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POLLUTION PREVENTION : ENGINEERING DESIGN AT MACRO-, MESO-, AND MICROSCALES

David T. Allen
Department of Chemical Engineering
University of Texas at Austin
Austin, Texas USA 78712

ABSTRACT : Billions of tons of industrial waste are generated annually in industrialized countries. Managing and legally disposing of these wastes costs tens to hundreds of billions of dollars each year, and these costs have been increasing rapidly. The escalation is likely to continue as emission standards become even more stringent around the world. In the face of these rapidly rising costs and rapidly increasing performance standards, traditional end-of-pipe approaches to waste management have become less attractive. The most economical waste management alternatives in many cases have become recycling of the waste or the redesign of chemical processes and products so that wastes are prevented or put to productive use. These strategies of recycling or reducing waste at the source have collectively come to be known as pollution prevention.

The engineering challenges associated with pollution prevention are substantial. This presentation will categorize the challenges in three levels. At the most macroscopic level, the flow of materials in our industrial economy, from natural resource extraction to consumer product disposal, can be redesigned. Currently, most of our raw materials are virgin natural resources that are used once, then discarded. Studies in what has come to be called industrial ecology examine the material efficiency of large-scale industrial systems and attempt to improve that efficiency. A second level of engineering challenges is found at the scale of individual industrial facilities, where chemical processes and products can be redesigned so that waste is reduced. Finally, on a molecular level, chemical synthesis pathways, combustion reaction pathways, and other material fabrication procedures can be redesigned to reduce emissions of pollution and unwanted by-products. All of these design activities, shown in Figure 1, have the potential to prevent pollution. All involve the tools of engineering, and in particular, chemical engineering.

I. Macroscale Pollution Prevention

Following the flow of material in our industrial economy, from raw material acquisition to product and waste disposal, provides perspective that is essential for pollution prevention. Such studies can help to identify whether materials currently regarded as wastes in one industrial sector could be viewed as raw materials by another sector. These studies also reveal what types of processes and products are responsible for waste generation, and identification of the source of a waste is the first step toward prevention.

This presentation will examine pollution prevention at the macroscale level from these perspectives. First, an overview of waste generation and management will be presented. This inventory of wastes helps to identify processes and products that may benefit from pollution prevention, but a mere listing of wastes and emissions ignores the complex interdependencies of many processes and products. Two related approaches are used to study the complex systems used to convert raw materials to products. One approach, called Industrial Metabolism [1], involves selecting a particular raw material, for example lead, and following it as it flows through processes and into products. A second approach, called Life Cycle Assesment [2], starts with a particular product and identifies all of the precursors that were required for the product's manufacture, use, and disposal. These three elements-waste invention, industrial metabolism, and life cycle assessment-form

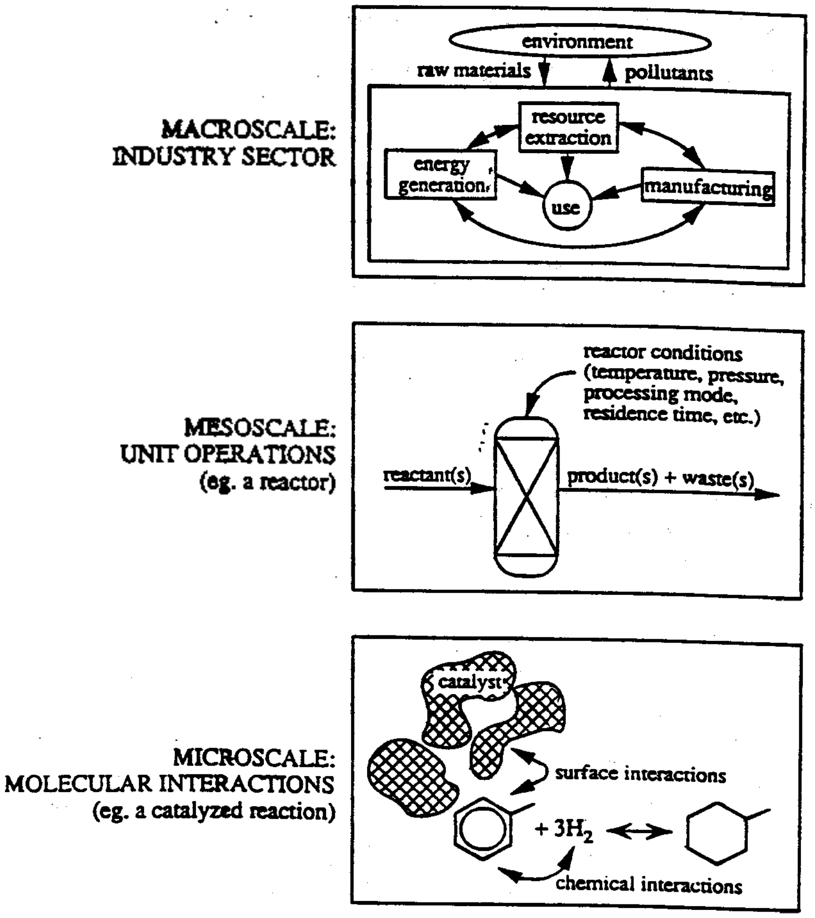

Figure 1. Pollution Prevention at Macro-, Meso-, and Micro-scales

the basis of pollution prevention at the macroscale.

An overview of waste generation and management in the United States

The best estimates available from national waste generation data bases indicate that more than 12 billion tons (wet basis) of industrial waste are generated annually in the United States [3]. Table 1 and Figure2 and 3 provide an overview of these waste streams.

The main points that will be emphasized in the presentation are:

· billions of tons of industrial waste are generated annually in the United States.

· only a few technologies (incineration, land disposal and various forms of wastewater treatment) are used to manage waste steams; there is relatively little use of innovative technologies

· waste steams frequently contain valuable materials at concentration levels suitable for recovery, however, relatively little material is reclaimed from wastes.

Industrial metabolism

Analysis of waste management data represents a first step in performing macro scale studies of material flows and identifying targets for pollution prevention. The next step is to integrate waste generation data with production data. These studies, which have been described as Industrial Metabolism [1], examine the sources and all the uses of particular materials. By integrating may be possible to identify targets of opportunity for recycling between industrial sectors.

Figure 4 is a simplified example of the industrial metabolism of lead [8].

Table 1. Industrial non-hazardous waste generation [5]

Waste Category	Estimated Annual Generation Rate (million tons)
Industrial Nonhazardous Waste[a,b]	7,600
Oil and Gas Waste[c,e]	
drilling waste[d]	129-871
produced waters[f]	1,966-2,738
Mining Waste[c,g]	>1,400
Municipa Waste[b]	158
household hazardous waste	0.002-0.56
Municipal Waste Combustion Ash[h]	3.2-8.1
Utility Waste[c,i]	
ash	69
flue gas desulfurization waste	16
Construction and Demolition Waste[i]	31.5
Municipal Sludge[b]	6.9
wastewater treatment	3.5
water treatment	
Very-Small-Quantity[b] Generator hazardous waste(<100 kg/mo)[b,c]	0.2
Waste Tiresg	24million tires
Infectios Waste[c,l]	2.1
Agricultural Waste	Unknown
Approximate Total	>11,387

[a] Not including industrial waste that is recycled or disposed of off site

[b] These estimates are derived from 1986 data.

[c] See SAIC [6]

[d] Converted to tons from barrels : 42 gals = 1 barrel, ∼17 lbs/gal.

[e] These estimates are derived from 1985 data.

[f] Converted to tons from barrels : 42 gal = 1 barrel, ∼8 lbs/gal.

[g] These estimates are derived from 1983 data.

[h] This estimate is derived from 1988 data

[i] These estimates are derived from 1984 data

[j] This estimate is derived from 1970 data

[k] Small quantity generatiors (100-1,000 kg/mo waste) have been regulated under RCRA, Subtitle C, since October 1986. Before then, approximately 830,000 tons of small-quantity generator hazardous wastes were disposed of in Subtitle D facilities every year.

[l] Includes only infectious hospital waste.

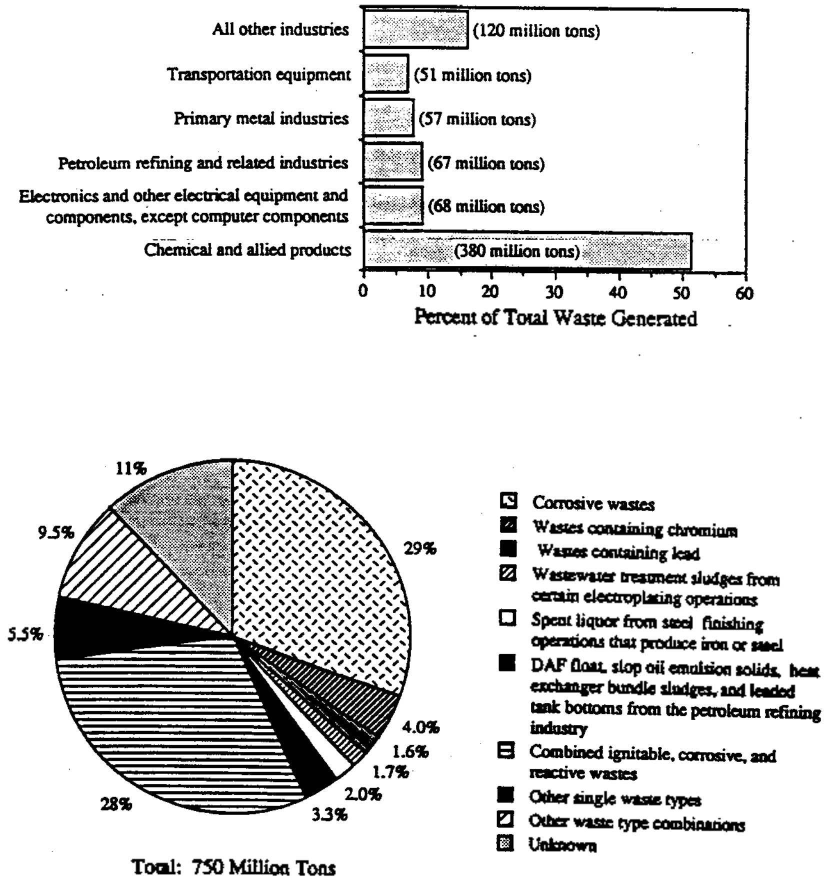

Figure 2. Hazardous waste generation [4]

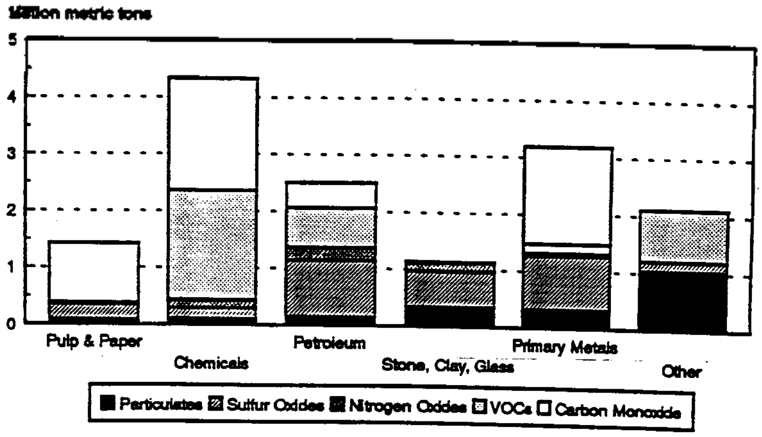

Figure 3. Industrial process air emissions[7]

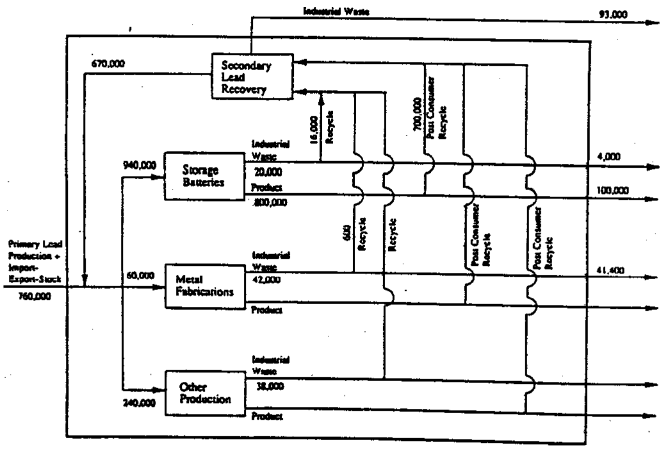

Figure 4. A simplified model of the industrial metabolism of lead [8]

The main points that will be emphasized in the presentation are:

- The data to necessary to map industrial metabolism is sparse
- a few materials, such as chlorine and metals have been mapped effectively
- understanding these flows can have important policy consequences.

Life Cycle Assessment

Life cycle assessment, like industrial metabolism, is a systems approach to examining material flows. In this case, the focus is on a product, rather than a specific material. A Life Cycle Assessment will map the flows of wastes, raw materials and energy associated with a product's manufacture, use and disposal. This portion of the presentation will describe the strengths and weaknesses of life cycle assessments and will describe how they are being applied in practice.

II. Mesoscale Pollution Prevention

Macroscale studies of pollution prevention, outlined in the previous sections, are useful in identifying research needs and targets of opportunity for pollution prevention. Once the targets have been identified, then the design of cleaner chemical processes and product can begin. Over the past decade, a variety of approaches have emerged. Some of these strategies are simply good housekeeping, maintenance, and operating practices. Frequently characterized as "low-hanging fruit," such methods have been extensively exploited in many manufacturing operations. A second tier of strategies involves relatively simple process modifications, employing currently available technology. Many of these approaches to waste reduction are still underutilized; some process modifications for reducing waste require technological innovation and are just beginning to be explored. Finally, product reformulation and raw material substitution have occasionally been used to reduce wastes. The U.S. Department of Energy's Office of Industrial Technologies [9] has summarized these approaches in the matrix of Table 2.

This presentation will examine generic methods and specific of each of these strategies for reducing wastes. The focus will be on the chemical process industries: chemical manufacturing and petroleum refining. Focusing on a particular sector will allow a fairly comprehensive treatment of waste reduction methods. In addition, an emphasis on chemical manufacturing and petroleum refining is relevant because these industries are responsible for over half of all hazardous wastes generated in the United States, they are also the source

Table 2: STRATEGIES FOR CLEANER TECHNOLOGIES

Strategies	Housekeeping measures	In-process recycling	Process redesign	Input substitution	Product changes
Timing of impacts	Near-term	Near-and midterm	Mid and long-term	Near-and midterm	Long-term
Capital cost	Low	Varies	High	Low	Moderate to high
Operation cost	Low	Low to moderate	Low	Moderate to high	Varies
Industry incentives	High	Moderate	Low	Moderate	Low
Energy-saving potential	Moderate	Moderate	High	Varies	High
Characteristic of industries where application is possible	All industries	All industries except those with very stringent or hogh quality demands	Frequently changing, high-tech industrial products: some commodity goods; consumer goods; manufacturers	Frequently changing, high-texh insudtrial products; job shops for industrial processes; some commodity goods; consumer goods manufacturers	Large-scale manufacturers of consumer goods
Industry example	Rubber, electroplating, textiles, chemicals	Electronic compounds. chemicals, appliances	Steelmaking, medical, chemicals equipment, automobiles	Electronic components, foundries, printing, paints, chemicals	Consumer electronics, chemicals

Table 3: EXAMPLES OF PROCESS MODIFICATIONS FOR WASTE REDUCTION

	Changes in operation practices	Currently feasible modifications	Process modifications requiring technology development
Storage vessels	Use of mixers to reduce sludge formation	Floating roof tanks, high-pressures tanks, insulated tanks	Process specific changes to liminate the need for storage, particularly intermediates
Pipes and valves	Leak detection and repair programs for fugitive emissions	"leakless" components	Process designs requiring the minimum number of valves and other components
Heat exchangers	Use of anti-foulants;innovative cleaning devices for heat exchanger tubes	Staged heat exchangers and use of adiabatic expanders to reduce heat exchanger temperatures	Heat exchanger networks to lower total process energy demand
Reactors	Higher selectivity through better mixing of reactants, elimination of hot and arid spots	Catalyst modifications to enhances selectivity or to prevent catalyst recycling	Changes in process chemistry; integration of reaction and separation units
Separators	reduce wastes for reboilers	Improvements in separation efficiencies	New separation devices, efficien for very dilute species

of approximately half of the releases of chemicals reported through the Toxic Release Inventory, and they are a significant source of wastes legally classified as nonhazardous. The presentation of pollution prevention methods will be divided into two broad categories: process modifications and product design/raw material substitution. To give the presentation on process modifications a logical structure, the waste reduction methods will be grouped using a unit operation approach. This approach recognizes that most chemical processes consist of a common sequence of steps or unit operations- raw material storage, reaction, separation and purification of products, healing and cooling of process streams, product storage-with similar design procedures and pollution prevention approaches. Waste reduction methods will be grouped according to the unit operation to which they apply. Thus, this presentation will develop a matrix of approaches to waste reduction in the chemical processes industries(Table 3). The rows of the matrix are common unit operation such as storage, pipes and valves, reactors, heat exchangers, and separation equipment. The columns of the matrix separate the methods into changes in operation practices, currently feasible changes in process technologies, and process changes requiring technology breakthroughs. Another set of methods for waste reduction involves synthesizing or restructuring the process flowsheet. Identifying flowsheet structures that minimize waste is a challenging task; however, a number of design tools have recently emerged that allow the problem to be approached systematically. This presentation will describe two of these methods; the hierarchical design procedures of Douglas [10], and the Mass Exchange Network (MEN) synthesis methods developed by Manousiouthakis and co-workers [11,12].

III. Microscale Pollution Prevention

While process changes for pollution prevention have been characterized in this presentation as macro- or mesoscale, many of the approaches that have been described rely upon a molecular-level understanding of chemical and physical processes. For example, the synthesis of new catalysts, which results in higher reaction yields and less wastes, relies on an understanding of surface chemistry. The design of highly selective separation technologies relies on an understanding of adsorption and other phenomena. The minimization of particular pollution relies on an understanding of aerosol physics and chemistry. These and a large number of other general engineering principles are employed in pollution prevention. A detailed discussion of all of these principles is beyond the scope of this presentation. So instead of attempting to be comprehensive, just a few select examples of molecular-level design for pollution prevention based on the author's own experiences will be presented. These case studies illustrate how general engineering principles are used as foundation upon which pollution prevention approaches are built.

IV. Summary

The design of chemical processes and products that minimize waste and prevent the formation of pollutants is now new. Decades of work in chemical engineering have focused on this very topic.

The results may have been called yield enhancement, energy efficiency, or by-product utilization, but the goal remained the same: to minimize raw material and energy utilization. Given that waste reduction and pollution prevention are not new concepts, their emergence innovative compliance strategies may seem unusual. What has driven their increased importance are the dramatic increases in costs associated with waste treatment, disposal, and liability, and a better understanding of the role of individual chemical species in pollutant toxicity. The former has changed the economics of waste treatment versus prevention so that it is now more economical in many cases to prevent the formation of a pollutant rather than to treat it. The latter driving force for pollution prevention is requiring a much more detailed understanding of the chemistry of processes and products. When concentrations of 3,4,7,8-tetrachlorodibenzodioxin at the part-per-trillion level can significantly influence the economics of a process, it is necessary to understand processes occurring at rates and concentrations orders of magnitude smaller than considered in previous designs.

The challenges of pollution prevention-more mass-efficient designs, characterized at the molecular level-can be met with traditional and emerging engineering tools. These tools can be applied at macro-, meso- and microscales. This presentation has attempted to summarize many of the approaches being used in pollution prevention at these three levels. At the macrolevel, guiding waste-reduction effort. At the mesolevel, the designs of traditional chemical process unit operation are bring modified so that the units produce less waste; new flowsheeting techniques involving pinch technology are being used to assess the mass efficiency of processes. Finally, at the microscale, wide-ranging studies are contributing to a molecular design of products and processes.

Because pollution prevention and waste reduction requires all of the tools of chemical engineering, this presentation is not comprehensive. It should instead be viewed as a starting point for a set of challenges that will face chemical process and product design for the foreseeable future.

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