype structures shown consisted of pyramidal structures built up from nickel (250 micron diameter drops formed at 1060ºF) and gold (75 micron diameter drops formed at 1400ºF). This leads to a reduction in environmental pollution by eliminating plating and etching.
- Microfabrication through UV laser photopolymerization. Scale down the stereolithography process to investigate forming micro-scale components through selective UV curing using conventional photopolymers. Sample structures showed dimensions of approximately 500 microns in dimension with feature sizes down to order of 10 microns.
- Grinding wheel design using embedded microfibers. SiC whiskers (1 micron diameter by 50 microns long) are embedded radially in an epoxy matrix to form a grinding wheel. Due to the identical whiskers, higher precision ground surfaces can be produced. Grinding is performed in a light load, high-speed condition. Currently testing the feasibility of diamond whiskers.

SEMI-DRY CUTTING RESEARCH AT THE NAGOYA INSTITUTE OF TECHNOLOGY

Prof. Matsubara has been conducting a project focusing on environmentally benign machining through semi-dry cutting. This is accomplished through a new nozzle design, which incorporates a mixing chamber and aerosol nozzle. Water enters the mixing chamber at three liters per minute, while vegetable oil is fed in at 3 ml per minute. Upon nozzle exit, water breaks up into droplets, which become nucleus sites for oil coating. Vegetable oil is used due to its bio-degradable disposal characteristics; however, it is used only once and disposed (e.g., no reuse of oil occurs).

This process has been successfully tested for turning, milling, and grinding operations, and results in lower machining temperatures (by approximately 30-40°C). Prof. Matsubara hypothesizes that there may also be advantages in terms of surface finish achievable, but this needs to be tested.

Site: **National Institute for Resources and Environment (NIRE)**
16-3, Onogawa, Tsukuba
Ibaraki, 305-8569
Japan
URL: http://www.nire.go.jp

Date Visited: October 18, 1999

WTEC Attendees: T. Gutowski (report author), D. Bauer, B. Bras, R. Horning, C. Murphy, T. Piwonka, P. Sheng, J. Sutherland, F. Thompson, D. Thurston, E. Wolff

Hosts: Mikio Kobayashi, Head, Rare Metals Division, Materials Processing Department
Yoichi Kodera, Senior Researcher, Hydrocarbon Research Division, Energy Resources Department
Keiji Handa, Head, International Cooperation Office

Other Attendees: Dr. Naotake Ooyama, Director-General, Mechanical Engineering Laboratory, AIST, MITI
Dr. Eng. Kohmei Halada, Team Leader (Ecomaterials Research Team), National Research Institute for Metals
Mr. Takayoshi Ohmi, International Research Cooperation Officer, Mechanical Engineering Laboratory, AIST, MITI
Prof. Dr. Toshio Sano, Director, Manufacturing Systems Department, Mechanical Engineering Lab., AIST, MITI
Dr. Mitsuro Hattori, Director, Machining Process Division, Manufacturing Systems Department, Mechanical Engineering Laboratory, AIST, MITI
Dr. Eng. Akira Sato, Director of Frontier Research Center for Structural Materials, National Research Institute of Metals, Science and Technology Agency

BACKGROUND

The panel visit started with an overview of operations at NIRE. NIRE is one of 15 institutes under the Agency of Industrial Science and Technology (AIST) which is under the Ministry of International Trade and Industry (MITI). NIRE is composed of nine departments:

- Global Warming Control Dept.
- Thermal Energy and Combustion Engineering Dept.
- Atmospheric Environmental Protection Dept.
- Hydrospheric Environmental Protection Dept.
- Environmental Assessment Dept.
- Energy Resources Dept.
- Materials Processing Dept.
- Geotechnology Dept.
- Safety Engineering Dept.

In 1999 they had 226 researchers, with an annual budget (including salaries) of ¥5 billion. There is no cash flow with industry, but in some cases equipment and space are provided by industry. Panelists received overviews of research projects in two areas: soft metallurgy and plastics recycling.

EBM ACTIVITIES

Soft metallurgy was described as the environment friendly processing of metals, often at lower temperatures or on site. Under this category several projects were described for the recovery of rare metals from processing. For example, a low temperature process for the extraction of Cu from $CuFeS_2$ was presented. The current technique is energy intensive, using a flash furnace, and releases SO_x. The proposed chlorination process, though quite complex, operates at 400ºC, which reduces energy, produces elemental sulfur and no slag. Details on energy saved or pollutants reduced were not given. The second soft metallurgy project was focused on the recovery of zinc from electric arc furnace gases by filtering and then condensation on ceramic powders. The method has advantages because it is simple, reduces energy and can recover Zn on site. A third project, which was briefly described, focused on the recovery of nickel and copper from surface plating by using solvent extractants.

The second major area, which was discussed at NIRE, was the recycling of plastics. The panel saw a project on the recovery of phenol, from both phenolic and epoxy resins by liquid phase decomposition. This research is based on the use of a hydrogen donating solvent such as tetralin and moderate temperatures (400ºC) to recover phenols from thermoset plastics. This route allows recovery of phenols at an efficiency of about 60 to 80% by weight directly from factory waste. This compares very favorably with current recovery scenarios based on pyrolysis and super critical water which can only give efficiencies of about 20% due to the recombination of radicals. Currently there is a small prototype facility built for this project that is being evaluated. Interest in this work has led to a joint research project with Sumitomo Bakelite, Hitachi Chemical and JVC to start next year. Work continues to look for a tetralin substitute. A photo of Dr. Yoichi Kodera in front of his liquid phase decomposition laboratory set-up is shown below (Figure D.1).

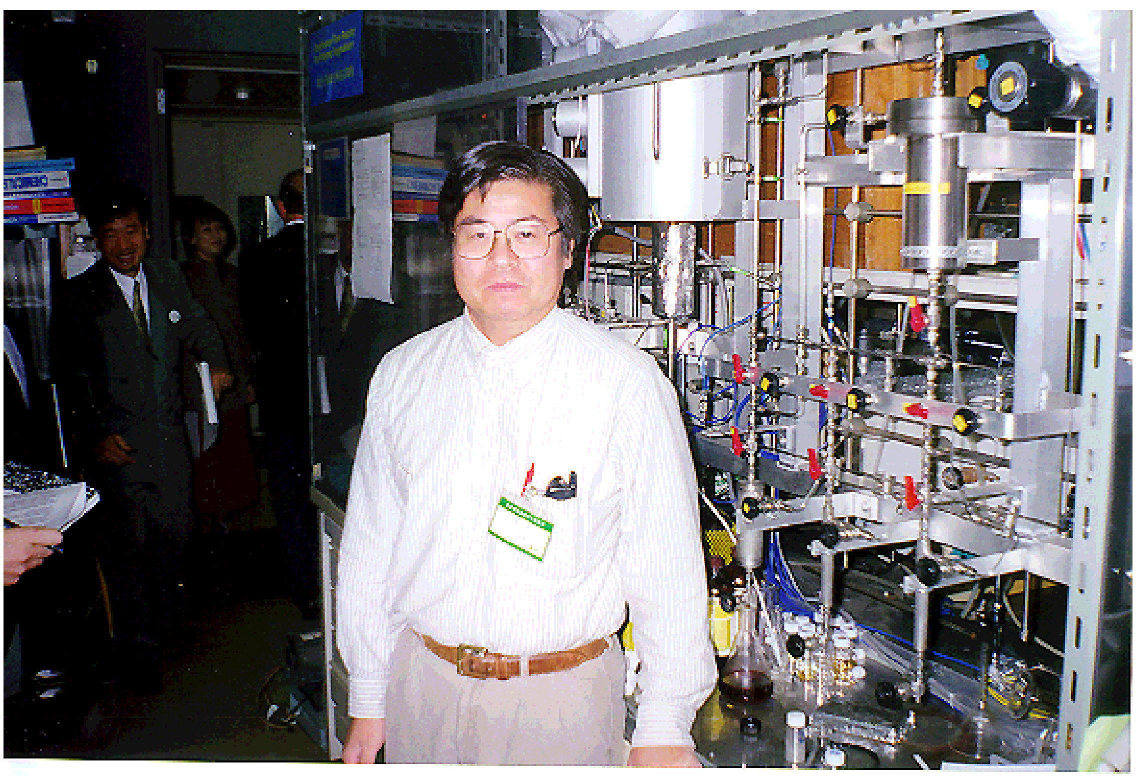

Fig. D.1. Dr. Yoichi Kodera in front of his liquid phase decomposition laboratory set-up.

Site: **NEC Corporation**
Resources and Environment Protection Research Laboratories
1-1, Miyazaki 4-Chome, Miyamae-ku
Kawasaki, Kanagawa, 216-8555
Japan

Date: October 19, 1999

WTEC attendees: B. Bras (report author), H. Morishita, D. Thurston, E. Wolff

Hosts: Mr. Sjunji Kishida, General Manager, Resources & Environment Protection Research Laboratories
Mr. Koichi Sohara, Senior Manager, Overseas Support, Environmental Management Division

INTRODUCTION

Mr. Kishida has been in the environmental area for the past three years. Mr. Sohara regularly visits NEC subsidiaries overseas, including those in the U.S.

EBM ACTIVITIES

NEC started to work on environmental issues over 25 years ago, and the laboratory will have its 26th anniversary this year. The environmental work started on pollution in waste water. Since then, the focus has changed many times. (A good overview of the history of NEC's environmental activities is presented in NEC 1999a, where there is also a good overview of key events in Japanese environmental activities.)

Both Mr. Kishida and Mr. Sohara see U.S. companies as not having good environmental attitudes. They see Europe as the leader, Japan as second, and the U.S. last in the environmental arena. However, a recent European investigation sees Japanese companies becoming first in the area.

Environmental activities are mainly handled at NEC Headquarters. Environmental auditing started in 1973 (NEC 1999a). In 1991, NEC's environmental charter was enacted. The charter can be found in (NEC 1999a, p. 49).

Motivation and Financial Issues

Mr. Kishida stated that the original motivation came from NEC's president Koji Kobayashi who decided that this was an area that NEC should pay attention to.

More recently, Mr. Kishida noted, there has been a significant interest in the EcoFund. This is a mutual fund with companies who are considered to be leaders in the environmental field. This fund has become more popular recently, and in the last 2-3 years, the stock of EcoFund companies has outperformed others.

Another driver is the green purchasing network and power. Mr. Kishida cited a case in which Ericsson recently cancelled a large order from a large American PC company due to environmental issues. According the Mr. Kishida, this is a well-known example in the computer industry and made quite an impact.

The financial advantage of NEC's environmental activities is not clear. This year, NEC has adopted environmental accounting and will keep track of financial savings. Many of NEC's environmental activities were self-motivated and seen as a social responsibility. It was explained that the Japanese top management considers reputation to be very important.

Mr. Kishida believes that, in the near future, financial benefits will come from the stock market. Return on investment calculations (called environmental accounting, see NEC 1999a, p. 36) have just started.

Currently, these efforts are focused on waste management targets (NEC 1999a, p. 8). Phase I started in 1985, now NEC is in Phase III of waste management.

Targets

Targets are set in the Corporate Environmental Plan. The main issue for each division is to develop environmentally conscious products. Negotiations with designers and engineers occur as well about the targets. Feasibility is discussed first. Targeting occurs after many discussions, and reasonable targets will emerge.

The targets listed in (NEC 1999a, p. 8) are for the domestic (Japanese) market. For oversea subsidiaries “rougher” guidelines are set based on cultural differences.

There is an environmental organization in each division and a general R&D group. All meet twice a year to discuss current issues. Many needs are identified during the discussions.

New Technology

Very safe flame-retardant plastics with both halogen and phosphorus free have been developed as follows:

- NuCycle plastic, supplied by Sumitomo DOW. This is a recylcable housing poly-carbonate material with silicone-based flame retardant (see NEC 1999a, p. 15).
- New IC molding resin without any harmful flame retardant, to be supplied by Sumitomo Bakelite (NEC 1999a, p. 20).
- Improved printed circuit boards (PCBs) are the next targets.

Many themes are currently under development. Prioritization is based on how long certain needs have existed.

Life-Cycle Assessment

NEC has also developed its own LCA software that satisfies ISO 14040. A key motivator for in-house software tool development (rather than using other commercially available tools) is the problem of translating software into the Japanese language. However, now NEC is faced with the challenge of translating their software for English speaking countries and subsidiaries, according to Mr. Sohara. Openness of tools is also a big issue, and a stumbling block in using currently available tools. NEC has incorporated the use of distributed access over the internet in its LCA software and database.

Examples were shown of new computer improvements that have been made in terms of energy, CO_2, etc. reductions. Another example shown is an LCA for a internet provider type information system (central server, hub, clients, etc.) with data for one year. Recently the focus is on corporate LCA, i.e., assessing the environmental load of the entire corporation, rather than specific products.

It was shown that NEC contributes 0.45 million tons of carbon annually, equaling 0.1% of the total Japanese emissions. NEC’s sales are 1% of Japan’s GDP. Supplier emissions are estimated at 0.94 million tons carbon (0.3% of Japanese emissions). User emissions are estimated at 0.3 million tons carbon (equal to 0.07% of Japan’s emissions). The supplier number includes mining, material, and component manufacture. NEC makes some in-house components like semiconductors. Many other parts are bought and assembled, so the environmental impact of NEC itself is relatively low from a manufacturing perspective.

An efficiency index calculation was shown. The efficiency index is calculated as net sales divided by the resource and energy consumption throughout the life cycle. A sample calculation was shown, indicating that NEC’s efficiency index is 3,737,000 million yen (domestic)—which, when divided by (0.94 + 0.45 + 0.30) million tons of carbon, results in an efficiency of about 2200 yen per kilogram carbon.

Software has also been developed for assessing human toxicity potential. The idea came from Europe. The NEC software will be commercially available soon.

Product Design

Key product concepts that are being pursued are:

- Modifiability (longer usage)
- Simplicity (greater recyclability)
- Use-flexibility (attractiveness for usage)

The "Eco-PC" was shown as an example. It is based on a modular concept, and each component has a single function. It is currently a laboratory prototype only.

The "SHARE" concept combines a computer and audiovisual entertainment system in 12 functional units (down from 32 separate and overlapping units and components). Each unit can be combined with other units to form whatever system is needed (e.g., a PC, TV system). For example, the monitor can also serve as a TV monitor and the speakers also connect to the computer.

Collaboration

Some collaboration exists with domestic universities regarding eco-design and new business styles (as in inverse manufacturing, e.g., with Prof. Kimura, University of Tokyo). NEC believes that reuse and a looping business economy will reduce the environmental load significantly.

Not much cooperation exists with other companies. There are no trade organizations for exchange of information. However, Mr. Kishida is personally interested in creating a network.

IN CLOSING

Mr. Kishida seeks to focus more on the corporate level impact and believes that economic gain and environmental excellence can go hand in hand. He wants to help NEC achieve this.

NEC activities in EBM from a production point of view are listed in (NEC 1999a, p. 5). Relevant evaluation is done by Mr. Kishida's group. Mr. Kishida feels that the goals are not satisfactory yet.

Both Mr. Kishida and Mr. Sohara voiced strong concerns about the lack of environmental activities and the amount of resource usage of the United States.

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NEC. Nd. "Research and Development," NEC, NSN 1079 Ver.3.

Site:	**Nippon Steel Corporation (NSC)** **Nippon Steel Building** **2-6-3 Otemachi, Chiyoda-ku** **Tokyo, 100-8071** **Japan**
Date:	October 20, 1999
WTEC Attendees:	D. Bauer (report author), T. Piwonka, J. Sutherland, F. Thompson
Hosts:	Nobuhiko Takamatsu, Senior Manager, Technical Administration & Planning Teruo Okazaki, Senior Manager, Global Environmental Affairs

BACKGROUND

Nippon Steel produces about 25% of Japan's steel, and Japan produces about 13% of global steel production (second after China). The steel industry accounts for 11% of total energy consumption in Japan. Seventy-eight percent of the energy consumed is coal. The use of petroleum in steel production decreased during the oil crisis of the early 1970s.

EBM ACTIVITIES

The (1967) Basic Law for Environmental Pollution Control and the 14 Environmental Laws of 1970 (Air Pollution, Water Pollution, etc.) resulted in increased industry investment in environmental measures in the early to mid 1970s. Most of the focus for this investment was in improved equipment energy efficiencies and end-of-pipe mitigative technologies.

Motivation for Environmental Activities

Municipal Air Emission Regulation/ Public Accountability

Since the 1970s, municipalities have developed agreements with local manufacturers, such as NSC, to reduce emissions to an agreed-upon level, commonly for NOx and SOx (also COD, benzene, PM, CO_2). Both the government and Nippon Steel monitor emissions for these municipal agreements. Attaining these values may be more costly for NSC, so there may be some incentive to shift production to areas where requirements are less stringent. The tradeoff is somewhat complicated, however, as highly regulated areas are likely to be urban centers, and thus, lower attainment costs in outlying areas may be offset by higher transportation costs for finished materials.

Whether or not there is a municipal agreement, companies still must publicly report their NOx, SOx, COD, benzene, PM, and CO_2 emissions.

COP 3/ Keidanren Voluntary Action Plan

The three elements of the "Kyoto mechanism," COP 3, are emissions reduction, technology transfer, and technology development. In response to the Kyoto Agreement, industrial sectors in Japan came to their own agreement in 1997, called the Keidanren Voluntary Action Plan. The steel industry's program (as led by the Iron and Steel Federation – JISF) under the plan has the following key points:

- Energy-saving efforts in steel-making
- Effective utilization of waste plastics
- Distribution of unused energy to surrounding areas
- Contribution to energy-saving society, with steel products and by-products
- Contribution to energy savings through technical assistance

Avoiding CO_2 was said to be the most important environmental problem in steel production.

Uses for Process Waste

Blast furnace slag is mainly used for cement and roadbed materials. Steel-making slag and dust sludge are used for other construction applications.

Technical Innovations and Challenges

Coal is especially important—beyond its use as an energy source—for its use as a reducing agent for ferrous oxide. If carbon (such as found in coal) is used as a reducing agent, this means that there will always be significant CO_2 emissions. Increasing the use of hydrogen as a reducing agent is a possibility—but it is expensive. One means for doing this, partially inspired by the coming April 2000 recycling law, is to use plastic (C+H). This is a process that is in development. There are a few challenges, such as removing chlorine and other potentially toxic emissions from the process, either through pre-process plastic sorting or through end-of-pipe means. Also, developing the logistics for sorting, collecting, and transporting post-consumer plastic to steel plants is quite challenging; the aim is to use an ambitious 11% of total Japanese plastic waste.

The Japanese auto industry uses relatively high quantities of steel (similar cars are lighter, but the percentage of steel is higher). Pressures toward further reducing auto weight/ increasing fuel efficiency may mean lower quantities of higher quality steel in cars, which in turn will mean less business for NSC, but other applications for steel (such as pipes) are being exploited. Current technical challenges in the development of automotive steel with a better performance-to-weight ratio include weldability and formability.

There has been a tradition of energy recovery efforts in the steel industry. Current recovery efforts involve the more challenging lower temperature (150-200°C) heat sources.

Collaboration with Customers and Other Researchers

A new trend is for customers to request a steel formulation with a certain type of environmental performance, such as no chrome plating. NSC works with customers on such requests.

Large companies, such as NSC, currently complete research projects, mainly on their own, but NSC aspires to change this. They are trying to develop better relationships with NRIM and with universities.

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Asamura, T. 1997. Eco-processes, eco-materials, and eco-systems in the steel-making industry. *Ecomaterials Forum.*

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Environmental control measures in Nippon Steel Corporation (1 page diagram).

Site: **New Earth Conference and Exhibition, Osaka, Japan**

Date: October 22, 1999

WTEC Attendees E. Wolff (report author), B. Bras

OBSERVATIONS

It became obvious that most companies visited by the panel had been actively engaged in environmental activities for a number of years. The principal driver for such actions had been the high cost of waste disposal and, in more recent years, the severity of air and water pollution.

Already known for their efficient manufacturing processes, Japanese companies have adopted policies calling for stringent conservation in materials and energy utilization. The environmental policies of Fuji Xerox, NEC, Hitachi, etc., have turned compliance with and adherence to ISO 14000 into operational requirements. Greater effort is required through annual improvement targets in each of these companies, with the ultimate goal of zero waste.

Additionally, such manufacturers as Nippon Steel, Hitachi Heavy Equipment, and Kubota Tractor have entered into new markets in environmental remediation. This was well demonstrated during the Osaka New Earth Conference and Exhibition, which acted as a showcase to the world. Here, full-scale demonstrations revealed the extensive engineering and development activities that resulted in:

- next generation high-temperature incinerators for municipal and industrial waste (by Nippon Steel)
- closed-loop residential and industrial waste and water treatment (by Kubota Tractor)
- mobile construction material separation equipment that processes and segregates all building materials during demolition and building rehabilitation phase (by Hitachi)

Hitachi also offers a product that reclaims contaminated soil at a rate of 80 m^3 per hour directly on location. The Takuma Company demonstrated a unique circulating fluidized bed boiler for waste and solid fuel combustion. Energy is provided through a steam-turbine-driven generator and distributed to local utilities.

More than 400 exhibitors presented commercial products that included new energy efficient household appliances, nighttime energy storage devices for residential and commercial air conditioning, and low pollution automotive products.

Significant waste reduction has occurred through the reuse of coal ash and waste treatment in building materials (cement and concrete additives, ceramic tiles), and through recycling plastic materials into furniture and as a fuel for incinerators.

The energy providing sector had several entries and has seen a 40% reduction in CO_2 emissions due to a variety of efforts, including liquefied natural gas, atomic power plants, geothermal, voltaic and wind power.

Clearly, the Japanese industrial base is turning its geographical disadvantages into new opportunities. By creating advanced remediation technology, their industries will become leaders in global markets as developing and developed countries strive to manufacture products with minimal impact on the environment.

Site: **National Institute of Materials and Chemical Research (NIMC)**
Agency of Industrial Science and Technology, MITI
1-1 Higashi, Tsukuba
Ibaraki, 305-8565
Japan

Date: October 19, 1999

WTEC Attendees: J. Sutherland (report author), D. Bauer, T. Gutowski, R. Horning, C. Murphy, T. Piwonka, P. Sheng

Host: Dr. Masagi Mizuno, International Research Liaison Office

INTRODUCTION

After a brief institute overview by Dr. Mizuno (400 staff) the visitors were escorted to three laboratories:

EBM ACTIVITIES

Biodegradable Polymers (Dr. Kazuo Nakayama)

Several types of biodegradable polymers are being examined, e.g., aliphatic polyesters, PBS (poly butylene succinate), PLLA (poly L-lactic acid), PCL (poly hexano-6-lactone). As is, these polymers are somewhat property-limited. To counter this effect, the researchers are examining property improvement through process optimization and the effects of the addition of carbon fibers for reinforcement. It is envisioned that the biodegradable polymers will be broken down by hydrolysis.

Environmentally Compatible Catalysts (Dr. Yuji Yoshimura)

Dr. Yoshimura spoke on the catalyst work underway at the institute. This includes efforts directed at the cracking of Naptha to produce lower olefins, reducing the energy by a factor of four via a simpler process, and producing ethylene and propylene. They are looking at zeolite modified with a layer of metal oxides for this process. Catalysts are also being applied for the production of cleaner diesel fuels, e.g., less aromatics and sulphur, to reduce NOx, CO, HC, and PM. They are also looking at noble metal catalysts, and are trying to make them more sulphur tolerant. Recent values obtained using their approach are below 10% for aromatics and 50 ppm for sulphur (the current sulphur standard in Japan is 500 ppm).

Near IR Spectroscopy for Plastics Sorting (Dr. Kazutoshi Tanabe)

The above-referenced technique is being used in an effort to identify a wide range of plastics. A number of samples have been used as trials for the development of a neural net identification scheme. The hardware/software setup is believed to be capable of identifying a large number of plastic types. As expected, darkly colored plastic samples present a problem for the scheme. Upon questioning from the visitors, Dr. Tanabe revealed that at present only PET is recycled in Japan, but that by April 2000 all plastics are to be recycled. At the time of the visit 40% of plastics are landfilled, 50% burned (viewed as recycling), and 10% recycled as material. Dr. Tanabe speculated that the landfilled plastics would need to be burned after April 2000, lacking any other solution. Efforts are underway to try to identify additives within plastics using the near IR spectroscopy technique as well.

Site: **National Research Institute for Metals (NRIM)**
Science and Technology Agency
1-2-1 Sengen, Tsukuba
Ibaraki, 305-0047
Japan

Date: October 19, 1999

WTEC Attendees: J. Sutherland (report author), D. Bauer, T. Gutowski, R. Horning, C. Murphy, T. Piwonka, P. Sheng

Hosts: Dr. Kohmei Halada, NRIM
Dr. Koichi Yagi, NRIM
Dr. Akira Sato, NRIM
Dr. Halada, Team Leader, EcoMaterials Research Team
Dr. Yagi, Supervising Researcher, 2nd Research Group (Advanced Nuclear Materials Group)
Dr. Sato, Director, Frontier Research Center for Structural Materials

DISCUSSION

Dr. Sato gave an overview of the institute. The institute is divided into research groups and centers. The institute has about 400 employees (300 researchers) and a total budget of approximately $120 million. He then spoke on the Frontier Research Center for Structural Materials that was established almost three years ago. Researchers from Nippon Steel and Mitsubishi Heavy Industries are collaborating with center personnel. The center's mission is "to decrease the environmental load and the total life cost of structural material by doubling the strength and life of steels." Four specific project initiatives are being undertaken:

- Development of 800 MPa High Strength Steel
  - This initiative is directed at identifying thermomechanical processing conditions that can be used to double the strength of standard 400 MPa steel. Lightly alloyed steel is the base material of choice because of the advantages it offers over more exotically alloyed steels in terms of weldability and recyclability. The goal of the thermomechanical processes is to produce ultra-fine grain sizes of one micrometer. Innovation is also being sought in terms of joining processes that are fast and require a minimum amount of heat—to avoid welding defects, minimize residual stresses, and provide high quality joints.
- Development of 1500 MPa Ultra-High Strength Steel
  - There is a need for steel with a strength in excess of 1500 MPa for application as bolts in the construction industry, lighter automobile parts, and cables in suspension bridges. The issue is not so much the strength but delaying fracture and achieving giga-cycle fatigue. To develop the steel, the center is examining martensitic steels that contain carbon-free boundaries and hydrogen trap sites. Martensitic steels with a large amount of nitrogen are also being studied.
- Development of Advanced Ferritic Steels for Boilers Utilizing Ultra-Supercritical Steam
  - The emphasis of this effort is on developing an advanced heat-resistant steel. High Cr ferritic steels are being studied with attention focused on long-term exposure to high temperatures because of coarsening of precipitates and dislocation recovery. Research is focused on stabilizing the tempered martensitic microstructure.
- Development of Steels Resistant to Marine Corrosion
  - This initiative is directed at developing steels that are resistant to weathering and corrosion in marine and offshore environments. Nanoscopic level studies seek to characterize and remove nonmetallic inclusions, because such inclusions trigger rust initiation in low-alloy steels and various forms of localized corrosion in stainless steels. New refining strategies such as cold-crucible techniques and electro-slag refining will be examined for these pure steels.

LAB TOURS

In one lab, researcher Nagai described the experimental apparatus used for thermomechanical processing. The machine is capable of heating the specimen and applying a bi-axial load and has achieved some success. The research team is working towards applying their technique to plate processing and scaling up their lab setup to a pilot plant.

In a second laboratory, a new arc welding process setup was described. Basically, the process seeks to reduce the area of the heat-affected zone. The process utilizes a narrow gap of approximately 5 mm and the location of the arc is oscillated up and down by varying the current.

Site: **Polyvinyl Chloride Industrial Association**
IINO Bldg., 2-1-1 Uchisaiwai-cho, Chiyoda-ku
Tokyo, 100-0011
Japan

Date: October 20, 1999

WTEC Attendees: T. Gutowski (report author), C. Murphy, P. Sheng

Hosts: Mr. Shinsuke Sasaki, General Manager, Quality Control, Taiyo Vinyl Corporation
Dr. Tetsuya Makino, Director, Environmental Services, Mitsubishi Chemical MKV Company
Mr. Hiromi Nii, General Manager, Environmental Div., Vinyl Chloride Dept., Mitsubishi Chemical Corporation
Mr. Takayuki Endo, Tokuyama
Mr. Shuichi Sasaki, Executive Director, Vinyl Environmental Council

OBSERVATION AND DISCUSSION

The Polyvinyl Chloride Industrial Association includes two groups concerned with environmental issues: the Vinyl Environmental Council (VEC), made up of PVC manufacturers—12 companies, both monomer and polymer manufacturers—and the Japanese PVC Environmental Affairs Council (JPEC), made up of PVC processors (including convertors or manufacturers of film, pipe, fittings, wire, cable, and flooring, etc.). VEC is working with ECVM (European Council of Vinyl Manufacturers) and U.S. organizations to exchange information and ideas. We met with representatives and members from both groups who reviewed progress in PVC recycling, and highlighted the durability of PVC to environmental effects. PVC was touted as a good candidate for recycling because of its durability, ability to be recycled repeatedly, multiple applications, and industry standards. For example, we were shown data for side molding on an automobile door after 13 years which was shown to have good properties retention in almost all categories. Our guests pointed out that this was flexible PVC and that rigid PVC might have similar results after 50 years. PVC has been shown to be recyclable as many as five times with acceptable properties. Recycled materials tend to be used in lower grade products such as floor tiles and slip-on shoes.

Panelists then received an overview of recycling scenarios for PVC. These included: (1) grinding and reprocessing of similar grades for use in various applications, including pipe, agricultural films, and window sashes; (2) reduction of PVC to feed stock monomer; (3) use of PVC as a reducing agent for a blast furnace (there is a project with NKK to produce 5,000 tons per year to be finished February 2000, and there are continuing experiments to expand the target to 8,000 tons per year to treat many kinds of applications); (4) the use of PVC in cement (with a pilot plant to produce 500 tons per year, completed this year); and (5) a gasification process for retrieving CO_2, H_2 and HCl as chemical raw materials, currently in the study stage, using no pre-dehydrochlorination and returning the PVC to its monomer state.

Two interesting PVC recycling projects were discussed in some detail. One was the recycling of PVC pipe back into pipe. Thirty-five percent of all pipe was recycled in 1997 and the goal is to have 70% recycled in 2000. By August, 1999, there were 12 recycling centers established throughout Japan with financial cooperation from VEC. Early in 2001, the number will be expanded to 18, with 50 or more intermediate collection centers being built per prefecture. The biggest challenges will be the expansion of recovery routes and development of new applications. JPEC has established a separate specification for recycled pipes to account for the diminished physical properties of recycled PVC (i.e., reduction in molecular weight, which reduces the strength). The application is limited to non-pressurized drain pipes. However, the specs are more than adequate for this application. There are four companies making pipe using recycled PVC, with one of the keys to success being the use of a good extruder.

Recycled pipe currently costs more than virgin pipe. This cost increase is offset by a subsidy from the Ministry of Construction (which is administered by municipal governments) and by a mandatory “clean-up fee" for property owners at construction sites. The clean-up includes sortation and recycling of all construction waste for both demolition and new construction. This recovery operation must be performed by a licensed individual trained to properly identify and sort materials.

The second interesting application we saw was a window sash for double pane windows. The sash consists of recycled PVC sandwiched between virgin PVC and PMMA. The virgin PVC provides an attractive white surface that shows on the interior of the house, and the PMMA is colored to match the exterior trim. The 70% of the resulting product that is composed of recycled PVC is hidden by these outer coatings. The success of this project required an innovative 3-materials extrusion process, based upon a 2-materials co-extrusion process developed by the Germans. The 3-materials extrusion process developed by the Japanese is being patented by Tokuyama, with plans to license the technology to other sash producers. This application enjoys the benefits of both having the recycled PVC material cost subsidized by the government and providing reduced energy loss from buildings. Hence the PVC sash is quickly replacing the more common aluminum sash, which is currently used in 90% of all windows in Japan.

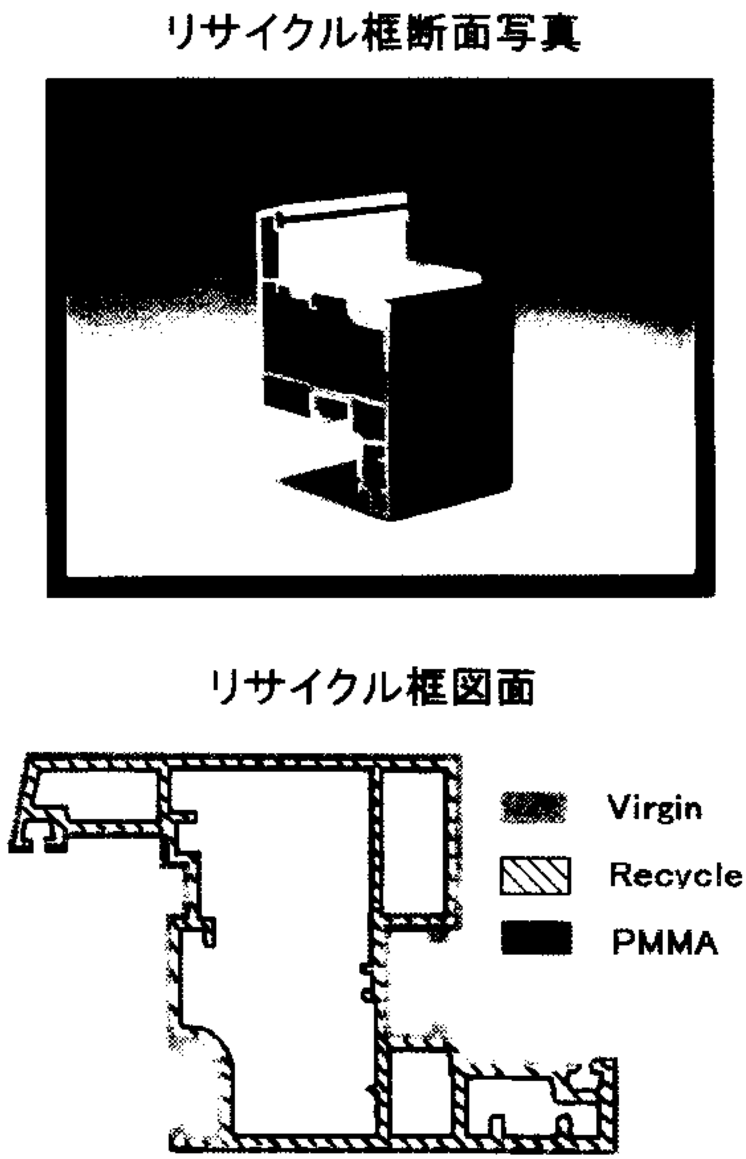

Fig. D.2. PVC sash consisting of recycled PVC sandwiched between virgin PVC and PMMA.

Site: **Sony Corporation**
Core Technology & Network Company
Gate City Osaki West Tower
1-11-1 Osaki Shinagawa-ku
Tokyo, 141-0032
Japan
URL: http://www.world.sony.com

Date: October 20, 1999

WTEC Attendees: C. Murphy (report author), T. Gutowski, R. Horning, P. Sheng

Host: Dr. Hideaki Karamon, Manager, Environmental Promotion Dept.

BACKGROUND

Sony is a global and diverse company with just under $70 billion in annual sales, for the year preceding March 31, 1999. Their operations consist of Group Headquarters, Digital Network Solutions, Home Network (TV and video), Personal IT (phones and PCs), Sony Computer Entertainment (play stations), Broadcasting and Professional Systems (studio cameras, etc.), Entertainment (movies, recordings), Insurance and Finance Business, and Core Technology and Network Co. This last unit, Core Technology and Network Co., includes energy, recording, magnetic, optical, ICs, manufacturing systems business, PWBs (Neagari), electronic devices, LSI R&D, and core tech R&D). At the time of the panel's visit, the company was undergoing a major reorganization.

Sony has a strong interest in environmentally benign manufacturing and products, as evidenced by their 48-page environmental report. In August, they had worldwide ISO 14000 certification with distributions as follows:

	Manufacturing			**Non-manufacturing**		
Location	ISO 14000 Certified Sites	Total Sites	Percent	ISO 14000 Certified Sites	Total Sites	Percent
Europe	12	12	100%	7	9	77.8%
U.S.	24	28	85.7%	0	19	0%
Japan	38	38	100%	8	42	19.0%
China	4	5	80%	0	1	0%
Asia, other	19	23	82.6%	7	17	41.2%
Total	97	106	91.5%	22	88	25%

PROBLEM IDENTIFICATION

Sony is currently responding to environmental concerns and regulations in Europe where they must compete for market share. One of the key areas that must be addressed is the European Union Directive on Waste from Electrical and Electronic Equipment (WEEE). At the time of the panel's meeting with Sony, Article 4 of the third draft of this directive stated that, "member states shall ensure that the use of lead, mercury, cadmium, hexavalent chromium, and halogenated flame retardants (PBDE, PBB) be phased out by January 1, 2004." Germany has also imposed a dioxin ordinance as of July 16, 1999. In addition, there is significant public awareness of these issues through Eco-labeling (TCO 99, Blue Angel) and product test magazines (*Consmentengids* and *Stiftung Warrentest*—similar to *Consumer Reports*), that identify and downgrade products that contain materials of concern. Recent technical publications report potential health hazards associated with flame retardants (Noren 1998; Sjodin 1999). Many of the major European companies (especially the Nordic ones) have self-imposed controls to eliminate PBDE/PBB and TBBA. The concern with PBDE is its potential to be converted to dioxin upon incineration (a primary form of waste management in Europe). While TBBA is more stable (less likely to form dioxin), there are still general health concerns with brominated products. In order of priority, Sony is focused on the elimination of halogenated flame retardants (used in plastics and printed wiring boards), lead (solder), and mercury (batteries). Dr. Karamon believes that elimination of lead will be the most technically challenging of the three.

CURRENT ACTIVITIES

Most of Sony's efforts are currently concentrated in the area of elimination of halogenated flame retardants. For televisions, this includes both the plastic housings and printed wiring boards. Options being considered include halogen-free phosphate esters and nitrite flame deterrents. Halogen-free boards are currently being massed produced, or are soon to be mass produced, and include double-sided CEM3, double-sided FR4, 4-layer epoxy-glass plated-through-hole (PTH), and 8-layer blind-via (BVH) boards. Due to low material volumes (for the alternative flame-retardant systems), Sony has had to absorb a 10% cost increase in an extremely cost-driven market. This is not as big a problem for single-sided boards (TVs) and double-sided boards (VCRs) as it is for multi-layer boards, where material costs are high and volumes are especially low.

Siemens is currently working on similar problems. Their goals include the manufacture of all components using Pb-free pins and solder joints, halogen-free plastic packages, and 100% recyclable materials. In addition, they are selecting low-energy manufacturing processes, and are designing components for low-power dissipation during use. However, they were recently forced to recall a number of parts due to thermal fatigue associated with Pb-free solder. Sony is very interested in cooperating with other companies on these issues, as there may prove to be significant technical challenges.

NEEDS AND CONCERNS

Dr. Karamon believes that cost, not environmental quality, is the overwhelming purchase discriminator for the Japanese consumer. In contrast, the European market appears to be relatively cost-insensitive. However, since it is not practical to have two separate product lines, Sony must find technologies that are both cost-competitive and environmentally sensitive.

A second issue is product take-back in both Europe and Japan. Sony has not yet determined how recycling might occur. Thermoplastics would probably be re-ground (rather than incinerated) and used in applications with broader mechanical specifications. One of the biggest concerns is collection at end-of-life. TVs are expected to be very expensive ($30 to $40 per set) and the cost may have to be passed along to the consumer. However, this would affect all manufacturers, not just Sony.

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Sony Corp. 1999. *1999 Environmental Report*. The environmental report, which provides a great deal of additional information and data regarding Sony's efforts in the area of environmentally benign manufacturing, is available on line at: http://www.world.sony.com/CorporateInfo/EnvironmentalReport/index.html. Objectives covered in the report include increased recycling of industrial waste, decrease in all releases to water, air, and soil, decreased energy consumption, resource conservation, "green" purchasing, decreased disassembly time, energy-efficient products, and a higher product recycling ratio.

Sony Neagari Corp. Catalog of products (the PWB Division).

Site: **Toyo Seikan Kaisha (Saitama Plant)**
950-2, Hosoya
Yoshimi-cho, Hiki-gun
Saitama, 355-0193
Japan

Date: October 19, 1999

WTEC Attendees: P. Sheng (report author), D. Bauer, B. Bras, T. Gutowski, C. Murphy, T. Piwonka, J. Sutherland, F. Thompson, D. Thurston, E. Wolff

Hosts: Dr. Yoshio Oki, General Manager, Technology Assessment Office, Deputy Director
Mr. Makoto Horiguchi, Manager, Office of Environmental Affairs
Mr. Masa Morotomi, Manager, Strategy and Planning, Corporate R&D
Mr. Susumu Saito, Engineering Manager, Saitama Plant

TULC PROCESS FOR STEEL CANS

Can Industry in Japan

The demand for beverage and food cans in Japan is robust, with a 1999 market size of roughly 37.8 billion cans. Unlike the United States, where aluminum is the material of choice in cans, the Japanese market is divided into 43% aluminum and 57% steel. Traditionally relegated to 3-piece cans, steel has made strong inroads in recent years to 2-piece cans mainly through the TULC process.

The main application area for cans in Japan is non-carbonated beverage containers, accounting for 57% of total can production. Beer containers account for another 19%; containers for alcoholic drinks, 11%; cans for carbonated beverages, 8%; food packaging accounts for the remaining 5%.

Motivating Factors

The primary motivating factors for TULC development are:

- Economic viability of steel cans versus aluminum dictated a need to improve upon the steel DWI process (weight savings, per unit cost, recyclability)
- Demonstration project for CO_2 reduction to comply with national target of 1% reduction per year in emissions

Description of the TULC Process

The Toyo Ultimate Lightweight Can (TULC) process is a combination of three innovations:

- Use of a TFS laminated with 20 micron thick polyester film on both sides
- A stretch draw and ironing process which creates thin side wall and bottom thickness without use of any lubricant or coolant, resulting in a can that is 4 grams lighter in weight (for a 350 ml can) compared with a steel DWI (draw and wall ironing) can. TULC bottom thickness is 0.18 mm, compared with a DWI can's bottom thickness of 0.225 mm.
- Development of a compact processing line which requires 50% less floor space and saves 48% in operating and maintenance costs compared with a steel DWI can line.

The TULC process was introduced in 1991. Since then, shipments have grown steadily to almost 6.6 billion cans in 1999.

A key element of the TULC process is supply of the laminated steel, which is produced by Toyo Kohan, a tinplate manufacturer and subsidiary of Toyo Seikan, from a Nippon steel stock material. The base cold rolled TFS strip is heated, then a clear PET film lamination is applied on the inside surface, while a white film is applied on the external surface.

Once the rolled steel is received at the forming line, the TULC-making process steps are as follows:

- Uncoil
- Cupping press
- Redraw press
- Heat-set oven
- Trimmer and light tester
- Printer and curing oven
- Necker, flanger and tester

Throughput rates are approximately 25 cans per second per line.

Environmental Advantages of TULC

TULC has shown environmental advantages over DWI processes in several areas:

- *Energy consumption.* TULC's energy consumption is much lower than DWI can. TULC consumes an average of 0.09 MJ/can, while steel DWI can consumes an average of 0.35 MJ/can in can making, with a life-cycle energy consumption estimated at 3.9 MJ/can compared with TULC's 2.79 MJ/can. Aluminum DWI can consumes less energy in can making (0.22 MJ/can), but has higher life-cycle energy consumption (6.0 MJ/can).
- *Wastewater generation from cleaning.* Use of forming lubricants necessitates a cleaning process and removal of an organic waste stream. A typical steel DWI can line consumes 9,163 m^3 of water per 50 million cans at rinsing process after ironing. This usage is eliminated from TULC process by dry forming.
- *Solid wastes with tin content.* Solid scrap accounts for approximately 12% of raw material mass due to pattern layout. The resulting scrap material in DWI can process, as well as quality rejects, has a significant tin component (0.3% for DWI cans, 0.15% for welded cans) which becomes a mixed solid waste and reduces recyclability. TULC improves the recyclability of the solid waste stream by introducing no tin into the solid waste stream. In general, Toyo Seikan estimates a reduction of industrial wastes for a production run of 50 million cans from 88,200 lbs for the DWI process to 265 lbs for the TULC process (waste solvent and lacquer).
- *Carbon dioxide from incineration of exhaust gas from the curing oven for lacquer coating (epoxy and acrylics).* DWI can process is estimated to generate 254 ton-C of carbon dioxide per 50 million cans, mainly through incineration of exhaust gas. By using PET as a laminate layer, which substitutes for organic coatings, carbon dioxide emission can be reduced to 79 ton-C in TULC process.

Can Performance

Can performance can be measured by two factors: flavor absorption and migration of organic substances. The PET co-polymer film shows a 10-fold decrease in absorption of limonene under 20-50°C temperature range compared with conventional can lacquer. Water-based lacquer coatings performed as well as PET film under room temperature, but performance degraded as temperature increased.

TULC cans also showed a 2 to 3-fold reduction in KMnO4 concentration in the beverage compared to DWI cans under hot pack (100°C for 30 minutes) and retort (125°C for 30 minutes) conditions.

TULC System Considerations

Due to the simplified steps involved in the TULC process, the line structure also shows some advantages. TULC lines generally require 50% less floor space compared with DWI can lines. There is also a 42% reduction in operating cost compared with steel DWI cans. Major operating cost savings areas include utilities (48% reduction in gas consumption, 38% reduction in electricity consumption), elimination of washer chemicals and water, and elimination of related industrial material handling. Maintenance costs are comparable to, if not slightly higher than, DWI can lines. Line investment is on the order of $50 million per line.

OTHER INNOVATIVE PROCESSES

Toyo Seikan has also developed two other innovative can making processes:

- *Aluminum TULC process.* Toyo Seikan has modified the TULC process for aluminum can making, with initially similar benefits over the aluminum DWI can process. Initial trials are still being conducted, so no quantitative data were given for aluminum TULC performance.
- *Diamond Cut process.* Toyo Seikan has been exploring techniques for improving the buckling strength of thin-walled cylinders as a weight reduction measure. One technique, called “Diamond Cut,” uses a rolling die to form a geometric pattern on the can side-wall to improve strength. This pattern is based on a pseudo-cylindrical concave polyhedral (PCCP) shell used in self-deploying space-based antenna structures, as well as inspired by Japanese *origami* patterns. Using “Diamond Cut,” a 30% weight reduction compared to conventional 3-piece cans can be achieved through reduction of side-wall thickness without loss of stacking rigidity.

Site: **Toyota Motor Corporation**
Toyota Kaikan Building
1 Toyota-Cho, Toyota-shi,
Aichi, 471-8572
Japan

Date: 22 October 1999

WTEC Attendees: T. Gutowski (report author), D. Bauer, H. Morishita, T. Piwonka, J. Sutherland, F. Thompson

Hosts: Mr. Yutaka Okayama, Project Mgr., Environment Affairs Div.
Mr. Tetsuo Iwai, Project General Mgr., Environment Affairs Div.
Mr. Kiyoko Otsuka, Project General Manager, Corporate Public Relations Div.
Dr. Hiroshi Igata, Assistant Manager, Technical Administration Div.,

DISCUSSION

It was clear from our visit that Toyota has a major commitment to improving the environment and reducing energy and materials consumption at its plants. Starting in 1998 its management has prepared comprehensive environmental reports for the company, which track expenditures, improvements, and outline a wide variety of environmentally conscious activities in which they are involved. For fiscal year 1998 Toyota estimates that it spent ¥97 billion on environmental related activities.

Some of these activities are implemented in the light of various regulations and agreements. For example, ISO 14001, the Kyoto Conference on global warming and the MITI recycling initiative for cars. It was also very clear that motivation to conserve energy and resources was already built into the system. The people at Toyota saw these ideas as a logical extension of "lean manufacturing." Furthermore, they conveyed to us the idea that the green approach was good for business. Toyota is a leader in developing clean burning engines and technology to meet regulations, and gave every indication that they plan to continue to lead in this area. For example in autumn of 2000 they will introduce their hybrid electric car for sale in the United States. This car, the PRIUS, is already on sale in Japan and some of the panelists had the opportunity to ride in it. Its performance in the city was quite satisfactory.

Some specific points that they discussed with panelists, or which were outlined in their booklet on environmental activities in the production area, are given below.

- Toyota has developed environmental purchasing guidelines for 450 suppliers. This includes encouraging suppliers to meet ISO 14001 by 2003, as well as asking suppliers for information on the materials contained in their products. Toyota mentioned that they have significant purchasing power in Japan and most suppliers comply with their wishes, but some suppliers sometimes resisted disclosing the nature of the materials in their products.
- Toyota has identified painting as one of the highest priorities for attention in the manufacturing operation. For example, in their 1999 environmental report they outlined techniques for reducing the waste of paint and the reduction of volatile organic compounds (VOC).
- Toyota has made continuous progress in the reduction and elimination of landfill waste. For example, their waste from production has decreased from 143,000 tons in 1990 to 47,000 tons 1998. But much of this reduction has gone to material recycling.
- Toyota is looking at reducing waste at the processing level, including elimination of wasteful operations and redesign of machine tools. For example, in their booklet they outline a machining process for dies, which originally included EDM. In the new process the part shape and dimensional tolerances are obtained directly by machining, eliminating several steps, including EDM. Toyota mentioned its attempts to consider environmental consequences at the equipment design stage, and their environmental report shows a new lathe designed by Kyoho Machine Works. This machine is smaller in size and better

matched to the task than its predecessor. This new press-in unit also switches from hydraulic power to electric power. This eliminates the need of continuously running hydraulic pumps.

- Toyota mentioned that they have set voluntary internal standards for waste and pollutants, and have identified over 2000 chemicals as substances to track and control.
- It was clear from discussions that Toyota hosts viewed the environmental movement in part as an extension of their "lean manufacturing," which has a strong emphasis on the reduction and elimination of waste. As an example in this area, hosts looked at energy requirements during production. In particular, it was pointed out how the energy consumption per unit tends to go up as production volumes go down. Hence they are redesigning equipment to consume less energy or to be able to be turned off when not in use.

TOUR OF THE TSUTSUMI PLANT

The Tsutsumi plant is an assembly plant, which can make eight different cars. It is the mother plant to the Georgetown, Kentucky, plant and supplies production engineering for the American plant. There are 5,600 employees assembling 2,000 kinds of parts from 140 suppliers. The plant produces about 1,400 cars per day over two shifts, during a five-day week. During the tour many standard and new features of the Toyota Production System were pointed out to panelists, including:

- instruction sheets, which help the workers assemble different kinds of cars on the same line
- "kanban" cards which allows timely delivery of parts for assembly
- "himo switch" which allows workers to stop the production line in the event of a problem
- "Andon" board which shows the line supervisor where the problem is so that it may receive immediate attention

In fact, during the tour the panel saw the production line stop at least three times. Panelists also saw a number of devices that made the workers' motions easier and less stressful. These include: a synchronized dolly which moved along with the car, carrying tools and parts; and a new seat which allowed the worker to sit down outside the car and then move into the car (called a Raku Raku seat). Also seen were plastic coverings on the front and rear fenders of the car to protect it from bangs and nicks.

In general, employees contribute ideas for production improvement at an incredible rate, averaging about 10 ideas per employee per year. Panelists were told that 97% of these ideas are implemented. Employees receive awards for the implemented ideas ranging from ¥500 to ¥300,000. Along one production line we saw floor conveyors which allowed workers to move along with the car. One additional item, which was mentioned to the panel just prior to the tour, was that Toyota is doing research into biological means for the reduction of CO_2 and has developed trees that can absorb CO_2 at approximately twice the rate of the typical tree. These trees will be planted in Australia at a plantation for producing lumber and for cleaning up the environment.

TOUR OF THE TSUTSUMI RECYCLING PLANT

The aim is to reduce the quantity of landfill waste from the Tsutsumi plant to zero by the end of October 1999. (Incinerated waste is also being reduced.) Tsutsumi plans on having no landfill material, and 1,300 tons of incinerated waste, in 1999; but 90% of incinerated wastes are thermally recycled (landfill waste was 568 tons and total waste was 7,032 tons in 1997). Materials previously landfilled numbered 28 different items. Activities are performed according to the philosophy, "When combined it's waste, but when sorted it's a resource." Employees are encouraged to come up with ideas for waste reduction and reuse. Some sample projects include:

- Door trim. After die cutting door trim, excess material is sorted into vinyl chloride and urethane resin. The vinyl chloride is recycled and the urethane resin is incinerated at high temperature.
- Vacuum cups. Vacuum cups are used to transport parts in the pressing process. Previously, they were landfilled at the end of their useful life. Now they are designed so that the materials can be separated, and the metal portion can be reused. (The rubber portion is incinerated.)

- Separating plant refuse. 190 tons of floor dust is generated per year, and 60% of this material is ferrous. The floor dust is separated in a multi-stage process. First, a rotary separator is used for rough sorting. Then, the smaller items are sorted in a 3-stage sieve-sorting machine. Next, further sorting occurs in a specific gravity sorting machine. Finally ferrous items are separated with a magnetic sorting machine. The ferrous material can then be recycled, and is used for construction applications.
- Use of phosphorous sludge. The bricks for the pavement of the parking lot and tiles for the outside walls of buildings are made (by an outside vendor) from phosphate sludge coming from cleaning prior to painting.

Site: **University of Tokyo**
Department of Precision Machinery Engineering
7-3-1 Hongo, Bunkyo-ku
Tokyo, 113
Japan

Date: October 20, 1999

WTEC attendees: D. Thurston (report author), D. Bauer, B. Bras, H. Morishita, T. Piwonka, J. Sutherland, F. Thompson, E. Wolff

Host: Professor Fumihiko Kimura

INTRODUCTION

Dr. Fred Thompson of the National Science Foundation first delivered an introductory talk describing WTEC and the panel's mission. Prof. Kimura then delivered a comprehensive and well-organized overview of his work in system modeling.

MAJOR PROJECTS

- Inverse Manufacturing Forum (sponsored by MITI)
- Alliance for Global Sustainability (MITI, ETH, UT)
- Intelligent Manufacturing Systems (intl. program with Europe, Japan, United States and Australia)
- Maintenance Engineering Chair

SYSTEMS MODELING OVERVIEW

"Virtual manufacturing" models products and manufacturing processes and their behavior. Simulation is employed. Simulation is a very powerful modeling tool, useful for problems for which a comprehensive mathematical optimization model either cannot be determined, or cannot be solved analytically. It is especially appropriate for problems where uncertainty regarding states and inputs can be modeled probabilistically. In manufacturing, the goal has traditionally been to predict and avoid error, or product defects.

An important EBM trend is the movement away from sale of physical products to sale of services. This trend has resulted in a need to shift research focus from manufacturing processes alone to the product life cycle, which includes customer use and product maintenance. The core technology is in systemization of life-cycle management of manufacturing knowledge, and prediction of product behavior through simulation.

The virtual manufacturing concept is thus extended to "design for the environment." The entire product life cycle should now be modeled, including maintenance engineering. "Information logistics" was cited as a key concept, which was defined as the "virtualization of products and processes" and developing products, which contain information regarding their life-cycle maintenance.

The step-function feature of the product quality control life cycle shows that product quality satisfies customer requirements at the time of initial purchase, but then slowly deteriorates after the initial purchase with the passing of time. If the product is not refurbished, it continues to deteriorate until disposal is necessary. If the product is refurbished, quality is then improved significantly, to satisfy customer requirements. With several cycles of refurbishment, the product (and/or component) has a longer useful life. After several cycles of refurbishment, the product is "upgraded," resulting in an even greater increase in product quality for the customer. As the focus changes from products to services, these refurbishments and upgrades may or may not involve the physical aspects of the product, but rather new or improved functions of the product.

In addition to traditional considerations such as initial manufacturing cost and product performance, new design decision variables (which result in tradeoffs) include:

- Design for long vs. short service life
- Design for high vs. low maintenance costs
- Upgrade/reuse at the factory vs. at user site
- Take-back cycle short vs. long

Marketing

Reuse of industrial components is not yet widespread in Japan, as in the auto industry. The focus here is moving into the consumer product realm. Japanese customers are not willing to pay extra costs to "buy green." Although the marketing materials of Fuji Xerox include references to recycling and "aiming at zero landfill," it should be noted that their customers are in general corporations (who might be concerned about their environmental image), rather than individual consumers. Prof. Kimura believes the trend is towards individual customers being more willing to "buy green" in the future.

Prof. Kimura mentioned that some companies keep repair costs high in order to stimulate greater demand for new products.

Example Case Studies

Several case studies were presented, including a paper feed mechanism, refrigerator, fax machine and camera. The camera example analyzed the shutter mechanism, where the wear effect on components was simulated. They are integrating FMEA (failure modes and effects analysis) into the assembly of components.

SUMMARY

Significant work has been done in developing simulation models for the product life cycle, which includes component reuse. The trend from providing products to providing services was seen once again.

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Kimura, F., T. Hata,, and H. Suzuki. 1998. Product quality evaluation based on behaviour simulation of used products. *Annals of CIRP*, Vol. 47, No. 1.

Kimura and Suzuki Laboratory. " Development of a Life Cycle Design Support System," Internal report for Alliance for Global Sustainability Project.

Site: **Institute of Industrial Science**
University of Tokyo
7-22-1 Roppongi, Minato-ku
Tokyo, 106-8558
Japan

Date: October 21, 1999

WTEC Attendees P. Sheng (report author), D. Bauer, B. Bras, T. Gutowski, C. Murphy, F. Thompson, D. Thurston, E. Wolff

Host: Prof. Ryuichi Yamamoto, President, Ecomaterials Society

HISTORICAL CONTEXT FOR ECOMATERIALS RESEARCH

Ecomaterials Research

Ecomaterials research in Japan was initiated in 1992 as a response to the U.S. Office of Technology published report *Green Products by Design*. This report was critical of Japanese research efforts in green products and spurred the Japanese government (especially MITI) to realize the importance of this field.

From 1993 to 1997, the Science and Technology Agency sponsored the first wave of activities through a National Research Project on Eco-materials. The initial activities focused on four areas:

- Soft processing: CFC-free cleaning, soft solution processing and reversible interconnects
- Easily recyclable materials: ferrous and aluminum based alloys (Fe-C-Si-Mn, Al-Mg-Si, Ti-Al-Fe, Al-Si-Fe), in-situ composites, magnesium alloys for TV cabinets (National/Panasonic), Toyota Super-Olefin Polymers, super metals, soil ceramics and recyclable formed aluminum
- Biodegradable materials: polyactic acid fibers (all natural), biopolyesters
- Alternative materials: mercury- and cadmium-free electric cells, lead-free optics, Cu-Zn alloys, PVC, halogen and lead-free electric wire, lead-free solder alloys and piezoelectric ceramics, porous clay fiber composites (substitute formed styrol), chromium-free Ecosteel with no dioxin emissions (PEP+Zn+steel), asbestos alternatives and green building materials

In 1997, the second stage ecomaterials research project was initiated with new material classes added:

- Renewable materials: chemically treated wood, wood and bamboo-ceramics, Misawa wood, eco-packaging, Kenaf pulp and bamboo-aluminum composites
- Recyclable materials: eliminate Cu and Zn impurities from Fe, bonded magnetic materials (Sm-Co, Nd-Fe-B), eco-cement using industrial wastes, TULC steel can, tile from discarded glass and recyclable PWBs
- Functional materials for energy applications: amorphous Fe-Si-B, electric double layer capacitors, thermo-electronic devices, solar cells, smart windows
- Long-life materials: durable concrete.

Other Research Initiatives

In 1995, MITI initiated a three-year study focused on inverse manufacturing (systems and process issues relating to disassembly, sortation and demanufacturing). In 1996, United Nations University initiated a research project on Zero-Emission Industry Clusters, which sought to refine the eco-park concept and develop supply chains where waste materials from one facility become the raw materials of another.

In 1998, MITI initiated a National Research Project on Life-Cycle Analysis (LCA). A key challenge currently facing researchers is the determination of a single index for LCA. Issues include characterizing quality and design of materials, as well as performance definitions. One attempt by Prof. Yamamoto to explain a single environmental index focused around eco-efficiency, defined as:

$$\text{Eco-efficiency} = \text{Performance} / \text{Life-cycle impact}$$

Where performance and life-cycle impact are a summation of several different factors. Each factor is normalized with respect to national emission levels and weighted to reflect regional importance. Impact factors considered include ozone depletion potential, acidification potential, and POCP.

GROWTH OF GREEN PURCHASING

Japanese consumers are generally believed to be more environmentally conscious compared to their U.S. counterparts. Market research in Japan indicates that approximately 20% of consumers in Japan can be classified as “green” consumers—that is, they are willing to pay a premium for green products. With increasing citizen awareness of landfill, dioxin and nuclear issues, green products have received higher visibility recently.

In business, the Green Purchasing Network was established in 1996 by the Japan EPA to set a guideline for green shopping and provide impact information on specific products. At some major companies, such as Fuji Xerox, the CEO ordered procurement specialists to purchase green products at an allowable 5% premium over regular products. The Taiwanese government is establishing similar guidelines with a 10% premium allowed.

DEVELOPMENT OF LEGISLATION AND CERTIFICATION REQUIREMENTS

The Japanese government initiated a packaging law in 1999 and will begin enforcing an electronic appliance recycling law starting 2001 (air conditioners, ranges, refrigerators and washing machines). Computing equipment will be the next class of products regulated. Japanese companies are currently piloting recycling processes based on this driver.

Currently over 2,300 sites in Japan have become ISO 14001 certified, including many non-manufacturing sites. Japan’s eco-mark Type 1 eco-label has been certified for over 3,300 products, but has not met widespread acceptance. MITI has also initiated a pilot study for introducing a Type-3 eco-label. Currently, each company self-certifies based on its own set of metrics.

FUTURE RESEARCH DIRECTIONS

Future research efforts on eco-material will focus on 11 topics:

- Material flows and rucksack analysis
- LCI/LCA
- Design for environment
- Clean technologies (return, reuse, remanufacture and recycle primary metals, rare earth, plastics, electronic materials, etc.)
- Renewable and biodegradable materials
- Alternative materials
- Functional materials (remediation, restoration, enzymes, energy)
- Safe disposal of toxic materials
- Standardization of recycled materials
- Material selection for packaging, electronic appliances, etc.
- Education and training

REFERENCE

Yamamoto, R. 2000. "Eco-innovation through green purchasing and investment." Paper presented at PACIFICHEM 2000 Conference, Hawaii USA, December.

Site:	**Applied Materials** **2901 Patrick Henry Drive** **Santa Clara, CA 95054** **URL: http://www.amat.com**
Date:	January 20, 2000
WTEC Attendees:	C. Murphy (report author), D. Bauer, E. Wolff
Hosts:	Terry Francis, CTO, Environmental Solutions Products Division

BACKGROUND

Applied Materials, one of the world's leading manufacturers of semiconductor equipment, offers equipment for most of the major processes used in wafer fabrication and in flat panel display manufacture. They began producing etch equipment approximately 20 years ago and expanded into CVD (chemical vapor deposition) and CVD/etch in the late 1980s. During the last five years their most aggressive advancements have been in the areas of CMP (chemical mechanical polishing) and copper interconnect (including both Cu metallization and low-K dielectric). The relatively new business group, Thermal Process and Implant, includes RTP (rapid thermal processing), epitaxial processing, and ion implant. Through acquisitions over the last few years they have moved into the equipment markets for reticle inspection, wafer defect detection and review, and metrology. With this month's purchase of ETEC, a mask making company, they plan to enter the mask making and inspection market, including reticle production. Applied Materials equipment is used in virtually every wafer fabrication facility in the U.S. and in most of the world.

Environmental efforts at Applied Materials are focused on helping their customers achieve better solutions. Areas of key concern are energy and water reduction and management of post-process waste, including gases. They have been a close partner with SEMATECH, and in cooperation with them have focused on the four environmental thrust areas identified by the SIA Roadmap, including reduction of PFC emissions, qualification of new chemicals, reduction in energy and water usage, and integration of ESH (environmental, safety, and health) impact analysis capability. In addition, Applied Materials is on the Industry Advisory Board for the NSF Center for Environmentally Benign Semiconductor Manufacturing at the University of Arizona. Through their facilities in Asia and Europe and a partnership with Infineon's "Fab of the Future" in Dresden, Germany, Applied Materials also has an appreciation of the environmental needs of these geographic areas as well as of the U.S.

MEETING

Problem Identification

One of the primary concerns for Applied Materials in the Environmental Solutions Products Division is identifying the drivers for improving environmental factors for the semiconductor industry. The general feeling is that the industry is responding reactively to individual symptoms rather than proactively to identified, prioritized, root causes that are understood as part of a systems analysis.

In the context of life-cycle assessment (LCA), Applied Materials personnel believe they have reasonably good inventory data. However, there are currently very little impact data, so while qualitative effects within the industry can be estimated, the quantitative impacts of the industry and the impacts relative to other industries are not well understood. For example, the semiconductor industry uses a great deal of electricity, so an understanding of the impact of power plants might be key to wafer fabrication. In the third area of

LCA, improvement, the primary concern is the apparent lack of understanding of the tradeoffs involved (i.e., there is significant potential for an improvement in one area to lead to a detriment in another). This is particularly true for yield, which is the paramount driver in semiconductor manufacturing. In addition, since "you can't fix what you can't measure," data are again an issue. Applied Materials also sees the need for enabling tools for analysis.

Applied Materials has manufacturing sites in Israel (metrology), England (implant), Austin, Taiwan, Korea, and Japan. In general they have found it critical to "act globally and react regionally," and to be sensitive to each individual culture (e.g., Japan is not Korea). They believe that this understanding will be critical in addressing environmental issues as well.

Current Activities

Applied Materials is engaged in a general program to improve environmental activities within the company, including DFE (design for environment) training for their employees. The ISO 14000 process is being phased in, based on its importance to the region and business unit. This is driven by customer requirements for ISO 14000 certification, as a condition of future equipment procurement. Applied Materials also identified an unexpected secondary benefit that was expressed by nearly every company that was visited on this trip: in addition to achieving the targeted environmental goals, focusing on environmental quality resulted in organizational and behavioral changes that decreased operation costs and improved overall product quality.

One of the key focus areas for Applied Materials is more efficient operation of the equipment that it supplies to its customers. They are working in partnership with Radian to develop a protocol to monitor energy use that is based on the recognition that energy consumption is not just a function of kilowatts per hour, but also on duty cycle, harmonic distortions, etc. In addition, "non-value-added resource evaluation" is used to identify process changes that can decrease start-up and idle times and equipment changes that can improve efficiencies. For example, a dual pump system for processes that must be performed under vacuum utilizes a remote (i.e., outside the clean-room), conventional pump for the initial pump-down, and a light, integrated point-of-use pump near the equipment to maintain vacuum pressure.

Applied Materials is currently working with UC-Berkeley to develop a tool-specific, module-based model called "Environmental Value Analysis." This is intended to provide a dynamic rather than a flat-sheet model to accommodate rapid changes in the semiconductor industry as well as variations due to geographic location. One of the areas of particular interest is water reduction, especially in the CMP process. Cascading water-use (i.e., from processes with tighter requirements to those with looser requirements) and water recycling are being evaluated.

While the focus is on the "use" phase of semiconductor processing equipment, "acquisition," "manufacturing," and "end-of-life" phases are also considered. There is a trend toward casting rather than machining equipment components, which results in better quality parts in addition to having a lower environmental impact. All product releases require that certain environmental criteria be met. At the initial end-of-life, Applied Materials will buy back, refurbish, and resell its equipment (customers must clean the equipment before shipping). Applied Materials had an incident in 1982 with its underground tanks that caused a site to be identified as a Super Fund Site. The effort to clean up the water, and to meet changing water quality standards, continues, with no external funding by the government.

Needs and Concerns

Several areas of concern were identified by Applied Materials. The key technical issues revolve around increasing efficiencies and process control. As concentrations decrease, the dynamic ranges increase, making control much more difficult. This is an issue in the area of cleans where extremely dilute solutions can be used, but only if they are even more pure than the ultra-pure solutions that are currently in use. (Note: "cleans" is a term used in the semiconductor industry to describe dilute wet-chemical (usually acid) processes that are intended to remove residual organics, thin oxidation layers, and/or particulate matter. These chemical cleans are typically followed by one or more rinse-steps.)

The process area where the most work will need to be done is in the area of metal deposition, especially with the increased use of organo-metallic precursors. The thermal budget of silicon is lower than is optimal for these materials, so it is likely that catalysts will have to be developed in order to avoid use of excessive amounts of gas required to get the desired deposition rates.

Management of gases downstream from etch and deposition processes also poses environmental challenges. For example, the fluorine used in etching produces undesirable by-products. If there were a process to form a benign dry-cake, rather than a wet-cake, the material could be reused. Operating pressures for many processes range from 100 to 10^{-9} torr, and gas separation for these high vacuum systems is problematic; cryo-pumps collect in a batch mode and separation has to take place off-line. Other pumping options are typically not viable because they have moving parts, and are therefore particulate generators. New materials being used in semiconductor manufacturing contain environmentally undesirable elements such as Ba, Sr, and Pb. Methods for keeping these out of the waste stream are of interest.

Climate control is a potential area of improvement. Chillers, as operated today, are relatively inefficient. They often try to maintain temperatures that are 2 to 4 degrees different from ambient. If the delta were instead about 15 degrees, they would operate much more efficiently. Depending upon local weather patterns, there could be as much as a 40% gain in power efficiency if the temperature of the fab could be increased by 8 to 10 degrees.

Applied Materials expressed a need for the development of an infrastructure and communication protocol that would enable them to take advantage of activities and modeling efforts taking place outside the semiconductor industry. The sense was that there may be solutions available to the semiconductor industry if the needs and constraints could be effectively communicated. One of the key issues is the extreme need for contamination-free environments at levels that are unique to this industry. This parameter is typically not fully appreciated by those outside semiconductor manufacturing. An evaluation tool that integrated the entire process flow (i.e., system level analysis) and which helped prioritize improvements also would be of value.

Applied Materials supports a closer alignment of industry and academia, but feels that this will require that students and/or faculty spend time in the manufacturing environment in order to sufficiently understand the issues and parameters. One solution that was suggested was development of intern programs.

Site: **Caterpillar Inc. Remanufacturing Facilities**
Corinth and Prentiss, MS
501 Cardinal Drive
Corinth, MS 38834

Date: 19 January 2000

WTEC Attendees: T. Piwonka (report author), B. Bras, E. Wolff

Hosts: M. Bridges, C. Meteer, L. West, S. Stark, E. Mathison

BACKGROUND

Caterpillar's remanufacturing operations began in 1972 in Bettendorf, Iowa, and the Mississippi facility first opened in 1982. Caterpillar has a corporate commitment to the environment in its manufacturing operations. A corporate publication stated in 1992 that "Caterpillar is committed to safeguarding the environment wherever it conducts business. We will establish, maintain, and follow environmentally responsible policies and practices; comply with applicable laws in both 'letter and spirit;' and respond openly and promptly to responsible inquiries about environmental issues as they relate to Caterpillar and its products. More specifically, we will:

6. Incorporate environmental considerations into design and manufacturing processes and ensure compliance by Caterpillar facilities worldwide.
7. Develop and apply technologies and processes that prevent pollution and minimize all forms of waste, especially hazardous waste. When waste prevention, avoidance, reuse and/or recycling aren't practical, we will handle and dispose of waste in a manner consistent with environmental regulations and public interest.

REMANUFACTURING OPERATIONS

Caterpillar operates three facilities in the Corinth area. The Sawyer Road plant receives incoming material for remanufacture. All remanufacturing assemblies, which include engines, hydraulic assemblies, cylinder packs, water pumps, fuel pumps, oil coolers, injectors, or other assemblies are called "cores." Sawyer Road receives an average of 160 tons of assemblies for remanufacture each day. Parts are cleaned and sorted at this plant. Dealers send the parts to Corinth; they are encouraged to use the packaging that the remanufactured parts are shipped in to ship other parts back to the plant.

The Cardinal Drive plant remanufactures diesel engines, crankshafts, blocks, and other components. At present eight engine models are remanufactured. However, each model has a number of variations, so the number of different engine types remanufactured is larger. Remanufactured engines are brought up to current design standards, are tested before shipment and receive the same warranty as new engines. They estimate that one of their engines should be remanufactured at least three times before it cannot be used again.

As not all components are recoverable, new parts are used where necessary during the remanufacturing process. New material content of cylinder blocks is currently 32%, cylinder heads 45%, and other components 35%. They are aggressively attempting to reduce the new material percentages, and have reduced usage from an historical average of 50%. The amount of scrap metal recycled to their foundry in Mapleton, Illinois, in 1999 was 235,526 lbs. of aluminum alloy, 16,865,767 lbs. of cast iron, and 5,680,509 lbs. of steel.

Most of the refurbishment of individual engine components consists of building up the worn surface by thermal spraying, laser cladding and welding, and then machining and grinding down and honing new surfaces. Many components are deliberately designed to permit one or two remanufacturing operations without requiring surface material addition. They have developed a proprietary method of repair welding cast iron in cylinder heads that produces a satisfactory cast iron structure. They are able to repair small (up to 1.5 inches in diameter) holes in engine blocks that result when the engine throws a rod (such engines are whimsically referred to as "ventilated blocks"). They are attempting to eliminate chromium plating operations by the use of thermal spray.

Cleaning operations include oil and grease removal, carbon build-up and paint removal, and rust removal. They use a mixture of baking soda and 10% alumina grit to remove paint and other surface contaminants. The liquid waste from the cleaning processes currently is being sent to a facility that uses it as a reagent in the neutralization of acidic liquid wastes from other companies, so this waste is not considered to be a hazardous waste. Even so, Caterpillar has reduced its liquid waste from 9 to 4.5 million pounds per year at the Corinth plant and aggressively pursue more environmentally friendly products to use in their processes. They recycle all packaging material; what they do not use internally, they sell to other manufacturers.

They have won several pollution prevention awards and have been recognized by the state of Mississippi for their recycling efforts. Once a year they hold an "amnesty day," where members of the community can bring hazardous materials (such as paints, thinners, etc.) to the community collection site, where Caterpillar helps others dispose of them. They also started an Earth Day celebration for area fourth grades where they teach environmental awareness and stewardship. They have expanded this to include other area industries and civic groups and will present their program to 2000 fourth graders from five counties this year.

The Prentiss facility remanufactures pumps, cylinder packs, connecting rods and oil coolers. Components such as turbochargers, starters, alternators, governors, and compressors are returned to the original equipment manufacturers, as are transmissions, clutch plates, brakes, hydraulic cylinders and rods, and electronics. The Prentiss facility is a team-oriented plant, while the other plants are more traditional top-down management. A number of operations are highly dependent on the skill of individuals who have specialized in repairs of that particular component during their employment at Caterpillar.

Plant personnel identified a number of areas where technology is needed to improve remanufacturing yields. These include:

- Process modeling for improved accuracy—e.g., a model of weld repair of compacted graphite iron
- Reduced energy consumption, particularly in the area of preheating in welding
- Higher strength materials, especially those used for surface restoration
- Reduced emissions from welding fumes
- Better, more environmentally friendly methods of paint and carbon removal, such as radical oxidation of soot, resonant frequency separation, or surface charge manipulation
- Recyclable cleaning fluids
- Better repair welding methods (current techniques produce too much porosity in welds)
- Low cost methods of crack detection and crack growth detection in castings and forgings
- Life prediction modeling to better predict remaining fatigue life in components
- Low cost inspection methods for cracks and coating adherence
- Separation methods to removal metal particles from the blast media
- Very low cost radiographic computer automated tomography scanning technology for receiving inspection
- In-process analytical tools that monitor the quality produced during the rebuild process
- Decision tools to determine the best process and cost alternatives in addition to life-cycle analysis

An interesting point made by plant personnel was that as components are designed to be lighter for better energy efficiency in operation, it becomes increasingly difficult to remanufacture them, and the number of times they can be recycled decreases. They also mentioned that paints and protective coatings that have to be removed in remanufacturing should be designed with remanufacturing in mind. In other words, it should be easy to remove, but still protect the component or assembly. One point brought up by a panelist was that as remanufacturing increases, the flow of scrap to the foundries, where it is an important part of the metallic charge, will decrease, driving up the cost of raw materials for the primary manufacturing operations (forging and casting).

Caterpillar expects to remanufacture its engines, and upgrades them each time they are remanufactured. This suggests that one marketing strategy to encourage remanufacturing would be to call it "planned upgrading."

The operations in Corinth were clearly being carried out with enthusiasm by the workforce and the management. Personnel have an understanding of the challenges and opportunities in recycling.

Site: **Casting Emission Reduction Program (CERP)**
McClellan Air Force Base
Technikon LLC
5301 Price Ave.
McClellan, CA 95652

Date: January 21, 2000

WTEC Attendees: E. Wolff (report author), D. Bauer, C. Murphy

Host: George Crandell, Product Test Engineering Manager

CERP was established in 1994 as a public/private partnership consisting of and representing the Department of Defense, EPA, USCAR, American Foundrymen's Society (AFS), and CARB. Initial funding provided $50 million to establish this center at a soon-to-be-decommissioned site within McClellan AFB. The original public funding is coming to an end and current operations have been targeted for closure by the Air Force, but the facility is in the process of obtaining additional funding to continue ongoing research and transitioning into a private research facility.

The principal CERP function of evaluating and assessing foundry process materials and the products' contributions to overall environmental impact, health, and risk issues had concentrated on development of measurement techniques and analysis. CERP made use of a state-of-the-art casting pilot system (including six-tons/hour electric coreless melting system) that includes full functional mold/core making capabilities, pouring stations, and casting shake out. During the first four years, its demonstration services focused largely on evaluating new foundry binder systems, equipment testing, and measurements instrumentation development.

Recently efforts have shifted towards new foundry process development and foundry process modifications, such as thin-wall iron castings and development of the advanced oxidation process for emissions reduction via in-process analysis. CERP has formed partnerships with various universities and technical organizations such as Penn State, UC-Davis, University of Alabama-Birmingham, and AFS to work on this and other future projects. Technology transfer for emission testing between the stationary and mobile emission sources is also a major area of research in cooperation with the American Industry/Government Emission Research (AIGER) program.

Advancements for additional process modifications and emission prevention could benefit from heat transfer models that incorporate kinetic reactions; however, current CERP funding will not permit such work.

Phenomena that lower emissions when treated water is injected (misted) into the exhaust system should be investigated. Such fundamental work should receive attention to avoid costly filtration and chemical treatments envisioned with current technology.

CERP would welcome NSF/DOE support for these initiatives.

Site: **Chaparral Steel/Texas Industries**
300 Ward Rd.
Midlothian, TX 76065

Date: June, 27 2000

WTEC Attendees D. Allen (report author), T. Gutowski, C. Murphy

Hosts Jon Brown, Manager, Environmental Services, Chaparral Steel
Mark Hill, Plant Manager, Midlothian Cement Plant

INTRODUCTION

Chaparral Steel is a core facility in an industrial complex that also includes an automobile shredding facility, a shredder flotation/separation facility, a cement plant, and an electric power plant. Members of the panel were interested in visiting this location because of the material exchanges that occur between the facilities and because of the role that the facilities play in product end-of-life management. The visit was arranged by Gordon Forward and was conducted by Mark Hill (Plant Manager) of the Midlothian cement plant and Jon Brown (Manager, Environmental Services) of Chaparral Steel.

Mr. Forward was the CEO of Chaparral Steel and has been active in the Business Council for Sustainable Development (BCSD). After Chaparral became a part of Texas Industries, which owned the cement plant at the Midlothian site, Mr. Forward initiated one of the most successful of the material exchanges at the Midlothian site. Slag produced at the steel mill, which had been a waste, is now ground into small aggregate and sent to the cement plant, where it is fed directly to the kiln. The use of slag as a cement kiln feed has a number of advantages beyond the obvious advantages of reducing material use and waste generation. Because the chemical form of the slag is a desirable intermediate in the formation of Portland cement, use of the slag reduces the need for some endothermic reactions, and therefore reduces some of the energy demand of the kiln. The lime-iron derivatives found in the slag also reduce the need to generate CaO in the kiln from limestone (calcium carbonate, $CaCO_3$). Since the reaction to form CaO from limestone generates carbon dioxide, use of the slag reduces generation of carbon dioxide. The environmental and economic benefits of this material exchange led Chaparral to commercialize this technology. The technology is now licensed to other cement/steel facilities.

OPERATIONS

The use of slag from the steel mill in the cement kiln was the earliest and most successful material exchange at the Midlothian site; others are planned or in place. For example, the cement kiln currently uses waste solvents and other waste organics for fuel. Calcium sulfate recovered from sulfur scrubbers will be used in the cement kiln and reduce the need to use naturally occurring $CaSO_4$ (gypsum or anhydrite), which is currently mined and transported from Oklahoma. In addition, carbon monoxide evolved during cement manufacture is used to reduce nitrogen oxides to nitrogen and oxygen. Other exchanges are being examined through a network of companies organized by Mr. Forward and a company spun off from the BCSD (Gulf Coast).

While the material exchanges occurring between facilities at Midlothian are novel, it should be noted that the individual facilities are also proactive in their environmental performance. For example, the cement facility is converting from a wet to a dry operation, which will reduce energy consumption and air pollutant emissions. In addition, the steel mill relies on iron recovered from scrapped automobiles, white goods and construction/demolition wastes. The recovery of iron from these sources is very efficient; however, the processing of scrapped automobiles, white goods and demolition wastes generates shredder residue, which is currently landfilled. To recover materials from this residue, which is primarily a mixture of non-ferrous metals and plastics, Chaparral Steel installed a multi-stage flotation separation device that separates metals from plastics, and halogenated from non-halogenated plastics. The use of these separated materials has been hampered, however, by the presence of trace levels of PCBs in the residues. The source of the PCBs appears to be capacitors and other electrical devices found in the source material. Identifying capacitors and other sources of PCBs within the diverse waste streams entering the facility is extremely difficult, yet just trace levels of PCBs can compromise the uses of the materials that could be recovered from the shredder residue. The challenge that Chaparral is facing in dealing with trace contaminants in product end-of-life management is likely to be duplicated by other product end-of-life management facilities.

OBSERVATIONS

The panel had three primary observations from this site visit:

- The Midlothian site provides a highly successful example of material exchanges between facilities
- Individual facilities at Midlothian are aggressively pursuing environmental improvements within their facilities, in addition to pursuing material exchanges
- The presence of trace contaminants in materials recovered from end-of-life products is likely to pose significant challenges in the use of these materials

Site: **DaimlerChrysler Corp.**
CIMS 482-00-51
800 Chrysler Drive
Auburn Hills, MI 48326-2757

Date: June 14, 2000

WTEC Attendees: J. Sutherland (report author), D. Bauer, T. Gutowski, C. Murphy

Hosts: Ross Good
Neil P. McKay
Patricia A. Strabbing
W. Charles Moeser
Kay F. Bedenis
Michael J. Curry
Kevin Slusarczyk
Jackie Savage
Ann Schlenker

BACKGROUND

DaimlerChrysler is one of the world's leading automakers with headquarters located in Stuttgart (Germany) and Auburn Hills, Michigan (USA). The visitors met with a large group of individuals representing various organizations with environment-related missions. Following the merger in 1998, DaimlerChrysler had 180 manufacturing plants, 440,000 employees, and sales of approximately $132 billion. Vehicle manufacturing accounts for 85% of sales (other business units include financial services, telecommunications, and aerospace). The hosts spoke with the visitors for about three hours on a range of topics relating to DaimlerChrysler and the environment.

ENVIRONMENTAL DIRECTIONS

In company literature, Werner Pollmann, Chief Environmental Officer of DaimlerChrysler AG, has written that, "Protecting the environment and conserving the natural foundations of life are fundamental tasks for DaimlerChrysler..." With this backdrop, discussion first focused on the motivational factors for DaimlerChrysler's attention to the environment. Factors described included (i) compliance with regulations, (ii) cost, (iii) competitiveness, and (iv) concerns over hazardous materials. It was noted that "green" needs to be considered as a part of everything that is done and that it needs to be reflected in attitudes and not just techniques. Also discussed was the fact that a balance must be achieved between environmental issues, vehicle cost, quality objectives, customer satisfaction, and product marketability. When any of these objectives conflict, a solution must be identified that responds to relevant system constraints (e.g., compliance with applicable regulations) and best responds to the objectives. It is believed that the best possible outcome also adds value to a DaimlerChrysler vehicle.

In a dialogue about the environmental challenges faced by DaimlerChrysler it was indicated that the company has always maintained a very proactive stance in regards to new regulatory requirements like MACT (Maximum Achievable Control Technology). In fact, it is often the leader in setting new industry standards in the U.S. It appears that, in contrast to their colleagues in Europe, the environmental staff in the U.S. spends much more of their time engaged in paperwork and permitting activities. It was reported that in some cases the permitting procedure may be inhibiting positive environmental changes, because any change in process, materials or controls will trigger a time consuming permit review (up to 18 months in some cases, even for minor changes.

As part of its Community Environmental Awareness Project, DaimlerChrysler is the one of the first automotive companies to include the surrounding communities, state agencies, environmental groups, and plant specialists in putting together information that explains the manufacturing processes in the plant. This also includes an explanation of how the environment is impacted or preserved as both compliance and proactive initiatives are pursued (e.g., the Sterling Heights Assembly Plant).

Very often, the environmental concerns of the auto industry are directed at the consumer use of the vehicles themselves. The concerns include the use of a diminishing carbon-based fuel resource, CO_2, SO_x, and NO_x emissions, other hazardous airborne pollutants, and a variety of miscellaneous pollutants. A California study that found that 90% of the emissions are produced by 2-5% of the vehicles on the road (and almost always these tend to be older vehicles) was then discussed. This then led to an exchange about alternative propulsion technologies (i) fuel cells, (ii) electric vehicles, and (iii) hybrid vehicles. The importance of considering full fuel-cycle emissions was emphasized (e.g., power plant emissions for an electric vehicle). The PNGV (Partnership for New Generation Vehicle) is on schedule to produce an up to 80 mpg prototype vehicle by 2004, but this vehicle may not meet the lofty emission standards or affordability goals set for the vehicle. Diesel technology is of interest particularly for near mid-term CO_2 reductions. It was postulated that fuel cells might represent the long-term solution, although they are unlikely to be affordable for several decades and will probably require significant fueling system infrastructure modifications (e.g. H_2 storage).

In terms of water quality, DaimlerChrysler has several plants in Mexico with technologies that allow them to be zero wastewater producers. As with most automotive plants near metropolitan areas, the plants in the Detroit area pre-treat their wastewater before discharging it to publicly owned treatment works (POTW). The concern was expressed that perhaps too much attention has been focused on point source discharges. These discharges have been regulated and their pollutant load has been reduced through the use of expensive treatment technologies. It was suggested that not enough attention is being devoted to non-point sources (e.g., agricultural runoff and storm water) which go untreated into water streams. The issue of water quality standards was discussed, and in particular the differences between pesticides and dissolved metals. Water analysis was also addressed, for example the effect of using regular versus reagent water and lab-to-lab variability—these issues point to the need to establish an acceptable testing standard.

Talk then shifted to the environmental issues associated with manufacturing processes. Cutting fluids and fluids from parts cleaning operations represent significant components in the wastewater effluent stream. Metals mixed with fluids are classified as contaminated scrap that carries with it a disposal cost—if the fluids were eliminated, the metals could be resold. Painting processes remain an environmental concern (in terms of energy, materials, air emissions, and solid waste disposal), as manufacturers move from solvent-based to water-based to powder paints. The pre-coats applied prior to the painting operations also present environmental concerns (whatever technology changes are considered, they must still produce a Class A surface). One answer to the challenge could be injection-molded components with molded-in color. Casting sand is yet another environmental challenge—rather than landfilling used sand, alternative uses for the sand are being explored (e.g., construction).

By 2002 all Chrysler group facilities will be certified according to the EEMS (Enhanced Environmental Management System) which is more stringent than ISO 14001. EEMS certification is performed independently by the U.L., and the whole EEMS process is tied to DaimlerChrysler's ISO 9000 process. Both the hosts and visitors discussed how ISO 14000 requires: a company-wide awareness, more than just a paper-work exercise, a significant training commitment, and company-wide standardization. Of course, whether it is EEMS or ISO 14000, any successful environmental system must be integrated into the fabric of the company (i.e., made part of the day-to-day activities), it cannot be viewed as a separate environmental program. DaimlerChrysler is trying to more fully integrate life-cycle analysis and other DFE tools into their engineering design activities.

Site: **DRI/HBI Use in the EAF – An Idea Whose Time Has Come?**
A Seminar presented by Midrex Direct Reduction Corp., Corus Tuscaloosa, Corus Mobile and American Iron Reduction, at The University of Alabama Bryant Center, Tuscaloosa, AL

Date: April 30 – May 2, 2000

WTEC Attendee: T. Piwonka (report author)

Hosts: Dr. Sara Hornby, Franz Sammt, John P. Kopfle, all from Midrex

The seminar was attended by 80 people, from all over the world, and included a tour of Corus Tuscaloosa, a mini-mill owned by Corus, the Company formed by the merger of the integrated steelmakers, British Steel and Hoogovens, which owns the Beverdijk, Holland, plant that was visited.

DIRECT REDUCTION OF IRON ORE

The manufacture of steel begins with iron oxide, which is the form the ore takes in most commercially viable deposits. The ore is reacted with carbon in the form of coke in a blast furnace to form iron that contains about 4.5% carbon in solution. To make steel, which contains between 0.01 and 2% carbon, this iron is reacted with oxygen. Carbon dioxide is produced in three areas during this process: during coking in the coke plant, during the reaction of coke with iron ore, and when oxygen is blown through the molten iron/carbon alloy.

A number of years ago a more direct method was developed: reacting the iron ore directly with a reducing gas, such as reformed methane (CH_4) which generates carbon monoxide (CO) and hydrogen (H_2) to reduce the oxide directly to form pure iron. This process has been growing for a number of years, and now is responsible for a significant amount of new iron introduced into the steelmaking process. The process conserves energy, as it takes place in the solid state rather than the liquid state, and eliminates one of the greenhouse gas reactions, as well as using a greenhouse gas, methane, as *the* reactant. The process is known as “Direct Reduction of Iron” or DRI. If the products, which are small spheres of iron about ¼" to ¾" in diameter, are briquetted into larger pieces (measuring 5" x 3" x 2"), the product is known as “Hot Briquette Iron,” or HBI. In 1999, 38.6 million tons of DRI and HBI were produced worldwide, consuming about 20% of the total iron ore produced.

DRI is primarily used in electric arc furnaces (EAF) as part of the solid charge. EAFs were designed to operate on solid charges of steel, generally scrap. “Hot metal” (liquid metal pig iron directly from the blast furnace) is rarely used. EAFs have been the primary melting unit in mini-mills, the (relatively) small steel manufacturing facilities that have transformed steelmaking in the United States. It is difficult today to obtain high purity scrap, since much current scrap reflects the alloy purity specifications of one or two decades ago when specifications were not as stringent. Today, however, it is recognized that it is necessary to produce steels with low “residuals,” as unwanted elements are called. DRI, which consists of pure iron with a small amount of oxide, is an attractive addition to the charge mix of EAFs. Interestingly, a few large foundry organizations are considering converting from cupola operations to DRI-fed EAFs as their primary melting sources, mainly to reduce the energy consumed in operating baghouses and other ancillary equipment required for cupola melting.

Unfortunately, due to the economics of the DRI process, it isn’t possible to completely reduce the iron contained in the ore in the DRI process. Also, between 2.5 and 5% of the DRI is “non-metallic” or “gangue” that contains unreduced oxides—CaO, SiO_2, Al_2O_3, MgO, etc. Carbon in the DRI exists primarily as iron carbide. When the charge melts, the unreduced iron oxide is exposed to the iron carbide, which reduces it and generates energy during the reaction (thus forming a greenhouse gas, CO_2). Depending upon the level of carbon in the DRI, and the site specific EAF operation, the electrical energy requirement from the arc can be reduced.

In operating an EAF to produce steel, the object is to melt the solid charge, which consists of scrap, DRI, and slag-forming materials such as lime, adjust the steel bath chemistry, and pour the steel. Chemistry adjustments, which include obtaining the proper carbon content as well as that of other desired elements while eliminating unwanted elements such as sulfur and phosphorus, require reactions with the slag that floats on top of the bath of molten steel. The science of steelmaking essentially consists of adjusting the slag so that it reacts properly with the elements in the bath of molten steel. In some cases there is no way to remove elements: for instance, copper, once in the alloy, cannot be removed. To lower the copper composition, it is necessary to dilute the alloy with pure iron. (The copper content of automotive scrap is generally higher than desired, as copper wiring in the vehicle is often entangled in the chassis during the shredding operation. EAF operators today consider copper in steel scrap a major problem.)

The slag recommended for use in EAFs is a “foamy” slag, one that contains tiny bubbles of CO. Foamy slags help insulate the steel bath and the electrode, and minimize heat loss. Foamy slags are created by the reaction of carbon and oxygen from the above mentioned oxides contained in the DRI, or from iron oxide (rust) on the scrap. However, it is hard to obtain an exact balance of carbon to oxygen in the charge make-up, and it is often necessary to add carbon (in the form of coke, graphite or coal) or oxygen to the bath by injecting them through a lance.

The DRI process is inherently a clean process, especially when reformed methane is used as the reduction gas, as the amount of carbon dioxide formed is minimized, and methane itself is consumed. When DRI is used as feed metal in EAF production of primary steel, CO_2 generation is cut 25 to 35% over basic oxygen furnaces, and a similar amount when it is substituted for pig iron in electric furnaces. When it is used to produce steel in mini-mills that combine it with scrap, CO_2 generation is cut nearly 90%.

As the use of EAFs has grown worldwide, heat times have decreased. Steel mill EAFs are built in a range of sizes, but most are in the 120 ton–150 ton range. It is normal to have heat times of 55 minutes or less (i.e., to produce 100 to 140 tons of steel from solid charges in 55 minutes—there are losses in slag and gaseous waste). One steel mill has reported heat times of under 30 minutes. From a greenhouse gas emissions standpoint, however, faster heat times are pushing the ability of the electrical generation systems to provide enough kW in the short time allotted for the heats.

Of course, as the amount of electricity used increases, the energy costs of the heats also increase. Steelmakers currently operate EAFs in the range of 280–425 kWh/ton (especially for scrap charges), depending on the local cost of electricity. There are a number of methods of reducing the electrical energy required: a DRI plant can be combined with an EAF, and the hot DRI charged directly into the EAF (although attempts to do so present formidable logistics problems for “brown field” sites). Energy for the process can also be derived from the chemical reactions that occur in the bath, especially the exothermic reaction between carbon and oxygen. This last reaction is the reason that some steelmakers prefer (or make) DRI with carbon contents deliberately raised to 1.8 to 2.8%, and then inject oxygen, or, alternatively, they will add carbon to the bath. While this lowers production costs, it increases greenhouse gas generation. One variation on this is to combine EAF dust from its baghouse (which is essentially iron oxide) and oily mill scale (also iron oxide, containing the hydrocarbons in metalworking lubricants) into a dry mix that is injected into the bath. This process provides a source of carbon and oxygen, and at the same time eliminates a source of landfill waste that the mill would otherwise have to dispose of.

The push for higher productivity (shorter heat times = lower cost/unit) in the steel industry is leading to the development of hybrid steelmaking processes that use scrap, pig iron, DRI or HBI, and carbon and oxygen additions to provide the extra energy units necessary to accelerate the process. It is hard to say whether this practice will increase or decrease the total greenhouse gas generation, as it is dependent on the method of electricity generation. As a first approximation, one would expect a decrease as the chemical energy is being used at the point of production (in the steel bath) rather than being generated at a distance and suffering transmission losses on its way to the steel.

Site: **DuPont Experimental Station**
(Telephone Conference)
Wilmington, DE 19880-0302

Date: June 21, 2000

WTEC Attendees: T. Gutowski (report author), C. Murphy

Host: John Carberry, Director, Environmental Technology

BIG PICTURE

Our discussion with John Carberry ranged over many important topics, including the chemical industry as a whole as well as DuPont's response to environmental issues. From a historical perspective, the chemical industry was one of the first targeted groups for environmental action. Over the last 15 years the progress of the industry has been significant. One can see DuPont's progress by going to their Web page and downloading their progress report for sustainable growth. Examples of DuPont's recent progress include 67% reduction in air toxic emissions since 1987, 87% reduction in airborne carcinogens since 1987, 39% reduction in greenhouse gases since 1990, 20% reduction in the Kyoto basket of gases since 1990, and flat energy consumption since 1990—in spite of a 28% increase in production. Perhaps one of the most dramatic statistics is that while DuPont was experiencing something over one hundred environmental incidents in the early 1990s, over the last two years they have had just two incidents in each year. Furthermore, as new industries are included in the toxic release inventory reporting requirements, it is now becoming apparent that the chemical industry contribution may be small compared to others.

Nevertheless, much needs to be done. In spite of a 30% reduction in global hazardous waste since 1990, the company still produces in excess of 1.5 billion pounds of hazardous waste from their U.S. facilities alone (1998 data, from DuPont, *Sustainable Growth Progress Report 1999*). Furthermore, DuPont has found new reasons for being environmentally friendly. They have moved from a position of regulation compliance to one of being proactive, and in fact, seeing environmental issues as an important point for competition. This new attitude is clearly stated in DuPont's 1999 progress report on sustainable growth: "We affirm to all our stakeholders, including employees, customers, shareholders and the public, that we will conduct our business with respect and care for the environment."

At this point our discussion turned to the complexity of the issues. For example, simply outlawing certain products or materials in the United States can result in them showing up at other places in the world. To aid in their assessment of environmental impacts, DuPont uses a variety of tools, in particular life-cycle inventory, and convenes a strategic environmental leadership group that reviews environmental issues business by business. The review of issues frequently uses a template based on the "Seven Concepts for Sustainability" developed by the World Business Council for Sustainable Development (WBCSD) and adapted (internally) for the chemical industry.

RECYCLING OF POLYMERS

Increasingly DuPont finds that customers are looking for recycled content in their products. DuPont has pioneered the recycling of polyester (see the E.I. du Pont de Nemours site report on our discussion with Robert Hirsch, Managing Director of DuPont Polyester Technologies). Our discussion of polymer recycling concluded that economic viability is still difficult, in large part because of collection economics. An example of a recycling technology which is feasible, but not yet economical, is methanolysis of polyesters. A success story for recycling involves the Tyvek® envelopes, which meet the requirement of UPS for 25% post consumer waste at acceptable cost. These strong durable envelopes are made from recycled milk bottles. Nylon 6 and 66 can be recycled, much of it coming from carpet. Again the issue is the collection and reverse logistics. In addition, future designs that incorporate fewer materials into the carpet design could make recycling economically viable by reducing separation costs. The recycling of plastics from automobiles may present certain advantages because of the collection infrastructure already in place in the form of the 10,000 automobile dismantlers in the United States.

PROCESSING

DuPont continually works on their chemical processing operations, often to reduce energy or emissions from their operations. In addition, DuPont has found it to be a good business strategy to expand that capability to also take on environmental issues for their customers. Several examples of this are listed below

- Dying the yarn at DuPont rather than at the customer's.
- Reformulation of photosensitive materials using both reformulated products and solvents. DuPont changed the formulation to eliminate a regulated solvent and also takes back spent solvent from the customer.
- Disposing of packaging. DuPont now produces bags that are compatible with their chemical contents. They have a bag called "ROTIM" which stands for "Return or Throw in Mixer." That is, the bag is made of materials similar to its contents so that it may be crumpled up and thrown into the compounding machine, once the pellet contents are used up.
- Developing aqueous developers to replace solvents.
- Developing water soluble box liners for agricultural chemicals—which can be dissolved in the application spray tank when empty, eliminating the need for the farmer to dispose of the empty box (regulated toxic waste).
- Reducing the hazard of polymer compounding by reducing the amount of unreacted monomer in the polymer.
- Supplying painted car parts at the manufacturer's site, versus just paint. In fact, they are very interested in looking into the "rent a chemical" business.

We also discussed biotechnology's advantages and pitfalls. They are focusing their attention on very high value added items, such as value added crops. Some of the advantages of the biomaterials approach include renewable raw materials and more benign processing operations. However, there may be some downsides, including more energy intensive, more wastewater, and higher cost raw materials. Hence, biomaterials and biotechnology should not be seen as a magic silver bullet to solve environmental problems.

RESEARCH AGENDA FOR NSF

John Carberry suggested areas where NSF might focus their attention:

- Look at energy production trade-offs for alternative schemes, including biomass. There is a need to track and quantify unit productivity versus impact on the environment. Fundamental science is needed here.
- PBT Predictive Models Based on Structure.
- NSF could play an important role as an organization which can convene the debate concerning bio fuels.
- Much attention should be focused on catalysts, particularly metal lignand and others that are "leave-in catalysts," to reduce the toxicity of polymers.
- Research is required to look into how to drive polymerization to higher levels and thereby reduce unreacted monomers in polymers.

Site:	**E.I. DuPont de Nemours** **(Telephone Conference)** **iTechnologies** **14 T.W. Alexander Drive** **P.O. Box 13999** **Research Triangle Park, NC 27709** **URL: http://www.dupont.com**
Date:	May 4, 2000
WTEC Attendees:	C. Murphy (report author), T. Gutowski
Host:	John W. Lott, Chief Environmental Officer, iTechnologies

BACKGROUND

DuPont iTechnologies, formerly known as the Electronic Products Division, is one of the most significant growth platforms within DuPont. The technology-driven portfolio provides differentiated, materials-enabled solutions for basically all of the world's leading manufacturers of electronic components and assemblies, packaging graphics, and producers of high-end commercial printing. The products are comprised of high-value materials and are based on DuPont's unique competencies in photopolymers (light-sensitive polymers), polyimides (temperature-resistant polymers), fine particle dispersions, films and laminates, and end-use development.

DuPont was highly involved in DARPA's Environmentally Conscious Manufacturing Program, and in cooperation with MCC managed two projects to look at alternatives to constructing printed wiring boards: fully additive copper with photoimagable dielectric and permanent photoresist. Both technologies were shown to significantly reduce water consumption and waste.

INDUSTRY OVERVIEW

Flame Retardants

Two key concerns for the electronics industry are flame retardants and lead-free solder. These are largely due to the European Commission's Directorate-General (DG) Environment directive on waste electrical and electronic equipment (WEEE). The directive bans the use of lead, mercury, cadmium, hexavalent chromium and certain flame retardants (PBB and PBDE) as of 2008. The concern with flame retardants is that they may form dioxins when incinerated (the primary method of plastics disposal in Europe and Japan). While it is accepted that chlorinated materials (among them fire retardants) lead to dioxin formation, there seems to be considerable doubt as to whether the same is true for the specific brominated fire retardants that are currently in use for electronic products. Further complicating the problem is the temperature at which the plastics are incinerated. The temperatures at which European plastics are burned are apparently high enough to prevent formation of dioxins. In Japan, however, older incineration units are used, and there is concern that they are incapable of reaching sufficiently high temperatures.

The IPC trade association, which represents manufacturers of printed wiring boards (PWBs) has a task force on flame retardants. John Lott provided us with copies of several presentations made during their most recent meeting. PWBs are typically constructed using epoxy-based resins (thermo-sets) for which there are no obvious alternative flame retardants. The IPC task force is beginning to investigate possible solutions with a focus on technical performance and cost. One approach is to use large organic aromatic molecules or nitrogen containing compounds that don't burn well. This works for polyimides, but not all other laminate materials.

The exterior cases for electronic products are constructed of thermoplastics. The most common of these are PC/ABS and ABS, which are flammable. Among the alternatives to brominated fire retardants that are being explored for thermoplastics are inorganic fillers such as MgO. However, these inorganic fillers require very high loadings that can have significant consequences for mechanical strength and electrical properties and therefore cannot be used in all applications. Another alternative is red phosphorus. However, phosphorus chemistry is not something that is commonly understood. When these flame retardants are burned, phospho-organic compounds could be formed that are very similar to nerve gas.

The point was made that it would be helpful if a new flame retardant was used by a larger industry in order to drive the economies of scale. For example, many of the current flame retardants are used in the garment and furniture industries, which use much larger volumes than the electronics industry. It would also be useful to know the full impact of proposed substitutes on the environment and human health.

Lead-free Solder

The European WEEE Directive also calls for the elimination of lead solder. Anticipation of the enactment of this directive has lead to a worldwide search for alternative materials and has bred international competition to use these solutions as a marketing strategy. What has been demonstrated by this free market dynamic is that solutions that are often welcomed as significant improvements to the environment because they eliminate an identified problem are often not fully evaluated themselves and may lead to additional problems. A case in point was the award winning "green" disk drive that was built with a bismuth solder instead of a lead solder. This, of course, eliminated lead, but the end-of-life treatment of the new bismuth solder was not well thought out. In fact, the bismuth solder was refused by the usual metal recycling industry because a great deal of their business involves recycling of copper and bismuth is a significant contaminant of copper. Therefore, the metal recycling industry did not want to handle bismuth at all. The story underlines the importance of thoroughly evaluating alternatives and suggests a potential inefficiency in free market competition when the environmental directive is not clear about the evaluation of the alternatives.

Other alternatives to Pb-solder materials typically use tin, copper, and silver, all of which have other issues associated with them that need to be investigated prior to extensive implementation. Examples of potential problems include possible metal migration and thermal aging that could result in reduced product reliability. In addition, most of the Pb-free solders require higher processing temperatures and will necessitate the use of substrate materials with higher T_gs than currently used. Most epoxy-glass laminate material has a T_g of 140°C; the new solders will probably require substrates with a T_g in excess of 160°C. This means that in addition to the energy increases required during the solder operation, the lamination process during PWB fabrication would also require higher temperatures. As this is the most energy-intense step in the creation of a board, this would have a significant effect on the overall energy-consumption budget.

Plastics Recycling

A primary barrier to plastics recycling is the low cost of virgin material relative to recycled. One of the cost drivers in plastics recycling is reverse distribution. This could be solved in part by using small, localized, modular "green factories" to reduce waste plastic to monomers. The factories would be modular so that they could be easily changed depending upon the feedstock. The transportation of the "harvested" monomer, which is quite dense compared to the waste plastic, would greatly improve the economics of this process. Dr. Lott mentioned a number of places where plastics recycling to the monomer level is currently taking place including a DuPont factory in Canada (reducing nylon to its monomer constituents). Delphi Automotive claims that they are doing closed-loop recycling of post-consumer PVC and polyester.

Flat Panel Displays

DuPont is interested in becoming a supplier of flat panel displays and/or the components thereof. Their move into this market would represent a collapse of the supply chain, which would greatly reduce the environmental impact for producing these displays and offer the opportunity to participate in take-back activities.

PARADIGM SHIFTS

DuPont has been very involved in materials (such as photo-polymers) that can be used to fabricate PWBs using blind microvias instead of plated through holes (PTH). This approach results in much denser wiring and requires fewer layers. This not only allows for boards to be smaller and thinner, but the electronic performance is also significantly improved. In general, these processes use less energy, water, and polymer. Another area of interest is light-pipe circuitry. The biggest technical challenge will be connection to the chip.

Site: **E.I. du Pont de Nemours**
(Telephone Conference)
Barley Mill Plaza, Bldg. 27/1156
Wilmington, DE 19880-0027 USA

Date: June 13, 2000

WTEC Attendees: C. Murphy (report author), T. Gutowski

Host: Dr. Robert G. Hirsch, Managing Director, DuPont Polyester Technologies

BACKGROUND

DuPont spun the very first Dacron® polyester fiber in 1949 and historically has been the world's largest producer of polyester. Polyethylene terephthalate (PET)—polyester—is used in a multitude of products, including textiles, industrial fibers, food containers and bottles, video and audiotapes, electrical insulation and capacitors, and hundreds of different kinds of films. In the early 1990s, DuPont developed a process for regenerating polyester, referred to as Petretec(SM) technology. This process reduces polyester back to the original starting materials, and as such it can handle relatively high levels of contamination and is also FDA approved.

TECHNOLOGY

DuPont's polyester regeneration technology is based on a process called methanolysis. This process, which converts post-consumer polyester waste into its constituents, dimethylterephthalate (DMT) and ethylene glycol (EG), was demonstrated in a Cape Fear, North Carolina facility where an existing DMT production unit was converted into a 100 million pound per year "pilot" plant. One of the primary benefits of this process is its robust character, with the ability to tolerate up to 5% contaminants in the input stream. This pilot plant clearly demonstrated the technical feasibility of the process by producing material that is indistinguishable from virgin. At the time the pilot plant was established, polyester bottle resin prices were between 65 to 75 cents a pound. Prices later fell to 32 cents per pound, the worst price drop in a 40-year history. If prices had held at the historical average of 55 to 60 cents per pound, the process would have been viable at volumes of a hundred million pounds a year. DuPont remains committed to licensing the technology. It was estimated that for the Cape Fear facility, the feed stream including collection and cleaning needed to be available at 10 cents a pound or less to make the process economically viable. For comparison, note that in many parts of the country landfill costs are on the order of 2 to 4 cents a pound, but their costs are rising steadily and the number of landfills is dropping precipitously.

There are multiple ways to recycle polymers. The most basic involves collecting, cleaning, melting and repelletizing. After this there are a variety of "depolymerization" techniques which break down the polymer to varying degrees. For polyester this includes glycolysis and hydrolysis. Finally, one can drive the reaction backwards to the original components. For polyester this step can be done by methanolysis, which is accomplished by exposing the polymer to vapor phase methanol at high temperature. In general, as you proceed down this chain, the recycling process becomes more robust and can handle increasingly higher impurity levels.

INFRASTRUCTURE

The biggest barriers to plastics recycling are frequently related to infrastructure, particularly reverse logistics and material preparation. Polyester is often recovered as film, which needs to be densified, or as polyester bottles, which need to be "chipped." The material then goes through a separation process (frequently density float), washing, filtration, and possibly densification prior to introduction to a chemical process.

Site: **Federal-Mogul Corp.**
World Headquarters
26555 Northwestern Highway
Southfield, MI 48034

Date: June 14, 2000

WTEC Attendees: D. Bauer (report author), T. Gutowski, C. Murphy, J. Sutherland

Hosts: William J. Zdeblick, Director, R&D
Roger Strelow, Director, Environmental, Health, and Safety

BACKGROUND

Federal-Mogul is a tier one automotive supplier, focused on powertrains (engine systems) but with business in other areas, such as lighting, brakes, wiper products, and ignition products. Current overcapacity in the industry (~20%) is creating business pressure to consolidate. In the past three years, partially as a result of numerous acquisitions, business has increased from under $2 billion to $7 billion. The large number of new acquisitions makes business practice standardization challenging. OEMs are also transferring some engineering responsibility to the larger suppliers, such as Federal-Mogul. This is making business more challenging.

ENVIRONMENTAL, HEALTH, AND SAFETY PRIORITIES

Federal-Mogul's EHS practices have traditionally focused on worker safety, using a safety scoring system (metrics such as work lost/ hours of operation) and compliance with local environmental regulations. Under the influence of ISO 14000, environmentally beneficial efficiencies (energy, material use, etc.) which also result in cost savings receive higher priority than non-environmentally beneficial potential cost savings. The sentiment was expressed that people in R&D and engineering need to become more versed in environmental issues so that new product development can be influenced earlier in the design cycle.

The majority of Federal-Mogul's plants recycle items such as chips and stamping punchouts, but there are no explicit requirements. Quantities of landfill waste are product-dependent. Waste chemicals are hauled by certified materials haulers.

MEETING CUSTOMER DEMANDS

Economics

Federal-Mogul clearly feels pressured by cost competition. Particularly in the U.S., cost is seen as the dominant decision driver for automotive customers; it is perceived as the primary focus for purchasing and sales in the OEMs. (In Europe the cost to quality importance ratio is more like 50/50.) Commonly, other attributes, such as precision and environmental performance, are constraints. (This means that improvements beyond the required levels are perceived to bring little benefit to Federal-Mogul.) Sentiment was also expressed that easy availability of price information over the internet and the increasing use by the OEMs of internet auctioning for commodity parts is exacerbating the price squeeze.

Manufacturing Process Standardization

There is desire to internally standardize manufacturing processes (both technologically and environmentally). This is an important aspect of Federal-Mogul's management system, and is challenging due to the large numbers of recent acquisitions. These are smaller companies that may be based in global regions that have different manufacturing process environmental priorities. A case was mentioned involving the use of TCE.

There is also pressure to manufacture according to the OEMs' desired practices; OEMs want to minimize risks associated with the introduction of new manufacturing processes. EPA also has a set of recommended best practices. For innovative new processes, the burden of proof is on the supplier. For a supplier, the path of least resistance is clearly to abide by these process standards.

ISO 14000

ISO 14000 will soon be a requirement for doing business. (It will probably not be a competitive advantage in the meantime.) Ford and GM have recently announced ISO 14000. Ford, in particular, has been helpful with ISO training seminars for suppliers. Federal-Mogul EHS policy mandates that all plants should be ISO 14000 certified no later than 2002.

Transition to Systems Design

With the transfer of engineering responsibilities from OEMs to suppliers, there is a corresponding shift from component (commodity) manufacture to system design and manufacture. For example, rather than producing pistons to certain OEM-specified tolerance quality specifications, there is a shift to producing engine systems with specifications such as noise, fuel economy, etc. Better performance under these system specifications can command a higher price (though OEM purchasers still may try to substitute lower cost components into designed systems). Thus, movement towards system design can lead away from exclusive focus on cost towards a more balanced focus on quality, and functional and environmental performance.

OTHER REQUIREMENTS

There is an electromagnetic energy standard in Europe that requires that electronic components are silent 30 feet away.

Beyond ISO 14000 certification, OEM requirements are generally "cookbook" constraints on material content, etc. Requirements relating European product take-back laws have not yet been transmitted through the supply chain.

PRIORITIES FOR FUTURE WORK

Research priorities include cleaner foundry technologies, more benign hard coatings (such as anodizing, hard plating, etc.), and more environmentally benign cleaning technologies. Another important area is facilitating access to environmental technologies through better data and information exchange protocols. Hybrid vehicles are seen as viable, and Federal-Mogul could build a hybrid engine. Some skepticism was expressed about fuel cells and explosion risks.

Site: **Ford Motor Company**
Ford Research Laboratory
PO Box 2053
Dearborn, MI 48121-2053
URL: http://www.ford.com

Date: June 15, 2000

WTEC Attendees: C. Murphy (report author), D. Bauer, T. Gutowski, T. Piwonka, J. Sutherland

Hosts: R.C. McCune, Manufacturing Systems
J. Braslaw, Materials Science Dept.
K.A. Waskiewicz, Facility Environmental Programs
J.C. Trabin, Advanced Manufacturing Engineering
I. Skogsmo, Environmental Safety Planning
R. Frederick, Corporate Responsibility
R.S. Marano, Chemical Engineering
B.R. Kim, Chemistry Dept.
S.A. Pezda, Emissions Control Analysis
R.A. Pett, Materials Science Dept.
J.L. Sullivan, Chemistry Dept.

BACKGROUND

Ford Motor Company was founded in 1903 and has its headquarters in Dearborn, Michigan. Ford Automotive Operations (FAO), which consists of Ford, Mercury, Lincoln, Volvo, Mazda, Aston-Martin, Jaguar, Land Rover, and Th!nk, is the largest producer of trucks and the second largest producer of passenger cars and vehicles worldwide. 7.2 million vehicles were sold in 1999, for a sales revenue total of $137 billion. In addition to FAO, Ford Motor Company includes Ford Motor Credit Company, Ford Motor Land Services Corporation, Quality Care, Kwik-Fit, and the Hertz Corporation.

William Clay Ford, Jr. (Chairman of the Board) and Jacques Nasser (President and CEO) have both made public statements regarding Ford's commitment to the “triple bottom line” (financial, environmental and social) and plan to create future markets based on a wide-range of stakeholders. One of the primary goals of the Ford Environmental System, implemented in 1996, is ISO 14001 certification on a global scale. Four Ford plants were the first automotive manufacturing facilities in North America to receive ISO 14001 certification and all manufacturing sites were certified by 1998. The company is now working with its first tier suppliers to help them become certified as well. Facilities such as the new assembly plant adjacent to the Rouge River in Dearborn, will be designed for a high level of environmental consciousness.

OPERATIONS AND MANUFACTURING

Environmental considerations in vehicle manufacturing are covered by five primary goals: (1) substitution of managed materials, (2) decreased resource consumption, (3) increased use of light weight materials and optimized structural designs, (4) pollution abatement, and (5) health and safety. One of the greatest environmental challenges to Ford (as with all automotive companies) is the painting process. While there has been an 80% reduction in solvent emissions (pounds per vehicle) in the last 20 years, this is still the largest area of concern. If all waste products and emissions for the painting process are taken into account, VOCs (Volatile Organic Compounds) are by far the most significant, accounting for 80% of the TRI (Toxic Release Inventory) data. Ford is pursuing five basic research areas for potential emissions reduction. These are: (1) paint-booth airflow, (2) controls for phosphate bath chemistry, (3) high transfer efficiency, (4) decreased volume of solvent, and (5) paint-booth simulation. Ford is investigating biological removal of VOCs from air and water used in painting operations.

The results of an investigation that examined VOC emissions from various paint systems were presented. The study included Ford and non-Ford plants worldwide. A plant using water-based slurry clear coat produces 20 g/m^2, whereas a plant using solvent-based clear coat (with vapor controls in place) produced 13 g/m^2. The explanation for these unanticipated results lies in where the system boundaries are drawn. If the entire process is taken into account, the solvent-based paint has lower VOC emissions (g/m^2) than the water-based paint because the equipment for the water-based system is much more difficult to clean and requires solvent to do so. A European competitor's plant using powder primer was found to produce 47 g of VOC emissions per m^2 of painted surface, contrary to the perception of lower emissions from powder paint. This is because the reporting requirements are such that a plant using powder paint for any of the three coats (primer, basecoat or clearcoat) need not report, and hence control, VOCs from other coating steps. Therefore, as is indicated by Ford's findings, actual overall emissions from a plant using powder paint can be higher than those from a plant using solvent-based paint with proper VOC controls in place.

The second greatest area of environmental concern is metalworking, where spent metalworking fluids and part-wash water are major sources of oily wastewater. Ford has found that one of the most effective means of reducing water usage is simply metering its use in order to increase awareness. In addition to washer process control, recycling methods incorporating oil removal and recovery have resulted in an almost totally regenerative system in one manufacturing operation (transmissions). Various physical, chemical and biological methods for treating the oily wastewater are being investigated. Oil mist reduction strategies and “dry” or “near-dry” machining are also under investigation and development. In conjunction with Wayne State University and the Lubrizol Corporation, Ford has developed a shear-stable polymer additive to reduce oil mist from metalworking operations.

Energy reduction is also of general concern. Ford's goal for the year 2000 is to reduce energy consumption by 2.25% , which they believe will be a challenge. In addition, they will be purchasing energy from natural gas rather than coal-fired sources whenever possible.

Material Selection

Ford has had longstanding programs in the development and use of lightweight materials—including polymers, composites, aluminum, high-strength steel, and magnesium—for reducing overall vehicle weight with attendant improvement in fuel economy. A number of manufacturing issues surround the widespread use of these materials in mass-manufactured vehicles. For example, typical concerns in manufacture of aluminum-intensive vehicles include the use of adhesives, sealers and fasteners for aluminum panels, which also increases difficulty of disassembly and recycling at end-of-life. Ford is also exploring increased use of painted plastic panels for exterior surfaces.

Life Cycle

Ford has had an active life-cycle group for the past eight years. The goal of this group is to help develop a picture of what it really means to be sustainable and identify how to get there. They have done extensive work in life-cycle inventory, a portion of this in conjunction with USCAR, and are now focusing on impact. In particular, they are trying to define a few of the most relevant categories. Boundaries are drawn around the factory and to some extent include Ford's suppliers, with the view that this is the appropriate sphere of influence. A major problem is the availability of information for the processes and materials considered for analysis. The need for an international (or at least a national) database was expressed.

Recycling

Ford seeks to be a leader in both recyclability and the use of post-consumer recycled materials in its products. In their 1999 *Environmental Report* (p. 19) the Focus is highlighted as an example. This car has an 85% recyclability potential by weight and has been designed to facilitate dismantling. (The American Plastics Council has recently initiated development of a roadmap to address the use of plastics in automobiles, with recovery and recycling being strategic targets.)

In order to more fully understand and capitalize on the dismantling aspect of the recycling process, Ford has recently acquired 25 automobile dismantlers. These dismantlers receive between 3 to 5 cents per pound for the vehicle hulk from the shredder, plus any values for the dismantled parts. In subsequent steps of vehicle shredding and materials processing, the metallics constitute the primary value source with most plastics currently remaining as auto shredder residue (ASR) which is either landfilled or may be used as a fuel source. The apparent paradox between end-of-life vehicle value based on weight by the dismantler, and needs for weight reduction of the vehicle, may favor the fuel economy benefit of weight reduction in the long run. A greater difficulty is associated with economic reclamation of polymers if their use fraction continues to increase.

The cost of recycling can be minimized in areas where parts or materials are already being recovered or where recovery is relatively simple. For example, the recycling of polypropylene cases used for batteries is economic because the acid and lead are already being recycled. Also, the polyethylene film used to cover new seats is easy to collect at the dealer.

Aluminum recycling is expected to be a challenge, largely in the area of sorting wrought from cast metal. This issue would potentially have a large influence on the economics of mass-produced aluminum body structures and their recycling. Other areas where work is needed for improved recycling capability are surface technologies and material identification (especially metals with binary systems such as high copper aluminum, black plastics and rubber products).

FUTURE ACTIVITIES AND CHALLENGES

Among Ford's challenges in the years ahead are the homologization of its business units to exploit best practices and methods in areas such as the environment, while also maintaining the individuality and distinctiveness of its brands. Volvo, for example is highly regarded with respect to its concern for the environment in its facilities and products, so that, for example, the parent organization may capitalize on an existing experience and knowledge base which can be shared throughout the enterprise. In the case of the emerging network of dismantlers, it may be possible, for example, to develop and incorporate a unified model for the appropriate environmental management system, thus exploiting the more specialized nature of these businesses and building on a common theme. In the context of ISO 14001, Ford is developing a uniform set of metrics, especially for VOC emissions and waste, that will allow for a universal coding, performance rating, and reporting of quarterly data.

Over the years, there has been a significant shift in thinking within Ford from a focus on “end-of-pipe” solutions to manufacturing emissions, to those emphasizing minimization and prevention. The great challenge ahead, as with many manufacturing companies, lies in the holistic integration of “design for the environment,” in which the product, manufacturing and environmental communities work concurrently on the totality of product “systems,” which now include their manufacture, use and disposal.

Site: **General Motors Corp.**
Chemical & Environmental Sciences Lab
GM Research & Development Center
30500 Mound Road
Warren, MI 48090-9055

Date: June 16, 2000

WTEC Attendees: J. Sutherland (report author), D. Bauer, T. Gutowski, C. Murphy, T. Piwonka

Hosts: Jerry D. Rogers
Ronald L. Williams
S. Darsh Kumar
Alan K. Henry

BACKGROUND

Founded in 1908, General Motors is the world's largest industrial corporation and vehicle manufacturer. In 1998, GM employed 594,000 people and partnered with over 30,000 supplier companies worldwide. GM has manufacturing facilities in 30 countries, and in addition to its automotive operations also has other business interests (e.g., financial/insurance services (GMAC), locomotive group, and Hughes Electronics Corporation). The corporate revenues for 1998 were over $155 billion and 83% of the revenues were associated with automotive operations. General Motors Automotive Operations includes: (i) GM North America (Buick, Cadillac, Chevrolet, GMC, Oldsmobile, Pontiac, Saab, and Saturn), producing 5 million vehicles and $94 billion in revenue in 1998; (ii) GM Europe (Cadillac, Chevrolet, Isuzu, Opel, Saab, and Vauxhall), 2 million vehicles and $25 billion in revenue; (iii) GM Asia Pacific, 150,000 vehicles and $3 billion revenue; and (iv) GM Latin America, Africa, and Mid-East, 500,000 vehicles and $7 billion revenue. GM spun off Delphi Automotive Systems in mid-1999, and as a separate entity it focuses on manufacturing automotive components/systems; revenues are approximately $30 billion.

ENVIRONMENTAL DIRECTIONS

Initial discussions were centered on the life-cycle inventory (LCI) performed by the United States Automotive Materials Partnership Life-Cycle Assessment Special Topics Group (USAMP/LCA). Many of these results of this LCI are described in the *Proceedings of the SAE Total Life Cycle Conference* that was held in 1998 in Graz, Austria. The LCI was jointly performed by individuals from GM, Ford, Chrysler, AA (Aluminum Association), AISI (American Iron and Steel Institute), and the APC (American Plastics Council). The LCI was performed on a generic 1995 mid-size vehicle (Chevrolet Lumina, Dodge Intrepid, and Ford Taurus), and the vehicle was organized into six systems (powertrain, suspension, HVAC, electrical, body, and interior). For each part within the vehicle, the material type and mass were identified. The generic vehicle had a mass of 1523 kg, used gasoline as a fuel source, had a fuel efficiency of 23 mpg (city 20 and highway 29 mpg), and had a service life of 120,000 miles. The following life-cycle stages were included in the study: (i) raw material acquisition/processing, (ii) part and sub-assembly manufacturing, (iii) vehicle assembly, (iv) use, and (v) disposition. For each life-cycle stage, data on the following characteristics were collected: energy usage, water consumption, air emissions (e.g., particulates, CO_2, and NO_x), water emissions (e.g., oils/greases and metals), solid wastes, and raw materials consumption. Key findings of the LCI include:

- Throughout the entire vehicle life cycle nearly 1000 GJ of energy is consumed and 2900 kg of solid waste is generated.
- The usage stage of the vehicle life cycle contributes 84% of the energy, 94% of the CO, 90% of the NO_x, 62% of the SO_x, and 91% of the non-methane hydrocarbon emissions.

- The material production and manufacturing stages of the life cycle have the following associated environmental burdens: 14% of the energy, 65% of the particulates, 94% of the water-borne metals, and 67% of the solid waste.
- The disposition stage of the life cycle has small environmental consequences, the exception being that 7% of the solid waste is produced at this stage.
- About 1400 kg of the solid waste is produced (roughly 80% from powertrain, suspension, and body manufacture) and 160 GJ of energy is consumed (nearly 60% associated with powertrain, suspension, and body manufacture) in the material production and manufacturing stages of the life cycle.

Conversation then shifted to activities associated with vehicle end-of-life (VEOL). The Vehicle Recycling Partnership (VRP), a consortium between GM, Chrysler, and Ford, has been examining this issue for several years. A number of take-back regulations (designed to reduce the amount of landfill at VEOL) are planned/being implemented in Germany and Japan, e.g., only 5% of the vehicle to be landfilled by 2015. This represents a challenge since at present about 75% of the vehicle (mostly ferrous and non-ferrous metals) are recycled in the U.S. To meet VEOL targets, a number of changes must be considered, including: product configuration, material selection, dismantling processes, shredding processes, sorting/recovery processes, and part reuse. The work of the VRP on the VEOL issue is reported in the *Proceedings of the SAE Total Life Cycle Conference.* As part of the VRP effort, a model for the material flows in the automotive industry has been established. This model includes such elements as automakers, vehicle usage, vehicle maintenance/repair, vehicle rebuild, dismantlers, shredders, and transforming/supplying industries. The model allows the stakeholders to understand what levels of recovery efficiency are needed for each element in order to meet the mandated targets. In the context of VEOL, it was noted that commercial dismantlers are profitable at recovering materials/components from used vehicles, and that in fact, GM has written up dismantling instructions for their European operations based on the procedures of the dismantlers.

A number of internal efforts are underway at GM that are directed at promoting the environment. First, GM participates in a number of consortia/organizations with other companies and government agencies on environmental activities. DFE (design for the environment) guidelines were distributed to design engineers within GM in 1993 and DFE groups have been established within the divisions to serve as resources. A company-wide initiative is underway to standardize the environmental performance criteria that are being used. A list of restricted materials has been distributed to GM suppliers, and the tier 1 suppliers have been notified that they need to be ISO 14001 certified by the end of 2002. It is believed that the management of environmental information across the supply chain represents a growing concern. It is also unclear how the spin off of manufacturing entities such as Delphi will impact the environment.

Life-cycle analysis (LCA) is gaining acceptance within GM as a tool for identifying improvement opportunities, e.g., processes with copious waste streams, high impact products, and large energy consumers. Factors being considered in the analyses include: resource depletion, energy usage, airborne emissions, ozone (both tropospheric and stratospheric), global warming, water usage, health/safety risks, and solid wastes. Several popular software tools (GaBI, SimaPro, and EcoBalance) are being used to perform the LCAs. Some of the perceived deficiencies within the existing LCA tools/framework are:

- Uncertainties and poor quality of the underlying data
- Missing data
- Large amount of time required to perform the LCA
- Spatial and temporal differences not properly reflected in the data
- Management often prefers a single number rather than multi-dimensional vector of results
- Subjective information

The systems view required to conduct the LCA represents a positive, but often overlooked, outcome of the environmental activity. Much work remains to more fully integrate LCA into the DFE activities and the design engineering processes currently being employed at GM. Also of interest would be a rapid method to compare product/process alternatives from an environmental standpoint.

In terms of the environmental issues associated with manufacturing, the following processes are being investigated: (i) machining-cutting fluid concerns, (ii) part cleaning-wastewater generation, (iii) casting, and (iv) painting. Much discussion then ensued on painting processes. Specifically, the pre-coating of the steel was identified as one desirable solution to some of the painting-related concerns. Steel coils delivered in a coated/primed form may offer the following advantages: improved corrosion resistance, reduced environmental burden, reduced paint shop investment, lower losses to rust/stain, and reduction in stamping process lubricants. Of course, the use of pre-coated/primed steel sheet in lieu of painting has a number of technical challenges: development of appropriate coating formulation, suitability for welding and forming operations, corrosion protection, adhesion properties, color matching, and compatibility with existing systems.

Site: **Interface Americas, Inc.**
P.O. Box 1503, Orchard Hill
LaGrange, GA 30241

Date: June 6, 2000

WTEC Attendees**:** T. Gutowski (report author), B. Bras, C. Murphy

Hosts: David H. Gustashaw, VP Engineering

INTRODUCTION

Interface Americas is part of the international company Interface Inc., with operations in Europe, Asia and the Americas and annual sales of $1.3 billion. Interface Inc. is a recognized leader in the worldwide commercial interiors market, offering floor coverings, fabrics, interior architectural products and specialty chemicals. The company is the world's largest manufacturer of modular carpets and also provides specialized carpet replacement, installation and maintenance services through its Re:Source Americas service network. Interface is also a leading producer of interior fabrics and upholstery products and produces raised/access flooring systems. The company produces adhesives and chemicals used in various rubber and plastic products, offers Intersept, a proprietary antimicrobial used in a variety of interior finishes, and sponsors the Environsense Consortium in its mission to address workplace environment issues.

Much of the motivation for Interface's position as an industrial leader in environmental responsibility comes from the company's founder, chairman and chief executive officer Ray C. Anderson. The company philosophy and operating guidelines were clearly and enthusiastically presented to us by David Gustashaw, vice president for engineering. The company takes a sensible "systems" approach to efficiency which can translate into both environmental responsibility and economic advantage.

A key feature of the systems approach is to know both where you are and where you want to go. This requires the use of metrics that are both accessible and easy to understand. For many companies, the key metric is cost, but there are lots of examples where local cost optimization can lead to system inefficiency. The right metrics proposed by Dave Gustashaw are: (1) mass balance, (2) energy balance, and (3) cost. According to Gustashaw a focus on the first can often incorporate the second and the third. This simplified approach allows a company to know its "gas mileage" and to get everyone working in the same direction. Knowing where you are on a systems level is extremely important.

Interface then builds on this knowledge. Their systems approach involves (1) quantification (metrics), (2) qualification, and (3) symbiosis. The idea is that symbiosis with nature will be good for the customer as well as all other stakeholders. Hence, Interface does not just sell carpet but attributes which are in the best interest of the entire system. This approach directs attention to previously ignored opportunities, for example attention to both air and water usage, an emphasis on increasing the product residence time with the customer, and a score of other details that will improve mass, energy and cost.

A good example of a product that embodies this approach is the Solenium carpet. Designed to reduce "mass" consumption, and therefore contribute to sustainability, this carpet has enhanced style and performance. This results in a 35% reduction in material intensity. To achieve this goal the company had to abandon the conventional tufting approach and pursue a different technology. They achieved their goal by designing and fabricating a completely new product using weaving technology.

TOUR OF PRODUCTION FACILITIES

On the tour we were led through the steps for the production of woven and tufted floor coverings. The major production steps are (1) incoming raw materials and warehousing, (2) yarn preparation, (3) tufting, (4) shearing, (5) finishing, and (6) packaging. During the tour we saw numerous examples of process improvements to reduce mass and energy consumption, and to reduce cost. These included energy-efficient oven technology, reductions in air and water consumption, and solar panels.

Site: **IBM**
5600 Cottle Road
San Jose, CA 95193

Date: January 20, 2000

WTEC Attendees: E. Wolff (report author), D. Bauer, C. Murphy

Hosts: Wayne Young, Sr. Engineer, Environmental Programs
Jim Dumanowski, Sr. Engineer, Environmental Programs
Raymond T. Wynn, Program Manager, Environmental Programs

INTRODUCTION

Discussions included policies, management, goals and accomplishments at the San Jose plant site, which designs hard disc drives and other storage devices. General guidelines for environmental policy are established at corporate headquarters in concert with manufacturing divisions; a global view is incorporated whenever manufacturing includes diverse locations.

EBM ACTIVITIES

Environmental policy dates back more than 25 years and now is encompassed in its technology for sustainable world policy. This policy has encouraged expenditures in product design and manufacturing equipment aimed at reduced energy consumption, reduced emissions from manufacturing processes, and reuse and recycling programs. Direction and dissemination of IBM's vision and goals is accomplished through the Corporate Environmentally-Conscious Product program (ECP) that encourages "design for environment" at IBM and its global supplier base. Metrics include products with upgradability to extend product life; products with re-use and recyclability; products that can be safely disposed at end of product life; products which contain and use recycled materials; and products that, through improved efficiencies, reduce energy consumption. Development of new materials and processes in sputtered coatings versus platings, using glass instead of aluminum substances, etc., have made remarkable contributions to the reduction of toxic waste and emissions. ECP metrics also include reducing the amount of manufacturing scrap, IBM-owned end-of-life machines and customer-returned equipment that IBM could send to landfills. In 1999, of the more than 59,000 tons of such waste, the company sent less than 3.7 percent to landfills. Additionally, increased recycling techniques achieved high enough quality levels that 100% of its IBM 6893 Intellistation ProE units could be converted from virgin plastic to recycled plastic.

A major thrust and achievement has been ISO 14000 accreditation for all IBM plants and corporate facilities by the end of 1998.

Furthermore, IBM managers believe that courses involving environmental attributes for products should be instituted at all universities.

Site: **Johnson Controls Inc.**
Automotive Systems Group
49200 Halyard Drive
P.O. Box 8010
Plymouth, MI 48170

Date: June 16, 2000

WTEC Attendees: T. Gutowski (report author), D. Bauer, C. Murphy, T. Piwonka, J. Sutherland

Hosts: George A. Mileskiy, Director of Environment
Ed Delahanty, Chief Engineer, Product Development

INTRODUCTION

Johnson Controls Inc. is a $16 billion (sales) company primarily in the automotive systems and controls markets. We met with the Automotive Systems Group (ASG), whose major products are complete automotive interior design and manufacturing, and batteries. JCI provides interior systems to virtually all major automobile manufacturers worldwide, and they are the world's largest battery manufacturer, selling both to OEMs and to the after market.

As a first tier automotive supplier operating in major automotive markets worldwide, JCI is in a unique position, subject to many different OEM and governmental requirements and specifications. An example of this effect is the multiple company-specific, banned-chemical "black lists." JCI's approach, when possible, is to produce a master list to apply to all customers. This type of solution is in the spirit JCI mentioned to us on several occasions—their goal is to meet or exceed their customers requirements and expectations.

PRESENTATION ON BUSINESS OPERATING SYSTEM

George Mileskiy, Johnson Controls Director for Environment, presented Johnson Controls Inc.-ASG's ambitious plan to implement a new business operating system (BOS). This plan presents a unique opportunity for Johnson Controls to integrate their commitment to the environment into their BOS. An important element of this system is to put in place one global environmental management system (EMS) that would satisfy ISO 14001. (Note that several Johnson Controls facilities currently hold ISO 14001 certification under independent systems that will be converted.) Johnson Controls is also discussing how to work within the supply chain to help their suppliers implement EMSs that will further ensure improved environmental performance and compliance overall. The BOS-based EMS, which represents a common operating system for all of Johnson Controls sites around the world, represents a very ambitious program which deserves attention and follow up. It has eight basic components, including the development of policy and processes, the identification and control of safety hazards and environmental aspects, compliance to regulatory requirements and internal standards, emergency and contingency planning and control, attention to measurables, objectives and targets, a component for education and training, attention to communication, and finally audit management review and systems assessment. The plan is integrated into engineering, leadership, and purchasing, but pays special attention to manufacturing because of the need and urgency of the issues in manufacturing plants. However, at the same time it shows sensitivity to the potential disruption to lean operations. Of particular importance is the realization that full implementation of health, safety and environmental issues will come about only when they are integrated into all of the key parts of business, and when they are tied directly with purchasing decisions. At the same time, there is an awareness of the need to demonstrate leadership and guidance to the smaller companies within the supply chain. JCI-ASG has developed assistance programs to help offset some of the potential disruption and cost impact that health, safety and environmental requirements may impose on their less-developed tier 2 and tier 3 suppliers.

PRESENTATION ON DESIGN FOR THE ENVIRONMENT

In a letter from John M. Barth, the President and Chief Operating Officer for Johnson Controls Inc., the company's commitment to protect the environment is clearly articulated. To this end, the company has developed a strategy and practices to meet their high environmental standards. They base many aspects of their environmental management system and design for the environment approach on the U.S. EPA "Design for the Environment Approach" document dated March 1999. This new commitment systematizes previous efforts and focuses attention through business practices, processes and review. They do this in particular by integrating environmentally conscious practices into their new product launch system. Components of DFE include design for environmental manufacturing, design for environmental packaging, and design for disposal and recyclability. Several examples of environmentally friendly materials and processes were shared with us. These include ECO-COR, a door material that includes renewable natural fiber and polypropylene blend, and AcoustiCOR headliner substrate that contains post consumer recycled PET fibers and PET fiber cushions. The raw material selection strategy targets class "C" surfaces and fabric covered parts for recycled material. They also include an internal recycling plan.

Although not mentioned during our visit, a trip to JCI's Web page will reveal that they are also one of the world's largest battery manufacturers. Batteries are one of the most highly recycled of all products, obtaining recycling levels on the order of 90% and higher. Battery acid is recycled by neutralizing it into water or converting it to sodium sulfate for laundry detergent, glass and textile manufacturing. The plastic is recycled by cleaning the battery case, melting the plastic and re-forming it into uniform pallets. The lead, which makes up 50% of every battery, is melted, poured into slabs and purified.

Site: **MBA Polymers, Inc.**
500 West Ohio Avenue
Richmond, CA 94804
URL: http://www.mbapolymers.com

Date: January 21, 2000

WTEC Attendees: C. Murphy (report author), D. Bauer, E. Wolff

Host: Michael (Mike) B. Biddle, CEO and President

BACKGROUND

MBA Polymers was formed in 1994 by Michael Biddle and Laurence Allen in order to expand research in the area of plastics recycling and to develop a commercially viable process for recovering plastics from mixed waste streams. Several of the company's key personnel are pioneers in the area of plastics recycling and were instrumental in the establishment of a plastics recycling technology group at Dow Chemical prior to the founding of MBA Polymers. The MBA Polymer facility includes a 90,000 square foot state-of-the-art research and commercial recycling operation. Funding has come from grants and research projects sponsored by industry (including automotive, electronics, and electrical), the American Plastics Council, and government agencies (including DoE, DoC, and EPA). Most recently the company raised equity funding for its commercialization from American Industrial Partners and the Silicon Valley Band of Angels. The emphasis at MBA Polymers is on developing automated processes for plastics separation. The company is closely aligned with current efforts in the area of electronic products recycling, including participation in IEEE's International Symposium on Electronics and the Environment, the EPA-sponsored Stakeholders Dialogue on Thermoplastics Recycling (managed by Tufts University), DOE's National Electronics Recycling Center, and DOD's DEER2 program (Demanufacturing of Electronic Equipment for Reuse and Recycling).

MEETING

Problem Identification

MBA Polymers estimates that there are between 15 and 20 billion pounds of engineering thermoplastics available for recycling each year. These high performance plastics are melted at relatively high temperatures and formed into components for many products, especially for the automobile and electronics industries. It is estimated that there are four billion pounds of total plastics per year from the automotive sector, and three to four billion pounds from electrical and electronics products.

Engineering plastics melt at a wide range of temperatures, and temperatures significantly in excess of the melting temperature can result in loss of impact strength and elongation for a particular type of plastic. Consequently, when commingled plastics are remelted in the recycling process, they tend to result either in a product with degraded mechanical properties (from overheating) or lumps (from the portions that are underheated). In addition, some plastics, such as PVC, tend to "poison" the mixture since the PVC degrades easily and one of the degradation products is HCl, which promotes the degradation of other plastics and can cause corrosion of processing equipment. Consequently, recycling of engineering plastics for use in high-end applications requires that they be sorted.

MBA Polymers conducted a study which showed that neither manual nor automated sorting of large pieces is economical (Aroloa, Allen, and Biddle 1998). The techniques evaluated included visual sorting (e.g., general appearance, use of molders labels), benchtop spectroscopy, and automatic spectroscopy-based processes. None of these methods resulted in a stream with the desired levels of purity and cleanliness. In addition, it is not economical to ship large pieces of plastic since the amount (weight) of material that can be shipped on a truck as whole parts is as much as 10 times less than if it is granulated. MBA's model, therefore, says that plastic should be densified (ground up) prior to shipping, and that sorting should take place on small (<1 cm^2) pieces of plastic.

A number of groups have developed sorting techniques for granulated thermoplastic based on density differences. While density separation provides a first-order sorting solution, additional processing is required in order to get relatively pure material streams. This is because the mean densities for different plastic types are very similar, but the density distribution for a given plastic type is relatively large and is influenced by fillers and other agents that are not direct functions of the specific polymer. Consequently, there is significant overlap in density distributions between the different thermoplastics.

As long as the material remains homogeneous, use and remelt do not appear to adversely affect the mechanical properties of engineering thermoplastics, as shown by several studies including one conducted by Dow Chemical (Biddle and Christy 1993). Consequently, the challenge is to create a homogeneous stream. This includes removing contamination (adhesives, paints, metal, etc.) as well as minimizing the amount of commingling in the plastics.

Current Activities

The targeted source materials for MBA polymers are those used by the electronics industry, in part because these are the most readily available, and include high-impact polystyrene (HIPS), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), and blends of PC and ABS. Flame retardant ABS and HIPS are included. MBA also recycles other engineering plastics such as polyphenylene oxide (PPO) and nylon.

Size reduction and liberation is a two to three step proprietary process. Whole loose parts can be processed at a rate of between 2000 and 5000 pounds per hour, primarily due to feed rate limitations; bales of parts or shredded chunks can be handled at rates of between 8000 and 10,000 lb/hr depending upon the material (e.g., PC is much harder to grind than HIPS). Incoming material is ground to pieces of several millimeters in order to be compatible with extruders. If the pieces could be ground a little larger, it would be easier to do color separation. The subsequent separation process can handle 6000 to 8000 lb/hr with variations in rate dependent upon composition. MBA separates granulated plastic and removes non-plastic materials using a highly proprietary, multi-stage process that is in part based on density. The specific process flow may vary depending upon the constituents of the incoming stream. Some color sorting is done, which improves the price by a few cents per pound. MBA does not use a chemically based solution as does Argonne National Labs, where ABS and HIPS are separated using a froth flotation process that relies on an acid pre-treatment to accentuate differences in surface tension.

Needs and Concerns

Mike Biddle believes that MBA Polymers has a good technical solution to separation of engineering plastics for recycling. He believes that the two biggest missing pieces are the means to generating economies of scale (creating significant volumes of uniform feedstock) and economic transportation. It also appears that the majority of computer and electronic equipment is being sent to third world countries today for recycling, making it very difficult to find sufficient sources of plastics to reach the economies of scale necessary to make recycling cost-effective.

Flame retardants (FR) are an issue for ABS and HIPS. For example, it is very difficult to test for specific types of brominated additives. Some types of brominated additives are considered more problematic than others, but all bromine-containing ABS or HIPS are lumped together as FR-ABS or FR-HIPS. This limits the sale of recycled ABS and HIPS to use in products that will not be distributed in Europe. In separate phone conversations with engineers at IBM and Dell, the author has found that this is a major deterrent for using recycled ABS. GE Plastics has a phosphorous-based flame retardant, but it is more expensive than the more commonly used halogenated varieties, and it does not yet appear in most post-consumer streams.

High levels of metal contamination slow down most processes. MBA is working to make the co-recovery of metals and plastics more efficient. Large amounts of stainless steel currently pose the biggest challenge.

It would be helpful if there were a methodology for determining the properties of a plastics mixture without making a 1000-pound batch and testing it. The combination of an in-line mid-IR spectrometer and an XRF might work, but it would have to be cost effective. In addition to characterizing the mix, it is important to identify potential contaminants that might "poison" the final product.

Closed-loop recycling is a challenge because grades and types of plastics are changed so frequently by the molders and because there is such a significant amount of variability. These changes are typically made in response to price fluctuations for raw materials. OEMs also have specifications that may be much tighter than actual tolerances. Opening up specifications might make it easier to use recyclate.

EPA's Buy Recycled program and other preferential procurement programs are helping to increase the demand for recycled materials. General Motors claims that they have loosened requirements to allow for more recycled content. However, there is still a great deal of work to be done in the area of market development.

Mike Biddle believes that there needs to be a more organized effort at the government level in the area of electronics recycling because so many agencies are funding similar projects. He suggests that one of the roles that NSF might play is in supporting curriculum development in the area of design for recycling. More generally, he advocates development of a curriculum supporting a holistic approach that integrates environment, business, economics, and design.

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(There have been over 20 papers published by MBA personnel in this area.)

Site: **Micro Metallics Corp. (Noranda Inc.)**
1695 Monterey Highway
San Jose, CA 95112

Date: January 21, 2000

WTEC Attendees: E. Wolff (report author), D. Bauer, C. Murphy

Host: Mike Mattos, Plant Manager

INTRODUCTION

Computer and consumer electronics contain substantial quantities of valuable materials that require extensive recovery processes to separate those for further use in products.

The parent company of Micro Metallics is Noranda Inc., a global producer of metals, metals exploration, and recycling.

EBM ACTIVITIES

Noranda's view of recycling considers this to be a core area and aligned with its mining and materials conversion processes. Partnerships to process, recycle, reuse, reclaim materials from electronic equipment were established with Hewlett-Packard, Xerox, Compaq, etc.

In addition to materials reprocessing, Micro Metallics also tests and remarkets electronic components to secondary U.S. markets. Micro Metallics employs a significant portion of its 270 employees in the software and hardware evaluation of received components. Unless the OEM specifically requires complete destruction, Micro Metallics solicits bidding for its evaluated and performance capable equipment. This contributes to the prolonged use and re-use so beneficial to environmental issues and adds to Micro Metallics's profitability.

Materials crushing and separation technology at the California facility rely upon proven process technologies from Noranda's portfolio; the systems integrations know-how to specifically develop for recycling had been internally developed as well. Plastics and metallic materials reclaimed from components have predetermined destinations. Metallic materials are reprocessed at Noranda's smelters and refineries. This combination of materials processing knowledge, refining capability, and partnerships with electronic manufacturers insure commercial viability (profitability) as well.

Capacity constraints at the Micro Metallics site may result in additional capacity expansion in the near future. Technology challenges that need to be addressed are improved methods for metallic material segregation. Current methods, i.e., eddy current and magnetic fields, do not sufficiently discriminate and separate the metallic materials.

Process control through in-line diagnostics would further enhance and maintain reliability of product.

Site: **National Center for Manufacturing Sciences**
3025 Boardwalk
Ann Arbor, MI 48197-3266

Date: June 15, 2000

WTEC Attendees: T. Piwonka (report author)

Hosts: Paul D. Chalmer, Ph.D., Business Area Manager, Environmentally Conscious Manufacturing
Daniel J. Maas, Chief Technical Officer

INTRODUCTION

The National Center for Manufacturing Sciences (NCMS) is located in Ann Arbor, Michigan. It was founded in 1984, and forms "cross-sector" consortia to study pre-competitive technology for manufacturing. It currently has approximately 200 industrial members. Funding is provided by membership fees (which are assessed on a sliding scale, depending on the size of the company) and federal and state programs. Company dues currently range from $2500 to $62,500. They are contemplating broadening their funding base by lowering dues.

EBM ACTIVITIES

NCMS carries out a number of technology development programs. Much of their work involves generating test data that member companies share. They also manage three Environmental Protection Agency Compliance Assistance Centers. Among current or recent projects are those on maintenance and logistics, semi-dry machining of aluminum, chromium-free and tri-valent chrome coating systems, biocide coatings for ship ballast tanks (to prevent contamination of ecosystems when ballast tanks are emptied), and molybdenum-free forging die lubricants.

Their representatives shared a number of concerns that they have about current trends in materials technology. They expressed doubt that composite materials would be truly amenable to economic recycling. They were also worried that current highly engineered tailored materials, such as those produced by laser deposition of graded structures, cannot be recovered at the end of their useful life. The specific example mentioned was thermal barrier coated graded tool steels.

They also expressed deep concern that contaminants were building up in scrap materials, such that they would eventually be unable to be recycled. To help solve this problem, they have developed a model which can be used to predict the eventual contaminant level after an unlimited number of iterations of recycling, given the percent contaminant in recycled material and the percent of recycled material added to virgin material in the feedstock. Model results indicate that it approaches a steady state. They were also worried that properties of new materials were, in general, not sufficiently characterized to permit them to be introduced into production. They suggested that an evaluation of the recyclability of new materials be included as a part of the material development process.

One other area of concern was joining of dissimilar materials, or materials that had highly controlled structures (such as micro-grain steels). While adhesives can join these materials, it is not clear what problems adhesives would give during dismantling or recycling.

Dr. Chalmer and Mr. Maas expressed grave doubts that "take-back" laws would be effective in the United States, as it is against the cultural norms in this country. They wondered whether tax incentives might be used to encourage environmentally sound manufacturing and product decisions. They also were concerned about the existence of methods of calculating the true environmental costs of pollution, and the difficulty of knowing how far back in the supply chain it was necessary to go to achieve an accurate estimate.

APPENDIX F. GLOSSARY

AA	Aluminum Association
ABS	acrylonitrile butadiene styrene
AFS	American Foundrymen's Society
AGVs	autonomous guided vehicles
AIGER	American Industry/Government Emission Research
AISI	American Iron and Steel Institute
APC	American Plastics Council
APRA	Automotive Part Rebuilders Association
ASR	automotive shredder residue
BAT	best available technology
BCSD	Business Council for Sustainable Development
BFRs	brominated flame retardants
BOS	business operating system
Br	halogens
CAA	Clean Air Act
CAD	computer aided design
CAE	computer aided engineering
CAFE	corporate average fuel economy
CALA	computer aided life-cycle analysis
CAM	computer aided machining
CARB	California Air Resources Board
CERP	Casting Emissions Reduction Program
CFC	chlorofluorocarbon
CIDI	compression-ignition direct-injection
CMOS	complementary metal-oxide semiconductor
CMP	chemical mechanical polishing
COD	chemical oxygen demand
CPUs	central processor units
CRADA	Cooperative Research and Development Agreement
CRTs	cathode ray tubes
CVD	chemical vapor deposition
D2P	design to prototype
DBDPO	decabromodiphenyl oxide
DCA	direct chip attach
DEER2	DOD's Demanufacturing of Electronic Equipment for Reuse and Recycling program
DFD	design for disassembly
DFE	design for the environment
DFR	design for recycling
DFS	design for sustainability
DOD	Department of Defense
DOE	Department of Energy
DMT	dimethylterephthalate
DRI	direct reduction iron
DWI	draw and wall ironing
EAF	electric arc furnace
EBM	environmentally benign manufacturing
EC	European Commission
EDIP	environmental design of industrial products
EDM	electrical discharge machining
EEA	European Environment Agency

EEMS	enhanced environmental management system
EG	ethylene glycol
EHS	environment, health, and safety
EIAJ	Electronic Industries Association of Japan
ELM	end-of-life management
ELV	end-of-life vehicle directive
EMAS	Eco-Management and Audit Scheme (EU)
EMS	environmental management systems
EOL	end of life
EP	environmental priority system
EPA	U.S. Environmental Protection Agency
ERC	engineering research center
EU	European Union
ECVM	European Council of Vinyl Manufacturers
ESH	environment, safety, and health
FAO	Ford Automotive Operations
FEM	finite element method
FhG	Fraunhofer Gesellschaft
FIFO	first in first out
FMEA	failure mode and effect analysis
FPDs	flat panel displays
FR	flame retardant
HAPs	hazardous air pollutants
HCl	hydrochloric acid
HDI	high density interconnect
HIPS	high impact polystyrene
ICEM	International Committee on Environment and Manufacturing
ICT	information communication technology products
IPC	U.S.-based trade association for the electronic interconnect industry
IPPC	Integrated Pollution Prevention and Control Directive (EU)
ISO	International Standards Organization
JEIDA	Japan Electronic Industry Development Association
JPEC	Japanese PVC Environmental Affairs Council
JSPE	The Japan Society for Precision Engineering
JSTP	Japan Society for Technology of Plasticity
LCA	life cycle assessment
LCI	life-cycle inventory
LEV	Low Emission Vehicle
LNG	liquid natural gas
MACT	maximum achievable control technology
MCC	Microelectronics and Computer Technology Corporation
MQL	minimal quantity lubrication
NAE	National Academy of Engineering
NEDO	New Energy and Industrial Technology Development Organization
NGOs	non-governmental organizations
NMP4	Dutch government’s fourth national policy act
NVMP	Nederlandse Vereniging voor Metaal- en Electro-Producenten, or the Dutch Association for Metal and Electro-Producers

OBDPO	octabromodiphenyl oxide
OEMs	original equipment manufacturers
OIT	DOE's Office of Industrial Technology
Pb	lead
PBBs	polybrominated biphenyls
PBDDs	polybrominated disbenso dioxins
PBDEs	polybrominated diphenyl ethers
PBDFs	polybrominated disbenso furans
PBDPO	polybrominated diphenyl oxides
PBS	poly butylene succinate
PC	polycarbonate
PCB	polychlorinated biphenyls
PCB	printed circuit board
PCs	personal computers
PCCP	pseudo-cylindrical concave polyhedral
PCL	poly hexano-6-lactone
PE	polyethylene
PeBDPO	pentabromodiphenyl oxide
PET	polyethylene terephthalate
PFC	perfluoro compound
PFL	plan for the life cycle
PHA	polyhydroxyalkanoate
PLA	polylactide
PLLA	poly L-lactic acid
PM	particulate matter
PMMA	polymethyl-methacrylate
PNGV	Partnership for a New Generation of Vehicles (U.S.)
POCP	Photochemical Ozone Creation Potential
POTW	publicly owned treatment works
PPO	polyphenylene oxide
PTHs	plated through holes
PVB	polyvinyl butyral
PWB	printed wiring board
QFD	quality function deployment
QFP	quad flat package
RCRA	Resource Conservation and Recovery Act
REM	recyclability evaluation method
ROS	Regional Overslag Station
ROTIM	return or throw in machine
RTP	rapid thermal processing
RTM	resin transfer molding
SBUs	small business units
SCRIMP	Seemann Composite Resin Infusion Molding Process
SIA	Semiconductor Industry Association
SMEs	small and medium-sized enterprises
SMT	surface mount technology
Sn-Pb	tin-lead
SOP	small outline package
SPE	Society of Plastics Engineers
SULEV	Super Ultra Low Emissions Vehicle
SUVs	sport utility vehicles

TBBPA	tetrabromo-bisphenol A, also referred to as TBBA
TCO	The Swedish Confederation of Professional Employees
TCE	trichloroethylene
TFS	tin free steel
TNO	Netherlands Organization for Applied Scientific Research
TPI	toxic potential indicator
TRI	Toxic Release Inventory
TSCA	Toxic Substance Control Act
TSOP	thin small outline package
TULC	Toyo Ultimate Lightweight Can
ULEV	ultra-low emission vehicle
USAMP/LCA	U.S. Automotive Materials Partnership Life-Cycle Assessment Special Topics Group
USCAR	U.S. Council for Automotive Research
VAMAS	Versailles Project on Advanced Materials and Standards
VARTM	vacuum-assisted resin transfer molding
VEC	Vinyl Environmental Council
VEOL	vehicle end-of-life
VOCs	volatile organic compounds
VRP	Vehicle Recycling Partnership
WEEE	Waste Electrical and Electronic Equipment Directive (EU)
ZEV	zero emissions vehicle

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[1] Note: see the WTEC WWW server (http://itri.loyola.edu) for a list of earlier JTECH reports (1984-89) available from NTIS.

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