Selected Reading Material

- **Robert A. Frosch and Nicholas E. Gallopoulos:**
  "Strategies for Manufacturing." *Scientific American* 261 (September 1989): 144–152.
- **H. C. Haynsworth and R. Tim Lyons:**
  "Remanufacturing By Design, the Missing Link." *Production and Inventory Management* (2nd Quarter 1987): 24–29.
- **Robert L. Kraft:**
  "Incorporate Environmental Reviews into Facility Design." *Chemical Engineering Progress* 88 (August 1992): 46–52.

Strategies for Manufacturing

Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment

by Robert A. Frosch and Nicholas E. Gallopoulos

People create new technologies and industries to meet human needs more effectively and at lower cost. Innovation is a major agent of progress, and yet innovators' incomplete knowledge sometimes leads to undesirable side effects. Such unforeseen consequences of new inventions are not unique to the feverish industrialization of the 19th and 20th centuries. The ancient Greek myths tell of Pandora and the box full of plagues, of Prometheus punished for stealing fire from the gods and of Icarus, who plummeted from the sky when the sun's heat melted the wax of his wings. In historical times the shift from rawhide to tanned leather, although it made for garments and tools that lasted much longer and were more comfortable to wear and use, brought stenches and disease, so that tanneries had to be segregated from the communities they served.

Today such inadvertent effects can have a global impact. Consider, for example, the invention of chlorinated fluorocarbons. Before CFC's were developed in the 1930's, refrigerator compressors contained ammonia or sulfur dioxide; either chemical was toxic, and leaks killed or injured many people. CFC's saved lives, saved money and provided such elements of modern life as air-conditioned buildings and untainted food. Only later did atmospheric scientists determine that CFC's contribute to global warming and affect the chemistry of the upper atmosphere, where they destroy ozone.

Such failures should not diminish the fact that technology has improved the lot of people everywhere. Standards of living in many parts of the world are better today than they were 20 or 30 years ago. Many of the adverse effects of industrialization have been brought under control by further applications of technology. Yet as the world's population and standard of living increase, some of the old solutions to industrial pollution and everyday wastes no longer work. There is often no "other side of town" where the modern equivalents of tanneries can be put, no open space beyond the village gates where garbage can be dumped and do no harm.

By the year 2030, 10 billion people are likely to live on this planet; ideally, all would enjoy standards of living equivalent to those of industrial democracies such as the U.S. or Japan. If they consume critical natural resources such as copper, cobalt, molybdenum, nickel and petroleum at current U.S. rates, and if new resources are not discovered or substitutes developed, such an ideal would last a decade or less. On the waste side of the ledger, at current U.S. rates 10 billion people would generate 400 billion tons of solid waste every year—enough to bury greater Los Angeles 100 meters deep.

These calculations are not meant to be forecasts of a grim future. Instead they emphasize the incentives for recycling, conservation and a switch to alternative materials. They lead to the recognition that the traditional model of industrial activity—in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of—should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process—whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products—serve as the raw material for another process.

The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living—and the developing nations are to raise theirs to a similar level—without adversely affecting the environment.

If both industrialized and developing nations embrace changes, it will be possible to develop a more closed industrial ecosystem, one that is more sustainable in the face of decreasing supplies of raw materials and increas-

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INDUSTRIAL PLANTS such as this oil refinery in New Jersey make the products and materials that sustain modern life. They also emit pollutants that are difficult to dispose of and that may have long-lasting adverse effects on the environment. Meeting environmental needs calls for manufacturing plants that not only produce goods more efficiently but also fit together into a more harmonious industrial ecosystem. At the same time, consumers must learn to use those products less wastefully.

ing problems of waste and pollution. Industrialized nations will have to make major and minor changes in their current practices. Developing nations will have to leapfrog older, less ecologically sound technologies and adopt new methods more compatible with the ecosystem approach.

Materials in an ideal industrial ecosystem are not depleted any more than those in a biological one are; a chunk of steel could potentially show up one year in a tin can, the next year in an automobile and 10 years later in the skeleton of a building. Manufacturing processes in an industrial ecosystem simply transform circulating stocks of materials from one shape to another; the circulating stock decreases when some material is unavoidably lost, and it increases to meet the needs of a growing population. Such recycling still requires the expenditure of energy and the unavoidable generation of wastes and harmful by-products, but at much lower levels than are typical today.

Today's industrial operations do not form an ideal industrial ecosystem, and many subsystems and processes are less than perfect. Yet there are developments that could be cause for optimism. Some manufacturers are already making use of "designed offal," or "engineered scrap," in the manufacture of metals and some plastics: tailoring the production of waste from a manufacturing process so that the waste can be fed directly back into that process or into a related one. Other manufacturers are designing packaging to incorporate recycled materials wherever possible or are finding innovative uses for materials that were formerly considered wastes.

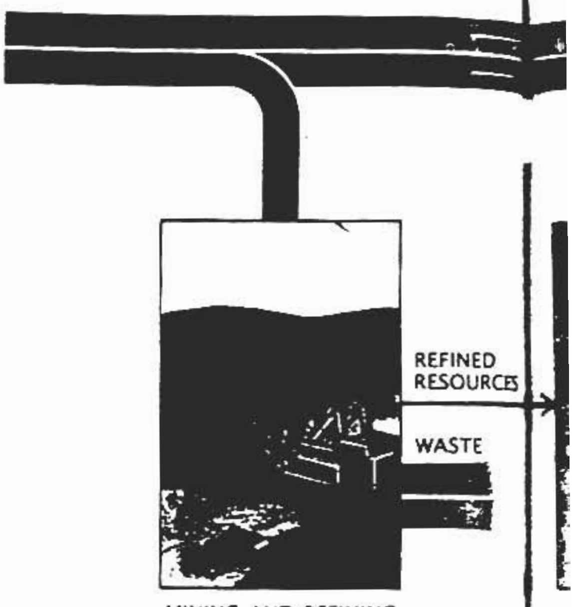
Three examples delineate some of the issues involved in developing self-sustaining industrial process systems: the conversion of petroleum derivatives to plastics, the conversion of iron ore to steel, and the refining and use of platinum-group metals as catalysts. We have picked these examples because each represents a different stage in the evolution of a closed cycle. Examining their workings and shortcomings should provide insight into how subsystems can be improved so as to develop an industrial ecosystem.

The iron cycle, in which recycling is well established, is a very mature process with a history dating back thousands of years, even though extensive production of steel did not begin until the 19th century. The plastics cycle, in which reuse is just beginning to make its mark, is less than 100 years old; the first completely synthetic plastic, Bakelite, was introduced shortly after the turn of the century. The platinum-group-metals cycle—in which reuse is common because of the high cost of the materials involved—is even younger: industrial noble-metal catalysts became widely used only in the early 1950's, and the widespread use of noble metals to reduce pollution from automotive exhaust dates back less than 15 years.

ESTIMATED LIFETIMES OF SOME GLOBAL RESOURCES

	CURRENT CONSUMPTION RATES		2030 RATES	
	RESERVES	RESOURCES	[illegible]	RESOURCES
ALUMINUM	256	805	[illegible]	407
COPPER	[illegible]	277	[illegible]	26
COBALT	[illegible]	429	[illegible]	40
MOLYBDENUM	[illegible]	256	[illegible]	33
NICKEL	[illegible]	163	[illegible]	16
PLATINUM GROUP	[illegible]	413	[illegible]	39
COAL	[illegible]	3226	[illegible]	457
PETROLEUM	[illegible]	83	[illegible]	7

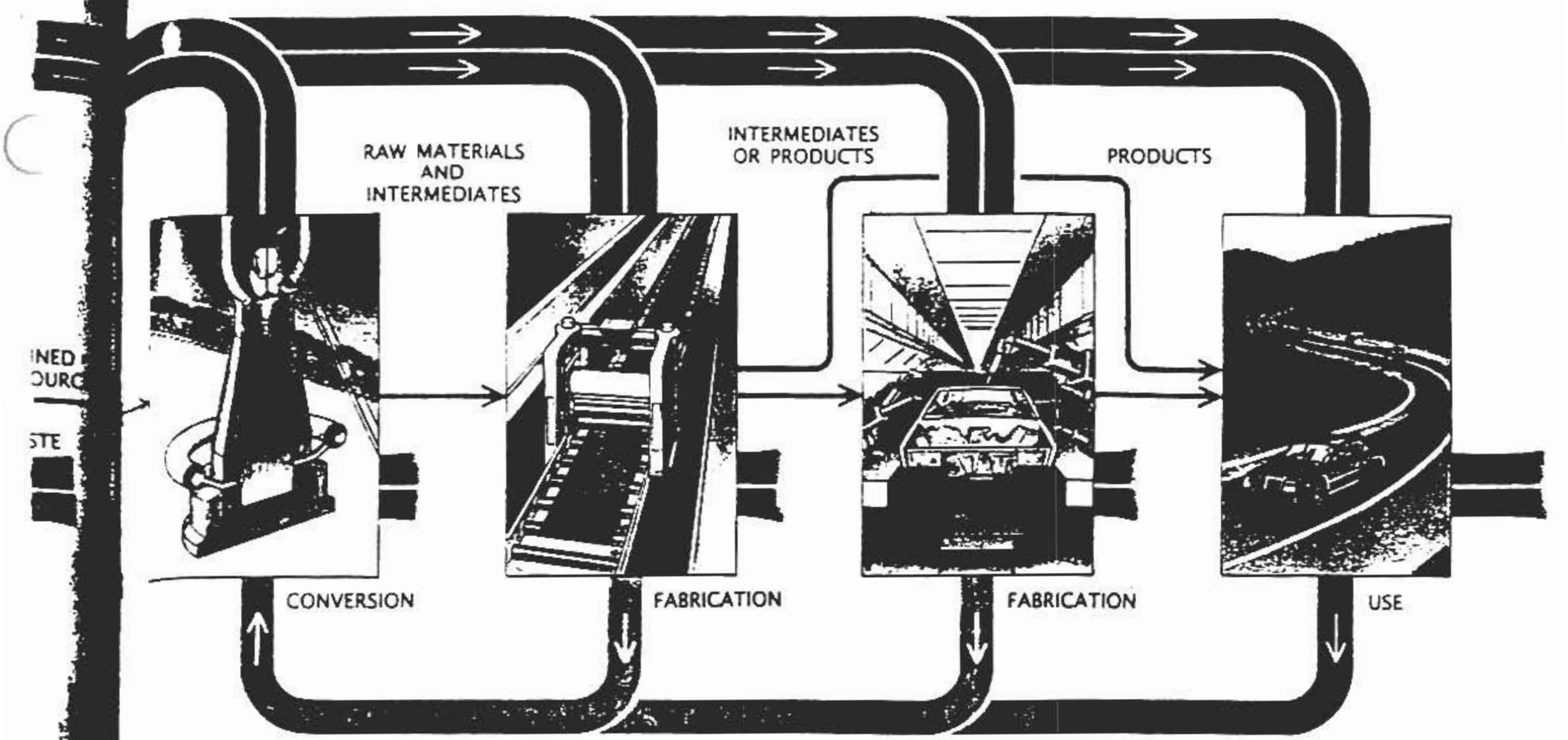
WORLD STOCKS of some essential raw materials will drop perilously low if less developed countries increase their consumption to match that of the industrialized world. Figures show reserves (quantities that can be profitably extracted with current technology) and resources (total quantities thought to exist). Estimates of years left until depletion are based on current global consumption (*left*) or on the assumption that in 2030 a population of 10 billion will consume at current U.S. rates (*right*).



INDUSTRIAL-ECOSYSTEM CYCLE starts with resources and progresses to a finished product that can be recycled (*blue*)

The plastics system is potentially highly efficient, but realizing that potential poses challenges that have yet to be met. Plastics are a diverse group of chemically complex compounds whose use has grown explosively, so that they now present a growing disposal problem. Plastics are formed into any number of products, and different plastic resins are difficult to distinguish. This difficulty leads to problems in collection, separation and recycling. Moreover, breaking plastics down to their original chemical constituents is often technologically infeasible or economically unattractive.

The drawbacks of plastics must nonetheless be weighed against their benefits. Plastic containers, for example, are safer than the glass containers they replace. Countless injuries, from minor cuts to severe lacerations, have been prevented by the substitution of plastic for glass in milk bottles and containers for bathroom products such as shampoo. Plastic containers are generally lighter than glass or metal ones, so that less energy is required to transport them; they also require less energy to make than glass or metal containers, especially if they are



after use to enter the cycle again as a raw material. (The iron and steel cycle is shown here.) At each stage in the manufacturing process, energy (*red*) and additional raw materials (*green*) are added, and waste heat and by-products are generated. In an optimal cycle, wastes are captured and reused either in the same manufacturing process or in a different one.

recycled. The Midwest Research Institute in Kansas City, Mo., determined that compared with glass containers, half-gallon polyvinyl chloride (PVC) containers require less than half the energy to produce and transport and consume one twentieth the mass of raw materials and less than one third as much water in their manufacture. They also generate less than half of the waste of glass manufacturing.

Each kind of plastic poses different problems depending on its particular composition and use. PVC, of which almost four million tons are produced every year in the U.S., is a particularly dramatic example of the complex threats plastics pose to the environment. PVC, which accounts for about one sixth of total plastic production, is made into products ranging from pipes to automobile parts to shampoo bottles. Its production requires both hydrocarbons and chlorine. (The chlorine makes the plastic's impact on the environment greater than it would be if only hydrocarbons were required—as is the case for polyethylene, for example.) Natural gas is the most commonly used feedstock for PVC in the U.S.; elsewhere it is naphtha, a petroleum fraction. In either case the feedstock is converted to ethylene, which is chlorinated to form vinyl chloride monomer; the monomer molecules are then linked to form PVC.

The efficiency of the production process has already been improved. For example, manufacturers have developed more efficient membrane cells for the electrolysis of sodium chloride to produce the required chlorine. (The sodium chloride, common table salt, is dissolved in cells through which a current flows; sodium ions migrate to one electrode, and chlorine ions migrate to the other. A membrane separates the two electrodes.) The membrane cells also eliminate the asbestos and mercury required in older electrolysis cells, thus reducing hazardous wastes.

Even so, the PVC production process exemplifies classic "end of pipe" control measures for reducing pollutants. Emissions of vinyl chloride monomer during manufacturing are tightly controlled, a practice instituted when it became known that the monomer is both toxic and carcinogenic. Unreacted vinyl chloride is generally stripped from the finished PVC by low-pressure steam. Most of the monomer is recovered and recycled, but some of it is present at concentrations too low for easy recovery and recycling; instead it is sent to an incinerator to be broken down. Scrubbers remove hydrochloric acid from the exhaust.

Recycling of PVC during manufacturing is fairly straightforward. Plants that make PVC products typically recycle almost all of their in-house scrap. At General Motors, for example, scrap generated in the manufacture of PVC parts such as decorative trim, seat covers and dashboards is segregated by color, reground, melted and used along with virgin PVC.

Once plastic enters the consumer market, however, recycling becomes considerably more complicated. Only about 1 percent of the PVC discarded by consumers is recycled. The wide range of products in which PVC is found makes collection and recovery more difficult, but it also creates interesting opportunities. For example, potential health hazards and liability concerns prevent recycled plastics from being incorporated into containers where the plastic touches food; recycled bottles may find their way into drainage pipes instead.

Other vinyl products that cannot easily be recycled can be burned to produce heat or electricity. PVC contains roughly as much energy as wood or paper, but its chlorine content poses problems: incinerators that burn PVC must have scrubbers to prevent emissions of hydrochloric acid, which contribute to acid rain. During combustion the chlorine can also form small amounts of dioxins, which are believed to be potent carcinogens. As a result, the incineration of discarded PVC is discouraged. Although recent tests by the New York State Energy Research and Development Authority have shown that properly designed and operated incinerators do not emit significant quantities of hydrochloric acid or dioxins, environmentalists and regulators are not convinced that incinerators would achieve such low emission levels in practice.

Because of its chlorine content, PVC is a worst-case example of the problems plastics pose. Other polymers such as polypropylene and polyethylene present fewer environmental hazards. They have physical properties similar to those of PVC, but they contain no chlorine. Polyethylene terephthalate (PET), the material used in carbonated beverage bottles, is recycled in nine states that have mandatory deposit laws: California, Connecticut, Delaware, Maine, Massachusetts, Michigan, New York, Oregon and Vermont. Bottles collected in these states account for 150 million of the 750 million pounds of PET resin produced every year. Recyclers pay from $100 to $140 per ton of PET, making it the second most valuable component of municipal solid waste after aluminum. The PET is reconstituted into resins for injection molding to produce products ranging from automobile parts to electronic devices or is spun into polyester fibers that go into pillows, stuffed furniture, insulated clothing and carpeting.

BEVERAGE CONTAINERS, seen here bound into bales at a major recycling center in New Jersey, can be reprocessed into plastic products such as polyester fiber and molded parts. Some 150 million pounds of bottles made from polyethylene terephthalate (PET) were collected last year from the nine U.S. states that have mandatory deposit laws; 750 million pounds are produced nationwide.

As the infrastructure for collecting and sorting PET and other consumer plastics grows, recycling rates should increase significantly. According to recyclers such as Wellman Inc., of Shrewsbury, N.J., which currently processes about 100 million pounds of PET a year, the market for recycled plastics is limited by collection efficiency rather than by demand.

The industrial system for iron presents a different picture. Techniques for recycling are well established, and there is a strong infrastructure for collecting scrap. Yet discarded metal continues to pile up in scrapyards and across the U.S. because there is not enough demand for it. Elemental iron, the predominant component of both steel and cast iron, is the backbone of modern life: it is used in roads, in the automobiles that pass over the roads and in buildings. In the U.S. iron production begins when ore is mined in huge open pits as deep as 100 meters or more. The ore is concentrated and formed into pellets at the mine and then converted into pig iron in a blast furnace, where it is heated with coke, limestone and air. The coke adds carbon to the mix, and the limestone and the oxygen in the air react with impurities in the ore to form slag, which is then removed. Small admixtures of other elements yield steel to be cast, rolled or forged into billets, slabs, beams or sheets.

Once iron has been formed into products, which are eventually discarded, its properties (especially its ferromagnetism) facilitate identification and separation. The enormous amount of iron in circulation makes recycling relatively easy and economically attractive. It is not surprising, therefore, that every year millions of tons of scrap join iron ore to produce steel products. The scrap generated by stamping steel parts for automobiles, for example, is recycled into engine blocks and other castings. All four foundries that GM operates rely entirely on scrap steel obtained from other GM operations and on scrap iron generated during the casting process.

Although iron recycling is a relatively simple process, the system is not a closed loop. Much of the scrap from discarded consumer products is not recovered but is scattered around the countryside, where it corrodes away a little every year and is considered a blight rather than an asset. In 1982 recoverable iron scrap amounted to 610 million tons; at the end of 1987 the figure had risen to more than 750 million. A major reason for the increase is that U.S. production of iron and steel during this period was the lowest it had been since the end of World War II. The demand for scrap to make steel decreased while iron and steel products continued to be scrapped at the previous rate.

Shifting patterns of steel manufacturing, both in the U.S. and around the globe, are responsible for the increase in scrap. One subtle culprit is a technology shift from open-hearth furnaces to basic oxygen furnaces for producing steel. Basic oxygen furnaces (so called because they make steel in a large closed vessel supplied with pressurized oxygen) require only 25 tons of scrap steel to be mixed with every 100 tons of pig iron from the blast furnace, as opposed to a nearly equal mix for the open hearth.

The shift to basic oxygen furnaces began in the U.S. about 1958, and today open-hearth furnaces account for less than 3 percent of total production. Open-hearth furnaces were replaced to improve manufacturing efficiency and reduce air pollution, but their disappearance led to a decline in iron recycling. In making these changes, steelmakers had no economic mechanism for taking account of the adverse environmental impacts of scrap accumulation or the possible long-term effects of consuming more iron ore for each unit of steel.

More recently minimills have been built that rely on electric-arc furnaces and consume scrap steel almost exclusively. These low-volume mills have increased their share of U.S. steel production, but not enough to compensate for the lost demand for scrap to feed open-hearth furnaces. Furthermore, minimills produce only a limited range of steel products, and many of those products must be made from scrap containing very low levels of impurities. Scrap that contains excess copper, for example, is not suitable for making sheet steel, because the resulting sheet is too brittle to form into products. If electric-arc furnaces are to make significant inroads into the U.S. stock of scrap iron, they must be coupled to production facilities that produce a wider range of products, and better techniques must be developed for dealing with impure scrap.

Platinum-group metals (platinum, palladium, rhodium, ruthenium, iridium and osmium) were, until the mid-1970's, part of a very efficient industrial system. These metals were

SCRAP METAL from the casting and machining of engine parts awaits recycling at a General Motors foundry in Defiance, Ohio. The company operates four foundries; they are supplied entirely by scrap from sheet-metal stamping, iron casting and machining operations. Despite the relative ease with which scrap can be recycled, millions of tons pile up every year in U.S. scrapyards for lack of ready markets.

once recycled with efficiencies of 85 percent or better, but the advent of catalytic converters for automobiles dealt this system a shock from which recycling rates are only now beginning to recover.

Recycling of platinum-group metals is dictated not so much by the environmental effects of their disposal as by their limited supply and the difficulties of mining and refining them. Ores contain only about seven parts per million of mixed platinum-group metals, so that about 20 million metric tons a year must be refined to produce 143 tons of purified metals—an amount that could fit into a cube roughly two meters on a side.

About 60 percent of the platinum-group metals mined is formed into metal products such as jewelry, ingots for investors and chemical-reaction vessels; these products are eventually recycled with almost complete efficiency. The remainder is used to make chemicals and catalysts for chemical plants, petroleum refineries and automobiles. Catalysts adsorb molecules on their surfaces and promote chemical reactions that either join the molecules together or break them into smaller ones. Catalytic converters for automobiles, which reduce exhaust emissions of hydrocarbons, carbon monoxide and oxides of nitrogen, are the most rapidly growing use of platinum-group metals; consumption rose from about 11.5 metric tons in 1975 to about 40 in 1988. Automobiles currently account for most of the yearly permanent consumption of platinum-group metals.

Platinum-group metals in industrial applications are recycled quite efficiently. Each plant uses large amounts of catalyst, so that the payoffs from recycling are clear. Used catalysts are generally recycled every few months, providing a large, continuing stream of materials for reclaimers to process. In chemical and pharmaceutical plants, for example, catalysts are typically recycled in less than a year, and about 85 percent of the platinum-group metals in them are recovered. Some petroleum refineries are even more successful, recovering up to 97 percent of their noble metals.

The automotive pattern of noble-metal use stands in sharp contrast to that of the process industries: there are tens of millions of catalytic converters, each of which contains only a few grams of platinum-group metals (less than two grams of platinum, for example), and the lifespan of about 10 years for an average car makes for a much slower turnover of recyclable materials. As a result, only about 12 percent of the platinum-group metals in catalytic converters is currently recycled.

Poor recycling rates for automotive catalysts can be blamed almost entirely on the lack of an effective means for collecting discarded converters. The technology for recovering platinum-group metals from the converters is quite well understood; a plant opened by Texasgulf Minerals & Metals, Inc., in Ala. in 1984 recovers 90 percent of the platinum, 90 percent of the palladium and 80 percent of the rhodium from used converters. Millions of individual converters, however, are dispersed among thousands of scrapyards and almost 2,000 automotive scrap recyclers. The cost of locating, collecting and emptying the converters and then transporting the catalyst to a reprocessing plant is sufficiently high so that recycling is not profitable for most refining operations unless the price of platinum exceeds $500 an ounce.

The outlook for catalytic-converter recycling is improving. Now that most of the first-generation of cars built with catalytic converters have found their way to U.S. scrapyards, there is a large, continuing flow of raw materials for recyclers. More important, an infrastructure for collecting spent converters is being established. Even Japanese companies such as Nippon Engelhard have set up collecting organizations in the U.S. to acquire automotive catalysts for reprocessing in Japan. In addition the introduction of more stringent emissions controls in Europe, where catalytic converters have not been required, will increase the demand for platinum-group metals, making recycling more profitable.

The life cycles of plastics, iron and the platinum-group metals illustrate some of the issues involved in creating sustainable industrial systems. Equally important is the way in which the inputs and outputs of individual processes are linked within the overall industrial ecosystem. This linkage is crucial for building a closed or nearly closed system.

Like their biological counterparts, individual manufacturing processes in an effective industrial ecosystem contribute to the optimal function of the entire system. Processes are required that minimize the generation of unrecyclable wastes (including waste heat) as well as minimize the permanent consumption of scarce material and energy resources. Individual manufacturing processes cannot be considered in isolation. A process that produces relatively large quantities of waste that can be used in another process may be preferable to one that produces smaller amounts of waste for which there is no use.

A good example of the subtleties involved is the dematerialization of manufactured goods—the use of plastics, composites and high-strength alloys to reduce the mass of products. The trend toward dematerialization has drawn increasing attention in recent years. The mass of a typical automobile, for example, has decreased by more than 400 kilograms since 1975; about 100 kilograms of the decrease are due to the substitution of aluminum and plastics for steel. Lighter cars burn less gasoline. Steel, however, is easy to recycle, whereas the composite plastics that have replaced it resist reuse. The net result may be an immediate drop in fuel consumption but an overall increase in the amount of permanent waste created and in the resources consumed.

Waste-minimization activities in U.S. industries have been aided by regulations developed in the late 1970's to control hazardous-waste disposal. The regulations, reflecting long-term environmental costs, have increased the cost of landfill disposal from less than $20 a ton to $200 a ton or more, making alternatives to disposal profitable. Many companies find it profitable to sell their wastes as raw materials. For example, Meridian National in Ohio, a midwestern steel-processing company, reprocesses the sulfuric acid with which it removes scale from steel sheets and slabs, reuses the acid and sells ferrous sulfate compounds to magnetic-tape manufacturers.

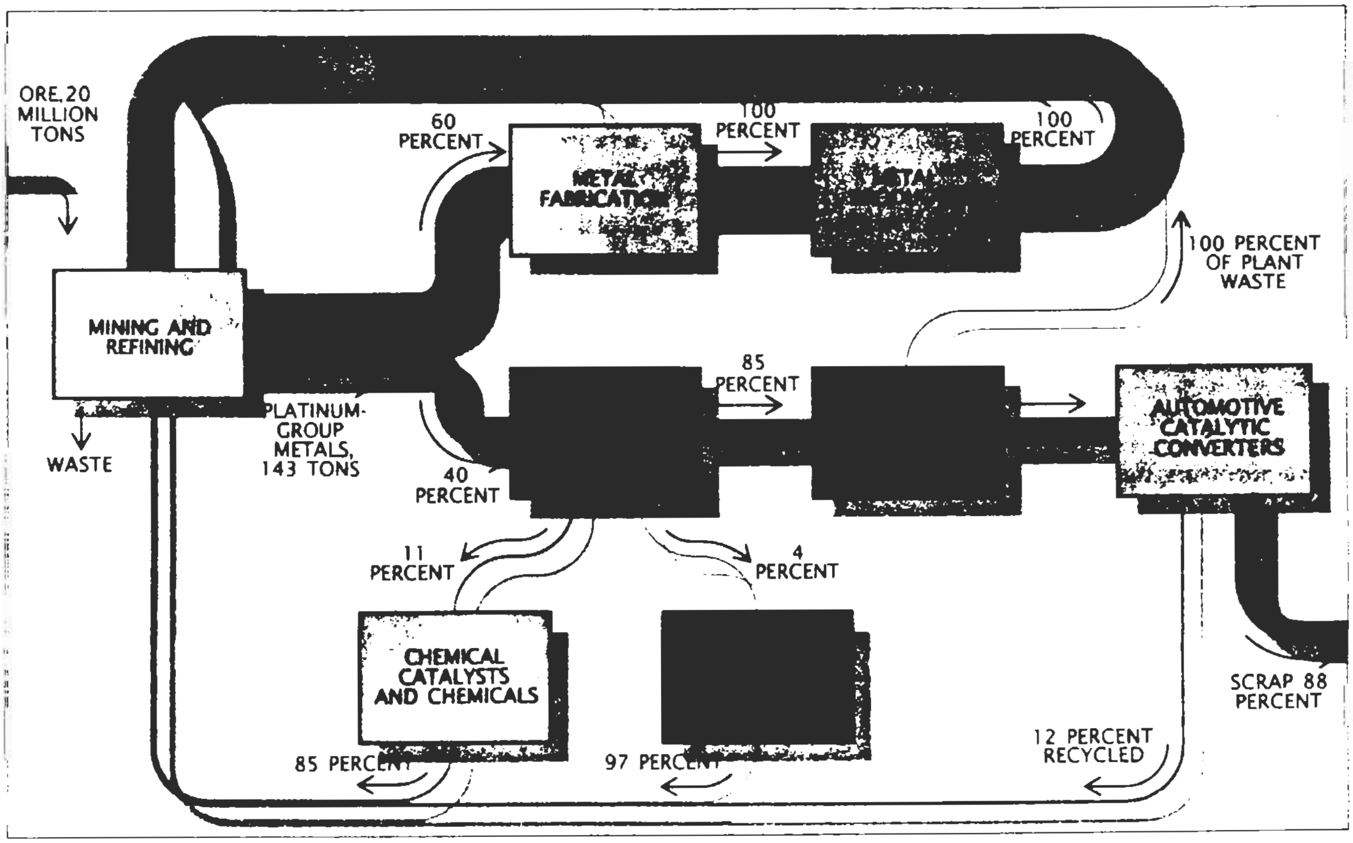
If the production of unrecyclable wastes is to be eliminated, similar steps must be taken for each of the low-level by-products in large streams of process effluents. Although emissions at each stage of such manufacturing processes may be relatively small, taken together they can cause serious pollution problems. Minimizing each of these myriad smaller emissions one at a time is a complex and potentially costly challenge.

The challenge can be met in part by implementing a multitude of relatively small changes. Some chemical plants and oil refineries, for example, have significantly reduced their hazardous-waste output by simply changing their procedures for buying and storing cleaning solutions and other low-volume chemicals. By doing so, they have been able to eliminate the need to dispose of leftover amounts.

At ARCO's Los Angeles refinery complex, a series of relatively low-cost changes have reduced waste volumes from about 12,000 tons a year during the early 1980's to about 3,400 today, generating revenue and saving roughly $2 million a year in disposal costs. The company sells its spent alumina catalysts to Allied Chemical and its spent silica catalysts to cement makers. Previously these materials were classified as hazardous wastes and had to be disposed of in landfills at a cost of perhaps $300 a ton.

Alkaline carbonate sludge from a water-softening operation at the refinery goes to a sulfuric acid manufacturer a few miles away, where it neutralizes acidic wastewater. (The acid manufacturer previously purchased pure sodium hydroxide for the same purpose.) A few outflow pipes have been rerouted to improve access for loading, and plant personnel must track the pH of their sludge, but the total investment has been minimal.

The ARCO refinery has also started to recover oil from internal spills and



PLATINUM-GROUP METALS are recovered efficiently from jewelry and other fabricated objects, two uses that constitute about 60 percent of consumption. Industrial catalysts and chemicals, also efficiently recycled, account for another 6 percent. The fastest-growing use for the metals is in automotive catalytic converters, an application marked by low recycling rates. The infrastructure is only now being set up to collect the millions of converters that enter automotive scrapyards each year, and to recover the approximately two grams of platinum (worth about $32 in mid-1989) in each converter.

other wastes in a new $1-million recycling facility. When the recycler is fully operational next year, it is expected to reduce wastes by another 2,000 tons. Off-site treatment or landfilling will still be needed for miscellaneous wastes such as solvents, spray cans and the several hundred tons of asbestos insulation being removed from the plant each year.

ARCO's situation is not unique: other major refiners and chemical manufacturers are engaged in similar efforts. For example, investments of $300,000 in process changes and recovery equipment at Ciba-Geigy's Toms River plant in New Jersey reduced disposal costs by more than $1.8 million between 1985 and 1988. Dow Chemical established a separate unit to recover excess hydrochloric acid, which it then either recycles to acid-using processes or sells on the open market. The operation recovers a million tons of acid a year at a profit of $20 million.

CONSUMER WASTES strain the capacity of landfills such as this one in Deptford, N.J. The environmental problems posed could be avoided by changes in disposal habits. Sorting trash to facilitate the recycling of paper, glass and plastics could simultaneously slow the filling of landfills and reduce the consumption of scarce resources.

By-products and effluents created during manufacturing represent only the supply side of the industrial ecosystem. The demand side is the consumer, who takes in manufactured goods and produces scrap that could be the raw materials for the next cycle of production. If the industrial-ecosystem approach is to become widespread, changes in manufacturing must be matched by changes in consumers' demand patterns and in the treatment of materials once they have been purchased and used.

The behavior of consumers in the U.S. today constitutes an aberration in both time and space. Whereas a typical New Yorker, for example, discards nearly two kilograms of solid waste every day, a resident of Hamburg or Rome throws out only about half that—as New Yorkers did at the turn of the century. Moreover, U.S. consumer habits and waste-management practices form a complex pattern that hinders efforts to reduce waste generation and the growing pressure on municipal landfills. The vast bulk of consumer wastes consists of organic materials and plastics that could relatively easily be composted, recycled or burned to produce energy but instead are stored in landfills, for which land was readily available in the past and where costs were low.

Today, as landfills across the U.S. near capacity, many communities have initiated garbage-sorting programs to reduce the amount of unrecycled waste; more initiatives are likely to follow. Some other countries have already instituted fairly sophisticated collection and treatment practices that go well beyond standard sorting and recycling. Japan, Sweden and Switzerland, for example, have set up collection centers for batteries from portable radios and other consumer products. The batteries contain heavy metals that render composted wastes unsuitable for fertilizing crops; the metals also contaminate fly and bottom ash from incinerators, so that the ash must be disposed of as hazardous waste.

An effective infrastructure for collecting and segregating various consumer wastes can dramatically improve the efficiency of the industrial ecosystem. The American consumer may have to stop heedlessly generating huge volumes of unsorted wastes, but living standards in the U.S. as a whole will not be affected. Moreover, landfills for municipal wastes are running out of space as rapidly as are those for industrial waste; consumers will soon find themselves facing the same economic incentives for waste reduction that producers face today.

Creating a sustainable industrial ecosystem is highly desirable from an environmental perspective and in some cases is highly profitable as well. Nonetheless, there are a number of barriers to its successful implementation. Corporate and public attitudes must change to favor the ecosystem approach, and government regulations must become more flexible so as not to unduly hinder recycling and other strategies for waste minimization.

Federal hazardous-waste regulations are a case in point. They sometimes make waste minimization more difficult than waste disposal. Because of the strict requirements for handling and documenting the treatment of wastes classified as hazardous, many companies choose to buy their materials through conventional channels rather than involve themselves in the regulatory process. A few states do encourage innovative treatment of wastes: California, for example, publishes a biannual catalogue that attempts to match waste generators with waste buyers—manufacturers who need the materials they produce. About half a million tons of hazardous wastes that would otherwise have gone to landfills were recycled in 1987. A dozen other state, provincial and regional waste exchanges operate throughout the U.S. and Canada.

In addition to promoting innovative waste-minimization schemes, governments need to focus on the economic incentives for sustainable manufacturing. Increased landfill costs have forced companies to improve industrial processes and reduce unrecyclable waste, but many small emissions are still controlled by classic end-of-pipe regulations that specify how much of each pollutant may be discharged. Companies must meet regulatory requirements, but there are no direct advantages for manufacturers who capture and treat low-level effluents or who shift to production processes with more benign by-products.

Conventional economic methods take into account only the immediate effects of production decisions. If a manufacturer produces nonrecyclable containers, for example, taxpayers at large bear the increased landfill costs; if a power plant reduces emissions that cause acid rain, communities elsewhere are likely to reap the benefits. Returns to the manufacturer or utility are generally indirect.

Instead of absolute rules, economists have long advocated financial incentives to reduce pollution. These include investment or research credits, tax relief, or fees or taxes imposed on manufacturers according to the amount and nature of the hazardous materials they produce. Such measures can help pay for treatment or disposal; more important, they give companies an incentive to change their manufacturing processes so as to reduce hazardous-waste production. Fees and taxes for pollution make environmental costs internal, so that they can be taken into account when making production decisions [see "Toward a Sustainable World," by William D. Ruckelshaus, page 166].

Pollution fees have come under fire from environmentalists and industrialists as "licenses to pollute" and as "distortions of the market." Both criticisms are potentially valid. Companies can treat fees that are too low as a cost of doing business and pass them on to customers; fees that are too high may force companies to reduce emissions of specific pollutants without regard to other environmental effects or to financial burdens.

Suitably set charges or incentives, however, can be an effective means for manufacturers to incorporate societal costs of pollution and waste into their cost accounting systems. As in the case of rising landfill fees for hazardous wastes, cost feedback for other pollutants could make it more attractive to solve problems at the source rather than to destroy or dispose of effluents once they have been created. Such fees enable manufacturers to share in the overall economic savings accruing from reduced levels of hazardous materials. Providing economic incentives would harness manufacturers' strong competitive drive to reduce costs. Indeed, manufacturers who ignore this imperative perish from the marketplace, a situation that would not change if the societal costs of pollution were allocated to them.

Economic incentives alone are not enough to make the industrial-ecosystem approach commonplace. Traditional manufacturing processes are designed to maximize the immediate benefits to the manufacturer and the consumer of individual products in the economy rather than to the economy as a whole. A holistic approach will be required if the proper balance between narrowly defined economic benefits and environmental needs is to be achieved. (Broadly defined, of course, economic and environmental goals are the same: bad places to live do not make for good markets.)

The concepts of industrial ecology and system optimization must be taught more widely. Current engineering and technological education either omit these concepts entirely or teach them in such a limited way that they have little impact on the approaches taken to the environmental problems associated with manufacturing. Changing the content of technological education, however, will not be enough. The concepts of industrial ecology must be recognized and valued by public officials, industry leaders and the media. They must be instilled into the social ethos and adopted by government as well as industry.

Government regulation of emissions at the local, national and international level will continue to play a strong role in the transition from traditional methods of manufacturing to an industrial-ecosystem approach. The transition to an ecosystem approach would be accelerated by the early adoption of economic incentives as part of the regulatory system.

To make regulation as effective as possible, officials must base their policies on sound technology and make allowance for technological change. Rules must be cast so as to encourage (or at least not discourage) the development of alternative processes and innovative methods for dealing with industrial by-products. Regulators must take advantage of industry's technological know-how so as to avoid counterproductive control measures. Such a wise regulatory framework will be almost impossible to construct unless government, industry and environmental groups abandon their current adversarial relationships and work together to solve their shared problems.

Even with an industrial-ecosystem approach in place, decisions about how best to allocate resources will not always be easy. Petroleum, for example, is not just a source of energy but also a raw material essential for manufacturing chemicals, plastics and other materials. Some analysts have argued that it should be used only as a raw material and not for energy. A similar argument could be made for using coal as a feedstock instead of as a fuel. On the output side, plastics can be burned for energy, recycled into new products or even reduced to their chemical constituents; it is not clear which choice is unequivocally sounder. Careful analysis of the consequences by "industrial ecologists" will be required to answer such questions.

The ideal ecosystem, in which the use of energy and materials is optimized, wastes and pollution are minimized and there is an economically viable role for every product of a manufacturing process, will not be attained soon. Current technology is often inadequate to the task, and some of the knowledge needed to define the problems fully is lacking. The difficulties in implementing an industrial ecosystem are daunting, especially given the complexities involved in harmonizing the desires of global industrial development with the needs of environmental safety.

Nonetheless, we are optimistic. The incentive for industry is clear: companies will be able to minimize costs and stay competitive while adhering to a rational economic approach that accounts for global costs and benefits. Equally clear are the benefits to society at large: people will have a chance to raise their visible standards of living without incurring hidden environmental penalties that degrade the quality of life in the long run. Remembering that people and their technologies are a part of the natural world may make it possible to imitate the best workings of biological ecosystems and construct artificial ones that can be sustained over the long term.

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REMANUFACTURING BY DESIGN, THE MISSING LINK

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While remanufacturing is a concept that has been around for some time, it is not a widely understood one. In fact, the word doesn't even appear in the current edition of the American Production and Inventory Control Society Dictionary [12]. It is not simply the repairing of a broken item, nor the "reconditioning" of a product:

> Remanufacturing is an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Usable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from both old and, where necessary, new parts to produce a unit fully equivalent—and sometimes superior—in performance and expected lifetime to the original new product. In contrast, a repaired or rebuilt product normally retains its identity, and only those parts that have failed or are badly worn are replaced or serviced [7].

As an example, The Trane Company, a leading air conditioning manufacturer, remanufactures air conditioning compressors and motors at a dedicated facility in Charlotte, NC. Failed units are received as exchanges for remanufactured compressors and are completely disassembled according to a schedule derived from the assembly plan. All unit identity is lost as parts are grouped for processing through various cleaning and refurbishing operations. These operations include motor rewinding and repair, crankshaft regrinding, replacement of worn bearing surfaces, and various surface restoration operations. Parts are sorted and inspected, and those meeting specifications are placed into inventory. This inventory of parts is supplemented with new parts as required. No distinction is made between refurbished and new parts, as they are functionally equivalent. The parts are then assembled into the finished units, which are carefully inspected and tested to ensure they meet the performance standards of a new compressor.

In spite of having maintained a relatively low profile over the years, the remanufacturing industry is much more than just a scattered collection of relatively small businesses. Albert S. Holzwasser, a watchmaker by trade, is credited with starting it all in 1929 when he formed Arrow Automotive Industries, Inc. in Boston, MA [13]. That company alone did just under $100 million in 1984 in the business of remanufacturing such automotive components as starter motors, clutches, and carburetors. Arrow Automotive employs over 1400 people and has plants in Spartanburg, SC, Morrilton, AR, and Santa Maria, CA in addition to research facilities in Natick, MA and a headquarters in Framington, MA [1].

While replacement parts for automobiles and trucks are the largest application of remanufacturing in the United States today [7], there are many other examples of its use. The remanufacture of jet engines by Pratt and Whitney is one in which the original equipment manufacturer (OEM) does the work. Not only does a remanufactured JT80 engine cost less than a new one ($900,000 plus trade-in instead of $1.6 million), but its performance will have been improved. Tests run on the first engine completing remanufacture indicate that fuel consumption betters new engine specifications by 4%. This yields an annual savings of over 92,000 gallons based upon average aircraft utilization. When compared with a major overhaul, which itself would cost $440,000, additional savings on parts would amount to approximately $130,000 [9].

United States Machine Tools Inc. of Hartford, CT is a company that has switched from the production of new machine tools to the remanufacture of ones 15 to 30 years old. In the past six years, sales have increased by 50% and buyers of such items as turret drills and milling machines are enjoying savings of from 30% to 60% on their good-as-new equipment [13].

The Trane Company uses remanufactured compressors to satisfy service replacement demand, including some in-warranty equipment failures. This offers several advantages, including lower pricing in the service-replacement market and reduced warranty expense. Customer acceptance has been enhanced by the warranty carried by the remanufactured compressor which is identical to that of a new compressor. An additional benefit, in the case of some models, is the avoidance of increased capacity requirements for production of new compressors, resulting in a capital spending avoidance.

These and many other examples have led a professor of manufacturing engineering at Boston University to predict that "remanufacturing is going to become a way of life [11]." He cites estimates of a doubling of the number of companies in the business to 600 in just the past four years to support his prediction [11].

All of this growth is not without problems, however [8]. One of the most obvious is a tendency for the consumer to disparage "used" goods, and this has particularly inhibited expansion in the consumer products area [7]. In the commercial arena, customers sometimes have difficulty in accepting the higher cost of remanufacture as opposed to a repair of the specific unit and occasionally demand certain appearance standards for refurbished parts in a remanufactured unit even though functionality or reliability are not affected. The difficulties in establishing efficient channels for the collection and distribution of worn out units, called "cores" by the industry, has been a constant problem. In fact, both independent remanufacturers and original equipment manufacturers listed core scarcity as the major factor limiting growth in this sector of their business [5]. In order for remanufacture to be a viable business, a sufficient population of cores must exist, and the cost of collecting them at the place of remanufacture must be reasonable. This cost includes both transportation costs and the price required to induce the holders of the cores to sell them to the remanufacturer. Remanufacture of a relatively new product is usually difficult to establish because of the lack of available cores. Since "the design of the original product can be a significant determinant of the products' 'remanufacturability' [5]," a lack of effort on the part of OEM designers to facilitate remanufacturing has not only been not helpful [8] to the industry, but has, at times, been intentionally obstructionist [13]. Even for established products, a remanufacturing program can be stopped by design changes to the product. This can result from extensive component redesigns, which can make "new" parts non-interchangeable with "old" parts and the "old" parts no longer available. It can also result from significant improvement in the new unit failure rate, which reduces the availability of cores.

There are a variety of reasons for OEMs to change their attitudes toward remanufacturing [6]. In the first place, if there is any significant price elasticity for the product in question, the sale of the lower priced remanufactured item can significantly expand the total market for the product and thereby expand the OEM's total market share. Secondly, by facilitating remanufacture, the trade-in value of an inoperative unit is enhanced, which encourages customer loyalty and repeat purchases. A third reason is that by establishing, or encouraging the establishment of, remanufacturing operations, another opportunity for the collection of product failure data is created, which can lead to improved design for future new unit production.

There are societal benefits from extensive remanufacturing as well [6]. By reusing a large proportion of the parts that make up the product, there are savings in both energy use and raw material consumption. Reduced costs for durable goods makes for greater consumer choice and higher standards of living. Since remanufacturing is relatively labor intensive, employment opportunities are created, especially for low and moderately skilled workers. Because many components from the original product become parts of the remanufactured one, the need for waste disposal or landfills is reduced.

Once the "enlightened" OEM sees remanufacture, either in-house or in coordination with an independent remanufacturer, as something that he can use to his economic advantage, there are a number of things that he can do to facilitate the process. Remanufactured items can be included as part of the total marketing effort. Consumer attitudes towards his particular "used," but remanufactured, product can be turned from either bad or indifferent to positive by advertising their lower cost and by offering "like new" warranties. Sales of new products can be increased by offering higher trade-ins on older models of the product that, because of remanufacturing, now have greater value to the OEM.

The new product distribution system used by the OEM can be converted to a "two-way street" for the collection and return of the cores needed to feed the remanufacturing system. The marginal cost of such a plan might be very low due to possibilities for using transportation systems that are presently only used for outbound traffic. Personnel productivity might well be increased because the extra overhead required to support this addition to an existing system would likely be minimal.

Much as manufacturing engineers work with design engineers to ensure a manufacturable product, the interaction should take place also to ensure a remanufacturable product. Seemingly simple details can hinder cost-effective remanufacture. In order for remanufacturing to succeed, the cost of salvaging and refurbishing most parts in a product must be less than the cost of new ones. If remanufacture is not considered in product design, a seemingly straightforward operation such as cleaning may require an amount of labor sufficient to push the cost of salvage beyond that of a new part. For example, effective cleaning of a chamber or vessel may be almost impossible unless access or disassembly has been enabled by design. Part wear tolerances must be considered in the design process so sufficient material is allowed for wear plus additional removal of material during remanufacture processing to restore proper surface finishes. For example, crankshafts are routinely ground to undersize dimensions for use in remanufactured engines and compressors. Other components, such as valves, have critical sealing surfaces which must be restored by grinding or lapping operations. Assemblies that are riveted, brazed, or welded together may be candidates for scrap rather than remanufacture because of the difficulty of disassembly.

There are a number of other things that can be done in the product design stage to facilitate remanufacture [5, 6]. One is to use more durable materials. For example, "lightweight castings tend to be difficult to remanufacture" and they "are damaged irrepairably in use more frequently and are also more prone to damage during the disassembly and handling of remanufacture [5]." Another is to design the product so as to minimize wear in those areas where moving parts come into contact with each other, as is done when ball bearings are substituted for bronze bushings. Different models of the same product should contain the maximum interchangeability of parts that is practicable [5, 6]. The extra costs incurred as result of these design changes would not necessarily have to be totally included in the sales price of the "new" product. The possibilities of their being spread over the resale of the same item several times as it is repeatedly remanufactured mean that at most only some fraction of them would have to be borne in the initial *price of the product.*

The lack of an appreciation for the advantages that can accrue from remanufacturing may be due, in part, to the fact that it is ignored by virtually all textbooks on production management. While such widely recognized authors as Buffa [2], Chase and Aquilano [3], Schonberger [11], and Cook and Russell [4] all point to the need to "interact with production designers in order to insure the production feasibility, maintainability, and reliability of the final product [4]," and recognize that "the obvious time to start thinking about basic modes of production for products is while they are still in the design stage [2]," they make no mention of similar requirements for remanufacture. In fact, remanufacture is not addressed in any context at all by most authors.

The time has come for American industry to expand its notion of the product life cycle to include remanufacturing. Instead of simply offering the consumer a process that goes from raw material to product to user to scrap, the concept should include the remanufacture of the product as an alternative to disposal when it becomes inoperable beyond simple repair. The remanufacturers could be the OEM or an independent competitor. Regardless of who performs the function, however, its existence should be "by design."

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Robert L. Kraft. "Incorporate Environmental Reviews Into Facility Design." Chemical Engineering Progress 88 (August 1992): 46-52. Reproduced with permission of the American Institute of Chemical Engineers.

Incorporate Environmental Reviews into Facility Design

Use this 10-step procedure and these checklists to identify and analyze all environmental issues and pollution prevention opportunities during the plant design process.

Robert L. Kraft,
E. I. du Pont de Nemours and Co.

As a result of increased environmental awareness and regulations in the 1960s, "end-of-pipe" treatment became the chief method of pollution control and waste management in the 1970s. While this method reduced (often effectively) the environmental impact of emissions and discharges to the environment, it became apparent that it was an expensive way to manage waste. In the 1980s, the emphasis shifted from end-of-pipe treatment to the reduction of wastes at the source and/or the reuse of wastes as more cost-effective waste management methods.

This approach has been used successfully in many existing facilities. Unfortunately, it is not always possible to minimize waste at the source or reuse it in an existing facility to the extent that would be desirable. The physical structure of an existing facility is already in place, and this inherently limits the flexibility and options available to reduce or reuse wastes.

During the early stages of new facility design, however, ample opportunity exists to implement design modifications that reduce the need for waste treatment via source reduction or reuse. This article details a 10-step procedure, summarized in Table 1, for use during the early design phases of a new project. Completing these steps will ensure that all environmental issues are addressed and that all opportunities to reduce waste have been effectively defined and analyzed. Furthermore, successful implementation of this procedure often results in a combination of environmental benefits and positive economic returns. For example, when we applied this technique to the design of a grassroots plant, the modifications identified reduced organic air emissions by 99% and carbon dioxide emissions by 22%, while providing an internal rate of return of 45% and a net present value of $6.4 million for a capital investment of $3.5 million. Economic returns will vary, but most projects can be expected to improve environmental performance with attractive economics.

1. Perform the initial assessments

The first step in the environmental review procedure is to conduct an initial screening of the project to see if there are any environmental issues and to perform two predesign assessments, an environmental site assessment and an evaluation of environmental baseline information.

The initial screening can be accomplished by answering the following questions:

- Does the project involve the use of chemical ingredients?
- Does the project involve equipment containing fuels, lubricants, or greases?
- Does the potential exist for reducing or eliminating wastes, internally recycling materials, or reusing byproducts?
- Are there potential problems with existing site conditions, such as the presence of contaminated soil and/or groundwater?
- Does the project have the potential to contaminate or impair groundwater or soil?
- Does the project involve the storage and transport of secondary waste?

If the responses to all of the above questions are negative, then the responses are documented and no further environmental reviews are required. If, however, the answer to any or all of these questions is yes, then environmental leadership responsibility for the project is assigned (Step 2) and the remaining steps are followed.

It is critical during Step 1 to perform an environmental assessment of the soil, groundwater, and surface water conditions within the proposed construction site. Many projects have suffered delays and unforecasted expenses due to site contamination. Therefore, the site should be checked for potential contamination as early as possible.

The site assessment should:

- determine whether site remediation is needed prior to construction;
- define the proper health and safety plans for construction activities;
- identify any regulatory requirements that apply; and
- determine the appropriate disposal options for any excavated soils.

A proper site assessment will provide several important benefits. It will guard against unexpected shutdowns resulting from the discovery of contamination after project construction and startup, and it will protect against potential liability to construction workers exposed to unsafe conditions. In addition, it can minimize the amount of soil that needs to be removed and ensure proper disposal, and identify construction techniques that are not subject to environmental constraints.

Environmental site assessments include reviews of files about past site operations, examination of aerial photographs, tests for potential soil and groundwater contamination, and identification of environmental constraints that could delay or prevent construction. These assessments can take from a minimum of three months to over a year to complete. Costs can range from $10,000 to over $1 million. Clearly the time and expenditures must be incorporated into the project time line and cost estimates.

In addition, it may be advisable to define and consider environmental baseline information, such as:

- background air quality prior to project start-up;
- current emissions at existing sites and potential impacts of these emissions on a new project (for instance, a new project may have low NO_x emissions, but surrounding facilities may emit high levels of NO_x);
- monitoring equipment needed to verify environmental compliance after start-up;
- impacts of the construction and operation of a new facility on existing waste treatment facilities and current air, land, and water permits; and
- whether an Environmental Impact Analysis (EIA) should be performed. EIAs are becoming common at greenfield sites, especially in Europe, and are generally performed by outside consultants or contractors.

Table 1. Use this environmental review procedure to evaluate new plant designs.

1. [illegible] initial screening and [illegible]
2. [illegible] project environmental leader[illegible]
3. [illegible] environmental [illegible]
4. [illegible] for any permit[illegible]
5. [illegible] environmental com[illegible]
6. [illegible] overall waste minimization [illegible]
7. [illegible] practices [illegible]
8. [illegible]
9. [illegible] treatment and disp[illegible]
10. [illegible] evaluations of w[illegible]
11. [illegible]
12. [illegible] environmental over[illegible]

2. Assign leadership responsibility

The second step is to assign the project environmental leadership responsibility. This role should be designated as early as practical so the leader can devote sufficient time to directing and/or coordinating the environmental analyses of the project.

The project environmental leader does not have to be an expert on environmental regulations or technology. Rather, the leader's role is to identify and coordinate the necessary resources and ensure that all the environmental analysis steps outlined in this procedure are followed.

3. Define environmental objectives

Next, the project's environmental objectives, or charter, is defined. Environmental objectives can include a statement supporting government regulations and company policy, a list of specific goals for emissions and discharges or reductions of emissions and discharges,

Table 2. Hierarchy of emissions and discharges.

- Carcinogens
- Hazardous and/or Toxic Substances
  - Air emissions
    - Specific regulated pollutants
    - Nonregulated pollutants
  - Liquid and solid discharges
    - Heavy metals
    - Locally regulated pollutants
    - Nonregulated pollutants
- Nonhazardous Substances
  - Very low concentrations of toxic
  - [illegible]
  - [illegible]
  - Liquid and solid emissions
  - [illegible] salts
- [illegible] Wastes
  - [illegible]
  - [illegible] Water and [illegible]
  - [illegible]
  - [illegible] Air (oxygen [illegible]
  - [illegible] and breathing [illegible]
- [illegible]
- Odor, visible plumes, [illegible] and noise should also be [illegible] may rank very high on the hierar[illegible] depending on the particular project.

and other project-specific objectives. These objectives focus preferentially on source reduction and recycling rather than waste treatment. They consider continuous process emissions and discharges based on a prioritized list, as well as noncontinuous or nonprocess emissions such as lubricants, fuels, spent oils, packaging material, stormwater runoff, and the like.

The sidebar is an example of an environmental charter (objectives). Table 2 presents a hierarchy (prioritized list) of emissions and discharges, and Table 3 lists various types of emissions and discharges. The charter and these lists should be used as a starting point and should be modified as appropriate for each individual project. Note that the hierarchy of emissions and discharges can vary depending on geographical location (for example, CO_2 may rank higher in the hierarchy in Europe than in the U.S.).

4. Identify permit needs

The next step is to define what permits, if any, are required to construct and operate a new facility. Permit requirements vary from country to country. Obtaining permits is often the most critical and time-limiting step in a project schedule. It can take anywhere from a few months to many years to obtain certain permits. Again, this process should be started as early as possible in the project cycle.

Permit requirements or limits are not always clearly defined and they can often be negotiated with government regulatory agencies. The types of permits required depend on the process involved, the location of the facility, the types of existing permits at an existing facility, and whether new permits or modifications to existing permits are needed. Typically, permits are required for any part of a process that impacts the environment, such as:

- any treatment, storage, or disposal system for solid or hazardous waste;
- exhaust of anything other than air, nitrogen, oxygen, water, or carbon dioxide (carbon dioxide may require a permit in the future);
- use of pesticides or herbicides;
- incineration or burning;
- dredging in a water body or any activity that impacts wetlands;
- erosion and sedimentation control;
- monitoring or dewatering wells;
- any action that constructs or alters landfills or land treatment sites;
- any system that constructs or alters water systems;
- any system that constructs or alters a process or sanitary wastewater collection or treatment system; and
- stormwater runoff.

Table 3. Types of emissions and discharges.

Direct process streams (including after treatment)
Fugitive emissions
Oils, lubricants, fuels, chlorofluorocarbons, heat transfer fluids, etc.
"Noncontact" process water (cooling tower water, steam, etc.)
Batch process wastes (dirty filters, fly ash, water washes, etc.)
Packaging materials
Old equipment disposal
Office and cafeteria waste
Contaminated soil
Contaminated groundwater
Sediment and erosion control
Stormwater runoff discharges
Construction debris

5. Determine compliance requirements

One also needs to define the environmental compliance requirements of the project. This involves making sure that the project meets all applicable environmental regulations and company guidelines. In general, compliance will be determined by the emission and discharge limits specified in the applicable permit.

It may, however, be desirable to go beyond the regulatory requirements and company goals to improve goodwill or image, proactively address possible future regulations (so as to avoid having to make expensive modifications after start-up), and improve the company's competitive advantage. The last factor is

Table 4. Checklist A — Stream-by-Stream Inventory.

1. Name of project (process step, production unit, plant)
2. Operating unit
3. Person completing this analysis
4. List each raw material and its major constituents or contaminants used in this process step, production unit, or plant
5. List each stream by type (feed, intermediate, recycle, nonuseful)

Stream Type	Stream Name and Number	State (Vapor, Liquid, Solid)	Quantity (Volume)	Potential Environmental Issue(s)

important because a company's environmental performance has increasingly become a more significant part of the public's purchasing decisions. If one decides to go beyond regulatory requirements, it is more desirable to do so via waste reduction or reuse than waste treatment.

6. Analyze waste minimization overall

The sixth step of the procedure is to perform an overall waste minimization analysis of the entire process. Note that new or exotic technology is usually not required to minimize waste — waste minimization is more likely to be hindered by attitudes based on limited information and experience than on a lack of effective technology. The means to reduce waste are imbedded in all aspects of production — there is no discrete "waste reduction technology."

In order to obtain meaningful waste minimization results, it is important to have a fairly accurate flow sheet identifying all major process streams and their composition.

First, classify all the process streams into one of four categories — nonuseful (waste), feed, intermediate, and recycle — and note potential environmental issues. Checklist A (Table 4) should be used for this analysis.

While the waste minimization analyses focus primarily on nonuseful streams, the feed, intermediate, and recycle streams should not be overlooked for opportunities to reduce waste at the source. Generally, impurities in the feed streams produce byproducts that can be eliminated by purifying the feed stream or purchasing a higher-purity raw material. Intermediate and recycle streams should also be analyzed to see if they should be altered or modified before further processing.

Next, focus on the nonuseful streams. Checklist B (Table 5) should be completed for each nonuseful stream. This checklist stimulates thinking about options for eliminating or minimizing the amount of waste that is generated

Environmental Charter

TO

Design facilities to operate as close to emission/discharge-free as technically and economically feasible

IN A WAY THAT

- Complies with existing and anticipated regulations as well as the established standards, policies, and company practices. Emission- and discharge-reduction priorities will be based on a hierarchy of emissions and discharges (see Table 2) and will include various types of emissions and discharges (Table 3).
- Develops investment options to reduce and/or eliminate all liquid, gaseous, and solid discharges based on best environmental practices. These options will be implemented if they yield returns greater than capital costs. Failing to meet this standard, options may still be implemented subject to nonobjection of the business, production, and research and development functions.
- Considers waste management options in the following priority order:
  1. Process modifications to prevent waste generation
  2. Process modifications so as to be able to
     a. Recycle,
     b. Sell as coproduct, or
     c. Return to vendor for reclamation or reuse. Where materials are sold or returned to the vendor, the project team should ensure that customers and vendors will operate in an environmentally acceptable manner.
  3. Treatment to generate material with no impact on the environment.
- Considers all potential continuous and fugitive emissions in the basic design data as well as all noncontinuous events such as maintenance and clean-out, startup, and routine or emergency shutdowns.
- Allows no hazardous wastes to be permanently retained on-site unless the site has a regulated hazardous landfill.
- Documents all emissions prior to and after waste minimization efforts.
- Interacts with other internal or external processes or facilities to generate a combined net reduction in emissions. Interaction that leads to a net decrease in emissions will be considered in compliance with this charter, *while that leading to a net increase in emissions will be considered not in* compliance.
- Where decisions are made to delay the installation of emission reduction facilities or to not eliminate specific emissions, considers providing for the future addition of such facilities at minimal cost and operating disruption.
- Lists, where possible, specific goals for emissions and discharges or emission and discharge reductions, especially with regard to hazardous and toxic substances.

SO THAT

New facilities will provide a competitive advantage in the marketplace based on their environmental performance.

[illegible]

Table 5. Checklist B — Stream-by-Stream Waste Minimization Analysis.

[illegible]

and, therefore, must be treated. Each nonuseful stream should be analyzed as follows:

1. Can it be eliminated or minimized at the source? If not,
2. Can the need for waste treatment be avoided or minimized via reuse, recycle, or coproduct sale? If not,
3. The stream will have to be treated to render it nonhazardous to the environment. (Waste treatment is discussed in Step 8.)

The first two routes often result in attractive economic returns in addition to environmental benefits. Treatment, while having environmental benefits, seldom has an economic return. For example, it might be advantageous to separate a gaseous raw material from a reactor purge stream prior to waste treatment and recycle or reuse it. In this manner, burning (treating) the material and the resultant combustion products would be avoided, while the raw-material cost savings may more than pay for the investment to perform the separation.

Finally, evaluate the operating conditions (e.g., temperature, pressure) and procedures, equipment selection and design, and process control schemes. While one of the greatest opportunities to minimize waste may be during the fundamental research that led to the process chemistry (e.g., raw materials, catalysts), minor alterations to operating conditions and/or equipment design and process control may also afford a significant opportunities to minimize waste generation at the source.

7. Apply "best environmental practices"

Next one should review the entire process to minimize or eliminate unplanned releases, spills, and fugitive emissions. This includes a review of all equipment pieces, seals, operating procedures, and so on.

When reviewing the project for ways to eliminate or minimize fugitive emissions, the following hierarchy should be used:

1. Prevent or minimize leaks at the source by eliminating equipment pieces or connections where possible and by upgrading equipment or replacing standard equipment pieces with equipment that leaks less or does not leak at all.
2. Capture and recycle or reuse so as to prevent or minimize the need for abatement.
3. Abate emissions so as to have no impact on the environment.

Checklist C (Table 6) will assist in this analysis.

Waste treatment is utilized only as a necessary last resort after all options to eliminate waste at the source or reuse wastes have been exhausted.

Table 6. Checklist C—Best Practices for Emission/Discharge-Free Facilities.

1. Name of project (process step, production unit, plant)
2. Operating unit
3. Person completing this analysis
4. What wastes or emissions will be generated [illegible]

[illegible]

Table 7. Checklist D—Stream-by-Stream Treatment/Disposal Analysis.

Fill out a separate form for each NONUSEFUL STREAM listed in Checklist A AND being discharged or emitted into the environment from this process step, production unit, or plant.

1. Name of project (process step, production unit, plant)
2. Operating unit
3. Person completing this analysis
4. Stream information (see non-useful streams on Checklist A, Question #5)
    Stream number
    Stream name
    State (V, L, S)
5. Does this stream:
    a. Contain toxic chemicals on any regulatory list? If yes, which ones?
    b. Become a hazardous waste under any regulations? If yes, is it a listed or a characteristic waste?
6. What permitting requirements are triggered if this stream is to enter the environment?
    Water:
    Land:
    Air:
    Local:
    Other:
7. Is treatment of this stream required before release to the environment? If no, what is the basis for this decision?
8. How is this stream, or wastes derived from treating it, to be disposed of?
9. If flaring of this stream is proposed, what alternatives to flaring were considered?
10. If landfilling of this stream, or wastes derived from it, is proposed:
    a. What can be done to eliminate the landfilling?
    b. Must this stream be stabilized before landfilling?
    c. Must this waste be disposed in a secure Class I hazardous waste landfill?
11. Is off-site treatment, storage, or disposal of this waste proposed? If yes, what could be done to dispose of this waste on-site?

8. Determine treatment and disposal options

The eighth step of the procedure is to define waste treatment for nonuseful streams that could not be reused or eliminated at the source. The goal here is to define the most cost-effective treatment method to render emissions and discharges nonharmful to the environment.

Remember, once nonuseful streams are treated, the resulting materials have little or no value. Hence, waste treatment seldom has attractive economics. Waste treatment is utilized only as a necessary last resort after all options to eliminate waste at the source or reuse wastes have been exhausted. Use Checklist D (Table 7) to analyze waste treatment.

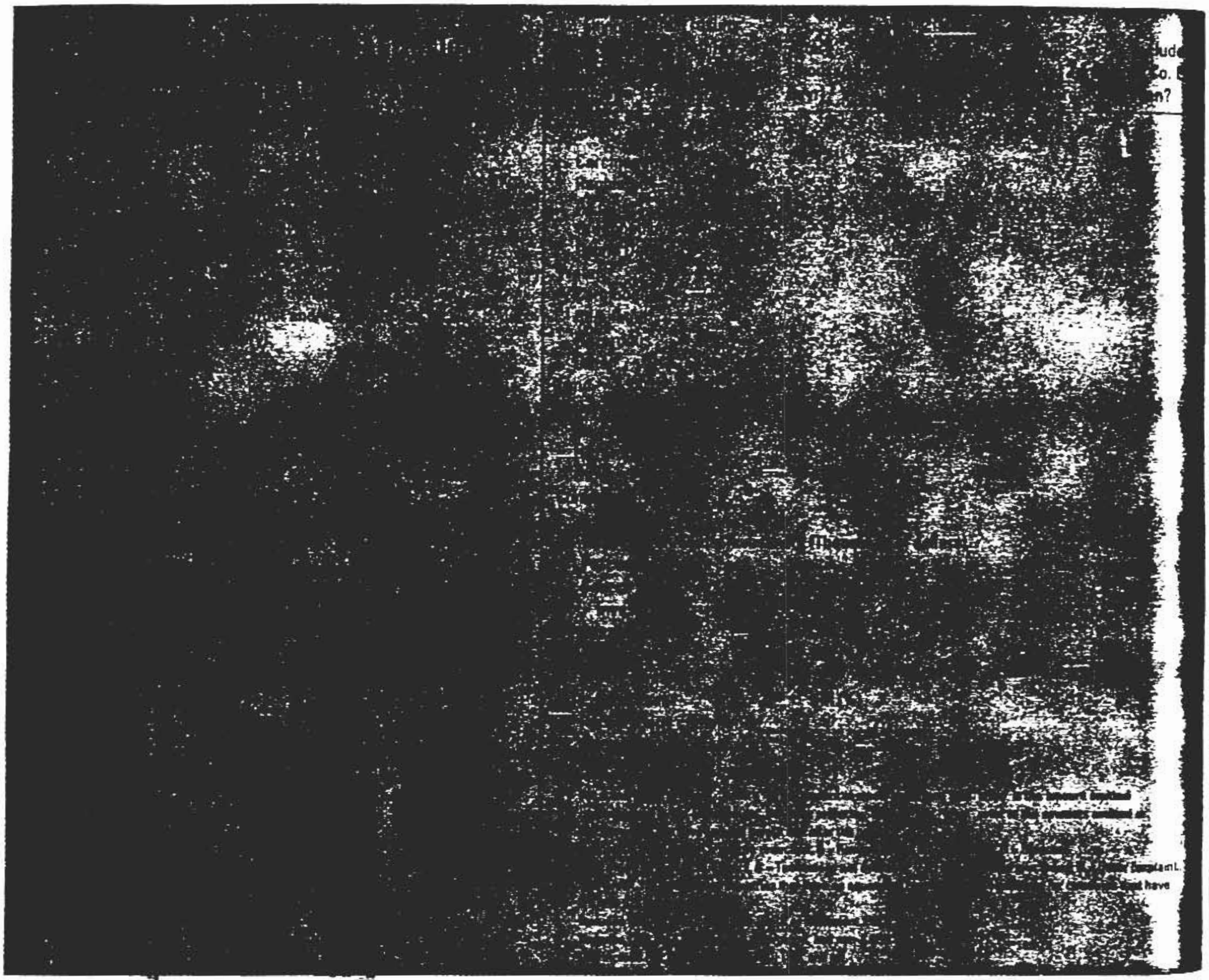
9. Evaluate the options

Performing engineering evaluations for Steps 6, 7, and 8 is the next step, and is especially important in cases where there is more than one option to achieve the same end result. To choose between options based on economic considerations one needs such information as capital investment, operating costs, revenues (if any), and the cost of capital. Net present value calculations and internal rates of return can be used to economically justify one alternative vs. another.

10. Summarize the results

The last step is to compile a project environmental overview or summary of the results of this review procedure. Checklist E (Table 8) is a suggested form for this report. If projects go through a formal approval procedure, this form shows that appropriate environmental reviews were conducted.

Finally, construction and startup



should be audited to ensure that the environmental recommendations are implemented.

An application

This 10-step procedure was recently applied to a major grassroots chemical facility. Of most interest are the efforts and results from Steps 6, 7, 8, and 9. A total of 1,500 personnel hours were devoted to meeting preparation, the meetings themselves, and meeting follow-up, at an estimated cost of $150,000 (2% of the pre-project design cost).

Three major design modifications resulted:

- feed purification;
- recovery of one of the raw materials from the reactor purge gas; and
- special pump seals and valve modifications to minimize fugitive emissions.

Note that none of the projects involved waste treatment, but rather source reduction and reuse.

Each design modification had a return on investment greater than the cost of capital. The combined environmental benefit of the three projects was a 99% (430,000-lb/yr) reduction in organic air emissions and a 22% (116-million-lb/yr) reduction in carbon dioxide emissions. The combined projects had an internal rate of return of 45% and a net present value of $6.4 million based on a capital investment of $3.5 million.

The combination of environmental benefits and attractive economic returns is not uncommon when the procedure outlined here is applied early in the design phase of a new facility with a focus on source reduction and reuse rather than waste treatment. CEP

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