The Industrial Ecology of the 21st Century

A clean and efficient industrial economy would mimic the natural world's ability to recycle materials and minimize waste

by Robert A. Frosch

The end of the 20th century has seen a subtle change in the way many industries are confronting environmental concerns: they are shifting away from the treatment or disposal of industrial waste and toward the elimination of its very creation. This strategy attempts to get ahead of the problem, so that society is not destined to face an ever growing mass of waste emanating from the end of a discharge pipe or the brim of a garbage pail. It seems likely that the next century will see an acceleration of this trend, a clear departure from the past emphasis—by industry, by government regulators and even by most environmental organizations—on late-stage cleanup.

The old attitude often resulted only in manufacturers dumping waste into their own "backyards," thus generating a good deal of what might be called industrial archaeology. That heritage currently puts many firms into the environmental cleanup business, whether they like it or not. But in the 21st century, industry may behave quite differently, so as to avoid creating more expensive burial sites that society will have to suffer or pay to clean up all over again.

What most people would like to see is a way to use industrial waste productively. Waste is, after all, *wasteful.* It is money going out the door in the form of processed material and its embodied energy. To avoid this inefficiency, manufacturers of the next century must consider how to design and produce products in such a way as to make the control of waste and pollution part of their enterprise, not just an afterthought. They will need to pay attention to the entire product life cycle, worrying not only about the materials used and created in the course of manufacturing but also about what happens to a product at the end of its life. Will it become a disposal problem, or can it become a source of refined material and energy?

Manufacturers are just beginning to seek new approaches in what may well become a comprehensive revolution. As such movements often do, these efforts are producing new ideas and a new set of buzzwords. Engineers had previously spoken of "design for manufacturing" and "design for assembly," and now we have added "design for disassembly," "design for recycling" and "design for environment" to our vocabulary. These terms mean simply that from the very start we are paying attention to the potential effects of excess waste and pollution in manufacturing.

Overcoming these problems is in part a technological problem—clever new technologies that can reduce or recycle wastes will surely play a valuable role. But the answer will not depend entirely on inventing breakthrough technologies. Rather it may hinge on coordinating what are fairly conventional methods in more prudent ways and in developing legal and market structures that will allow suitable innovation. These efforts will involve complex considerations of product and process design, economics and optimization, as well as regulation and handling of hazardous materials. Strangely, there has been relatively little general examination of these issues, although there are many individual cases in which such thinking has been employed.

For example, Kumar Patel of AT&T Bell Laboratories has described an interesting approach being taken in a section of its microelectronics fabrication business. Engineers at that division of Bell Labs were concerned because several of the raw materials, such as gallium arsenide, were particularly nasty. They dealt with this difficulty by using, in effect, the military technology of binary chemical weapons, in which two chemicals that are not very hazardous individually combine within a weapon to make one tremendously hazardous substance. Bell Labs now avoids having to keep an inventory of one highly toxic material through a simple process that brings together its much less hazardous chemical constituents right at the spot where the combined compound is used. This is essentially a just-in-time delivery system that matches production to need and obviates disposal of excess. Bell Labs concluded that the company amortized the investment in new equipment in less than a year by eliminating the extra costs of storing, transporting and occasionally disposing of the hazardous compound.

A Lesson from Nature

Beyond solving as much of the waste problem as possible within each company, we have to think about industry in the future on a larger scale. We need to examine how the total industrial economy generates waste and pollutants that might damage the environment. Viewing industry as an interwoven system of production and consumption, one finds that the natural world can teach us quite a bit. The analogy with nature suggests the name "industrial ecology" for this idea (although this term is increasingly coming into use for a diverse set of practices that might make industry pollute less).

The natural ecological system, as an integrated whole, minimizes waste. Nothing, or almost nothing, that is produced by one organism as waste is not for another organism a source of usable material and energy. Dead or alive, all plants and animals and their wastes are food for something. Microbes consume and decompose waste, and these microorganisms in turn are eaten by other creatures in the food web. In this marvelous natural system, matter and energy go around and around in large cycles, passing through a series of interacting organisms.

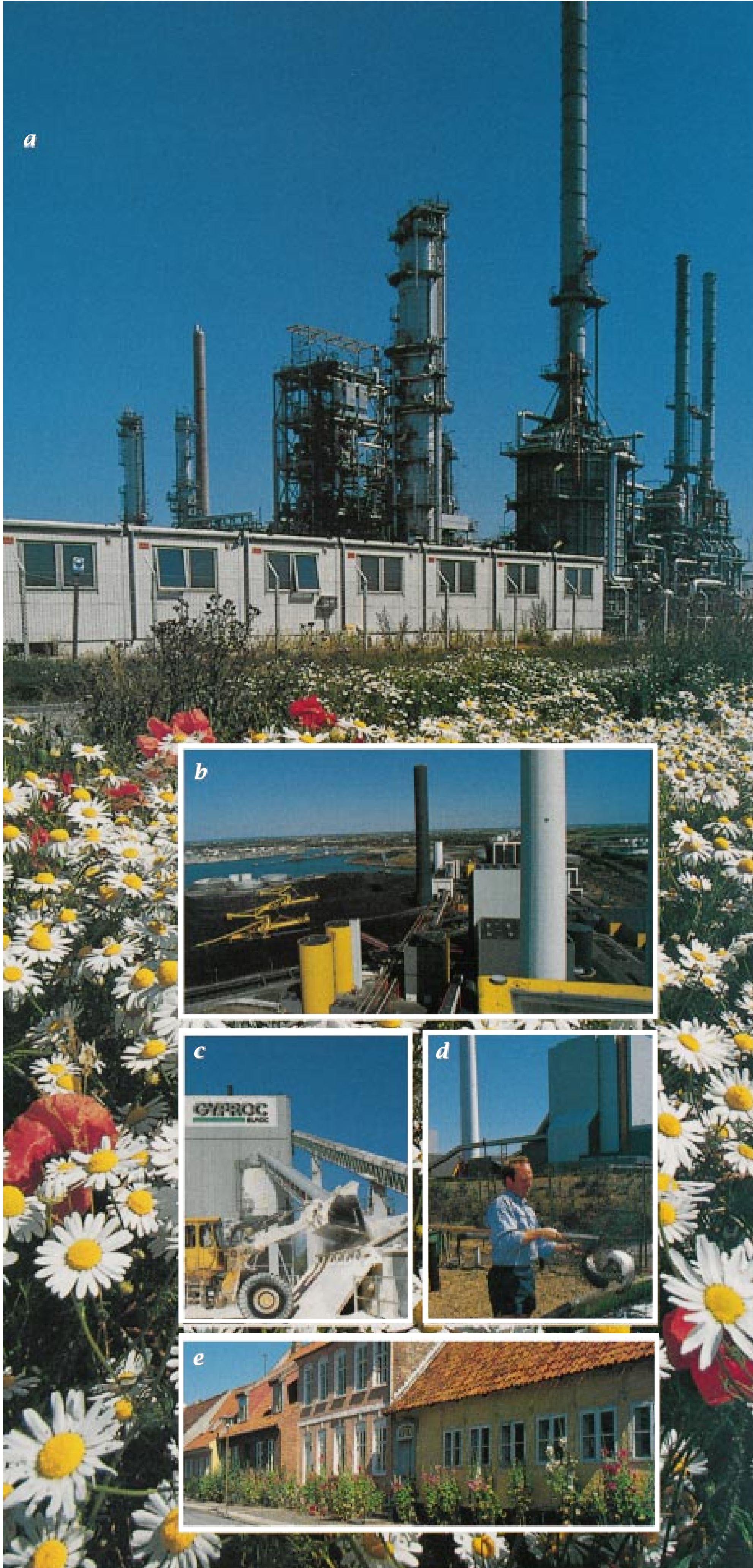
With this insight from the natural ecological system, we are beginning to think about whether there are ways to connect different industrial processes that produce waste, particularly hazardous waste. A fully developed industrial ecology might not necessarily minimize the waste from any specific factory or industrial sector but should act to minimize the waste produced overall.

This is not really a new or startling idea. There are companies that have sought this minimization for a long time. The chemical and petrochemical industries are probably ahead of most others. They characteristically think in terms of turning as much as possible of what they process into useful product. But in the future, industrial countries will want all producers to be thinking about how they can alter manufacturing, products and materials so that the ensemble minimizes both waste and cost. Such requirements need not be onerous: a company might easily change to a more expensive manufacturing process if it prevents the generation of waste that the firm had to pay to have taken away and if it creates materials for which there are customers.

Many requirements must be met for this redirection to be accomplished. As incentive for designing and producing something specifically so that it can be reused, companies will need reliable markets. Many early attempts at recycling failed because they just collected materials—a pointless exercise unless somebody actually wants to use them. If there are going to be markets for what would otherwise be waste, information will need to be available on who has what, who needs what, who uses what. This information is typically inaccessible now because companies tend to be secretive about their waste streams. (If competitors know about the by-products produced, they might deduce protected trade secrets.) We will have to invent ways to get around this difficulty.

Antirecycling Laws

In addition to the need for more complete market information, society requires a novel kind of regulation to make a true industrial ecology possible. Frustrations with regulation frequently arise because we have fostered and developed environmental laws that attempt to deal with one problem at a



PHOTOGRAPHS BY RUDDI CHRISTENSEN *Gamma Liaison*

KALUNDBORG, DENMARK, represents a model industrial ecosystem. An oil refinery (*a*) employs waste heat from a power plant (*b*) and sells sulfur removed from petroleum to a chemical company. The refinery will also provide sulfur (as calcium sulfate) to a wallboard producer (*c*) to replace the gypsum typically used. Excess steam from the power plant also heats water for aquaculture (*d*), while it warms greenhouses and residences (*e*).

time. The current regulatory framework focuses on disposing of or treating industrial wastes without regard for the possibility of minimizing or reusing them. In fact, it often acts to thwart recycling. Once a substance is classified as hazardous waste, it becomes extraordinarily difficult to do anything useful with it, even if the material is identical to a "virgin" industrial chemical readily bought and sold on the open market.

For example, if a manufacturer produces waste containing cyanide, a toxic hydrocarbon or a heavy metal, the company will likely be controlled by strict environmental laws. Unless the firm can overcome excruciatingly complex bureaucratic barriers, it will probably not be allowed to process that material into a salable product or even to transport it (except to a disposal site). Yet anyone can easily go to a chemical manufacturer and buy cyanide, hydrocarbon solvents or heavy metal compounds that have been newly produced. (Their manufacturer generally has a standing permit for packaging, transporting and selling these substances.)

A particularly interesting example comes from the automotive industry's treatment of steel. Anticorrosion measures produce a zinc-rich sludge that in the past was sent to a smelter to recover the zinc and put it back into the process stream. But a decade ago regulations began listing such wastewater

The Ultimate Incinerators

While the world waits for industry to develop processes so efficient they do not produce waste, the problem of safely disposing of our garbage persists. The idea of loading toxic or other forms of waste on board a spacecraft and blasting them into the sun seems, at first glance, a nice solution to the earth's trash woes. At 5,500 degrees Celsius, the surface of Sol would leave little intact. But considering the amount of garbage each human produces—three to four pounds per day, on average—launches would simply be too expensive to conduct regularly. Add the possibility of a malfunction during liftoff, and space shots of waste seem impractical.

Instead some researchers are taking the opposite tack: bringing a bit of the sun to the earth. By sending a strong electric current through a rarefied gas, they can create plasma—an intensely hot gas in which electrons have been separated from atomic nuclei. The plasma, in turn, reaches up to 10,000 degrees C. (Conventional incinerators, using fossil fuels, reach no more than 2,000 degrees C.) In the presence of this demonic heat, hydrocarbons, PCBs and other toxins that lace contaminated soil and ash break down, yielding molten slag that hardens into inert and harmless glassy rocks suitable for road gravel. Unlike their smoke-belching conventional counterparts, plasma incinerators burn more cleanly, emitting one fifth as much gas. Some designers propose capturing this gas, which is combustible, for use as fuel.

LOUIS J. CIRCEO *Georgia Institute of Technology*

PLASMA TORCH cooks contaminated soil, changing it into inert, glassy blocks.

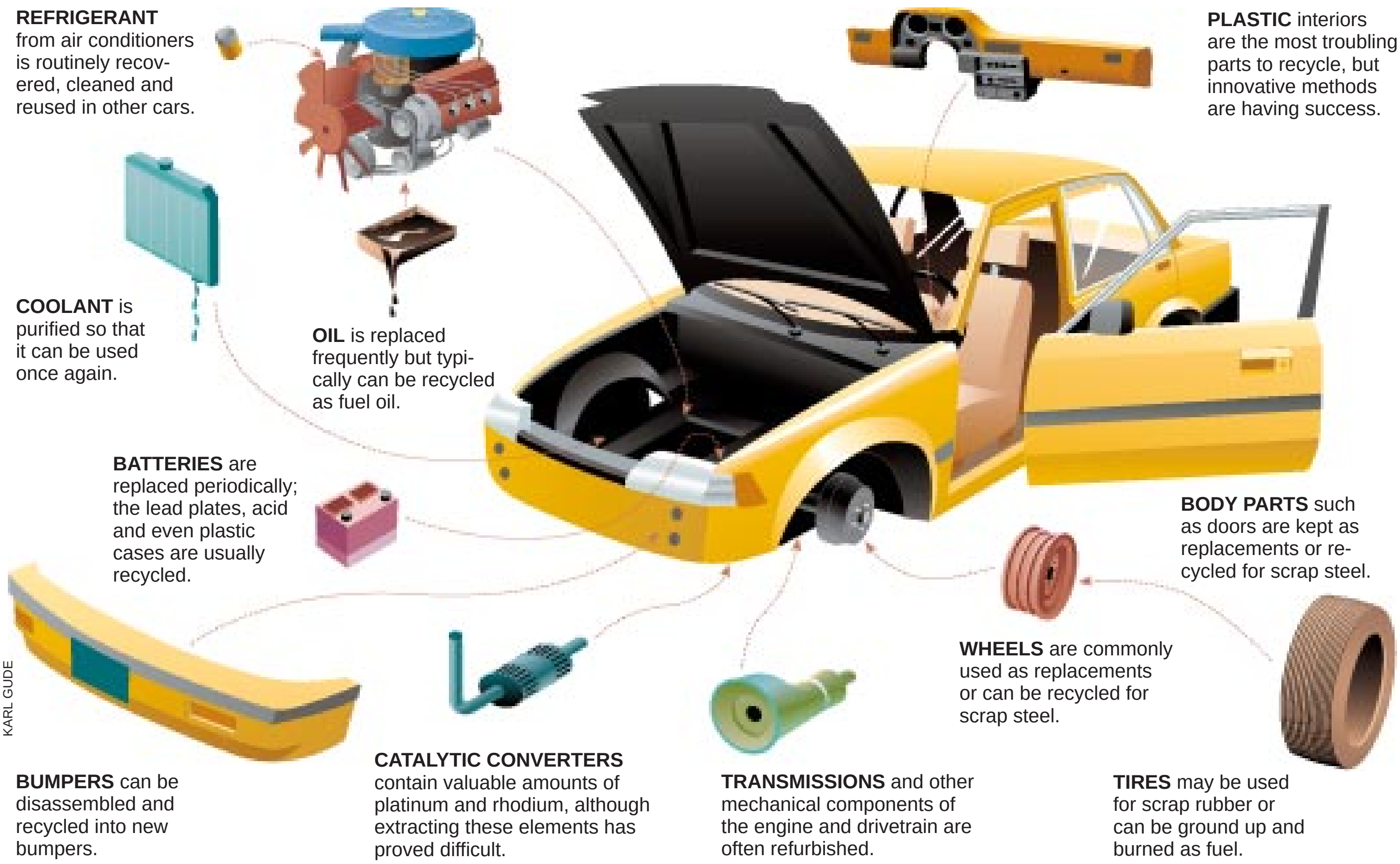
With so many pluses, it seems that plasma should have been cooking waste a long time ago. The hurdle has been economic: plasma can vaporize nonhazardous waste for about $65 a ton, whereas landfilling costs less than half that amount. But as landfill space dwindles and stricter environmental codes are adopted, plasma waste destruction is becoming more competitive. For treatment of toxic waste, it may even be cheaper. Daniel R. Cohn of the Massachusetts Institute of Technology estimates that a full-scale plant could operate for less than $300 a ton—less than half the current cost of disposing of hazardous waste.

The more reasonable economics have encouraged many institutions to set up pilot furnaces. "The whole technology is starting to pick up around the world," notes Louis J. Circeo of the Georgia Institute of Technology, where some of the largest furnaces are located. Near Bordeaux, France, a plant destroys asbestos at the rate of 100 tons a week. The Japanese city of Matsuyama has a facility designed to handle the 300 tons of incinerator ash that comes from the daily burning of 3,000 tons of municipal waste. Construction of a furnace that could torch 12 tons of medical waste a day is under way at Kaiser Permanente's San Diego hospital. Circeo thinks it is even feasible to treat existing landfills: just lower some plasma torches down nearby boreholes.

Plasma need not be hot; it can also exist at room temperature. Cohn and his colleagues are testing the idea of using "cold" plasma to destroy toxic vapors. The physicists create such plasma by firing an electron beam into a gas, a process that severs electrons from nuclei and thus converts the gas into plasma. Volatile organic compounds passed through the plasma are attacked by the free electrons, which break down the chemicals. Last year the workers tested their trailer-size unit at the Department of Energy's Hanford Nuclear Reservation site in Richland, Wash., where up to two million pounds of industrial solvents have been dumped since the complex's founding during the Manhattan Project. They vacuumed out some of the carbon tetrachloride in the ground and then pumped it into the chamber of cold plasma, which transformed the toxin into less harmful products that were subsequently broken down into carbon dioxide, carbon monoxide, water and salt.

It may be a while before toxic waste is a distant memory or before you can zap your kitchen trash into nothingness with the flick of a switch, but many researchers are betting that plasma waste destruction is becoming a reality. Circeo, for instance, hopes to raise $10 million for a plasma plant that can destroy the 20 tons of garbage that revelers and others at the 1996 Olympic Games in Atlanta are expected to generate daily. "In five to 10 years," he predicts, "you're going to see plasma technology springing up all over the place."

—*The Editors*



AUTOMOBILE RECYCLING is one of the most successful examples of reuse of a manufactured product. About 75 percent of a typical car can be recycled in the form of refurbished parts, useful fluids and scrap materials. This process can, however, be taken further. New methods to separate and recycle plastic components, for example, offer the possibility of removing even more material from the waste stream and returning it to the manufacturing cycle.

treatment sludges as hazardous. The unintended consequence was that the smelters could no longer use the sludge, because it had become, in name, a hazardous material—the regulatory requirements for accepting it were too severe. The zinc-rich sludge was redirected to landfills, thereby increasing costs for automobile manufacturers and producing a waste disposal problem for the rest of society.

This situation clearly illustrated what can be a serious problem: well-meant environmental regulation can have the bizarre effect of increasing both the amount of waste created and the amount to be disposed, because it puts up high barriers to reuse. It might be viewed as antirecycling regulation. This peculiarity appears to have occurred essentially by inadvertence: industrial supplies, whether toxic or not, are controlled by different statutes—and often by a different part of the government—than are materials considered waste. A priority for the future will be a cleanup of that aspect of the nation's regulatory machinery.

With adequate effort the next century will see many improvements in environmental laws as well as in specific environmental technologies. But the most important advance of all may be the fundamental reorganization that allows used materials to flow freely between consumers and manufacturers, between one firm and the next and between one industry and another. As much as we need to excavate the industrial archaeology left over from the past, we also need to draw lessons for the future from these ghastly sites, create an industrial ecological vision and formulate a system of law and practice to enable it.

The Author

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Further Reading

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