CHEMTECH

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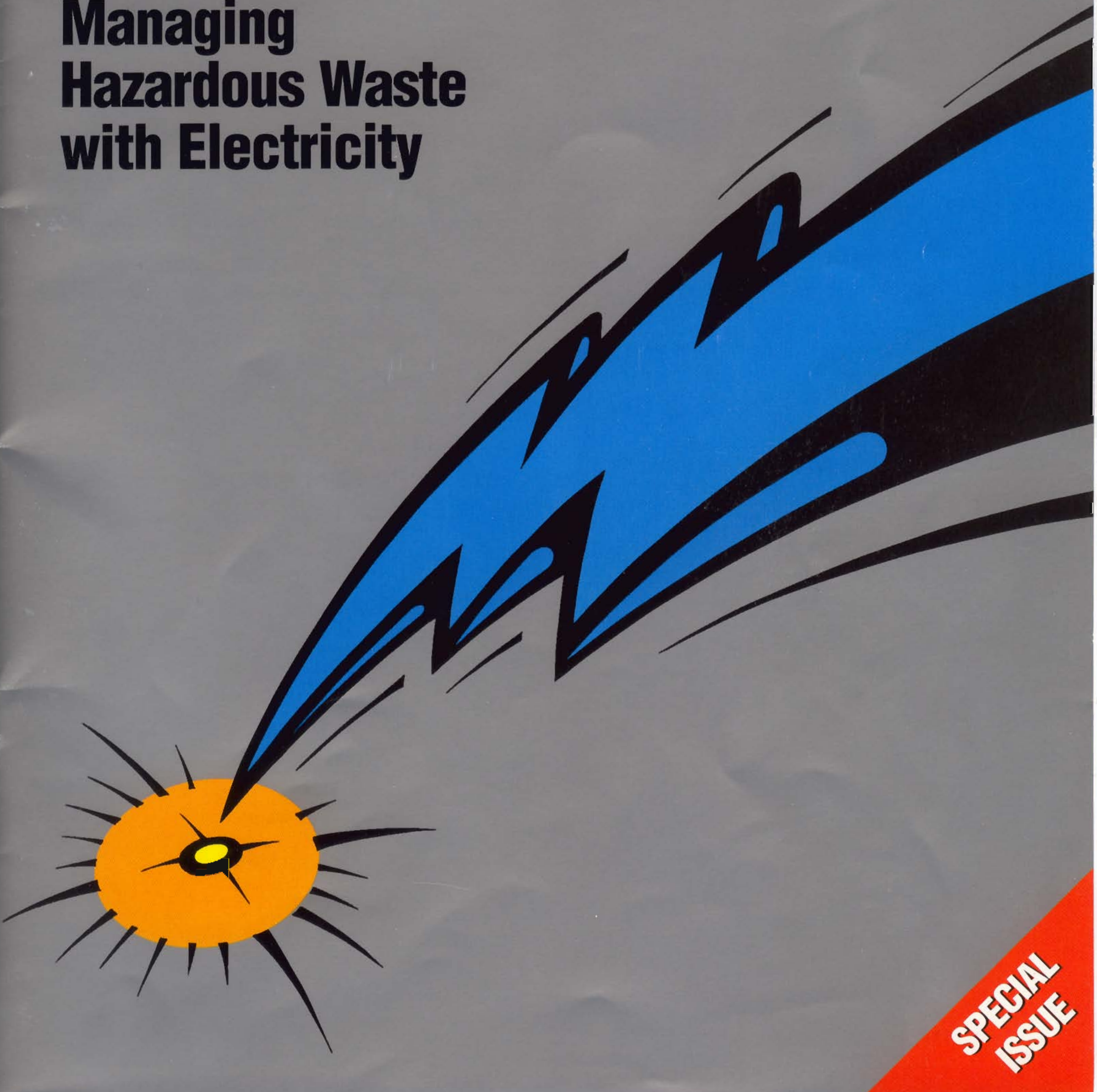
Managing Hazardous Waste with Electricity



SPECIAL ISSUE

Minimize waste by managing process design

Process integration techniques are inherently conservation oriented because they are supposed to enhance process efficiency (and save money) by minimizing the use and/or maximizing the recovery of energy and materials.

Frank W. Buehner
Alan P. Rossiter

Process integration is highly compatible with and complementary to the philosophy of pollution prevention. Preventing pollution requires overall process designs that are intrinsically environmentally friendly, not only the addition of pollution control equipment. Because process integration techniques provide a basis for analyzing and developing designs in their entirety, they can readily be focused on pollution prevention objectives. Here we describe how process integration techniques are being applied to pollution prevention problems and use examples to illustrate three main areas of process integration: pinch analysis, knowledge-based approaches, and numerical and graphical optimization approaches (*1*, *2*).

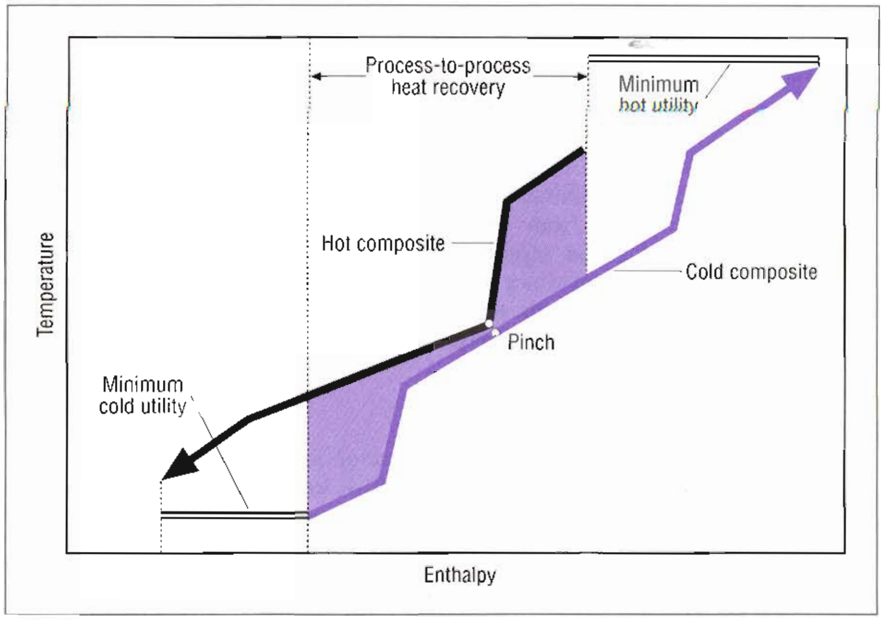


***Figure 1.* Thermal pinch analysis uses composite curves to show where heat flow is restricted.** The composite curves are derived from a stream-by-stream analysis of the heat sources and sinks within a process plant.

Thermal pinch analysis

Thermal pinch analysis is based on rigorous thermodynamic principles used to construct plots and perform simple calculations that yield powerful insights into heat flows through processes. The technique is widely used to determine the scope for energy savings in industrial operations and to define possible process changes to reduce intrinsic energy consumption. During the past 15 years pinch analysis has become the method of choice for identifying a wide range of process improvement options, including optimal plant utility systems and cogeneration schemes, heat exchanger networks (HENs), capacity increase, yield improvement, and—of course—emission reduction (*3*). Other important technical developments made with the use of pinch analysis include pressure drop optimization, multiple-base-case design, distillation column thermal profile analysis, low-temperature process design, batch process design, total site integration, emissions targeting, and water pinch (*4*).

In the environmental context, thermal pinch analysis is useful in determining the extent to which energy consumption can be reduced for the same amount of product manufactured. This approach generally results directly in reductions of NO_x, SO_x, CO, and CO_2 (*5*, *6*). It also guides the engineer in the generation of design options for reducing other process-related emissions.

The key concept of thermal pinch analysis is the concept of heat flow as a function of temperature based on driving force, the simplest representation of which are the hot and cold composite curves (*7*). The composite curves are derived from a stream-by-stream analysis of the heat sources and sinks within a process plant, and then overall energy availability and energy demand profiles are developed in terms of temperature and heat load (Figure 1).

Most processes display a pinch—a region on the plot at which the curves come very close together. It represents a restriction in the flow of heat within

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The authors are with Linnhoff March Inc.

the process and sets a practical limit on the possible amount of heat recovery. Analysis of these curves provides targets for hot and cold utility consumption and for process–process heat recovery. Targets, in this context, are realistically attainable goals based on thermodynamic and economic principles. One unique aspect of targets defined by pinch analysis is that targets can be obtained before detailed design, thus allowing the designer to explore various options without the added time and expense of carrying out detailed simulations and costings.

The early use of pinch analysis for emissions reduction is illustrated by the results of a major energy-saving campaign at BASF's Ludwigshafen (Germany) factory in the early and mid-1980s (*8*). A number of techniques were applied to reduce energy consumption, including changes in product mix, modifications in the site heat and power system, and various other efficiency improvements. Pinch analysis, then in its infancy, also formed a major part of the campaign, and pinch methods were used to improve the heat integration of most of the major processes on the site. A simple payback of one year or less, based on energy-saving potential alone, was required for each project.

The campaign's total energy savings (as fuel) amounted to 790 MW, and these savings were achieved with increased production. The improvements in energy efficiency in the individual processes directly reduced the fuel firing requirements at the factory. Combustion-related airborne emissions and ash residues therefore decreased. In addition to these benefits, wastewater discharges were also reduced, because less water treatment was required for steam and cooling water. The emission reductions were substantial.

Carbon dioxide	240 ton/h
Sulfur dioxide	1.5 ton/h
Nitrogen oxides	0.8 ton/h
Ash	46 lb/h
Carbon monoxide	15 lb/h
Wastewater from water treatment	77 ton/h

Significantly, these benefits, accompanied by a reduction in energy-related operating costs, were obtained "automatically" when the energy efficiency of production processes improved.

The difference between process integration and process simulation

Process integration is used to identify the most appropriate flow sheet structures and optimize flows and equipment sizes. Process simulation, on the other hand, is used to develop accurate heat and material balances and physical properties data for a given flow sheet. Process integration is used to change the design itself, whereas process simulation is used to understand the operating characteristics of the current design.

Process integration activities can often be carried out with only limited data about the process under consideration. To apply process simulation fully, however, there must be sufficient information to define all flows, compositions, temperatures, pressures, and equipment sizes. Both process integration and process simulation are essential to the development and improvement of process designs, and these closely related activities generally take place in parallel.

The methodologies of industrial process design do not, in general, attempt to invent new types of equipment or unit operations. On the contrary, they are meant to ensure that existing process technologies are selected and interconnected in the most efficient ways (e.g., in constructing heat exchanger networks with the optimal balance of capital and energy costs). These same basic methods, useful for minimizing cost, can also be used to explore the three-way relationship among capital cost, operating cost, and environmental optimization.

More recently, pinch analysis has been used explicitly to reduce emissions. In 1991 and 1992 German chemicals giant Bayer conducted a systematic study of CO_2 emission reduction options at their Leverkusen factory using total-site pinch analysis as part of their effort to reduce combustion-related emissions (*9*). Leverkusen, Bayer's largest facility, provides for a wide range of chemical processes (batch and continuous, organic and inorganic) at the site. The factory's power station burns coal and fuel gas to produce steam at 110 bar. This steam is let down through turbines to 31 and 6 bar, at which levels it is used for process heating.

The study identified many opportunities for reducing CO_2 emissions while lowering energy costs, including heat integration and various process changes within the individual production unit as well as modifications to the steam/power system. The maximum theoretical scope for CO_2 reduction was 28%. However, if only projects with an incremental payback of fewer than three years were implemented, this percentage decreased to 8%. For many energy integration projects, short payback times can exclude potentially large energy reduction projects and their directly related pollution reduction effects.

WaterPinch analysis

In general, reducing wastewater can be accomplished by reducing a plant's freshwater demand by process operation improvements, for example, by replacing water cooling with air cooling, improving controls of boilers and cooling-tower blowdowns, or increasing the number of extraction stages to reduce water demand. Another method is to increase water reuse in the process and utility systems. This system works if the outlet water from one operation can satisfy the requirements of another operation or, in some cases, the same operation. The water may require some treatment before reuse. The two main reuse options are direct, where the outlet water from one unit operation can directly satisfy the water demand of another operation (the outlet water is clean enough for the next operation), and regeneration, where the outlet water from one operation is treated (regenerated) to make it suitable for use in another water-consuming operation. Types of regeneration include simple pH adjustment and physical removal of unwanted impurities by filtration, membrane separators, sour-water strippers, ion-exchange systems, and other means.

Traditionally, freshwater use and wastewater generation have been reduced by considering design improvements in individual unit operations or by identifying water reuse opportunities across unit operations without systematic consideration of the overall process or the total site. Recently, such an approach was developed to maximize water reuse within processes and sites (*10*). This approach has been modified and dubbed WaterPinch.

The WaterPinch analysis method uses two main tools: visualization and rapid screening, for design options; and mathematics, for quantification of results. The WaterPinch approach is represented in Figure 2 (p. 66). It uses purity as the vertical axis and water flow rate as the horizontal axis. Each water-related process operation has input and output water streams. There can be several input and output water

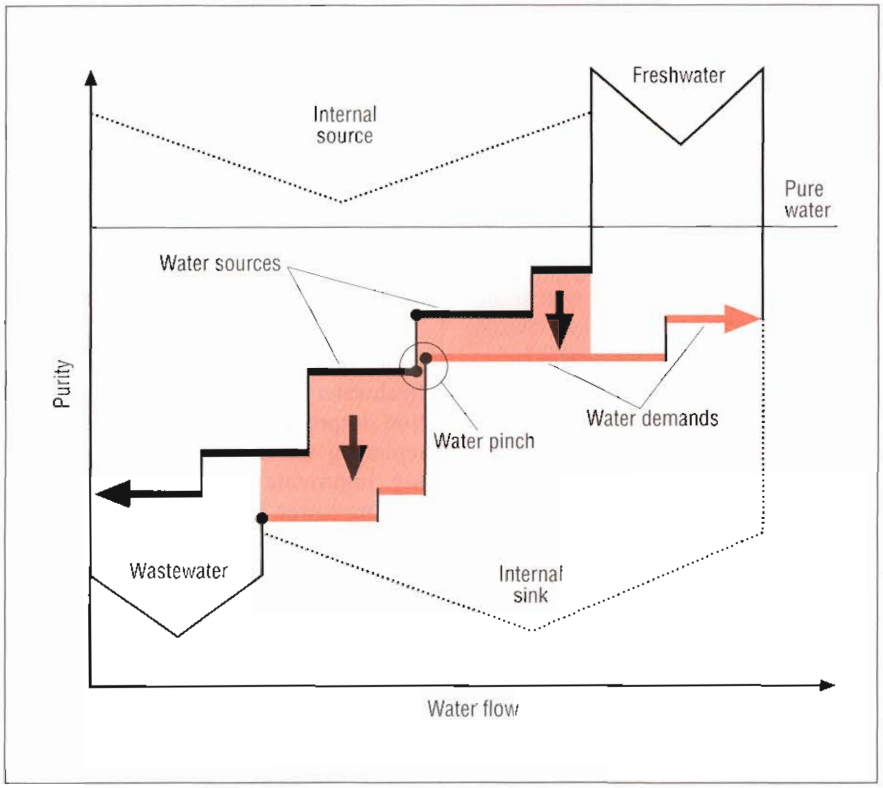


***Figure 2.* WaterPinch analysis can suggest ways to use less water in a process.** The input water streams of all the water-using operations are plotted in a demand composite form to define the water demand for the overall plant, and the output water streams are plotted to construct the source composite for the plant. The overlap between the source and the demand composite (shaded areas) indicates the scope for reuse.

streams at different purities for a single operation. The input water streams of all the water using operations are plotted in a "demand composite" form to define the water demand for the overall plant (Figure 2). Similarly, the output water streams for all the operations are plotted to construct the "source composite" for the plant. Constructing the demand and source composites is similar to constructing the thermal composite curve, shown in Figure 1.

The overlap between the source and the demand composite (shown by the shaded areas) indicates the scope for reuse. The available overlap is limited by the "pinch point" between the source and the demand composite. Minimum freshwater demand and wastewater generation without water mixing are also identified in Figure 2. This point is described in more detail later.

The representation also guides the designer to identify specific design actions to increase water reuse (Figure 3). By combining water sources from units A and B, we generate a mixture of intermediate purity, shown as "Mix." This mixture relieves the existing pinch-point bottleneck, allowing further overlap of the source and demand composites and increasing overall recovery in the process. This WaterPinch diagram also provides design guidelines. For example, water demand C should be satisfied by a mixture of water from the outlets of units A and B with some water from unit D. The WaterPinch approach therefore not only sets the targets but also recommends appropriate network design changes that maximize the reuse of water.

The visual representations can also be implemented in an equivalent mathematical form. The mathematical tool, involving a mixed-integer, nonlinear programming algorithm, allows the user to handle complex water networks with ease. The user can switch between mathematical and visual modes at any stage. The mathematical tool allows the user to handle complex water networks with ease. For example, systems with multiple contaminants and several operations can be analyzed in a reliable, quantitative manner. For large problems, the user may find it easier to start with the mathematical tool and visualize simplified solutions. The mathematical tool also allows consideration of practical issues, such as geographical and operability constraints or different costs of freshwater and treatment.

Unilever (Vinamul, Warrington, England). This factory produces more than 200 products including paints, glues, and adhesives. The polymer emulsion process is a complex batch operation. Product specifications are tight, and different products are made in the same vessels, which must be cleaned to prevent cross-contamination. Historically, to guarantee product integrity, the plant used large quantities of freshwater supplied to each individual user (Figure 4, p. 68). Changing environmental perceptions and rising costs for raw water and municipal water treatment prompted the company to reevaluate its philosophy.

Given the number of chemical components required to produce all of the products at Unilever, it was clearly not feasible to evaluate flows and concentrations of each compound. However, it was possible to treat all product compounds in water as a single contaminant without significant loss of accuracy (*11*). With the use of the WaterPinch procedure, a new design was developed that requires only one new intermediate storage tank and some alterations to piping and drainage systems. The practical results involved use of contaminated water at specified pressures for precleaning and a final wash and use of freshwater only where required. If this new procedure is implemented, site freshwater demand and wastewater production will decrease by 50 and 65%, respectively.

In this particular case, the direct savings in freshwater makeup costs and wastewater discharge costs are probably less than $100,000/year—not large compared with total processing costs; however, the modified design reduces the volume and increases the concentration of the effluent. This result should significantly reduce the capital cost of municipal treatment. A new treatment technology currently under development could result in total recovery of the product species from the effluent for recycling. Combining this new technology with wastewater minimization could result in significant savings and would also be a major step toward zero waste discharge.

Monsanto Chemical (Newport, Wales). Effluents from seven process units at Monsanto's site are currently collected together, adjusted for pH, and then discharged along an outflow into the River Severn estuary. The United Kingdom's National Rivers Authority indicated that discharge levels would not be acceptable after

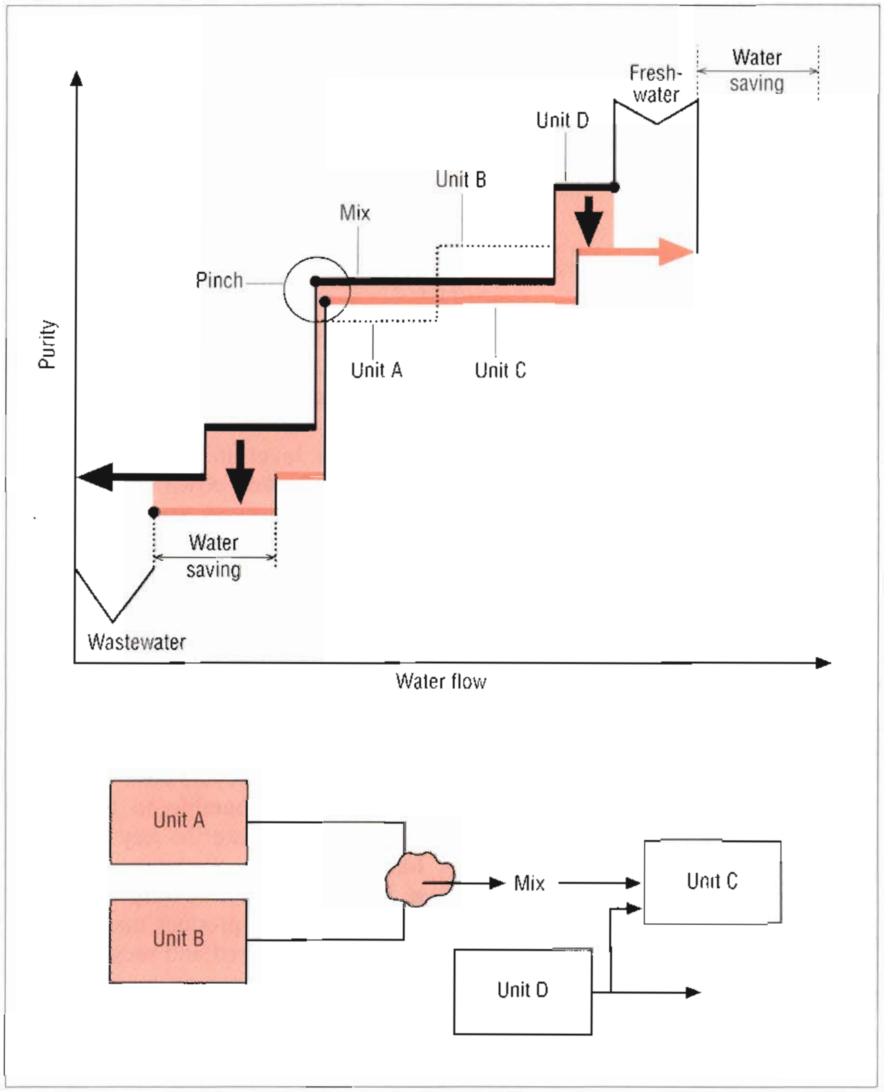


Figure 3. **The WaterPinch representation also guides the designer to identify specific design actions to increase reuse of water.** By mixing water sources from units A and B, we generate a mixture of intermediate purity (Mix). This relieves the existing pinch-point bottleneck, allowing further overlap of the source and demand composites and increasing the overall recovery in the process. Top: The targeting and visualization step. Bottom: The resulting design.

1997 and that discharge of chemical oxygen demand (COD) had to be reduced by 90%. The cost to achieve this reduction was estimated at $15 million.

The WaterPinch study results indicated that site freshwater use could be reduced by 30% in a cost-effective manner. Consequently, the decrease in effluent volume would have a significant effect on the size of the effluent treatment facility; however, reducing the COD load was of importance as well. The projects that were identified not only reduced wastewater flow but also reduced the COD load by 76%. For the remaining effluent, a pinch analysis method for the design of a distributed effluent treatment system was used. This method combines streams for special treatment when appropriate and segregates them when required. In this case, a small reed bed was recommended. The final effluent volume to be treated was reduced by 95%, and the capital cost for the reed bed was approximately $500,000.

Other benefits resulted from the study as well, such as savings of $300,000/year in water and $700,000 in other raw materials (these recovered raw materials would be lost in a centralized treatment facility). In the end, Monsanto was able to solve a difficult environmental problem without an unproductive investment of $15 million; the total investment was $3.5 million, and the company gained an operating cost savings of $1 million annually.

This project won *The Chemical Engineer*'s Excellence in Safety & Environmental Award, sponsored by the Institution of Chemical Engineers, in 1995 (*12*).

Knowledge-based approaches

The knowledge base we're considering is founded on the many universal features common to almost all industrial processes. A knowledge-based (or expert) system is used to describe a class of artificial intelligence applications embodying a system of rules based on an area of expert knowledge. However, we use the term in a broader sense, describing all process synthesis and process integration methods that build on an accumulated knowledge base of proven ideas. These ideas include processing steps for material conversion, material separations, material recycling, and energy utilization.

Typically, processes involve the conversion of one or more feeds into one or more products. Some type of material conversion step—commonly, a reactor—is required, but in some cases, unit operations such as crystallization or digestion may be involved. The material from the conversion step is usually not the final product. Unconverted feed materials and byproducts or wastes must be removed; thus, some type of separation is needed. Again, the type of separation system varies with the process. Distillation is generally regarded as the workhorse of the refining and petrochemicals industries; fractional crystallization is often used for close-boiling systems; and various types of solid–liquid separators (e.g., filters, centrifuges, and hydrocyclones) are common in processes making crystalline inorganic and organic products. Paper machines that separate pulp from white water are one example of solid–liquid separation in the pulp and paper industry. Notwithstanding the array of equipment types, the basic requirement for processes is the same across all the industrial sectors: separation of material into product and nonproduct streams.

The fate of the separated materials is also similar in most processes. Streams intended as products may be in their final form as they leave the separation system, or they may require some further processing step or steps (such as drying, agglomeration, or further purification). Nonproduct streams are generally recycled or purged. Thus, there are only a few structural options in the design of most processes.

Another common denominator for

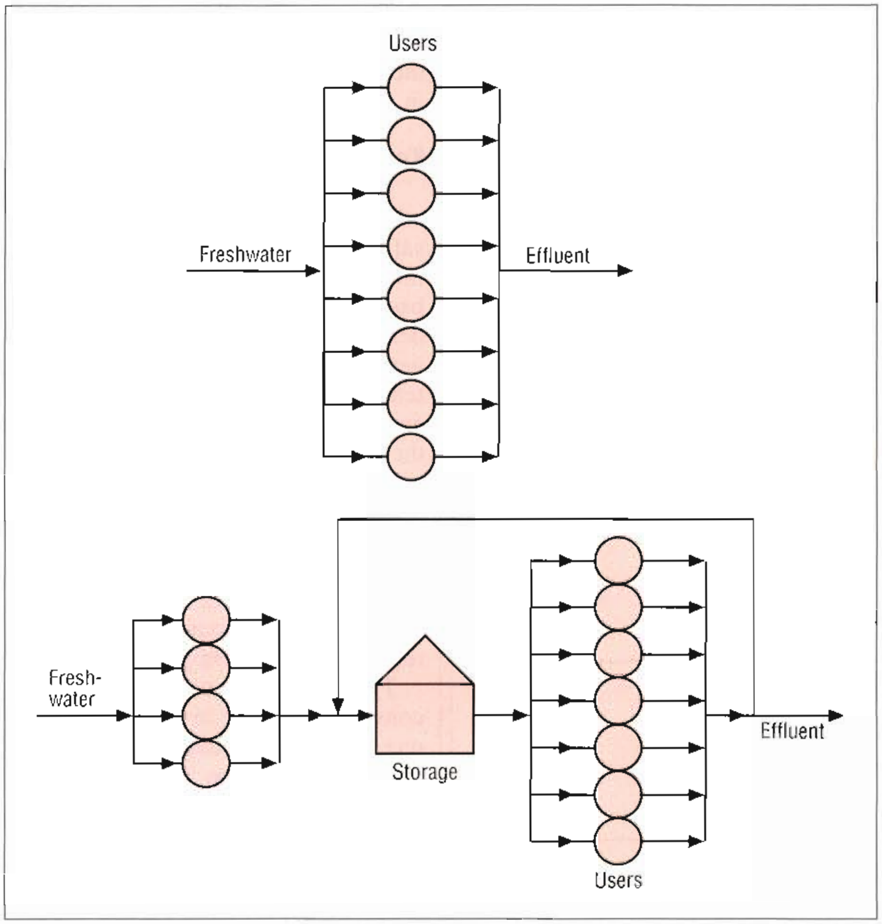


Figure 4. **Decreasing water use in a polymer plant.** By applying the wastewater pinch procedure to the original design (top) for Unilever's Vinamul factory, a new design (bottom) was developed that requires only one new intermediate storage tank and some alterations to piping and drainage systems.

all industrial processes is energy. Thermal energy is typically supplied by steam, fired heaters, or electric heaters of various types. Heat may be removed by ambient cooling (using air or water) or, at lower temperatures, by refrigeration. It may also be recovered within a process by heat exchange between process streams. Mechanical energy (usually derived from steam turbines, gas turbines, or electricity) is used for pumps and compressors as well as to drive other items of process equipment.

The differences among individual processes are obviously significant and should not be ignored. However, the foregoing discussion illustrates an important truth: The similarities are far greater than the differences—even when considering industries as varied as oil refining, pulp and paper production, pharmaceuticals manufacture, and food processing. This premise forms the foundation of the knowledge-based methodologies developed for generating new process designs and identifying promising retrofit options.

In the context of waste minimization, knowledge-based approaches include the transfer of specific pollution prevention ideas directly from one application to others (*13, 14*); hierarchical design and review procedures, in which the logical sequence of flow sheet evolution provides a framework for identifying and evaluating waste minimization options (*15, 16*); and, of course, artificial intelligence (*17*), in which computer programs mimic human thought processes to develop "clean" process designs.

These approaches can be used for developing new designs or for identifying retrofit options, often starting with minimal data. In new plant design, use of this type of procedure generally results in one or more "good" designs for the process—those that would be cost-effective with low emissions. In retrofits, they typically generate a list of potential process improvements for use in revamp projects.

Amoco (Yorktown, VA). The methodology used in this retrofit study of a refinery was a hierarchical review (see box). It was applied to the crude unit, fluid catalytic cracker (FCC), and the sour-water system at Amoco's 53,000 BBSD Yorktown Refinery (*16*). Several process improvement opportunities were identified, all based on known technologies and available equipment types, but in several instances with novel applications. The procedure enabled these ideas to be generated very quickly, with only limited process data. The basic concepts are illustrated by the following discussion of the recycle/reaction structure of the FCC.

At this level in the analysis, the process is broken down into its major component sections (typically, reaction and separation) with interlinking streams and recycles (see box **Hierarchical review**). Where data are available, one can assess the impact of reactor conditions on waste formation and evaluate some of the major tradeoffs in the process. These trade-offs typically include reactor conversion, separation and recycle cost, and waste generation attributable to byproduct reactions. Here are the key questions for this level.

- Do any "waste" output streams contain feed or product material that could be recovered and recycled?
- Can reaction conditions be altered to minimize formation of "waste" byproducts?
- Can "waste" byproducts be recycled to extinction?

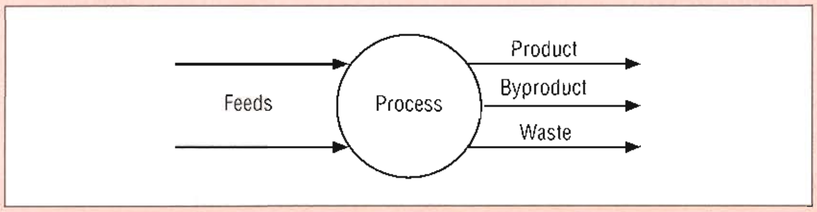
When these questions were applied to the FCC, two significant options were generated. First, the reactor uses 26,000 lb/h of steam from the utility steam system. If this steam were replaced with steam generated from process water (e.g., contaminated condensate from the distillation section of the unit), then the liquid effluent from the FCC could be greatly reduced. Although this steam would contain volatile hydrocarbons from the process water, it should not pose a problem because it is returned directly to the process. Moreover, these volatile hydrocarbons would be recovered in the reactor, thereby reducing hydrocarbon losses.

Second, used washwater is collected at several points and then purged from the process. If it were recovered and recycled (or if recycled water from other sources could be used for washing in place of freshwater), then the freshwater usage and wastewater generation could be reduced by up to 10,500 lb/h.

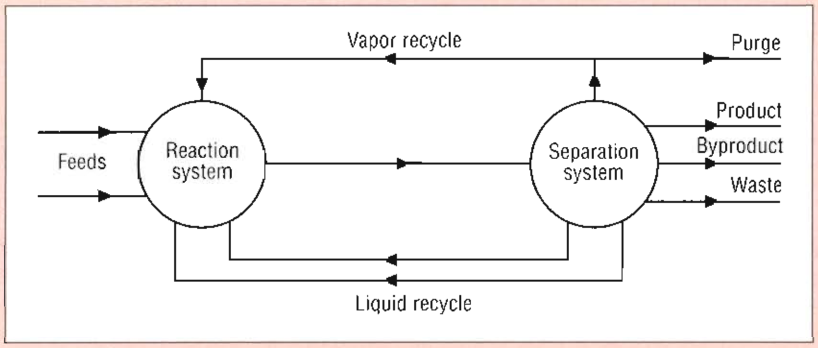
Besides providing environmental

Hierarchical review

Hierarchical review provides a systematic evaluation of the process flow sheet. The basic premise is that process design proceeds via a series of decisions that involve progressively greater levels of detail. For example, the most basic questions are whether the process is to be operated continuously or in batch mode, which product(s) will be produced, and which feed(s) should be used.



After resolving these issues, consider the recycle structure and material conversion aspects of the design. Here is a vapor–liquid recycle structure typical for many petrochemical processes.



Further details, such as the separation system, vapor recovery and/or product drying options (where needed), and heat integration can then be added. Only after these conceptual choices have been made is it appropriate to consider the selection and design of individual equipment items.

By identifying the key decisions and implementing them in the correct order, one can identify good design or retrofit options with minimal effort and rework. At each stage there are certain questions to address, heuristics to apply, and trade-offs to consider.

Historically, the questions and heuristics have focused on optimizing the trade-offs between capital and operating costs. Applied in the environmental context, the focus changes: The objective becomes the generation of new design or retrofit options for source reduction or beneficial recycle. Where appropriate, end-of-pipe options are also identified.

Steps in a numerical approach to reducing emissions

1. List emission sources, emission rates, and applicable pollution prevention and control options. This establishes a "base case" and defines the scope of the study.

2. Establish the range of application and the cost relationships for each of the waste minimization or control technologies. Cost versus benefit is determined for each individual technology, using data from the literature or from vendors.

3. Determine the mutual compatibility of each technology with each of the others. Certain technologies cannot be used together; others can be combined, but their joint benefits are less than the sum of their individual benefits. These relationships must be defined.

4. Calculate the maximum reduction in emissions achievable with each technology and each permissible combination of technologies, and then determine the corresponding total cost. Apply the cost and emission relationships established in step 2 and the compatibility rules established in step 3. Total annualized cost (TAC) is a very convenient basis for comparing costs

$$\text{TAC} = (\text{operating cost}) + b \times (\text{capital cost})$$

where b is the "annualization factor."

5. Establish which technology or combination of technologies provides the "least-cost solution" for any given reduction in emissions. This can generally be done simply by inspecting the results obtained at step 4. However, if many options must be evaluated, spreadsheet methods or mathematical programming techniques may be more appropriate.

6. Plot the results (minimum cost vs. emission rate). The table of least cost options generated at step 5 can be plotted directly as a minimum TAC-versus-emission rate plot. This curve represents the lowest expenditure required to reduce emissions from the base case to the specified level using the available technologies. Alternatively, the TAC values can be divided by the reduction in emissions (compared with the "base case") to give a "minimum average control cost plot" (shown in Figure 5, p. 70).

benefits, all of the projects identified in the Yorktown study result in savings in raw materials and/or utilities (water, steam, or fuel). The potential benefits and savings of the identified projects include

- eliminating surplus water in the sour-water system, reducing a potential source of odors;
- reducing desalter brine flow by 30%;
- recovering up to 7300 bbl/year of raw material (with equivalent reduction in loading in water treatment plant);
- saving more than 30 MMBtu/h in fuel firing; and
- recovering another 20 MMBtu/h in fuel gas.

Numerical and graphical optimization approaches

There are a variety of numerical optimization approaches, from simulation using simplified mathematical models of the process to sophisticated mathematical programming methods. These approaches are often combined with cost equations to quantify the impact of design decisions on process economics. Graphs can provide a visual representation of the effect of varying design and/or operating parameters and often enhance the usefulness of the results.

These approaches have been applied to a number of environmental problems. For example, simple mathematical models have been used to develop cost-versus-emissions limit curves (*18*). These curves allow engineers and regulators to explore the impact of process changes on cost and emission levels as well as to define the most cost-effective means of achieving an emission target. More sophisticated techniques (linear and nonlinear programming, with and without mixed integers) have been used in many different applications. Such methods include minimizing water use and decreasing wastewater generation rates from production facilities (*19*), minimizing waste in

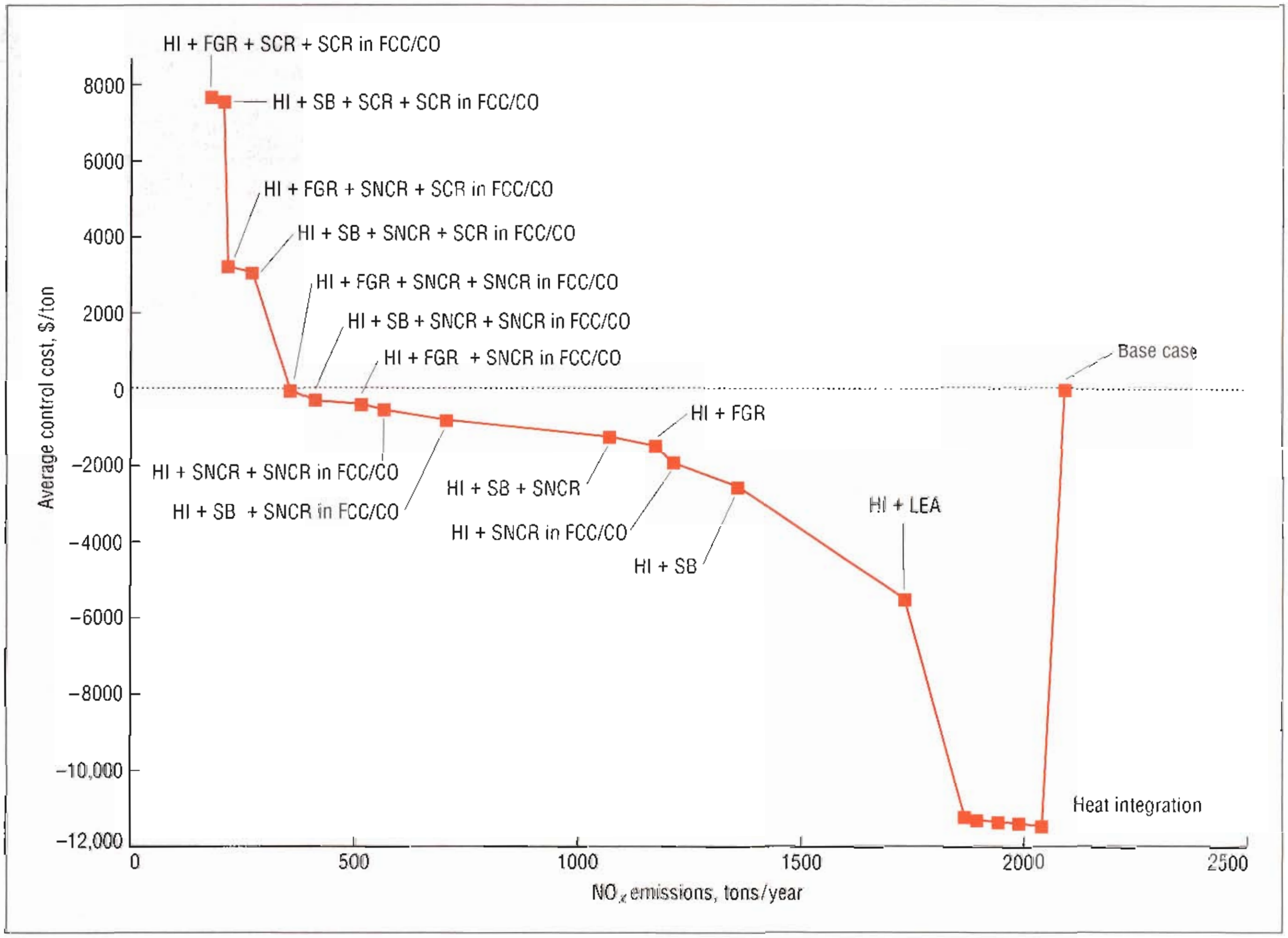


***Figure 5.* The first 10% reduction in emissions can be obtained at a "profit" by heat integration.** In this minimum average control cost plot, the operating cost savings exceed the annualized capital cost for the heat integration modification, and the compliance cost is negative. Additional reductions require more expensive control technologies. FCC/CO, the fluid catalytic cracking unit with its associated CO boiler. Other abbreviations are shown in Table 1.

pulp and paper operations (*20*), and synthesizing reverse-osmosis networks for waste minimization (*21*). Similar approaches have also been used for real-time optimization to minimize emissions; for example, mixed-integer linear programming techniques can be used for optimizing the selection of on-line plant utility system equipment to minimize NO$_x$ emissions (*22*).

Simple numerical and graphical procedures provide a very useful means for representing the relative costs and benefits of competing technical options for pollution prevention. They can be used in new design and retrofit applications and are particularly well-suited to dealing with options for reducing airborne emissions. This approach, therefore, is a powerful tool for identifying cost-effective strategies for reducing air pollution from industrial facilities. The principal steps are summarized in the box for a system in which the goal is to reduce NO$_x$ emissions.

The procedure is illustrated by an example based on NO$_x$ emissions from an oil refinery (*23*). The main NO$_x$ sources were boilers, furnaces, and the FCC unit and its associated CO boiler (*24*).

Boiler/furnace	Emissions, lb/MMBtu fired
Fuel gas	0.2
Residual fuel oil	0.43
FCC/CO	0.3

These figures include allowances for both "fuel NO$_x$" and "thermal NO$_x$." The FCC/CO value includes coke burned in the regenerator and fuel gas fired in the CO boiler, and the literature value has been adjusted to account for this.

The options considered for minimizing NO$_x$ emissions include the conservation methods, combustion modifications, and stack gas controls shown with their cost-and-benefit data in Table 1. The A value of 0.27 was used for the annualization factor b, which is equivalent to requiring a 15% rate of return with a 5-year plant life.

The minimum average control cost plot is shown in Figure 5. The base case refinery has NO$_x$ emissions of 2086 tons/year (0.12 lb/bbl). The first 10% reduction in emissions can in fact be obtained at a "profit" by heat integration, because the operating cost savings exceed the annualized capital cost and the compliance cost is therefore negative. Beyond this point, fuel gas is in excess and would have to be flared, so there is no incentive for additional heat integration. Further reductions in NO$_x$ emissions require different (and increasingly expensive) combinations of control technologies. For all of these options, either operating costs are not reduced or the annualized capital cost exceeds the operating cost reduction. Consequently, the average control cost rises on Figure 5 as each one is added.

The maximum reduction in NO$_x$ emissions using the available technologies is 91.8%, yielding an emission rate

Table 1. Costs of NO_x control options

Technology	Capital cost, $/(MMBtu/h)	Cost implications, $/ton NO_x removed		% NO_x reduction
		Operating cost	Savings	
Heat integration (HI)	None[a]	NA	11,000–25,000	10–30
Low excess air (LEA) burners	1920	NA	640–1550[b]	15
Staged fuel or staged air burners (SB)	1920	None	None	55
Flue gas recirculation (FGR)	3500	75[c]	NA	75
Selective noncatalytic reduction (SNCR)	1300	800	NA	70
Selective catalytic reduction (SCR)	30,000	1100	NA	85

Source: References 24 and 25.

[a] The scope and economics of heat integration are site specific and are most easily estimated using pinch analysis.

[b] Fuel savings = 1%.

[c] Per year/(MMBtu/h).

NA, not applicable.

of 175.5 tons/year. However, it is significant that the net savings attributable to heat integration exceed the net costs of the other options for reductions of up to 80.5% (406.8 tons/year released). The average control cost is negative for reductions up to this level. Beyond this point, it becomes necessary to incorporate selective catalytic reduction (SCR) into the control strategy for the FCC/CO boiler, causing a steep rise in costs. In effect, the final 231.3 tons/year of NO_x elimination costs nearly $15 million/year ($65,000/ton). The market rate for NO_x offsets is in the range of $25,000–$30,000/ton. However, some current legislation mandates the use of SCR in certain applications.

Only a few scenarios were considered in this particular study, and the list of options is not exhaustive. However, it is a simple matter to add further options (e.g., fuel substitutions) and rank them alongside those considered here, using the same procedure.

This graphical approach has two main benefits. First, it provides a generic methodology for evaluating and ranking available industrial waste minimization and pollution control technologies. The plots obtained using the procedure give a clear, concise, and easily understood representation of the economic implications of environmental compliance options. Designers and plant owners thus have a good basis on which to make decisions about technical solutions to emission problems. Second, it introduces a rational basis for establishing "standards of performance" for each industry or each manufacturing site. The approach is also consistent with the concept of "market-based" environmental legislation and could therefore be useful in developing future environmental regulations.

Assistance

Government agencies and industrial sources are available to assist companies who generate waste products by funding of energy, air and water pollution studies and projects (*25*). These sources offer additional incentives for decreasing pollutants released to the environment.

In the United States, the Electric Power Research Institute, the U.S. Department of Energy, the U.S. Environmental Protection Agency and the Gas Research Institute, are among those who help fund programs meeting specific criteria. The electric utilities help fund projects assisting customers to become more profitable and continue to be viable in the marketplace. Other local programs in the United States help fund regional and local pollution issues.

In Canada, the Federal Agency, Natural Resources Canada, funds programs. The European Community (EC) also offers incentives for reducing pollution: In Holland, Novem, Gasunie, and the International Energy Agency fund studies for improving energy efficiency and reducing CO_2 generation. A number of covenants have been made between branches of industry and the Ministry of Economic Affairs to be 20% more efficient in the 10 years from 1990 to the year 2000.

The THERMIE project for the promotion of energy technology is a vital part of the EC's strategy for meeting the energy challenges that must be faced today for a secure tomorrow. In Spring 1995 a European Union regulation introduced special public recognition for companies that demonstrate outstanding efforts to improve environmental performance. Under the Eco Management and Auditing Scheme (EMAS), firms meeting an auditing scheme similar to the International Standards Organization 9000 quality certification can display an EMAS logo on their publications and stationery and in image advertising (*26*).

Conclusions

Extensive regulations face industry, and it is unclear where and when the current situation will end (*27–30*). It is clear that, for many industries, eliminating pollution generation is better than facing the ongoing, never-ending list of regulations that now exist and will be promulgated in the future.

Process integration methods can be applied to a wide range of pollution prevention problems—new designs and retrofits; vapor, liquid, solid, and multimedia discharges; and continuous and batch operations. The three types of process integration described here have somewhat different areas of application and tend to yield different, yet complementary, results. Consequently several methods are often used together when addressing a design problem. The numerical optimization approach is most appropriate when only a few well-defined design options require evaluation. For complex processes with multiple variants, the simulation effort can become overwhelming, and the other approaches—especially knowledge-based methods—are needed to identify potentially attractive options and narrow the scope of the problem. The pinch approach is good for identifying fundamental insights into heat transfer and mass transfer problems, which can result in step-change design improvements.

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Addresses for assistance

Electric Power Research Institute (EPRI)
PO Box 10412, Palo Alto, CA 94303

U.S. Environmental Protection Agency (EPA)
401 M St., SW, Washington, DC 20460

Gas Research Institute
8600 West Bryn Mawr Ave., Chicago, IL 60631

Natural Resources Canada
1615 Blvd Lionel-Boulet, Varnnes, Quebec J3X 1S6, Canada

Gasunie
Postbus 19, 9700 MA Gröningen, the Netherlands

Thermie 1994
"The Promotion of Energy Technology for Europe," Commission of the European Communities, Directorate-General for Energy, THERMIE 1994, 226–236 Av. de Tervuren, B-1150 Brussels, Belgium (Fax: Mr. W. Folkertsma +32-2-205.05.77)

International Energy Agency (IEA)
IEA Heat Pump Centre, Novem, PO Box 17, 6130 AA Sittard, the Netherlands

Novem
Novem Utrecht, St. Jacobsstraat 61, Postbus 8242, 3503 RE Utrecht, the Netherlands

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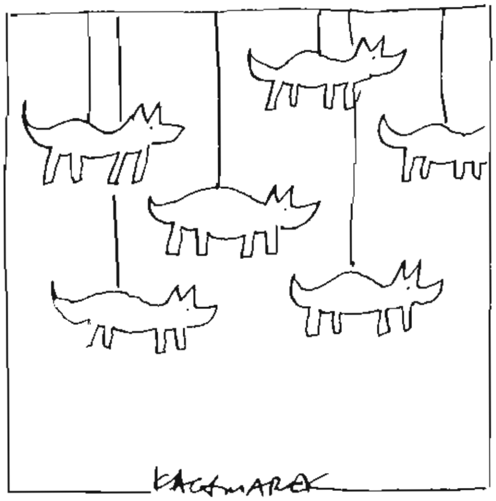
Frank W. Buehner is the sales and marketing manager of Linnhoff March Inc. for North America (9800 Richmond, Houston, TX 77042; 713-787-6861). He holds B.S. and M.S. degrees in chemical engineering from Cleveland State University. For the past 20 years he has been involved in promoting methods for reducing air, water, and noise pollution. His current responsibilities include energy reduction, process debottlenecking, and emissions reduction for the refining, petrochemical, and pulp and paper industries.

Alan P. Rossiter is operations manager and a principal consultant with Linnhoff March Inc. His work with Linnhoff March has involved many waste minimization, capacity debottlenecking, and energy conservation projects. Before joining Linnhoff March he worked for ICI in process design, plant operations, and research. He received his B.S., M.S., and Ph.D. degrees in chemical engineering from the University of Cambridge (U.K.). He is a chartered engineer and a registered professional engineer (Texas).

IMAGINATION IN SCIENCE

Whatever we are allowed to imagine in science must be consistent with everything else we know—that the electric fields and the waves we talk about are not just some happy thoughts which we are free to make as we wish, but ideas which must be consistent with all the laws of physics we know. We can't allow ourselves to seriously imagine things which are obviously in contradiction to the known laws of nature. And so our kind of imagination is quite a difficult game. One has to have the imagination to think of something that has never been seen before, never been heard of before. At the same time the thoughts are restricted in a straitjacket, so to speak, limited by the conditions that come from our knowledge of the way nature really is. The problem of creating something which is new, but which is consistent with everything which has been seen before, is one of extreme difficulty.

Richard P. Feynman



Suspended animalization