

## CHEMICAL ENGINEERS AND ENVIRONMENTAL STEWARDSHIP

*“The more clearly we can focus our attention on the wonders and realities of the universe around us, the less taste we shall have for destruction.”*

*Rachel Carson, Silent Spring, 1962*

Many date society’s awareness of the need to maintain and improve the environment to the 1962 publication of Rachel Carson’s book, *Silent Spring*. While Carson’s exposé focused on the indiscriminate use of pesticides, it also created a broad awareness of the impact human activities can have on the environment and helped usher in a new era of environmental advocacy.

Traditionally, organized efforts to address environmental concerns were focused largely on sewage and water treatment, which were primary concerns for many early societies and governments. The treatment of water to make it potable and of sewage to make it safe for disposal has been handled most often by civil or sanitary engineers working in the municipal sector.

Industrial activities have also long contributed harmful pollutants to the air, waterways and land, but for years few were concerned. Specific incidents began to raise concern among the populace, such as the 1952 London smog blamed for the death of 12,000 citizens, but they were generally considered aberrations. During the 1960s, a number of industrial accidents and widely publicized pollution incidents occurred, which began to galvanize public opinion. Ever since the nascent environmental movement began to take shape, industry has been considered the culprit (mostly true), and the chemical engineer has long been vilified as the perpetrator (far from true).

Chemical engineers are relative late-comers to the environmental arena, but many blame chemical engineers and their industrial activities for creating many types of industrial pollution. Their broad academic training in both chemistry and engineering, however, makes it possible to harness the basic principles of chemical, physical and even biological conversions to reduce the volume and toxicity of existing airborne or waterborne pollutants and solid waste streams, to design or redesign processes inherently less polluting than their historic counterparts, and to develop more effective monitoring

devices and control strategies to increase detection efficiency and to ensure optimal conversion rates (and thus minimize byproduct waste streams).

As such, chemical engineers are well suited to address the complex environmental challenges routinely present in so many industrial sectors. They often function as part of a multidisciplinary team in these efforts, providing the framework to identify the problem and design practical, economical solutions once the key issues have been identified.

### **Maintaining air quality**

Chemical engineers have a tremendous impact in identifying and solving a broad range of complex air pollution challenges such as the design of “end-of-pipe” solutions involving add-on pollution control technologies used to capture and/or neutralize hazardous pollutants prior to discharge to the atmosphere. They design and engineer new chemical process operations (and re-engineer and optimize existing ones) to minimize or prevent the formation of hazardous or regulated pollutants. They also design imaginative monitoring devices based on an ever-expanding array of detection methodologies, which provide accurate, real-time monitoring of target species at the sensitivity range of parts-per-million (ppm) and even parts-per-billion (ppb).

### **Treating water and wastewater**

Water pretreatment requires a multidisciplinary approach, and chemical engineers contribute significantly to water management including the development of widely used commercial-scale technologies and systems to purify raw water for drinking suitable for human consumption. Their contributions also include the treatment of raw source water to produce inlet process water that meets the requirements of chemical process operators, petroleum refiners, manufacturers of pharmaceuticals, foodstuffs, semiconductors and other industrial products, of industrial wastewater streams containing a complex mix of harmful chemical compounds to meet regulatory requirements and are suitable for discharge to public waterways, and of sewage to make the resulting streams suitable for discharge.

### **Focus on Pollution Prevention**

Environmental strategies to manage airborne and waterborne pollutants and solid-waste streams have historically emphasized end-of-pipe treatments that reduce the volume, toxicity, or mobility. By the 1980s, engineers shifted attention further up the proverbial pipeline and began increasingly to develop pollution prevention strategies to improve

chemical process operations in many ways and to minimize or eliminate the formation of hazardous or regulated pollutants in the first place.

Chemical engineers routinely design and optimize complex industrial operations for commercial-scale chemical transformations, while minimizing the formation of unwanted chemical byproducts. Over the past several decades, concerted pollution prevention efforts have helped industrial operators reduce their overall impact on the environment, which also have improved overall operating efficiency and reduced energy consumption, thereby reducing overall operating costs and improving long-term profitability. Interestingly, environmental improvements often go hand-in-hand with improving energy efficiency. When industrial operators reduce the amount of energy consumed by an industrial process or switch to “cleaner” fuels, such efforts not only help to reduce the emissions produced by the combustion of fossil fuels, but often achieve greater overall operating efficiencies. One of the best known examples is the “Pollution Prevention Pays” program instituted by 3M Corporation in 1975. In the 30-plus years since its inception, it has saved more than \$1 billion by preventing the release of more than 2.5 billion pounds of pollutants.

## Protecting the Earth

Over the past several decades, many in the engineering community have strived for a more ambitious overall operating philosophy, sustainable development, in which the world is viewed as having limited natural resources and being a finite “sink” for wastes in the face of a growing world population that is continuously placing increasing demand on the world’s limited resources, especially nonrenewable raw materials and fuels. With sustainability goals in mind, people aim to conduct all of their personal and industrial activities in a way that leaves the planet earth in the same or better condition for future generations. Such efforts are driven by the belief that, as one sage once wrote, “the earth was not given to us by our grandparents, but lent to us by our grandchildren.”

This wonderful ideal is often undertaken by using both such simple techniques as recycling and reuse to maximize the use of every resource consumed and such complex efforts as highly engineered solutions for a closed-loop or zero-discharge operation. Such an approach allows the waste streams from one operation to be used as the feedstocks or energy sources for another. Chemical engineers are at the forefront of developing processes that not only minimize raw materials required to produce a product, but also those that maximize the reuse of waste streams from other process operations to minimize the consumption of virgin materials and fuels as well.

## Environmental inventions

Chemical engineers often work closely with professionals from other scientific and engineering disciplines to protect and improve the environment. Among noteworthy environmental technologies developed by chemical engineers are the automobile catalytic converter, flue gas desulfurization systems removing harmful gaseous pollutants from power generating plants and industrial facilities burning fossil fuels, technologies purifying drinking water and treating contaminated industrial wastewater for safe discharge to public waterways or maximum reuse by industrial facilities, and technologies for the effective recycling of post-consumer waste streams.

*Catalytic converter for reducing pollution from automotive exhaust.* One of the hallmarks of modern life is the widespread ownership and use of cars, trucks and buses, which rely on the combustion of petroleum-derived gasoline or diesel fuel. While many think industrial smokestacks as a major cause of urban smog and other types of air pollution, it did not take long for society to realize that engine exhaust from these fleets of transportation vehicles was also a major contributor. Engine exhaust from motor vehicles contains numerous toxic species and compounds, particularly carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and unburned hydrocarbons (most often as particulate matter), all of which contribute to smog formation and are harmful to human health and damaging to the environment. (Note that NO<sub>x</sub> and unburned hydrocarbons—most often as particulate, all of which contribute to smog formation and harm human health and damage the environment, because fuels are largely desulfurized.)

Over the past several decades, engineers have commercialized significant improvements in engine technologies, such as the use of more efficient fuel and air management systems with better emissions control strategies including cleaner-burning fuels and catalytic systems to destroy harmful engine emissions from gasoline- and diesel-powered cars, trucks and buses.

The chemist, Carl Keith, and chemical engineer, John Mooney, who worked for many years at Engelhard Corp. (Iselin, N.J.), are credited with inventing the catalytic converter, now a standard feature used to reduce harmful pollution from automotive exhaust. (In 2006, chemical company BASF AG of Ludwigshafen, Germany, acquired Engelhard, and has been renamed BASF Catalysts LLC). The catalytic converter invented by Carl Keith destroyed only the carbon monoxide and unburned hydrocarbons in engine exhaust.

The chemical industry's cooperative efforts broadened its pollution-destruction capabilities and created a commercially viable unit. In particular, Corning Glass (Midland, Mich.) developed and manufactured a temperature-resistant honeycomb

structure onto which the precious metal catalyst could be deposited. This provides two distinct advantages of maximizing the surface area and minimizing the catalyst required. This is important, since the catalysts used for catalytic converters require a blend of the costly precious metals (platinum, palladium, and rhodium).

Once coated with the catalyst, this porous ceramic honeycomb provides a robust, high-surface area structure over which the hot automotive exhaust gases are passed. For this important honeycomb substrate, now the “gold standard” for catalytic converters, the team at Dow Corning received the 2003 National Medal of Technology. Established by an act of Congress in 1980, this medal is the highest honor awarded by the U.S. President to America’s leading innovators (<http://www.technology.gov/Medal/default.htm>).

The original catalytic converter was replaced in 1981 by an improved, three-way catalytic converter that was also developed by Mooney and Keith, for which they received the 2002 National Medal of Technology (<http://www.technology.gov/Medal/Recipients.htm>). This new converter removes three categories of pollutants: nitrogen oxides ( $\text{NO}_x$ ), unburned hydrocarbons, and carbon monoxide. Before catalytic converters could be used effectively by cars, trucks, and buses, parallel engineering efforts were needed to improve the composition of the gasoline pool, to remove certain constituents that are not only harmful to human health, but whose presence compromises the effective operation of the catalytic converter. In particular, when present in gasoline, sulfur and lead create respiratory and neurological problems (especially in children), and poison the active sites on the converter’s catalyst, rendering it ineffective.

Chemical engineering expertise was required to remove sulfur and lead from gasoline. For instance, since lead additives were initially blended into gasoline to give it desired performance characteristics and improved “anti-knock” capabilities, chemical engineers were needed to produce lead-free gasoline that did not incur performance tradeoffs when burned in automotive engines. Because sulfur is removed most effectively upstream in the refinery, additional changes were needed in the petroleum refinery to remove sulfur from the crude feedstocks used to produce gasoline.

Catalytic converters, developed to destroy unwanted pollutants from automobile exhausts, have also been used in many other types of engines that burn petroleum-derived fuels. Engineers are continuously working to develop new, improved catalysts that will work with diesel fuel and achieve higher conversion rates required to meet increasingly stringent future emission standards.

**Flue gas desulfurization.** The boilers used by power plants to generate electricity typically burn copious amounts of coal or heavy oil, and the combustion process

produces an exhaust stream that contains significant amounts of airborne pollutants, such as sulfur dioxide ( $\text{SO}_2$ ), which forms acid gases when dissolved in water or combined with water vapor.

Prior to the passage of the Clean Air Act of 1970 and its Amendments of 1990, the acid gases and other pollutants in power plant exhausts created significant environmental problems. For instance, when acid gases are able to accumulate in the atmosphere, they can come down as acid rain, making lakes and other waterways inhospitable for fish and other living organisms, including vegetation and trees.

High levels of  $\text{SO}_2$  in the atmosphere have also been implicated in the increased incidence of asthma and other pulmonary stress. Prior to the implementation of widespread government regulations in many industrialized nations, such pollution made it to result in hospital visits and lost sick time. Until the passage of the sweeping Clean Air Act and its Amendments, which mandated severe reductions in  $\text{SO}_x$  and other airborne pollutants from power plants, facility owners rarely installed costly, capital-intensive pollution-control systems on their own. Today, decades of strict regulatory requirements on coal-fired power plants and the increasing use of cleaner-burning natural gas have helped significantly clean the air and reduce the damaging effects of acid rain.

The control technology of choice for the effective removal of the acid gases from coal- and oil-based combustion processes has been flue gas desulfurization (FGD) with a wet process the most widely FGD system. During the process, the incoming sulfur-laden exhaust stream is contacted inside the scrubber with a circulating liquid sorbent stream (most often a slurry of alkaline reagents, such as pulverized lime or limestone) and the acid gases are converted to neutral salts and other solid byproducts such as calcium sulfite and calcium sulfate, which are removed and, after treatment, converted to a gypsum product that can be sold. New FGD scrubbers routinely remove 95% of  $\text{SO}_2$  and can be designed to remove 99% of  $\text{SO}_2$  from the boiler flue gas (data from the Institute of Clean Air Companies--<http://www.icac.com/i4a/pages/index.cfm?pageid=3401>).

Chemical engineers are intimately involved closely in designing the chemical conversion process and equipment for wet scrubbing, and today wet scrubbers are routinely used in coal-burning power plants in the U.S. to help meet strict federal and state mandates on acid gases such as  $\text{SO}_2$  and hydrochloric acid (HCl). They are also used by other chemical process plants and industrial facilities that use fossil-fuel-based combustion processes. Among scrubber configurations available, spray towers using banks of high-pressure nozzles to atomize the scrubbing liquid into a fine cloud of tiny, reactive droplets are the most widely used. The high surface-area-to-volume ratio of the droplets

intensifies the contact between the acid-laden flue gas stream and the scrubbing liquid and promotes the neutralizing reactions.

The contributions of Enrique Iglesia and Ralph Yang have been invaluable in the ongoing evolution of engineered pollution control. Iglesia, Professor of Chemical Engineering at UC Berkeley, has long been involved with the design, synthesis and characterization of inorganic solids, important catalysts for chemical reactions in energy use, petrochemical synthesis and environmental protection. He has been awarded 37 patents, and in 2003 he received the R.H. Wilhelm Award in Chemical Reaction Engineering from AIChE and in 2005 the George A. Olah Award in Hydrocarbon Chemistry from ACS.

Ralph Yang, Professor of Chemical Engineering at the University of Michigan, received the Clarence (Larry) G. Gerhold Award from AIChE's Separations Division in 1997 for outstanding contributions in research, development and application of chemical separations technologies for the removal of harmful pollutants before producing harmful emissions. Among his achievements are groundbreaking work on the development of desulfurization sorbents via pi-complexation that selectively adsorb sulfur from diesel fuels and zeolites that remove nitrogen from transportation fuels.

In addition to developing wet scrubbers, chemical engineers have also been active in the development of improved petroleum-refining techniques such as hydrotreaters that use hydrogen gas and a catalyst to desulfurize various petroleum fractions to produce fuels that have significantly reduced sulfur levels and thereby reduce the production of SO<sub>2</sub> when the fuel is combusted.

Furthermore, to enable the ongoing use of coal, the most plentiful and least expensive of all of the fossil fuels, chemical engineers also work hard developing and commercializing viable gasification routes. By using coal gasification, this inexpensive feedstock can be used to generate electricity without the considerable emissions produced by coal combustion or to produce a broad slate of petrochemicals and fuels from coal, instead of more expensive crude oil or natural gas.

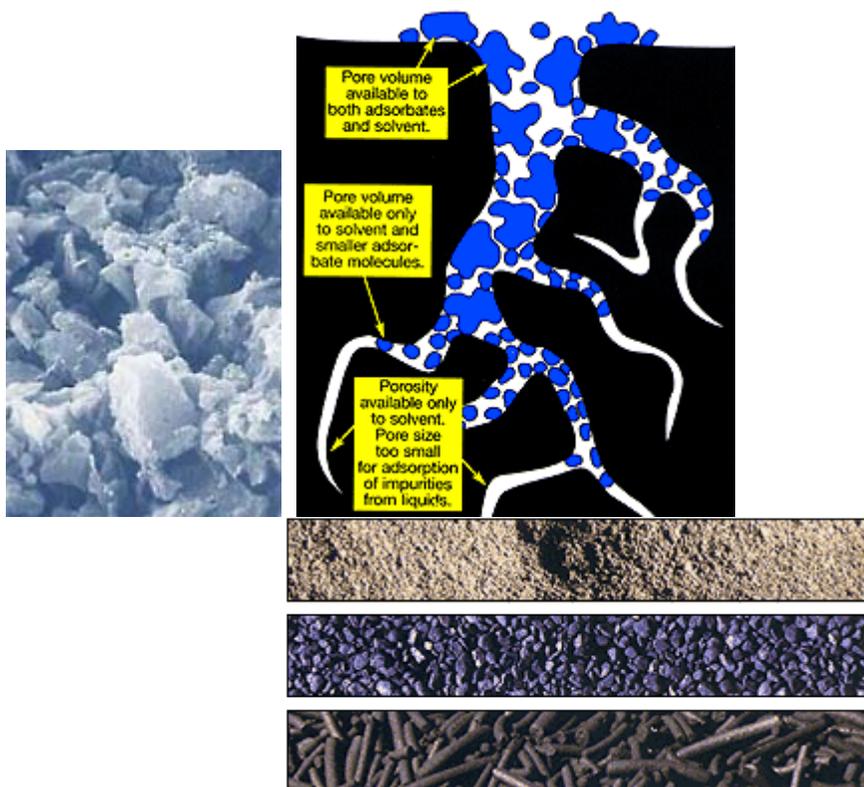
During coal gasification, an oxygen-blown, partial-oxidation gasifier is used to convert the initial feedstock (most often coal, as well as natural gas, petroleum coke, and other low-value refinery residues, or biomass) into an intermediate synthesis gas or "syngas," which largely comprises carbon monoxide and hydrogen. To produce electricity, the sulfur is first removed from this concentrated syngas stream, and then the syngas is burned in a gas turbine. To maximize efficiency, the turbine's waste heat is typically used to produce steam, which then powers a secondary steam turbine that generates additional electricity (such a setup is called an integrated gasification combined cycle, or IGCC,

facility). Chemical engineers have also devised novel strategies to further refine this coal-derived syngas to produce a broad slate of transportation fuels and petrochemicals. The Fischer-Tropsch process, developed in the 1920's to produce transportation fuels, has been adapted to many uses including promising applications of biomass gasification to produce "green" transportation fuels from plant materials.

***Water purification and reuse.*** Historically, water was considered so plentiful that there was little concern over its scarcity, but today in the face of burgeoning population growth and increased industrialization throughout the world, it is critical to conserve precious water resources and to implement engineered solutions to cost-effectively purify and reuse contaminated water sources. As a result, raw source water and contaminated industrial and municipal wastewater sources are now routinely treated so that its quality and composition are suitable for reuse as the inlet water for various industrial processes. Such water sources can also be treated rigorously to produce potable drinking water and to meet the exacting water purification regulations and technical requirements of such industry sectors as foodstuffs, pharmaceuticals and semiconductor manufacturing.

Modern-day water treatment, which is applied to raw water sources from rivers and lakes, to wastewater streams discharged from industrial facilities, or even to sewage streams, routinely employs a variety of chemical engineering principles. Treatment trains typically integrate site-specific combinations of physical and chemical separation systems based on, for instance, vacuum or pressure filters, centrifuges, membrane-based systems, distillation towers, carbon-based and zeolite-based adsorption systems, chemical-based oxidation treatments, and other approaches.

Activated carbon is a highly absorbent form of carbon produced when charcoal is heated. The resulting activated carbon has an extremely intricate pore structure with exceptionally high internal surface area. Published reports note that activated carbon can have surface area exceeding  $1,000 \text{ m}^2/\text{g}$ , which means that just 5 g of activated carbon has the surface area of a football field. Activated carbon, in both pellet and powdered form, has long been used to effectively remove impurities from both gaseous and aqueous waste streams, as shown below (reproduced with permission from the Norit web site).



Membrane-based separation processes (based typically on membranes made from cellulose acetate, ceramics or such polymers as polyacrylonitrile and polyvinylidene fluoride), are another notable chemical engineering contribution to the treatment of water and wastewater. During water treatment, membranes are used generally to separate target species from a tainted water stream, allowing purified water to diffuse through the membranes and collect on one side of the membrane, while the impurities are then concentrated on the other side. Since the use of membranes to desalinate seawater was first demonstrated in 1958, numerous membrane-based desalination processes have been developed.

Several competing designs are available for industrial membrane-based separation systems such as tubular, hollow-fiber, plate-and-frame, and spiral-wound configurations, each of which was designed to maximize the membrane surface area and reduce pressure drop during operation. Performance improvements based on ongoing advances in membrane materials and system configuration are always being pursued.



Since about 85% of child sickness and 65% of adult illnesses are thought to be produced by water-borne viruses, bacteria, and intestinal protozoa, resulting in diarrhea, tuberculosis, and worse, water-treatment trains typically employ some type of advanced oxidation techniques. Chlorine-based oxidation is the most widely used and is very effective, but the transportation, storage and use of chlorine present significant potential health and safety risks, so in recent years increased attention has been devoted to developing advanced oxidation treatments safer and more effective than chlorination. A variety of alternative advanced oxidation systems are available, which use ultraviolet light, hydrogen peroxide, and ozone to oxidize and disinfect water streams by destroying the unwanted organic contaminants.

Many chemical engineers have lent their career expertise to the development of imaginative environmental technologies, several of whom are mentioned below:

Lawrence K. Cecil, who spent much of his career at the University of Arizona, was a pioneer in water purification and reuse.

Walter Weber, Jr., considered by many as the father of activated carbon treatment of water and wastewater, is renowned for his 1972 classic book, *Physicochemical Processes for Water Quality Control*. He is Professor of Environmental and Ecological Sciences and Engineering in the Department of Chemical of Engineering at the University of Michigan, a member of the National Academy of Engineers, and the 2007 recipient of the Lawrence K. Cecil Award for excellence in environmental applications of chemical engineering..

Kam Sirkar at the New Jersey Institute of Technology works on finding ways to create extraordinarily tiny membrane pores. Today, he and his colleagues are pursuing the development of nanoporous membranes, whose nanometer-sized pores provides an opportunity for unimaginably exacting separations (one nanometer equals one-billionth of one meter)..

Joseph DeSimone at the University of North Carolina (Chapel Hill) pioneered to create a family of nontoxic surfactants based on the enhanced solvency of liquid carbon dioxide and developed systems to use these safer solvents help the chemical, automotive, aerospace, electronics, petroleum-refining, pharmaceutical, pulp-and-paper and other sectors to reduce or eliminate the use of hazardous organic and halogenated solvents as cleaning agents, process aids and dispersants. In 1997, he was awarded the Presidential Green Chemistry Challenge Award from the U.S. Environmental Protection Agency.

*Waste recycling.* In manufacturing, certain industrial waste streams can be used effectively as a feedstock or energy source for other processes. Successful reuse of waste streams (whether reused internally or sold to a different facility) minimizes the volume of waste that requires costly treatment or is ultimately sent to landfills and helps offset the total amount of raw materials and fuels needed by the process, thereby reducing overall costs for the manufacturer or chemical process operator.

Any successful recycling, whether it involves reusing industrial waste streams or recycling post-consumer waste such as plastic, glass or newspaper, must meet three basic challenges: A suitable collection infrastructure; appropriate reprocessing techniques, if needed, the waste stream suitable for reuse; and a need or a market for the recycled waste stream. Chemical engineers have long been developing technically feasible and economical reprocessing methods to maximize the reuse of industrial waste streams and effectively convert post-consumer wastes into valuable products.

Aluminum is the most valuable component of the waste stream. Almost two thirds of the aluminum cans and 85-90% of the aluminum in cars are recycled. A can made from

recycled aluminum requires 95% less energy than a can from ore. In 2006, 54 billion cans were recycled, saving the equivalent of 15 billion barrels of crude oil (data from Earth911 <http://earth911.org/blog/2007/04/02/facts-about-aluminum-recycling/>). Tin cans had been recycled to supply steel mills and support the war effort during World War II, but in the U.S. the practice fell into disuse in the 1950s and 1960s when disposable goods came to represent not just convenience but increased affluence as well. In the late 1960s, when the greater public awareness of environmental issues renewed recycling efforts of collecting household wastes for reuse and recycle, and rapid increases in the raw metal price prompted industrial waste streams such as copper wire to be recycled.

Today, many municipalities have established infrastructures in place to sort, separate, and collect household waste streams, which are then recycled, greatly reducing the ultimate volume of municipal waste that ends up in landfills. This is especially critical for nonbiodegradable wastes, such as plastic, glass and metal. Chemical engineers and metallurgists work together to perfect effective metal-recycling techniques. For instance, while recycled stainless steel cans can be blended back into a steel mill with little or no interim processing, the traditional process for producing aluminum cannot use recycled aluminum without additional processing. One such process was developed in the 1960s. First, any lacquer, paint, or labels are removed from the recycled aluminum cans in a heated oven, which then are chopped into small pieces and added to a molten aluminum bath, along with chemicals to dissolve any impurities. The chemicals and impurities are eventually skimmed off. The remaining aluminum composition is checked for quality and formed into ingots, which are then sent to the fabricators for use in cans and other aluminum products.

The use of recycled aluminum brings significant savings in both energy and pollution compared with the energy-intensive processes required to mine and treat bauxite ore to produce virgin aluminum. For instance, producing 1 ton of aluminum cans from recycled cans saves 5 tons of bauxite. And the reuse of aluminum can reduce air pollution by 99% and energy consumption by 95%, compared to the production of virgin aluminum from bauxite.



Aluminum is the most valuable component of the waste stream. Almost two thirds of the aluminum cans are recycled, and 85-90% of the aluminum in cars is recycled. A can made from recycled aluminum requires 95% less energy than that from ore. In 2006, 54 billion cans were recycled, saving the equivalent of 15 billion barrels of crude oil (data from Earth911 <http://earth911.org/blog/2007/04/02/facts-about-aluminum-recycling/>).

Paper is another large-volume product that is now routinely recycled on a widespread basis. Similar to the issues associated with aluminum recycling, paper mills cannot simply use recycled paper as a substitute for virgin tree pulp. Recycled paper is contaminated by printing ink and a broad slate of other treatment chemicals used to achieve the desired quality of various paper stocks. The process for recycling paper begins with blending recycled paper and water to produce a pulp slurry. A deinking process removes the ink and other chemical additives, and a filtration step then removes any solid impurities.

Because recycled pulp has shorter fibers than virgin pulp, its exclusive use would not produce a strong recycled paper. To achieve the appropriate quality, recycled paper is typically produced by blending some virgin pulp (typically produced from wood chips) with the recycled pulp. This blended pulp is then sent to the papermaking machine to produce newsprint or other recycled paper products. Today, over 70% of the newsprint in the U.S. are collected for recycling, and most of the recycled newsprint goes back into producing additional newsprint. It took about 30 years to achieve this recycling rate, because the initial quality of the recycled paper was not sufficient, and the collection infrastructure and market for recycled paper were not properly established.

For any process operation that converts raw materials into finished products, the formation of any waste stream steals from the bottom line. When monies are wisely spent

on upstream recycling and pollution prevention, the return on investment and savings come in the form of reduced raw material consumption, fuel use, and waste treatment and disposal costs.

Chemical engineers, who routinely use chemical and physical principles to solve practical problems, are in an ideal position to champion such ambitious environmental goals. As the chemical engineering community continues to pioneer broad-ranging, imaginative pollution prevention initiatives that are able to reduce an industrial facility's "environmental footprint," such improvements also result in better operating efficiencies and higher product yields, reduced costs, and increased profitability. ***That's engineering at its best.***