Pollution Prevention from Chemical Processes

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GLOSSARY

Bioaccumulative Material that accumulates in organisms, for example, lead, mercury, and DDT.

Chemical process A chemical process normally consists of a reactor section where the feed materials are reacted to the desired product(s) followed by a series of separation devices to separate the product(s) from any by-products, solvents, catalysts, etc.

Material balance Compound-by-compound listing of materials in the pipes and vessels of a process.

Persistent compound Material that does not or only slowly biodegrades, for example, PCBs and DDT.

Process flow diagram A drawing of process pipes and vessels.

I. INTRODUCTION

"POLLUTION PREVENTION" became environmental buzz words of the 1990s. No matter what one chooses to call the task or technology of reducing waste and emissions from a chemical process—pollution prevention, waste minimization, source reduction, clean technology, green manufacturing, etc.—the challenge of implementing process changes that actually reduce waste generation is often formidable. Engineers and scientists faced with developing and implementing a pollution prevention program for a business or a manufacturing site face many obstacles, technological, economic, and societal. Some of these obstacles are real, while many others are only perceived to be real.

The traditional approach to process design has been to first engineer the process and then to engineer the treatment and disposal of waste streams. However, with increasing regulatory and societal pressures to eliminate emissions to the environment, disposal and treatment costs have escalated exponentially. As a result, capital investment and operating costs for disposal and treatment have become a larger fraction of the total cost of any manufacturing process. For this reason, the *total system* must now be analyzed simultaneously (process plus treatment) to find the best economic option.

Experience in all industries teaches that processes which minimize waste generation at the source are the most economical. For existing plants, the problem is even more acute. Even so, experience has shown that waste generation in existing facilities can be significantly reduced (greater than 30% on average), while at the same time reducing operating costs and new capital investment.

In this article, we present a broad overview of the path to an effective pollution prevention program. The phases and individual steps of this proven methodology are applicable to both large-scale and small-scale problems. The focus of the methodology is on identifying pollution prevention engineering technologies and practices that will change what is happening *inside* the pipes and vessels of the manufacturing process, rather than just on simple procedural or cosmetic changes. In fact, many of the techniques and tools that support the methodology can be easily applied by chemists, process engineers, and project engineers to individual waste streams within a process or facility. For example, the methodology has been and continues to be successfully practiced inside the DuPont Company. We present a list of pollution prevention engineering technologies and practices that nicely complements the methodology and provides a useful knowledge base for quickly identifying possible process changes that reduce waste generation and emissions.

II. HISTORY OF POLLUTION PREVENTION

No single dimension of the solutions for environmental problems has captured the imagination of engineers, scientists, policy-makers, and the public like pollution prevention. In the space of two decades (1980–2000), the philosophical shift and the record of accomplishment has made pollution prevention a fundamental means for environmental management. This effort actually began during 1976–1980 when 3M Corporation initiated the 3P program and North Carolina adopted waste minimization as a state-wide priority for managing emissions from industry. By 1990, virtually all of the *Fortune* 1000 U.S. corporations had pollution prevention as the first emphasis in describing their approach to the environment. The shift from 20–50 years of conventional pollution control to a preventative approach was dramatic because of the reversal in priorities.

The adoption of pollution prevention as a clearly differentiated approach to environmental improvement began in U.S. industry and policy during the late 1970s. While examples of improved efficiency and hence less waste had existed since the start of the Industrial Revolution, the distinct explosion of successes in pollution prevention did not occur until the mid-1980s. Figure 1 shows an approximate time line of this period.

The early creation at the 3M Corporation of money-saving innovations that reduced chemical losses to air, water, or land was widely publicized. However, propagation into other large corporations was almost nonexistent. The efforts through university research and state programs (beginning in North Carolina) to illustrate the benefits of pollution prevention, and a steady presentation of principles such as the creation of the pollution prevention hierarchy and roadmaps, extended over the early to mid-1980s. In 1986–1988, the improved information regarding chemical losses to the environment as a part of the U.S. EPA Toxic Release Inventory (TRI) Program precipitated action. A number of CEOs of large corporations challenged their companies, in a very public fashion, to reduce these chemical losses. As the autocatalytic effect spread to other

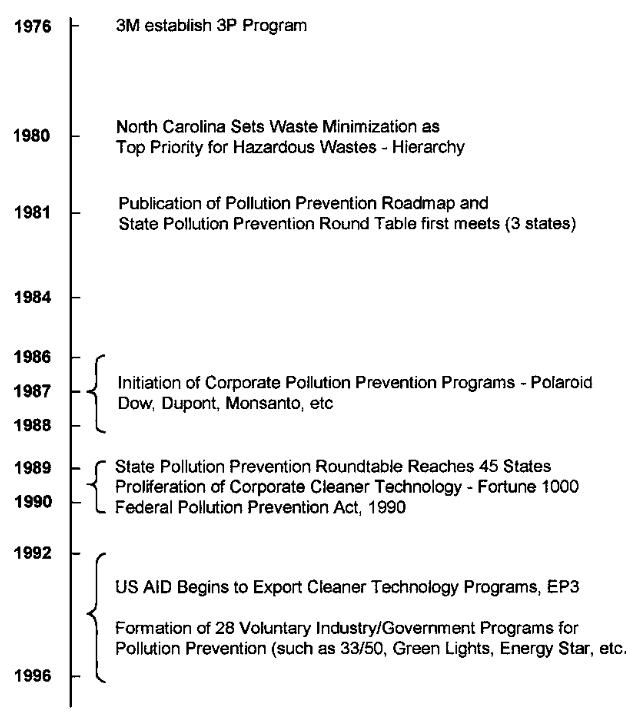

FIGURE 1 General historical sequence for growth of cleaner technology in United States.

companies and whole industry associations or sectors, the policy of priority for pollution prevention took shape in the United States. The outcome has been impressive, not necessarily uniform, but achieving a philosophical shift to cleaner manufacturing. These events are even more impressive when it is recognized that virtually all of the individual changes to manufacturing have been cost-effective (a generally held rule of a 2-year payback on capital investment).

Use of the term pollution prevention is common in the United States, but is actually one of many nearly synonymous terms, which include the following:

Waste minimization
Cleaner production
Waste reduction
Clean technology
Source reduction
Environmentally benign synthesis
Environmentally conscious manufacturing
Green chemistry
Technology for a sustainable environment
Sustainability
Green engineering

Use of a particular terminology usually is linked to the forum in which the debate is occurring and hence these terms have subtle differences, but share the major emphasis on prevention. That is, all of these descriptors refer to the intuitive perspective that it is advantageous to manage chemical losses or wastes generated from the top of a hierarchy for waste minimization. In addition, there is a certain trend to reinvent terms with new government initiatives.

III. WASTE AS POLLUTION

An industrial waste is defined as an unwanted by-product or damaged, defective, or superfluous material of a manufacturing process. Most often, it has or is perceived to have no value. It may or may not be harmful or toxic if released to the environment. Pollution is any release of waste to the environment (i.e., any routine or accidental emission, effluent, spill, discharge, or disposal to the air, land, or water) that contaminates or degrades the environment.

Figure 2 depicts a typical manufacturing facility. Inputs to the facility include raw materials to produce the saleable product(s), water, air, solvents, catalysts, energy, etc. Outputs from the facility are the saleable product(s), waste energy, and gaseous, liquid, water, and solid wastes. In contrast, a manufacturing facility with an absolute minimum (but not zero) amount of waste being generated is shown in Fig. 3. Inputs to the facility include only the raw materials to make the saleable products(s) and energy. The only significant outputs are saleable products.

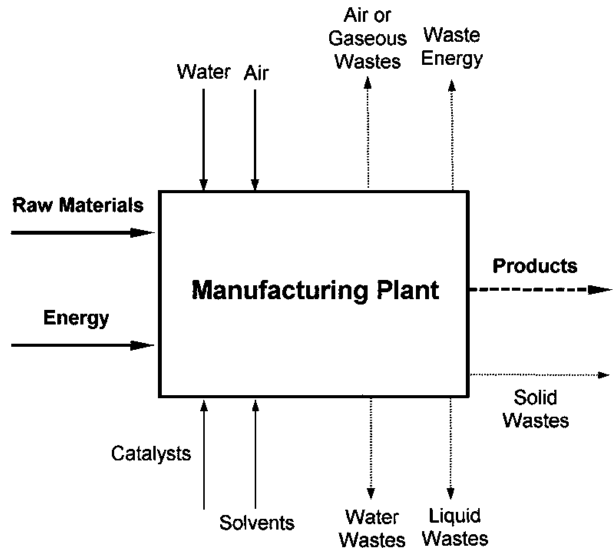

FIGURE 2 Plant with pollution.

IV. HOW DOES ONE DEFINE POLLUTION PREVENTION?

We define pollution prevention fairly broadly, in keeping with the actual practices widely utilized by industry. This definition is any cost-effect technique aimed at reducing chemical or energy-related emissions that would subsequently have to be treated. In keeping with the generally voluntary nature of U.S. pollution prevention activities, the double hurdle of technical and economic feasibility are met in a pollution prevention option (Fig. 4).

This definition manifests itself in the form of the pollution prevention hierarchy shown in Fig. 5. In this hierarchy, safe disposal forms the base of the pyramid, and minimizing the generation of waste at the source is at the peak.

The U.S. Environmental Protection Agency (EPA) definition of pollution prevention recognizes actions which encompass the upper three levels in the hierarchy: minimize generation to segregate and reuse. The U.S. EPA

FIGURE 3 Absolute minimum waste generation facility.

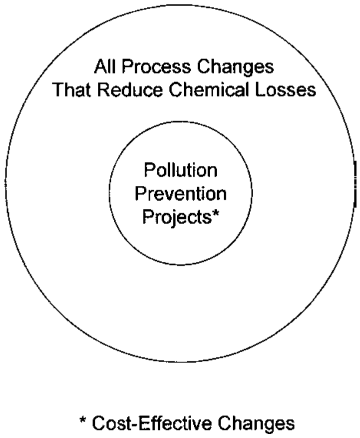

FIGURE 4 Context of pollution prevention within all possible process changes.

defines the hierarchy shown in Fig. 5 as environment management options. Industry defines as pollution prevention the upper five levels, from minimize generation to recover energy value in waste. The European Community, on the other hand, includes the entire hierarchy (levels 1–7) in its definition of pollution prevention, as is done in this article.

A definition of each tier in the pollution prevention hierarchy is given below:

1. *Minimize generation.* Reduce to a minimum the formation of nonsaleable by-products in chemical reaction steps and waste constituents, such as tars, fines, etc., in all chemical and physical separation steps.

2. *Minimize introduction.* Minimize the addition of materials to the process that pass through the system unreacted or that are transformed to make waste. This implies minimizing the introduction of materials that are not essential ingredients in making the final product. Examples of introducing nonessential ingredients include (1) using water as a solvent when one of the reactants, intermediates, or products could serve the same function and (2) adding large volumes of nitrogen gas because of the use of air as an oxygen source, heat sink, diluent, or conveying gas.

3. *Segregate and reuse.* Avoid combining waste streams together without giving consideration to the impact on toxicity or the cost of treatment. For example, it may make sense to segregate a low-volume, high-toxicity wastewater stream from several high-volume, low-toxicity wastewater streams. Examine each waste stream at the source and determine which ones are candidates for reuse in the process or can be transformed or reclassified as a valuable coproduct.

4. *Recycle.* A large number of manufacturing facilities, especially chemical plants, have internal recycle streams that are considered part of the process. In this case, recycle refers to the external recycle of materials, such as polyester film and bottles, Tyvek® envelopes, paper, and spent solvents.

5. *Recover energy value in waste.* This step is a last step to attain any value from the waste. Examples include burning spent organic liquids, gaseous streams containing volatile organic compounds, and hydrogen gas for the fuel value. The reality is that often the value of energy and resources required to make the original compounds is much greater than that which can be recovered by burning the waste streams for the fuel value.

6. *Treat for discharge.* This involves lowering the toxicity, turbidity, global warming potential, pathogen content, etc., of the waste stream before discharging it to the environment. Examples include biological wastewater treatment, carbon adsorption, filtration, and chemical oxidation.

7. *Safe disposal.* Waste streams are rendered completely harmless or safe so that they do not adversely impact the environment. In this article, we define this as total conversion of waste constituents to carbon dioxide, water, and nontoxic minerals. An example is subsequent treatment of a wastewater treatment plant effluent in a private wetlands. So-called "secure landfills" would not fall within this category unless the waste is totally encapsulated in granite.

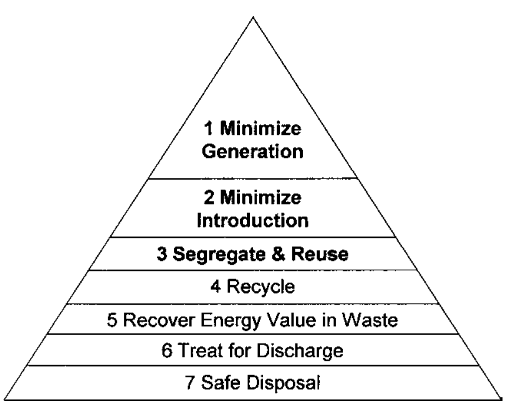

FIGURE 5 Pollution prevention hierarchy.

In this article, we will focus on the upper three tiers of the pollution prevention hierarchy; that is, minimize generation, minimize introduction, and segregate and reuse. This is where the real opportunity exists for reducing waste and emissions while also improving the business bottom line.

V. DRIVERS FOR POLLUTION PREVENTION

Since the early 1960s, the number of federal environmental laws and regulations has been increasing at a rate three

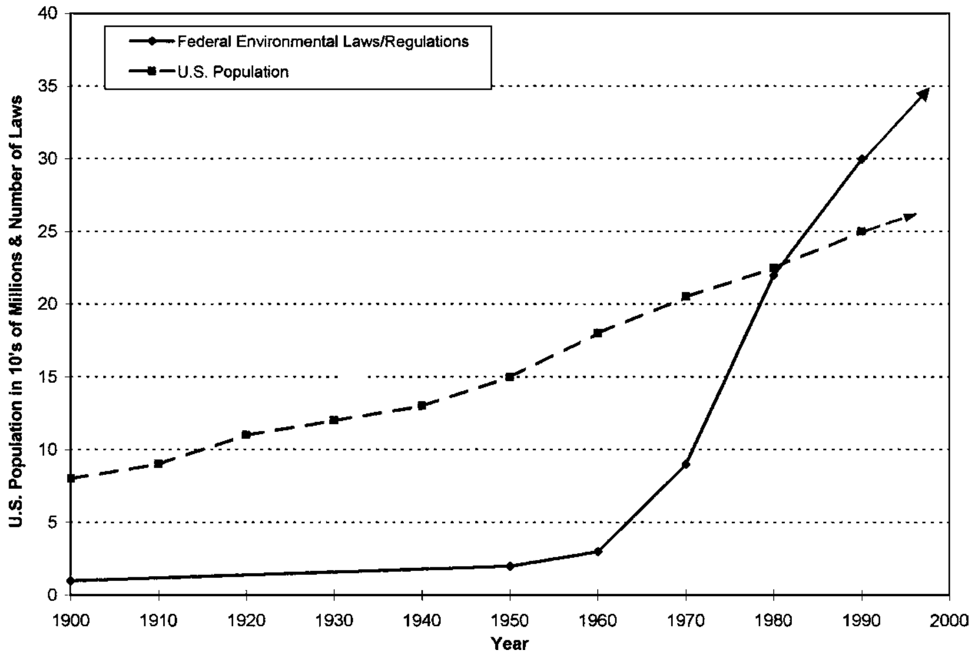

FIGURE 6 Comparison between the increase in federal environmental laws and the U.S. population with time.

times that of the United States population. In 1960, there were only 3 federal environmental laws on the books; now there are more than 30. This does not even include the much larger number of state environmental laws. Figure 6 shows both the population growth in the United States and the number of federal environmental laws and regulations as a function of time. The reality is that laws and regulations use command and control to force industry to comply.

Toward the end of the 1980s, many more industries were beginning to turn to pollution prevention as a means of avoiding the installation of expensive end-of-the pipe treatment systems. It was becoming clear to many that the succession of increasingly stringent regulations with time would ultimately lead to a complex, expensive series of treatment devices at the end of a manufacturing process, each with its own set of maintenance and performance issues.

Those industries and businesses which began to accept and implement pollution prevention solutions instead of treatment found that they not only reduced waste generation, but they also made money. As a result of these experiences, various governmental agencies began to incorporate pollution prevention requirements into new environmental laws. Congress recognized that "source reduction is fundamentally different and more desirable than waste management and pollution control," and passed the Pollution Prevention Act in 1990.

Corporate experience has shown that the six major drivers for pollution prevention are:

1. The increasing number and scope of environmental regulations and laws.
2. Ability to save money and reduce emissions or conserve energy.
3. The rising cost and changing nature of regulations of waste treatment.
4. Greater government oversight and control of business operations.
5. More awareness by corporations in the value of pollution prevention to the business bottom line and to the customer.
6. The heightened awareness in society of the need for sustainability of the planet.

The first and second major drivers for pollution prevention, as described above, are regulations and laws and the cost of waste treatment. Extrapolation of the two curves in Fig. 6 would imply that future laws and regulations will be even more stringent and, if solved by end-of-pipe treatment, even more costly.

Figure 7 shows conceptually the cost incurred by the business to generate waste versus the amount of waste produced by a manufacturing process. Along the right-hand portion of the cost/waste curve, some processes are far to the right, whereas others are closer to the conceptual minimum. The goal of pollution prevention is to move expeditiously toward the conceptual minimum while continuing to be cost-effective. The "economic zero," as indicated by the vertical dashed line, is the point where the slope of the curve reverses itself and normally becomes very

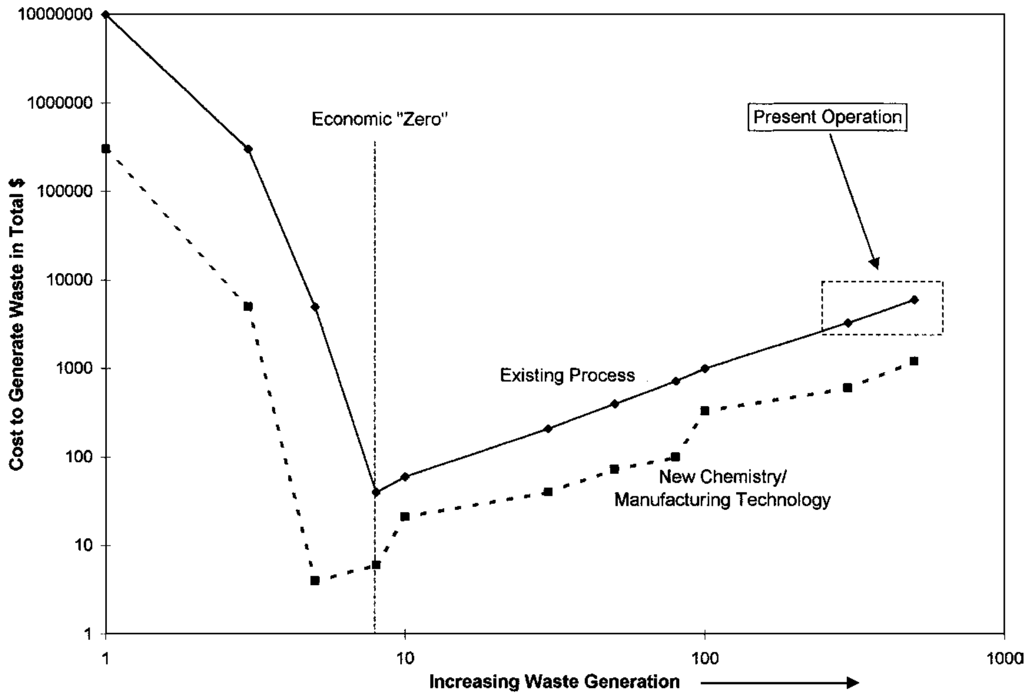

FIGURE 7 Waste generation versus business cost.

steep. Further reducing waste generation, then, requires a significantly greater capital investment, e.g., replacing large piece(s) of equipment or unit operations. Instead, to further reduce the level of waste being generated while simultaneously reducing the cost to generate this waste, new chemistry or new engineering technology is required (i.e., a new process). This is indicated by the broken curve on Fig. 7.

Federal, state, and local governments are demanding more and more information from manufacturers: not only the size, composition, and properties of waste streams that are generated, but also what chemicals are added to the process to manufacture the final product, and descriptive information on how these chemicals are used within the process. The third major driver for pollution prevention, then, becomes control of the business. When a business does not make any waste or is below a *de minimus* level, then only a minimum amount of information is required by the governing bodies; hence, business information is conserved. Thermodynamic principles govern that zero waste is not possible, and the technical challenge is develop manufacturing processes that produce minimum waste.

Figure 8 depicts schematically the degree of control business leadership has over a business versus governmental control as a function of the amount of waste being generated by a process. Normally, there will be a *de minimus* level of waste generation below which the regulations require only minimal governmental oversight, that is, the business controls its own destiny. However, as the level of waste generation increases, so does the amount of governmental oversight. As a result, business leadership has less control of their business and is less able to respond to various business factors that might improve their bottom line. The *de minimus* point for a regulatory "zero" is normally below that for the economic "zero," yet a business still might voluntarily choose to spend additional capital investment to increase control.

Recognizing the value of pollution prevention to the business and the customer, progressive companies are developing corporate goals to motivate their employees to reduce the amount of waste being produced. Examples include the 3M Corporate Environmental Conservation Policy and the DuPont Company's Safety, Health and the Environment Commitment of zero waste generation and emissions, which is shown in Fig. 9.

The environmental group Grassroots Recycling Network is developing a Zero Waste Policy Paper for consumer products. The net result is that society is beginning to expect that the products and processes of the future will not generate waste and are recyclable or biodegradable.

For the businesses that have implemented pollution prevention programs, the amount saved or earned has been quite dramatic. For example, in the 3M Company, the Pollution Prevention Pays (3P) Program netted \$350 million for their U.S. plants from 1976 through 1987 while reducing waste generation by more than 425,000 tons per year.

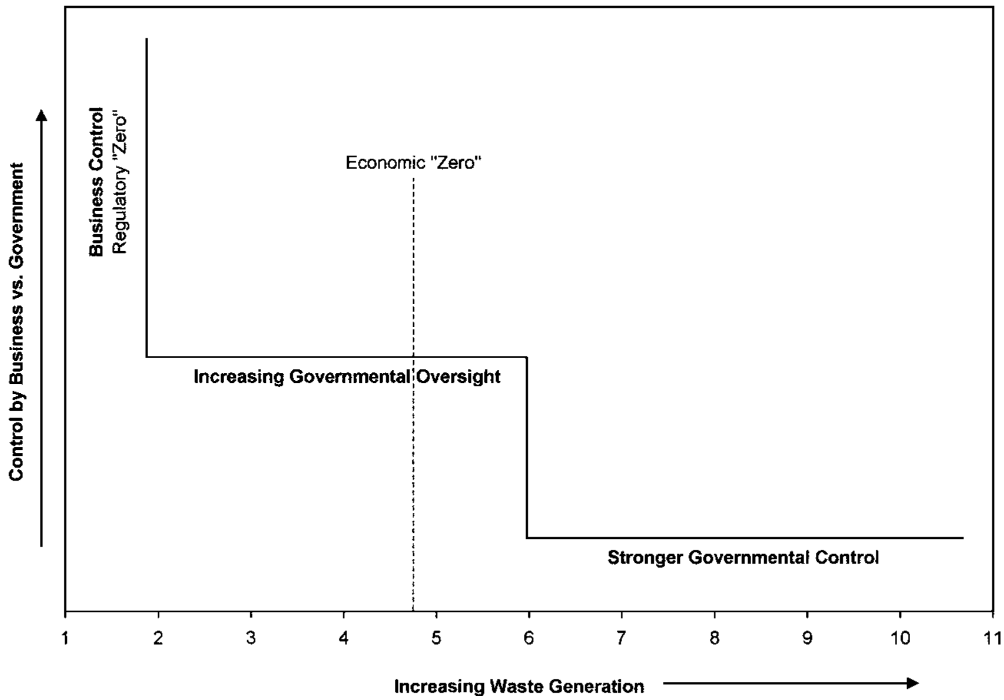

FIGURE 8 Waste generation versus business control.

A second example is the joint EPA/DuPont Chambers Works Waste Minimization Project, which resulted in a savings of $15 million per year for only $6.3 million in capital investment and led to a 52% reduction in waste generation.

The DuPont Company has also instituted a corporate Environmental Excellence Award program. Of the typical 550 submissions per year, approximately 70 pass the first screening and 12 are finally selected as winners. For the years 1994–1996, more than $200 million per year positive return and $320 million in avoided capital expenditures was realized for the 210 programs that passed the first screening.

The fifth main driver for pollution prevention, which is growing in importance, is sustainability, i.e., building a sustainable global economy or an economy that the planet is capable of supporting indefinitely. Pollution prevention is one of three ways that a company can move toward sustainability. A second way is product stewardship, where a manufactured product has minimal impact on the environment during the full manufacturing life cycle. A third step toward sustainability is through clean technology, that is, technology which has a minimum impact on the environment. Examples include (1) avoiding the use and manufacture of toxic, persistent, or bioaccumulative compounds and (2) replacing high-temperature and high-pressure processes with biotechnology routes which can manufacture products at ambient conditions.

VI. THE RECIPE FOR SUCCESS

After participating in over 75 waste reduction or treatment programs, one thing has become clear—there is a recipe for success. We have found that successful pollution prevention programs are characterized by the following four success factors:

1. Commitment by business leadership to support change and provide resources.
2. Early involvement of all stakeholders in the process.
3. Quick definition of the cost for end-of-pipe treatment, which subsequently becomes the incentive for more cost-effective pollution prevention solutions.
4. Definition and implementation of pollution prevention engineering practices and technologies that improve the business' bottom line.

The "path to pollution prevention" chart shown in Fig. 10 brings together the essential ingredients for a successful pollution prevention program, whether large or small. The core pollution prevention program or methodology is shown in the center column, and consists of three phases: the chartering phase, assessment phase, and implementation phase. The other boxes in Fig. 10 (shown with dotted lines) outline supporting information, tools, and activities that are essential to the success of the program. In many ways, these help to expedite the completion

The DuPont Commitment

Safety, Health and the Environment

We affirm to all our stakeholders, including our employees, customers, shareholders and the public, that we will conduct our business with respect and care for the environment. We will implement those strategies that build successful businesses and achieve the greatest benefit for all our stakeholders without compromising the ability of future generations to meet their needs.

We will continuously improve our practices in light of advances in technology and new understandings in safety, health and environmental science. We will make consistent, measurable progress in implementing this Commitment throughout our worldwide operations. DuPont supports the chemical industry's Responsible Care® and the oil industry's Strategies for Today's Environmental Partnership as key programs to achieve this Commitment.

Highest Standards of Performance, Business Excellence
We will adhere to the highest standards for the safe operation of facilities and the protection of our environment, our employees, our customers and the people of the communities in which we do business.

We will strengthen our businesses by making safety, health and environmental issues an integral part of all business activities and by continuously striving to align our businesses with public expectations.

Goal of Zero Injuries, Illnesses and Incidents
We believe that all injuries and occupational illnesses, as well as safety and environmental incidents, are preventable, and our goal for all of them is zero. We will promote off-the-job safety for our employees.

We will assess the environmental impact of each facility we propose to construct and will design, build, operate and maintain all our facilities and transportation equipment so they are safe and acceptable to local communities and protect the environment.

We will be prepared for emergencies and will provide leadership to assist our local communities to improve their emergency preparedness.

Goal of Zero Waste and Emissions
We will drive toward zero waste generation at the source. Materials will be reused and recycled to minimize the need for treatment or disposal and to conserve resources. Where waste is generated, it will be handled and disposed of safely and responsibly.

We will drive toward zero emissions, giving priority to those that may present the greatest potential risk to health or the environment.

Where past practices have created conditions that require correction, we will responsibly correct them.

Conservation of Energy and Natural Resources, Habitat Enhancement
We will excel in the efficient use of coal, oil, natural gas, water, minerals and other natural resources.

We will manage our land to enhance habitats for wildlife.

Continuously Improving Processes, Practices and Products
We will extract, make, use, handle, package, transport and dispose of our materials safely and in an environmentally responsible manner.

We will continuously analyze and improve our practices, processes and products to reduce their risk and impact through the product life cycle. We will develop new products and processes that have increasing margins of safety for both human health and the environment.

We will work with our suppliers, carriers, distributors and customers to achieve similar product stewardship, and we will provide information and assistance to support their efforts to do so.

Open and Public Discussion, Influence on Public Policy
We will promote open discussion with our stakeholders about the materials we make, use and transport and the impacts of our activities on their safety, health and environments.

We will build alliances with governments, policy makers, businesses and advocacy groups to develop sound policies, laws, regulations and practices that improve safety, health and the environment.

Management and Employee Commitment, Accountability
The Board of Directors, including the Chief Executive Officer, will be informed about pertinent safety, health and environmental issues and will ensure that policies are in place and actions taken to achieve this Commitment.

Compliance with this Commitment and applicable laws is the responsibility of every employee and contractor acting on our behalf and a condition of their employment or contract. Management in each business is responsible to educate, train and motivate employees to understand and comply with this Commitment and applicable laws.

We will deploy our resources, including research, development and capital, to meet this Commitment and will do so in a manner that strengthens our businesses.

We will measure and regularly report to the public our global progress in meeting this Commitment.

FIGURE 9 The DuPont commitment to safety, health, and the environment.

of the program and increase the likelihood of choosing the best options to improve the process and reduce waste generation.

The dotted boxes on the right-hand side of Fig. 10 show the information and tools available to help jump start, maintain, and increase the effectiveness of the pollution prevention program. These include:

1. How to quickly estimate the incentive for pollution prevention.
2. Generalized pollution prevention technologies and practices that apply across different industries.
3. A shortcut economic evaluation method to quickly screen the better options.

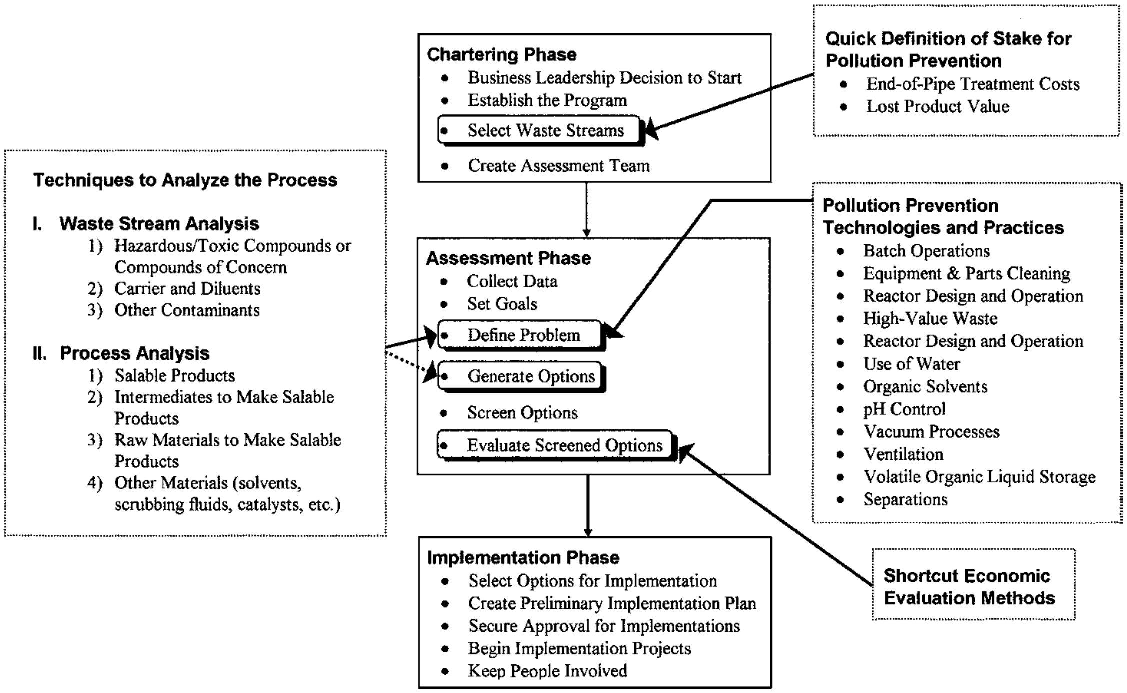

FIGURE 10 The path to pollution prevention.

The left-hand side of Fig. 10 describes two techniques to divide the waste generation problem into smaller, comprehensible parts: a waste stream analysis and a process analysis. These two analysis techniques are used to help better define the problem as well as to focus energy on the true source of the waste generation problem. The first technique, waste stream analysis, is based on the premise that most waste streams contain a carrier, such as water or air, that drives end-of-pipe treatment costs, and compound(s) or contaminants of concern that drive the need to treat the stream.

Meanwhile, the second technique, process analysis, is based on the assumption that most processes contain (1) valuable compounds and molecules that result in a saleable product (i.e., products, intermediates to make the products, and raw materials to make the intermediates/products) and (2) other compounds that add to the cost of manufacturing, which includes waste treatment costs.

VII. PROGRAM ELEMENTS

The path to pollution prevention shown in Fig. 10 is applicable at all phases of a project. In most cases, the methodology has been applied at the plant level. However, the same methodology can be used when a process is first conceived in the laboratory and at periodic intervals through startup and normal plant operation.

A. Chartering Phase

This initial phase of the pollution prevention program consists of four steps: securing business leadership support, establishing the program, selecting the waste streams, and creating a core assessment team.

1. Business Leadership Decision to Start

The decision to begin a pollution prevention program can be triggered by one or more of the drivers listed below:

- Legal requirement, i.e., state or federal regulations.
- Public image and societal expectations. This may be fueled by an adversarial attitude in the community toward the facility or process or the desire to lead the environmental movement instead of being pushed.
- Large incentive for reducing new capital investment in end-of-pipe treatment.
- Significant return by reducing manufacturing costs.
- Need to increase revenues from existing equipment.
- Corporate goal.

2. Establishing the Program

This task helps prepare the plant or manufacturing area for a successful pollution prevention effort. A key aspect of this task is to have a team leader for the program.

3. Selecting the Waste Streams

A typical process generates several major waste streams and many minor ones. The goal should be to select one or more of the major streams for the first round of waste assessments. If successful with these major streams, additional waste streams can be targeted, including minor ones, in a second round of assessments.

4. Creating an Assessment Team

In this step, a core team is selected which consists of four to six people who are best able to lead the program, perform the waste assessments, and implement the recommended process improvements. At smaller and medium-sized facilities a single individual may undertake the bulk of the pollution prevention tasks, or consultants can be used.

B. Assessment Phase

The assessment phase in many ways represents the heart of the pollution prevention program. It also tends to be where many engineers and scientists find the most enjoyment and personal satisfaction. For this reason, there is always a tendency to bypass the "softer" chartering phase and jump right into the assessment phase. This is generally a mistake. We consistently find that programs that bypass the chartering phase fail. This is because they fail to incorporate the first two major success factors listed in the recipe for success: obtaining commitment from business leadership to support change and provide resources and seeking the early involvement of all stakeholders in the process. These two major success factors arise from the chartering phase itself. However, it is also recognized that in some cases the successful implementation of the assessment phase on small projects by one or two champions could earn subsequent commitment by the business leadership for larger projects. Each company has a characteristic style for undertaking change, and the champions need to utilize these methods to accomplish their pollution prevention goals.

The assessment phase consists of tasks which help the team to understand how the target waste streams are generated and how these wastes can be reduced at the source or eliminated.

1. Collect Data

The amount of information to collect will depend on the complexity of the waste stream and the process that generates it. Material balances and process flow diagrams are a minimum requirement for most pollution prevention assessments.

2. Set Goals

This task helps the team to analyze the drivers for pollution prevention and to develop the criteria necessary to screen the options generated during the brainstorming session.

3. Define Problem

The team begins to understand the targeted waste streams and the processes that generate these streams. The waste stream and process analyses techniques are used in this step to facilitate understanding of the problem.

4. Generate Options

When the team has developed a good understanding of the manufacturing process and the source and cause of each waste stream, it should convene to brainstorm for ideas to reduce the generation of these materials.

5. Screen Options

In a separate meeting, the core assessment team will revisit the options generated during the brainstorming process to reduce the number of credible ideas carried forward.

6. Evaluate the Screened Options

More detailed engineering and economic evaluations are performed on the screened options to select the best option(s) to implement.

C. Implementation Phase

The goal of this phase is to turn the preferred options identified by the team into actual projects that reduce waste generation and emissions. Options are first selected for implementation. This should be a natural follow-up to the screening and evaluation stages described above. Next, the team needs to develop an implementation plan that includes resource requirements (both people and money) and a project timeline. This is one of the reasons that having a project engineer on the core assessment team is valuable. Third, the team must secure approval and begin project implementation. Often, this step will be according to customary local practice. Finally, people need to be kept involved throughout the entire pollution prevention program. The team leader should always be working to build and maintain momentum.

VIII. THE INCENTIVE FOR POLLUTION PREVENTION

There are several ways to determine the incentive for pollution prevention. The choice will depend on particular circumstances; that is, does a waste treatment or abatement system already exist or is a new treatment or abatement system required? Three approaches to determine the incentive for pollution prevention are described below. They are the incentive based on new end-of-pipe treatment, raw material costs, and cost of manufacture. Each of these approaches is discussed in detail below.

A. New End-of-Pipe Treatment

Gaseous and aqueous waste streams often require capital investment for new facilities or an upgrade of existing equipment, e.g., replacing an in-ground wastewater treatment basin with an aboveground treatment system in tanks. Solid wastes (both hazardous and nonhazardous) are normally handled with existing investment (e.g., site hazardous waste incinerator) or shipped off-site for disposal. In the latter case, commercial disposal costs (including the cost of transportation) serve as the incentive for pollution prevention.

1. Gas Streams

A major opportunity for savings is to reduce the flow of diluent or carrier gas (often air or nitrogen) at the source. For a gas stream containing both particulates and halogenated volatile organic compounds (VOCs), the minimum capital investment to abate this stream is about $75 per standard cubic foot per minute (scfm) of waste gas flow.

2. Wastewater Streams

Simply speaking, wastewater streams fall into one of two general categories, those that are biologically treatable and those requiring pretreatment or stand-alone nonbiological treatment (such as chemical oxidation, stripping, and adsorption). When treating dilute aqueous organic waste streams at the end of the pipe, consideration must be given to source reduction of *both* water flow and organic loading. Substantial reductions in capital investment can result by reducing water flow and contaminant loading at the source. The magnitude of these reductions will vary with technology type, hydraulic flow, and concentration; however, the *minimum incremental* capital investments for new treatment facilities are as follows:

Biodegradable aqueous waste	
Incentive based on hydraulic flow	$3000 per each additional gallon per minute (gpm)
Incentive based on organic loading	$6000 per each additional pound organic per hour (lb/hr)
Nonbiodegradable aqueous waste	
Incentive based on hydraulic flow	$1000 per each additional gpm
Incentive based on organic loading	Some technologies are sensitive to organic loading and some are not

B. Raw Materials Cost

Waste stream composition and flow rate can be used to estimate the amount of raw materials lost as waste. The product of the amount lost to waste and the purchase price sets the incentive for pollution prevention in terms of raw material cost alone.

C. Cost of Manufacture

The cost of manufacture includes all fixed and variable operating costs for the facility, including the cost for raw materials. The cost of manufacture should be cast in the form of dollars per pound ($/lb) of a key raw material. Another number that is readily available is the product selling price in dollars per pound of product. Depending on the state of the business—excess capacity or sold out—one of these two numbers can be used to determine the incentive for pollution prevention.

- For a business operating with excess capacity, the product of the cost of manufacture ($/lb raw material) and the amount of raw material that goes to waste (either directly or as a by-product of reaction) sets the incentive for pollution prevention.
- For a sold-out business, every additional pound of product can be sold; therefore, the product of the product selling price and the additional amount of product that can be sold determines the incentive for pollution prevention.

IX. RESOURCES

In many respects, the best set of resources for generating waste reduction ideas consists of a business' own people. However, a business will sometimes need to bring other expertise to the table to supplement its own resources. Some examples of other resources include a brainstorming facilitator, technical specialists, outsiders or wildcards, and sources of pollution prevention ideas found in the literature.

If a person cannot be found in the business who can facilitate a brainstorming session, then a consultant, possibly someone at the local university or college, will be needed.

The outsiders or wildcards should be good chemical engineering and process chemistry generalists, and not directly associated with the process. The technology specialists should be skilled in the engineering unit operations or technology areas that are most critical to waste generation in the manufacturing process, for example, drying, particle technology, reaction engineering, pumps. Most midsize to large companies can identify the outsiders, wildcards, and technology specialists internally. For smaller firms, sources of wildcards and technology specialists include academia, engineering consultants, and research institutes.

A wealth of information is available on pollution prevention successes across many industries; however, it is primarily packaged in the form of process-specific case histories. As a result, the information is not organized in a sufficiently generalized way so as to allow the rapid transfer of knowledge from one type of industry to another. To help the practitioners of pollution prevention—engineers and scientists—more quickly to generate ideas, this process- or industry-specific information has been transformed into generalized knowledge that can be more easily implemented by project teams and existing manufacturing facilities. The information is organized in a "unit operations" format to facilitate widespread used across different processes and industries (right-hand column of Fig. 10).

Other sources for ideas are available, many on the Internet. Some examples include the following:

- The Chemical Manufacturers Association publication, "Designing Pollution Prevention into the Process: Research, Development & Engineering," Appendices A and B
- The "Industrial Pollution Prevention Handbook" by Harry M. Freeman
- The U.S. EPA's Pollution Prevention Directory (published annually)
- The U.S. EPA's Pollution Prevention Information Clearinghouse (PPIC)
- The U.S. EPA's Office of Pollution Prevention and Toxics (OPPT)
- The U.S. EPA's Pesticide Environmental Stewardship Program
- The U.S. EPA's Environene (environsense) database
- Case histories in journals such as *Chemical Engineering Progress*, *Journal of Chemical Technology and Biotechnology*, *Chemical Engineering*, *Environmental Progress*, *Pollution Prevention Review*, and so on
- State pollution prevention offices or centers. Many states offer services to small- and medium-sized businesses (over 13,000 case studies are available on the Internet at www.P2PAYS.org)
- Private consultants or consulting firms
- Private consortia and organizations, for example, AIChE's Center for Waste Reduction Technology (CWRT), the Center for Clean Industrial Treatment Technology (CenCITT), and the National Center for Manufacturing Sciences (NCMS)
- Pollution prevention or waste minimization centers at universities, for example, the UCLA Center for Clean Technology, the Pollution Prevention Research Center at North Carolina State University, and the Emission Reduction Research Center at the New Jersey Institute of Technology (NJIT),
- Numerous other Internet sites, such as those of the Great Lakes Pollution Prevention Centre in Canada and the Pacific Northwest Pollution Prevention Resource Center.

A review on using the Internet for pollution prevention was published by Scott Butner (1997) at the Battelle Seattle Research Center. All of these resources can be used to help prepare a brainstorming team for the generation of ideas.

X. ENGINEERING EVALUATIONS OF THE PREFERRED OPTIONS

Engineering evaluation is the application of a full range of engineering skills to business decision making. It aids decision making by translating technical options into economic impact, guidance that is fundamental to business decisions. The evaluation quickly focuses on only those data and analyses which are essential to quantify technical and economic feasibility. For each preferred option, the evaluation involves the following:

- Defining the commercial process
- Flowsheeting
- Analyzing the process
- Defining manufacturing facilities
- Estimating investment and manufacturing cost
- Analyzing economics
- Assessing risk

The evaluation provides an objective view for decision making that is grounded in both engineering science and economics.

XI. WASTE STREAM AND PROCESS ANALYSES

Properly defining and subdividing the problem ultimately leads to the best pollution prevention solutions. The goal is to frame the problem such that the pertinent questions arise. When the right questions are asked, the more feasible and practical solutions for pollution prevention become obvious. Analyzing the manufacturing process in this manner before and during the brainstorming session will often result in an improved process that approaches an absolute minimum in waste generation and emissions.

A. Waste Stream Analysis

The best pollution prevention options cannot be implemented unless these are identified. To uncover the best options, each waste stream analysis should follow four steps:

1. List all components in the waste stream, along with any key parameters. For instance, for a wastewater stream these could be water, organic compounds, inorganic compounds (both dissolved and suspended), pH, etc.

2. Identify the compounds triggering the concern, for example, compounds regulated under the Resource Conservation and Recovery Act (RCRA), hazardous air pollutants (HAPs), and carcinogenic compounds. Determine the sources of these compounds within the process. Then develop pollution prevention options to minimize or eliminate the generation of these compounds.

3. Identify the highest volume materials (often these are diluents, such as water, air, a carrier gas, or a solvent) because these materials or diluents often control the investment and operating costs associated with end-of-pipe treatment of the waste streams. Determine the sources of these diluents within the process. Then develop pollution prevention options to reduce the volume.

4. If the compounds identified in step 2 are successfully minimized or eliminated, identify the next set of compounds that has a large impact on investment and operating cost (or both) in end-of-pipe treatment. For example, if the aqueous waste stream was originally a hazardous waste and was incinerated, eliminating the hazardous compound(s) may permit the stream to be sent to the wastewater treatment facility. However, this may overload the biochemical oxygen demand (BOD) capacity of the existing wastewater treatment facility. If so, it may be necessary to identify options to reduce organic load in the aqueous waste stream.

B. Process Analysis

In the manufacturing facility in Fig. 2 all of the materials added to or removed from the process are valuable to the business. Therefore, to help frame the problem for a real manufacturing facility, a process analysis should be completed.

For either a new or existing process, the following steps are taken:

1. List all raw materials reacting to saleable products, any intermediates, and all salable products. This is "list 1."
2. List all other materials in the process, such as nonsaleable by-products, solvents, water, air, nitrogen, acids, bases, and so on. This is "list 2."
3. For each compound in list 2, ask "How can I use a material from List 1 to do the same function of the compound in list 2?" or "How can I modify the process to eliminate the need for the material in list 2?"
4. For those materials in list 2 that are the result of producing nonsaleable products (i.e., waste by-products), ask "How can the chemistry or process be modified to minimize or eliminate the wastes (for example, 100% reaction selectivity to a desired product)?"

Analyzing the process in these ways and then applying fundamental engineering and chemistry practices will often result in a technology plan for driving toward a minimum waste generation process. Other key ingredients for a successful pollution prevention program are a proven methodology and the ingenuity of a savvy group of people to generate the options.

XII. WHEN SHOULD ONE DO POLLUTION PREVENTION?

The continuum depicted in Fig. 11 shows the relative merits of when a pollution prevention program should be implemented. The decision of how far to move toward the lowest waste and emissions design will depend on a number of factors including corporate and business environmental goals, regulatory pressures, economics, the maturity of the process, and product life. It is safe to say, "the earlier, the better." If one can make changes during the R&D stage of the process or product life cycle, then one has the best opportunity to make significant reductions in waste generation at the source. However, as one moves down the continuum from R&D through process design and engineering and post-startup operation, one's

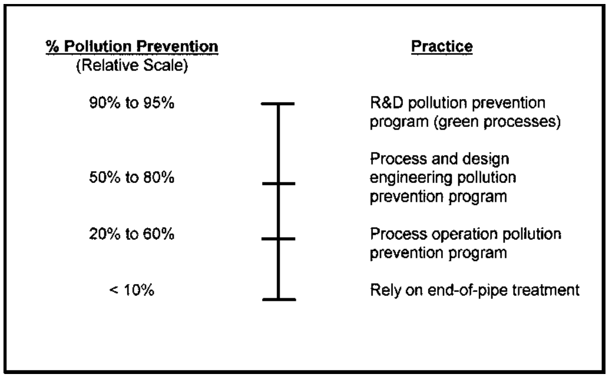

FIGURE 11 Pollution prevention methodology continuum.

dependence on end-of-pipe treatment grows. At the bottom of the continuum is a total reliance on end-of-pipe treatment. Here, pollution prevention may be manifested in the form of energy savings or a reduction in air flow to the abatement device, etc.

A. Pollution Prevention during Research and Development

Research and development programs typically progress through three distinct phases: process conception, laboratory studies, and pilot plant testing. The level of effort and detail required in pollution prevention assessment depends on the particular R&D phase. Generally speaking, studies are qualitative during process conception, semiquantitative in laboratory studies, and quantitative in pilot plant testing. The basic steps in a pollution prevention study, however, are the same in each phase.

During process conception, reaction pathways, inherent process safety, general environmental impacts of products, and waste streams are studied, and pollution prevention concepts are formulated.

During laboratory studies, reaction chemistry is confirmed, waste streams are characterized, process variables are tested, pollution prevention options are identified, data are collected for the pilot plant and process design, and the potential impact of environmental regulations is determined.

During pilot plant studies, laboratory results are confirmed, process chemistry is finalized, key process variables are tested, equipment design is evaluated, and waste characteristics are defined. It is especially important at this stage of R&D that all major environmental cost areas are understood as these relate to the overall viability of a commercial project.

B. Pollution Prevention during Process and Design Engineering

While the greatest opportunity for cost-effective waste reduction at the source exists at the R&D stage, additional opportunities may exist during process engineering and should be explored. The potential to reduce waste and pollutant releases in this stage is impacted by the selection of process configuration (batch versus continuous, for example), process conditions (such as temperature and pressure), manufacturing procedures, design and selection of processing equipment, and process control schemes.

As a project moves into the detailed design stage (sometimes referred to as the "mechanical design stage" or "production design"), source reduction opportunities typically diminish. The main reason is that the process and preliminary plant design become fixed and the project becomes schedule-driven. The focus at this stage shifts from the chemical process to equipment and facility design. The emphasis at this point should be to protect groundwater from spills and to minimize or eliminate fugitive emissions.

C. Pollution Prevention during Process Operation

If the pollution prevention program began during the research stage, then a pollution prevention analysis is not necessary until 3 years after startup of the process. Ideally, a pollution prevention program should be completed every 3–5 years.

For a process that does not have a history of doing pollution prevention, a pollution prevention program can generally realize a greater than 30% reduction in waste generation and a greater than 20% reduction in energy usage.

XIII. CASE STUDIES

Four case studies are presented below which exemplify the role of the structured pollution prevention program methodology, the value of quickly defining the incentive for pollution prevention using the cost of end-of-pipe treatment, and the benefits of using the waste stream and process analyses to parse the problem at hand. Five case studies are also presented illustrating pollution prevention results at each of the stages described in Fig. 11.

A. Program Elements—U.S. EPA and DuPont Chambers Works Waste Minimization Project

In May 1993, the U.S. EPA and DuPont completed a joint 2-year project to identify waste reduction options at the DuPont Chambers Works site in Deepwater, New Jersey. The project had three primary goals as conceived:

1. Identify methods for the actual reduction or prevention of pollution for specific chemical processes at the Chambers Works site.

2. Generate useful technical information about methodologies and technologies for reducing pollution, which could help the U.S. EPA assist other companies implementing pollution prevention/waste minimization programs.
3. Evaluate and identify potentially useful refinements to the U.S. EPA and DuPont methodologies for analyzing and reducing pollution and/or waste generating activities.

The business leadership was initially reluctant to undertake the program, and was skeptical of the return to be gained when compared against the resources required. After completing a few of the projects, however, the business leadership realized that the methodology identified revenue-producing improvements with a minimum use of people resources and time, both of which were in short supply.

The pollution prevention program assessed 15 manufacturing processes and attained the following results:

- A 52% reduction in waste generation.
- Total capital investment of $6,335,000.
- Savings and earnings amounting to $14,900,000 per year.

Clearly, this is a very attractive return on investment, while also cutting waste generation in half. No matter which methodology was used, the EPA's or DuPont's, the results were the same. The key to the site's success was following a structured methodology throughout the project and allowing creative talents to shine in a disciplined way.

B. Incentive for Pollution Prevention—Gas Flow Rate Reduction

A printing facility in Richmond, Virginia, uses rotogravure printing presses to produce consumer products packaging materials. Typical solvents used are toluene, isopropyl acetate, acetone, and methyl ethyl ketone. Driven by the U.S. EPA's new source performance standards for the surface coating industry, the site installed a permanent total enclosure (PTE) around a new press so as to attain a 100% VOC capture efficiency. Leaks from the hot air convection dryers and other fugitive emissions from the coating operation are captured in the press enclosure and routed, along with the dryer exhaust, to a carbon adsorber for recovery. Overall VOC removal efficiency for the enclosure and recovery system is greater than 95%. While many rotogravure press installations use the total pressroom as the enclosure, this facility was one of the first to install a separate, smaller enclosure around the new press. Notable features of the enclosure include the following:

- Quick-opening access doors
- A dryer which serves as part of the enclosure to minimize the enclosure size
- VOC concentration monitors which control air flow to each dryer stage to maintain the dryers at 25–40% of the LEL (lower explosive limit)
- Damper controls which maintain a constant exhaust rate from the enclosure to ensure a slight vacuum within the enclosure.

If the pressroom had been used as the enclosure, the amount of ventilation air requiring treatment would have been close to 200,000 scfm. Instead, the use of the enclosure and the LEL monitors reduced the air flow to the adsorber to 48,000 scfm. This resulted in an investment savings for the carbon adsorber of approximately $5,000,000. The installed cost of the 1700-ft^2 enclosure was only $80,000, or $47/ft^2. Knowing the investment required to treat the entire 200,000 scfm provided a clear incentive for the business to reduce air flow at the source through segregation.

C. Waste Stream Analysis—Nonaqueous Cleaning

In a sold-out market, a DuPont intermediates process was operating at 56% of peak capacity. The major cause of the rate limitation was identified as poor decanter operation. The decanter recovered a valuable catalyst, and the poor operation was caused by fouling from catalyst solids. Returning the process to high utility required a 20-day shutdown. During the shutdown, the vessel was pumped out and cleaned by water washing. The solids and hydrolyzed catalyst were then drummed and incinerated. A waste stream analysis identified three cost factors: the volume of wastewater that had to be treated, the cost of the lost catalyst, and the incineration cost.

An analysis of the process and ingredients indicated that the decanter could instead be bypassed and the process run at a reduced rate while the decanter was cleaned. A process ingredient was used to clean the decanter, enabling recovery of the catalyst ($200,000 value). The use of the process ingredient in place of water cut the cleaning time in half, and that, along with continued running of the process, eliminated the need to buy the intermediate on the open market. The results were a 100% elimination of a hazardous waste (125,000 gallons per year) and an improved cash flow of $3,800,000 per year.

D. Process Analysis—Replace Solvent with a Process Intermediate, Product, or Feed

At a DuPont site, organic solvents used in the manufacture of an intermediate monomer were incinerated as a hazardous waste. These organic solvents were used to dissolve and add a polymerization inhibitor to the process. Alternative nonhazardous solvents were considered and rejected because these solvents would not work in the existing equipment. However, with the help of process analysis techniques, the intermediate monomer was found to have the same dissolution capacity as the original organic solvents. As a result, the site replaced the organic solvents with the intermediate monomer. By utilizing existing equipment, realizing savings in solvent recovery, and reducing operating and incineration costs, the project achieved a 33% internal rate of return (IRR) and a 100% reduction in the use of the original solvents.

E. R&D Phase

1. Waste Reduction through Control of the Reaction Pathway

In hydrocarbon oxidation processes to produce alcohol, there is always a degree of overoxidation. The alcohol is often further oxidized to waste carboxylic acids and carbon oxides. If boric acid is introduced to the reactor, the alcohol reacts to form a borate ester, which protects the alcohol from further oxidation. The introduction of boric acid terminates the by-product formation pathway and greatly increases the product yield. The borate ester of alcohol is then hydrolyzed, releasing boric acid for recycle back to the process. This kind of reaction pathway control has been applied to a commercial process, resulting in about a 50% reduction in waste generation once the process was optimized.

2. Waste Reduction through Catalyst Selection

For chemical processes involving catalysis, proper selection of catalysts can have a major impact on product formation. One example is the ammoxidation of propylene to form acrylonitrile. Different catalysts result in a wide range of product and by-product yields. By-product yields of 50–80% (based on carbon) have been reported in the literature. Use of a different catalyst provided a 50% reduction in waste generation by increasing product yield from 60% to 80%.

F. Process and Design Engineering Phase

1. Reuse Reaction Water in Wash Step

A dehydration reaction generates a continuous stream of water, which requires disposal. A separate product wash step uses deionized water, which is also disposed. Testing verified that the dehydration water could replace the deionized water in the wash step without product quality impacts. Initial concerns about product quality were unfounded. Total waste generation was reduced by the quantity of dehydration water which is reused.

2. Groundwater Protection

At a grassroots facility, one company utilized a groundwater protection strategy which included several construction tactics not required by current environmental regulations. Chemical storage tanks were designed with double bottoms to allow leak detection before environmental damage. Similarly, one nonhazardous process water pond was constructed with synthetic liners to eliminate the possibility of groundwater impact from any pollutants. Nonhazardous process water ditches, traditionally used in chemical plants, were replaced with hard-piped sewer lines to eliminate the leak potential inherent with concrete.

G. Existing Process Operation

1. Reduced Hazardous Waste Generation

At a chemical manufacturing site, a series of distillation columns are used to purify different product crudes in separate campaigns. At the conclusion of each campaign, a portion of product crude was used to wash out the equipment. When the crude became too contaminated, it was sent for destruction in a hazardous waste incinerator. First, an analysis of the washing procedure of a decant tank indicated that only 1/10 of the product crude wash material was really needed to effect cleaning. Second, a dedicated pipeline for each crude was installed, thus eliminating the need to flush the line between campaigns. Third, an extended and improved drainage procedure was developed for a large packed-bed distillation column. Finally, the product specifications were relaxed, so that fewer washes were required to maintain product specifications. Capital investment for these process changes was $700,000; however, the project had a positive net present value of more than $3 million, and realized a 78% reduction in waste generation.

XIV. CONCLUSION

Pollution prevention is becoming an integral part of business operations, both new and existing. As the drive toward a more sustainable human society strengthens, pollution prevention will become even more necessary for a business to survive. There are large opportunities to do both pollution prevention and improve the economic return on manufacturing processes. Everyone in a business can contribute to reducing manufacturing waste. In this article we described pollution sources, pollution prevention techniques, and how everyone can contribute to pollution prevention.

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