SETTING PRIORITIES FOR POLLUTION PREVENTION R&D IN THE CHEMICAL INDUSTRY

Bruce Cranford, U.S. Department of Energy
Jack Eisenhauer, Energetics, Incorporated

The development and application of pollution prevention technology in industry is often a synthesis of many considerations. Although companies are primarily driven by the need to reduce wastes to meet regulations and lower control costs, they also seek to increase energy efficiency, reduce material purchases, increase labor productivity, and improve product quality. To achieve these multiple benefits companies must carefully analyze various operating factors and consider a diversity of engineering and managerial perspectives in the project selection process.

Government and non-profit industrial associations that sponsor research, development, and demonstration of pollution prevention technology face a similar challenge. R&D managers must judge which technologies will yield the greatest overall benefit to industry, government, and the public. They must evaluate candidate projects based on their ability to improve environmental performance, reduce energy use, reduce consumption of natural resources, increase industrial competitiveness, and contribute to other policy and business goals. They must also determine which organizations or combination of organizations are best suited to perform the R&D. Collaborations among industry, academia, and government have been shown to offer significant advantages in accomplishing R&D objectives, provided that each organization is used for its greatest strength.

R&D program managers use various methods for setting priorities for their programs. While industrial managers consider numerous factors when selecting projects, choices can usually be rationalized on economic grounds using financial measures that reflect the best available projection of costs and expected returns. Government managers are faced with the challenge of having to satisfy multiple national policy objectives such as reduce emissions, reduce energy use, and increase employment, which are not measured or valued on a consistent basis. This paper describes two complimentary approaches for targeting technologies and products related to the chemical process industry that are expected to yield the greatest national return on R&D investment. The first approach consists of statistical analysis of the production and operating characteristics of manufacturers of specific chemical product classes. This approach can reveal interesting patterns of waste generation but requires extensive data and is limited due to the confidentiality of plant-specific data. The second approach relies upon expert technological and managerial perspectives to identify the major waste problems and technology R&D solutions for a range of corporate situations. These perspectives, which are obtained through facilitated workshops, provide a valuable consensus on opportunities and priorities but do not contain the objective rigor of quantitative data analysis. Together, however, these two approaches provide complimentary information to help identify R&D opportunities and set priorities.

Nowhere are the opportunities to prevent pollution richer and more complex than in the chemical industry. By nearly every measure, the chemical industry is a prime candidate for pollution prevention, energy savings, and associated cost savings (Figure 1) (DOC 1994b). The chemical industry produces nearly 2 billion tons of waste each year and is responsible for one-fourth of all energy used in manufacturing (Eisenhauer 1994). It is responsible for 91% of all hazardous wastes in industry and spends the most for pollution abatement and control -- $6.3 billion in 1993. It is also vitally important to the U.S. economy, posting

Figure 1. Chemical Industry Profile

Employment (1992):	850,300
Value of Shipments (1992):	$305.8 billion
Trade Balance (1993):	+$15.1 billion
Avg. Hr. Wage (1992):	$15.25
Energy Consumption (1991):	5.05 quads
Energy Expenditures (1991):	$15.9 billion
Waste Generation (multiple):	1.84 billion tons
Pollution Control Costs (1993):	$6.3 billion

a $15.1 billion trade surplus in 1993 (DOC 1994a). Accordingly, investments in pollution prevention R&D within the chemical industry are expected to yield very large environmental and economic benefits.

At the same time, the chemical industry manufactures over 50,000 different chemical substances and serves many different markets, making it difficult to apply broad solutions to waste problems. The industry consists of key segments that include organic chemicals, inorganic chemicals, paints and coatings, adhesives and sealants, and agricultural chemicals. Products from these segments feed into related industries such as drugs and pharmaceuticals, plastic resins, soaps and detergents, and cosmetics. The chemical industry also supplies a multitude of products to other major industries such as pulp and paper, automobile production, textile, agriculture, and printing.

The U.S. Department of Energy's Office of Industrial Technologies has used several methods to identify opportunities for pollution prevention and set R&D priorities. This program, which funds industrial pollution prevention and energy efficiency R&D projects in collaboration with industry, states, and other federal agencies, focuses on industries and problems that present substantial waste reduction and energy saving opportunities. For the past three years, DOE has worked cooperatively with the Center for Waste Reduction Technologies (CWRT) and the Bureau of Census to assess opportunities for chemical pollution prevention. More recently, DOE has embarked on a bold initiative with the entire chemical industry, led by the American Chemical Society, the Chemical Manufacturers Association, and the American Institute of Chemical Engineers, to develop a vision of the future of the industry and the technology and research needed to achieve it. The evolution of these collaborations and related efforts to establish R&D priorities for the chemical industry are outlined below.

TARGETING INDUSTRIES

DOE analyzed the manufacturing sector to determine which industries face the most significant waste and energy challenges. Because waste reduction is tied to many operating considerations, several important factors were examined: energy use, nonhazardous waste, hazardous waste, toxic releases, air emissions, and pollution abatement costs. Several economic measures were also considered such as value of shipments and capital expenditures. The results indicate that of the twenty major manufacturing industries, five industries -- chemicals, petroleum, pulp and paper, primary metals, and stone, clay, and glass -- account for the vast majority of waste generation, energy use, and pollution control expenditures. This is not surprising considering the size and nature of these industries. All are *process-oriented industries* that are characterized by continuous processes, high water consumption, large byproduct streams, heavy chemical production and use, and diverse and unique waste profiles. They are also "weight-reducing" industries that use large quantities of raw materials to produce much smaller quantities of finished product. Accordingly, the Office of Industrial Technologies has reoriented its technology program to focus on the research needs of seven energy- and waste-intensive process industries. The chemical industry ranks very high for each characteristic and is thus a prime target for pollution prevention and energy efficiency improvements (Table 1).

Table 1. Relative Importance of Manufacturing Industries

Rank	Energy Use	Nonhazardous Waste	Hazardous Waste	Toxic Waste	Air Pollutants	Pollution Control Costs	Value of Shipments	Capital Expenditures
1st	Petroleum	Pulp & Paper	*Chemicals*	*Chemicals*	*Chemicals*	*Chemicals*	Food	*Chemicals*
2nd	*Chemicals*	*Chemicals*	Petroleum	Primary Metals	Primary Metals	Petroleum	Trans. Equipment	Trans. Equipment
3rd	Primary Metals	Primary Metals	Primary Metals	Petroleum	Petroleum	Pulp & Paper	*Chemicals*	Food
4th	Pulp & Paper	Stone, Clay, Glass	Electronics	Fabricated Metals	Pulp & Paper	Primary Metals	Industrial Equipment	Electronics
5th	Food	Food	Metal Fabrication	Electronics	Stone, Clay, Glass	Food	Electronics	Industrial Equipment

POLLUTION PREVENTION OPPORTUNITIES IN THE CHEMICAL INDUSTRY

Chemical products are pervasive throughout industry and are often the primary source of environmental concern among manufacturers. Nearly every industry uses chemicals as material inputs, to clean parts and equipment, to protect surfaces of products, etc. The interdependency between the chemical industry and their industrial customers has been the cause of much of the economic success of the chemical industry and a cause of recent concern over future market growth. Faced with increased environmental regulations and associated costs, many manufacturers are turning to alternative processes that greatly reduce their use of traditional solvents, coatings, adhesives, and detergents. The ability of chemical companies to respond effectively to emerging customer needs for cleaner production and products will help determine the future profitability of the industry.

Many of the major chemical companies have recognized the need to consider a comprehensive approach to pollution prevention. These companies have looked at upstream and downstream consequences of their material requirements, production operations, product use, and disposal in a life-cycle context. This perspective, sometimes referred to as industrial ecology, considers the major sources of waste generation in an integrated system. In setting R&D priorities in the chemical industry, the full range of pollution prevention options for chemical plant design, chemical production, and chemical use should be evaluated.

Two basic approaches were used by DOE to target the technologies and products related to chemical production and use that can yield large returns on R&D investment. The first approach consists of data analysis of the production and operating characteristics of manufacturers of specific chemical product classes. This approach can reveal interesting patterns of waste generation but requires extensive data and is limited due to the confidentiality of plant-specific data. The second approach relies upon expert technological and managerial perspectives to identify the major waste problems and technology R&D solutions for a range of corporate situations. These perspectives, which are obtained through facilitated workshops, provide a valuable consensus on opportunities and priorities but do not contain the objective rigor of quantitative data analysis. Together, these two approaches provide complimentary information to help identify R&D opportunities and set priorities.

Data Analysis

The Bureau of the Census (BoC), in a joint effort with DOE's Office of Industrial Technologies, has analyzed a wide range of detailed economic, energy, and waste data on U.S. manufacturers. Their most recent analysis examines the relationship between several economic and operating factors and the level of toxic intensity (toxic waste releases per dollar of production) for specific product classes within the chemical industry (Streitwieser 1993). BoC developed an econometric model that analyzed the effect of labor costs, energy costs, capital costs, plant location, plant age, materials costs, and electricity costs on the toxic intensity for 2,158 chemical plants in 112 chemical product classes (five-digit SIC level) using the 1987 Census data set. Their model was able to explain 57 percent of the observed variation in toxic intensity across plants (adjusted $R^2 = 0.571$).

The model results were examined in conjunction with the distribution range of each product class, the total toxic releases, and the number of plants to identify chemical sectors that are prime candidates for pollution prevention R&D. Of particular interest was the distribution range which provided insight to the variation among similar plants. Results of the BoC analysis are shown in Table 2.

Table 2. Priority Chemical Product Classes for Pollution Prevention R&D

Industry	SIC
Finishes for equipment manufacturers	28512
Thermoplastic resins and plastics	28213
Themosetting resins and plastics	28214
Liquified refinery gases	28691
Special purpose coatings	28513
Synthetic rubber	28220
Chemical preparations	28995

Expert Judgements

Data analysis cannot serve as a substitute for the technological insights that can be gained from the judgements of experienced professionals in the industry. These insights, which help guide specific R&D investment decisions, have been obtained by DOE through a series of workshops that focus on different aspects of chemical production, process design, and chemical use. The results of these workshops, which were jointly planned and sponsored by the Center for Waste Reduction Technologies, go a long way toward establishing national pollution prevention R&D priorities for chemical manufacture and use.

The first workshop, ***Waste Reduction R&D Opportunities in Industry***, was held in 1991 (Eisenhauer 1991). While the topics covered several manufacturing industries, the strong representation from the chemical process industries favored problems and opportunities facing these industries. The participants, fifteen senior technology and environmental managers from CWRT's industrial membership, identified 13 categories in which R&D is needed to exploit pollution prevention opportunities in chemical production. Over 80 distinct R&D needs were identified by the participants, covering areas such as process control, materials substitution, separation techniques, and byproduct reuse.

Table 3. Pollution Prevention R&D Priorities for Chemical Producers

Separation Techniques
- Separation of dilute organics from water*   - Salt recovery from aqueous streams   - Low-cost sorbent regeneration process*
Process Development
- Alternative in-process separation techniques for organic/inorganic/aqueous*
Pollution Prevention
- Dilute VOC emission control*
Byproduct Reuse
- Sludge detoxification process
Design Concepts
- Recovery alternatives to incineration   - Total water reuse*
Analysis
- Setting priorities for waste reduction*
Post-Consumer Recycling
- Post-consumer recycling, upgrading, & separation
* *Top priority areas*

The workshop participants were asked to identify their most important R&D needs. A summary of the top selections is shown in Table 3. A more detailed assessment of problems, solutions, and R&D activities was conducted for the six priority areas indicated in Table 3. The findings of this workshop were used by both DOE and CWRT to initiate several projects in their respective R&D programs.

In November 1994, the CWRT held a strategic planning meeting to revisit the priorities and needs of their industrial members. Six priority needs were identified: total water reuse, VOCs in dilute air, separative reactors, fundamental understanding of high selective reaction process, pollution prevention database, and in-situ soil remediation. With the exception of the last two areas which are not strictly pollution prevention technologies, these results closely match the results of the 1991 workshop.

The second workshop, ***Environmental Considerations in Process Design and Simulation***, was jointly sponsored by DOE, CWRT, and the Environmental Protection Agency (EPA) in 1992 (Eisenhauer and McQueen 1993). This workshop topic was more narrowly defined: how to incorporate environmental concepts in the design stages of process development. If properly executed, relatively small investments to improve process simulators and design tools could lead to substantial materials and energy savings that accrue year after year.

This workshop included leading national experts in process design drawn from a community of industrial design engineers, software developers, university professors, and federal R&D managers. The fifty participants carefully assessed how process simulation can take advantage of the latest advancements in design methodology, simulation techniques, computer architecture, and programming models. Opportunities were examined for four separate areas: *environmental considerations in process design, model needs, design tools and simulators,* and *data needs.* This collaboration among the industrial, university, and federal R&D communities produced a general national consensus on process simulation needs for pollution prevention. Summary results are shown in Table 4.

In February 1995, DOE held a follow-up planning workshop to identify priorities for process design tool R&D that are consistent with the needs of the seven process industries that are the focus of the Office of Industrial Technologies programs (DOE 1995). The most important process design tools identified by the workshop participants were quantitative risk analysis tools, a materials selection tool directed towards end-use, chemical reaction pathways, separation technologies, and on-line and global optimization to provide cost/benefit analysis for risk-based design.

The third major workshop, ***Waste Reduction R&D Priorities for Industrial Manufacturers***, was held in 1993 as a joint effort between DOE and CWRT (Eisenhauer and McQueen 1994). This workshop examined the special needs of the chemical user community -- manufacturers outside the process industries that engage in material fabrication, assembly, and finishing operations. These firms use chemicals in small to moderate amounts for more specialized tasks and may not be able to take advantage of the pollution prevention technologies available to large manufacturers and users that handle large byproduct streams.

The workshop included fourteen participants representing several industries including electronics, automotive, aerospace, pharmaceuticals, chemical producers, and several national centers engaged in industrial pollution prevention R&D. Two areas were examined: opportunities in finishing and assembly operations and opportunities in environmentally conscious manufacturing. The key results of this workshop are summarized in Table 5.

Comparison of Results

Comparing the R&D priorities of the chemical producers workshop with those of the chemical users workshop reveals interesting similarities and

Table 4. Chemical Process Design Needs

Process Synthesis
- Develop methods to synthesize chemical processes - Evaluate alternative reaction pathways - Determine "ultimate" limiting process efficiencies - Develop expert systems for process synthesis - Couple synthesis and simulation
Dilute Streams
- Improve simulation tools for dilute streams - Determine reaction rates and byproducts - Determine equilibrium partitioning constants
Optimization Methodologies
- Develop non-linear optimization strategies - Enhance stochastic modeling and optimization - Develop methods for dynamic optimization of processes
Modeling Techniques
- Improve probabilistic and stochastic modeling techniques - Develop large-scale modeling methodologies - Employ parallel computing techniques
Rate-Based (Non-Equilibrium Processes)
- Characterize non-equilibrium phenomena - Improve interfacing and sequencing of rate-based processes
Environmental Costs
- Define costs of various end-of-pipe treatments - Define/quantify intangible costs - Develop methods to allocate costs to processes and products
Environmental Impact Assessment
- Develop an environmental impact index - Develop quick risk assessment techniques - Link ecological and process models
Process Characterization
- Integrate property data into models and simulators - Improve characterization of trace components - Predict environmentally troublesome byproducts

Table 5. Pollution Prevention R&D Priorities of Chemical Users

Finishing and Assembly
- Sensors - Protocol for risk analysis - Dry process development - Life cycle analysis - Materials compatibility testing - Chromium elimination - Development of recovery systems - Methods for measuring cleanliness
Environmentally Conscious Manufacturing
- Tools for estimating environmental impacts - Production control tools and systems - Use of recycled material - Small-scale, economical treatments - Clean part manufacturing - Internal accounting standards for env. costs - Standard methods for characterizing process flows - Ideal/modular separations equipment - Separation technology for post-consumer wastes

Table 6. NCMS Environmental Research Priorities

Environmental Area	*Responses (Total=75)*
Solvent substitution - CFC, VOC	31
Solid waste disposal/minimization (mostly hazardous)	12
Heavy metal source reduction	11
Air emission abatement	11
Air emission monitors	7
Aqueous treatment/recovery	7
Solvent and paint disposal	6
Non-CFC refrigerants, working fluids	6
Plating waste disposal/ recovery	5
Metals and toxic recovery from sludge	5
Soil remediation	5

differences. Several common needs were identified in which R&D investments by industry and government could advance technologies that offer major pollution prevention benefits. These areas include separations, sensors and controls, cleaning, material substitutes, biological controls, and a variety of assessment tools and methodologies. While there were no major areas of disagreement between the groups, there was a difference in emphasis. The chemical producers emphasized the need for a variety of separation technologies and techniques to reduce mixed waste streams and to enable in-process recycling. The chemical users emphasized the need for several types of assessment methodologies and common standards for conducting analysis. These include areas such as life cycle analysis, environmental assessment methods, risk protocols, and environmental cost accounting procedures. The chemical users also placed more emphasis on post-consumer waste issues because many of the products of these companies are purchased directly by consumers.

Related Efforts

Several government and industry organizations have undertaken related efforts to evaluate pollution prevention opportunities and help set R&D priorities related to chemical production and use. The National Center for Manufacturing Sciences (NCMS), which represents about 200 leading U.S. manufacturers, operates six cooperative R&D programs including one on Environmentally Conscious Manufacturing. A 1993 survey of NCMS members asked which specific environmental areas would benefit most from cooperative research. Of the 75 respondents, 31 identified solvent substitution to reduce CFC and VOC emissions as the dominant research area. Other leading priorities are shown in Table 6 (Wixom 1993).

In May 1995, the NCMS Environmentally Conscious Manufacturing group initiated a new survey of member research needs. Members were asked to indicate topics of strong interest within eight key areas: 1) manufacturing solvents and their substitutes; 2) reduce discharge of metals; 3) design, testing, and modeling tools; 4) regulatory and policy issues; 5) recycle, remanufacture, reuse; 6) reduced emissions from coating, stripping, and adhesive processes; 7) education and training; and 8) remediation and treatment. The results of the survey are expected to be available in July 1995.

DOE's Office of Energy Research completed a research needs assessment for waste plastics recycling in December 1994 (DOE 1994). The purpose was to identify technological options for waste plastic recycling that offer significant national energy benefits compared to direct combustion of these wastes in advanced waste-to-energy power plants. The study considered a systems approach that considers the energy associated with collection, sorting and reclamation, and reprocessing or chemical conversion. DOE's approach involved an intensive review of literature, use of expert consultants, interviews, surveys, site visits, a two-day conference, and a 28-person peer review panel. The study identified numerous research needs, including four areas that deserve the highest research priority:

1) development of low-cost and efficient processes to separate and purify plastics,
2) analytical methods and instruments to identify plastic constituents in mixtures,
3) improvements in the properties of immiscible plastic mixtures, and
4) development of new uses and applications for reprocessed/recycled plastics.

TOWARD A CHEMICAL INDUSTRY TECHNOLOGY ROAD MAP

Perhaps the most comprehensive effort to identify technology needs and research priorities in the chemical industry is currently underway through the Technology and Manufacturing Competitiveness Task Group. This group was formed in 1994 by leading organizations in the chemical industry to identify and meet the future technology needs of U.S. chemical manufacturers and users. The group enjoys broad industry involvement through the participation of the American Chemical Society, the Chemical Manufacturers Association, the American Institute of Chemical Engineers, and the Synthetic Organic Chemical Manufacturers Association. The Task Group is developing a comprehensive technology vision and road map for the industry for 2020. Of the four work groups that have been established, the group on New Chemical Sciences and Engineering Technologies (NCSET) has the greatest responsibility for identifying new chemical process research priorities.

In May 1995, the Task Group met to review and critique the draft technology visions of each of the work groups. The NCSET work group developed initial research priorities within six categories: chemical synthesis, biotechnology and bioprocessing, materials, process science and engineering, chemical measurement, and computational technologies. Because pollution prevention in the chemical industry is integral to the processes, many of the priority research needs identified by NCSET are similar to those identified in the DOE-CWRT workshops. For example, improved separations, tools to model chemical synthesis, devices for measuring hazardous waste streams, and life-cycle analysis tools were all noted as research priorities.

The technology road map developed by the NCSET work group and the overall Task Group will be used by DOE's Office of Industrial Technologies (OIT) to help guide their research program for the chemical industry. OIT has structured much of its technology program around meeting the energy, environmental, and economic challenges of seven energy- and waste-intensive industries: chemicals, petroleum refining, forest products, steel, aluminum, metal casting, and glass. This approach, known as the *Industries of the Future* concept, begins with the development of an industry vision by companies, industry associations, and research groups that comprise the industry. Where appropriate, OIT facilitates this process and encourages industry to develop a technology road map and associated research and development agenda. In the case of the chemical industry, the NCSET provides an existing and logical forum for developing R&D priorities. OIT plans to develop its program around these priorities where they match OIT's mission requirements and are appropriate for federal involvement.

CONCLUSIONS

The efforts of the chemical industry over the past five years to confront the future environmental and energy challenges of its companies and customers will help sustain the United States as the global leader in responsible chemical production. By investing in new research to improve chemical production processes and meet product needs of customers, the chemical industry will continue to increase profits and remain a critical component of the U.S. manufacturing base.

The integration of data analysis and expert judgments provides a powerful method for identifying major pollution prevention needs in industry and setting R&D priorities accordingly. Since many of the research areas include technologies that have very broad applications, partnerships will be required to jointly identify and perform the R&D.

These partnerships should include the appropriate partners for the problem at hand -- the industry being affected, its suppliers and customers, university and government researchers, States, and federal agencies.

The three DOE-CWRT workshops described above were not originally envisioned as a related series. They also preceded the data analysis by BoC and could not take advantage of their results. An ideal approach would start with a detailed analysis of industrial waste patterns to identify priority industries and waste streams. This would be followed by very focused workshops to elicit expert opinions on technical barriers to pollution prevention and the R&D that can help overcome them. Such workshops should involve a range of industry interests in the specific topic area as well as a cross section of potential R&D performers from industry, universities, and federal laboratories.

It should be noted that top-down R&D planning represents only one approach for funding pollution prevention research. Many innovative pollution prevention ideas are generated outside the priority research areas and warrant support. The success of Dow's *Energy Contest* and *Waste Reduction Always Pays* program, 3M's *Pollution Prevention Pays* program, and DOE's *National Industrial Competitiveness through Efficiency: Energy, Environment, Economics (NICE^3)* program, are examples of highly successful pollution prevention/energy efficiency programs that solicit bottom-up ideas for technology projects. The best strategy for pollution prevention research programs should include some bottom-up activities to complement top-down R&D plans.

Identifying technology needs and prioritizing research is only the first step in solving environmental problems. The more difficult challenge is to effectively engage the research and development community in pursuing priority R&D areas and using the results productively. Some federal programs have not been effective in translating well-defined priorities into relevant research proposals and successful projects. The true value of the Technology and Manufacturing Competitiveness Task Group and OIT's *Industries of the Future* initiative will be in their ability to translate research needs into technology solutions.

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