Water Use in Industries of the Future: Chemical Industry[1]

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4.1 Chemical Industry

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4.1.1 Introduction to the Chemical Industry

The chemicals industry is very large and diverse, as documented elsewhere (Energetics, 2000). It provides many of the fundamental materials and building blocks used in other industries, including the other Industries of the Future. The industry has been divided into several major sectors based on groupings of Standard Industrial Classifications (SICs) by the Office of Management and Budget (OMB, 1987, 1997):

- Industrial inorganic chemicals
- Industrial organic chemicals
- Plastics and rubbers
- Pharmaceuticals
- Soaps and cleaners
- Paints and varnishes
- Agricultural chemicals

This industry is a key component of the U.S. economy, with annual shipments of over 360 million tons of product, at a value estimated at almost $400 billion (DOC; 1997, CMA, 1998). A 1994 Manufacturing Energy Consumption Survey (MECS) estimated energy use in the U.S. chemical industry for that year at about 5.3 quads (quadrillion BTU) (MECS, 1994). Table 4.1-1 shows approximate 1997 production volumes for leading categories:

TABLE 4.1-1
Top Chemical Categories: Annual Production

Category	1997 Production
Top 50 Chemicals	364.2 million tons
Organic	141.7 million tons
Inorganic	102.4 million tons
Agricultural Chemicals	44.9 million tons

Source: CMA, 1998

Unlike several other Industries of the Future, the chemical industry is characterized by a wide variety of products and processes. Hundreds of different chemicals are produced, and there can be several routes for the manufacture of a given product, so that water and energy use for a particular product might vary significantly across companies. Even within the same company, more than one process might be used in the manufacture of a single chemical. Also, water historically has been essentially free and unlimited in supply for many regions of the United States. In the chemical industry, it is rarely used as a primary feedstock or reactant, but rather for cooling, so there has not been a strong driver to force the tracking of its use. Thus, the chemicals industry has not traditionally tracked the usage of water in its processes.

Data searches over the past 5 years for CWRT have found some anecdotal data on chemical industry water use, but nothing comprehensive. This conclusion was verified for this study through contacts with several major chemical companies, trade associations, and internal consultants, each of whom described the measurement and recordkeeping of water usage as sporadic at best.

Because of the increasing importance of water scarcity issues, a basic understanding of water usage in the chemical industry is important in identifying and modifying key processes that could help the industry meet anticipated standards and limitations. In order to present such an analysis in the face of scarcity of actual water use data in chemical processes, the PEP Yearbook International, prepared by SRI Consulting, was used as the basis of the numbers presented in this chapter. This yearbook contains design data on 908 chemical processes, including steam, cooling, and process water usage. Data from these individual uses were added to estimate "total water" for individual processes. Annual totals were estimated by means of the base capacity of each process.

Although actual energy data are more readily available than water data, energy estimates from the PEP yearbook were used for the sake of consistency. Electricity, fuel oil, and natural gas consumption were added together to estimate total energy requirements.

4.1.2 How Water is Used in the Industry

Consumptive and Return-Flow Uses

According to design data, the various processes in the worldwide chemical industry have the capacity to use over 100 trillion gallons of water annually (SRI Database). Although there are some consumptive uses, such as water in the product and evaporative losses, most water used by the chemical industry is for return-flow applications. In fact, most is used as non-contact cooling water, without contacting the chemical being produced. The exact quantity of water that is consumptive is unknown because the available data were reported only as cooling, steam, or process water. However, it is estimated here that less than 5 percent of water used is incorporated into final products in the chemical industry. Comprehensive data on the amount of evaporative losses in the chemical industry were not available, but the largest source of evaporation probably is cooling towers.

Major Uses

Based on design data for unit processes listed in the PEP yearbook, the largest use of water in the chemical industry is for cooling, with steam (e.g., heating and autoclaving) and process water (for mixing, dilution, reactants, wash, or rinse water) being the other significant uses. Chemical facilities are made up of varying combinations of these unit processes and water flows between processes. Cooling water recycled through cooling towers is not accounted for in the design data for individual unit operations. Therefore, actual distribution of water at the facility level is different from design data for individual processes. Historical data on distribution of water use at the facility level is scant; however, it is estimated that process cooling, process dilution, and steam production represent the most significant water uses at chemical facilities.

In a similar manner, the estimated total water use capacity of 100 trillion gallons per year for the chemical industry is a summation of base design capacities for each chemical process identified in the SRI database, and could be thought of as a theoretical upper bound for potential water use by the industry. Water reuse, especially closed-loop cooling with cooling towers, is not accounted for in this estimate. Such water reuse reduces the amount of total freshwater withdrawal by the industry. The proportion of cooling water recirculated through cooling towers versus once-through cooling is not documented, so that the actual world-wide freshwater withdrawal by the chemical industry is not known, but is probably substantially less than 100 trillion gallons per year. Where open-cycle cooling with cooling towers is used, it can represent up to 90–95 percent reduction in freshwater withdrawn for cooling purposes, with a commensurate reduction in return flow [3]

4.1.3 Major Water Users in the Chemical Industry

Ten processes account for over 95 percent of the water used in the chemical industry. As shown in Figure 4.1-1, six methods for producing Synthesis Gas (or “Syngas”) are responsible for the use of over 87 percent of the industry’s total water use capacity. Another 7 percent is used in the production of hydrogen. The annual total estimates are based on the representative base capacities of the processes. The numbers in Figure 4.1-1 are water capacity, to illustrate how much water is involved in these processes. They do not take into

[3] CH2M HILL, 2002. CH2M HILL Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

account recycle of water used for non-contact cooling and boiler feed, which can reduce actual consumptive use by over 90 percent from the numbers shown in Figure 4.1-1. This fact is discussed further in the next subsection.

As one would expect, based on the distribution of water use described in the previous section, 9 of the 10 processes shown in Figure 4.1-1 are heavy cooling water users. The exception is production of Synthesis Gas from bituminous coal by gasification, which is the seventh highest annual water user. The process relies on large amounts of steam and process water to reduce the total water use by more than an order of magnitude.

The chemicals that have the highest volume of production in the United States are not among the highest water users, nor are they the most water intensive processes, discussed in the following subsection. As shown in Table 4.1-2, their water use is more closely correlated with their rank in production volume. Total consumptive use is estimated using assumptions for typical recycle rates for the various water use categories. Actual water use practices vary, so that the consumptive waster use is an estimated range.

Certain processes use large amounts of water on a per pound basis. Table 4.1-3 shows the top 10 per pound water users in the chemical industry. The per pound water table represents the sum of cooling, steam, and process water requirements per pound for these processes. As with Table 4.1-2, recycle of boiler feed and cooling water is estimated to give a range for consumptive water use. Of these processes, only Ethylene Plant Feedstock is among the highest annual water users (Figure 4.1-1). The combined annual total of the top 10 per pound water using processes is only 0.7 percent of the annual water usage in the chemical industry.

Cooling Water Intensive Processes

Not surprisingly, given the proportion of water that is used for cooling, the chemical processes represented in Figure 4.1-1 also account for the top 10 cooling water users on a per pound basis. In fact, the cooling water requirements are

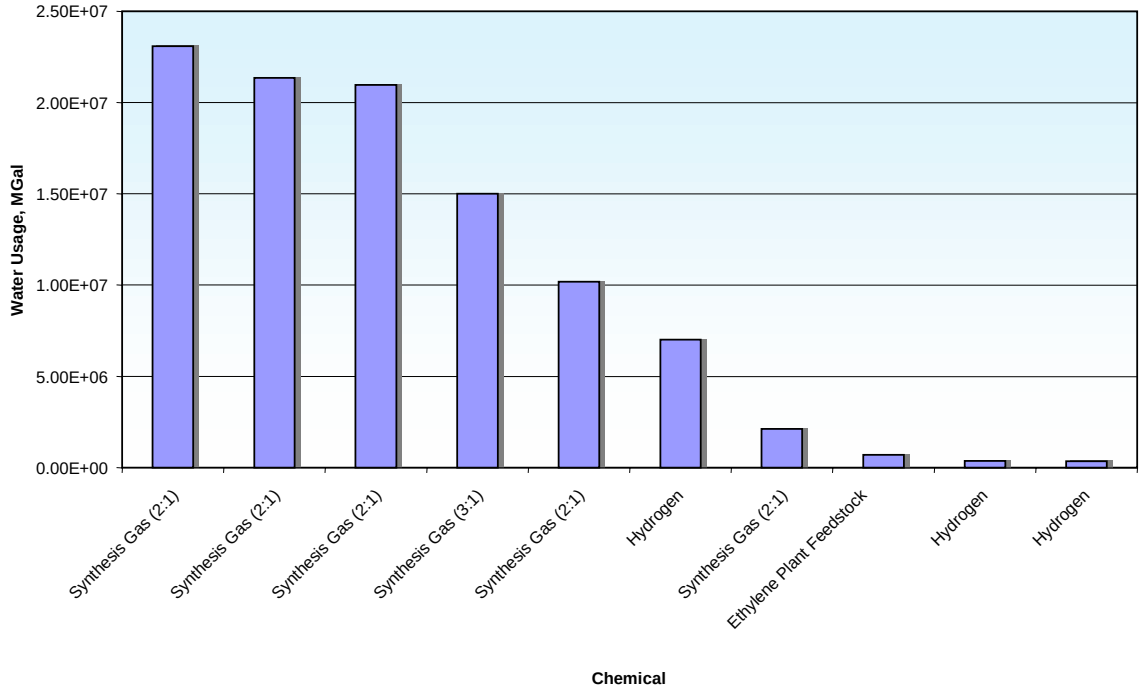

FIGURE 4.1-1
Highest Annual Water Users

TABLE 4.1-2

Water Usage of the Top Volume Manufactured Chemicals

	Cooling Water		Process Water		Water for Steam		Total Water Use Capacity	Typical Range of Consumptive Use (lb/lb)
	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled[2]	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled	lb/lb of product	(Total Water Use less fraction recycled)
Nitrogen	676	90 - 95%	N/A	Varies Widely - as low as 0%	N/A	80 - 99%	676	30 - 70
Ethylene	198		3.6		14.5		216	10 - 30
Ammonia	140		0.9		N/A		141	7 - 15
Phosphoric Acid	135		4.2		1.3		141	10 - 20
Propylene	135		2.4		0.8		138	9 - 18
Polyethylene	82		0.5		0.4		83	4 - 9
Chlorine	70		3.0		1.8		75	6 - 12
Sulfuric Acid	66		0.4		-0.4		66	3 - 7
Oxygen	21		N/A		N/A		21	1 - 2

1. Source: 2002 PEP Yearbook International, published by SRI Consulting.
2. Source: Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

TABLE 4.1-3

Highest Per Pound Water Users

	Cooling Water		Process Water		Water for Steam		Total Water Use Capacity	Typical Range of Consumptive Use (lb/lb)
	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled[2]	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled	Amount Used (lb/lb of product)[1]	Typical Fraction Recycled	lb/lb of product	(Total Water Use less fraction recycled)
Silicon Nitride	15529	90 - 95%	N/A	Varies Widely - as low as 0%	249	80 - 99%	15778	770 - 1600
Silicon, High-Purity, Silane Decomp	13878		28.8		N/A		13907	700 - 1400
Polyaryloxyphosphazene	8674		5.3		195		8873	400 - 900
Ethylene Plant Feedstock	5321		N/A		N/A		5321	250 - 550
D-phenylalaniline	3866		N/A		194		4060	200 - 420
Permethrin, Kuraray	3503		85.1		32		3620	250 - 450
Permethrin, Sagami	3419		82.6		31		3533	250 - 450
Silicon, High-Purity, Chlorosilane Reduction	3430		5.1		N/A		3435	180 - 360
Aramid Spun Yarn	2802		26.6		40		2868	170 - 320
PI Film, Fluoropolymer	2796		N/A		N/A		2796	140 - 280

1. Source: 2002 PEP Yearbook International, published by SRI Consulting.
2. Source: Approximation Analysis, assuming an average temperature rise of 50 degrees Fahrenheit for processes, and 6 cycles of concentration for typical cooling towers in the industry.

essentially indistinguishable from the total water requirements. However, Permethrin by the Sagami Process and High Purity Silicon by the Chlorosilane Reduction Process are reversed in order of cooling water usage because High Purity Silicon has a slightly larger cooling water requirement while Permethrin has a higher steam and process water usage for a higher total water usage. Because of these visually undetectable differences, a separate chart for the top 10 cooling water processes is not included.

Process Water Intensive Processes

Figure 4.1-2 depicts the 10 chemical industry processes that use the most process water. Of these, only the Permethrin processes are also shown in Figure 4.1-1 for high per pound total water usage. Only the Hydrogen and Synthesis Gas by gasification of bituminous coal appear on the chart of highest annual water users (Figure 4.1-1). As shown in Figure 4.1-2, the total water requirement (represented largely by cooling water) is significantly higher than the process water for all but three of the processes. Figure 4.1-2 does not account for recycle of cooling water or boiler feed water in the total water requirement, but shows total capacity for water use. Actual consumptive water use for each of the chemicals shown is lower, and varies on a per pound basis between different facilities because of different operating practices.

Steam Intensive Processes

The most steam intensive processes in the chemical industry are represented in Figure 4.1-3. The top 3 steam users are also among the top 10 per pound water users shown in Figure 4.1-1. Only Hydrogen appears on the list of highest annual total water users in Figure 4.1-1. With the single exception of Ethylene production, which actually results in an overall net generation of water, the total water requirement per pound is significantly higher than the steam usage alone for the most steam intensive processes. Figure 4.1-3 does not account for recycling of cooling water or boiler feed water in the total water requirement, but shows total capacity for water use. Actual consumptive water use for each of the chemicals shown is lower, and varies on a per pound basis between different facilities because of different operating practices.

4.1.4 Relationship of Water to Energy

Because the largest uses of water are for cooling and steam, water use and energy use are closely tied in the chemical industry. However, because the chemical industry has not historically tracked its water usage, it is difficult to quantify that relationship. For example, the top 10 total per pound water users, as shown in Figure 4.1-4, are not all high energy users, and a distinct correlation between water use and energy use is not well defined. However, the amount of energy consumed by the high volume of cooling water used in the chemical industry is intuitively high (though the specific amount is not available). The energy represented by electricity, fuel oil, and natural gas might for some processes be considerably less than the energy consumed by cooling water.

The processes that use the highest per pound amounts of total electricity, fuel oil, and natural gas are shown in Figure 4.1-5. As with Figure 4.1-4, the highest water users are not the highest energy users. However, the two High Purity Silicon processes shown in Figure 4.1-3 among the highest per pound water users also require the highest amounts of electricity, fuel oil, and natural gas forms of energy. Three of the processes, Synthesis Gas, Ethylene Plant Feedstock, and Hydrogen, are also among the highest annual total water users shown in Figure 4.1-1.

As with Figures 4.1-2 and 4.1-3, Figures 4.1-4 and 4.1-5 do not account for recycling of cooling water or boiler feed water in the total water requirement, but show total capacity for water use.

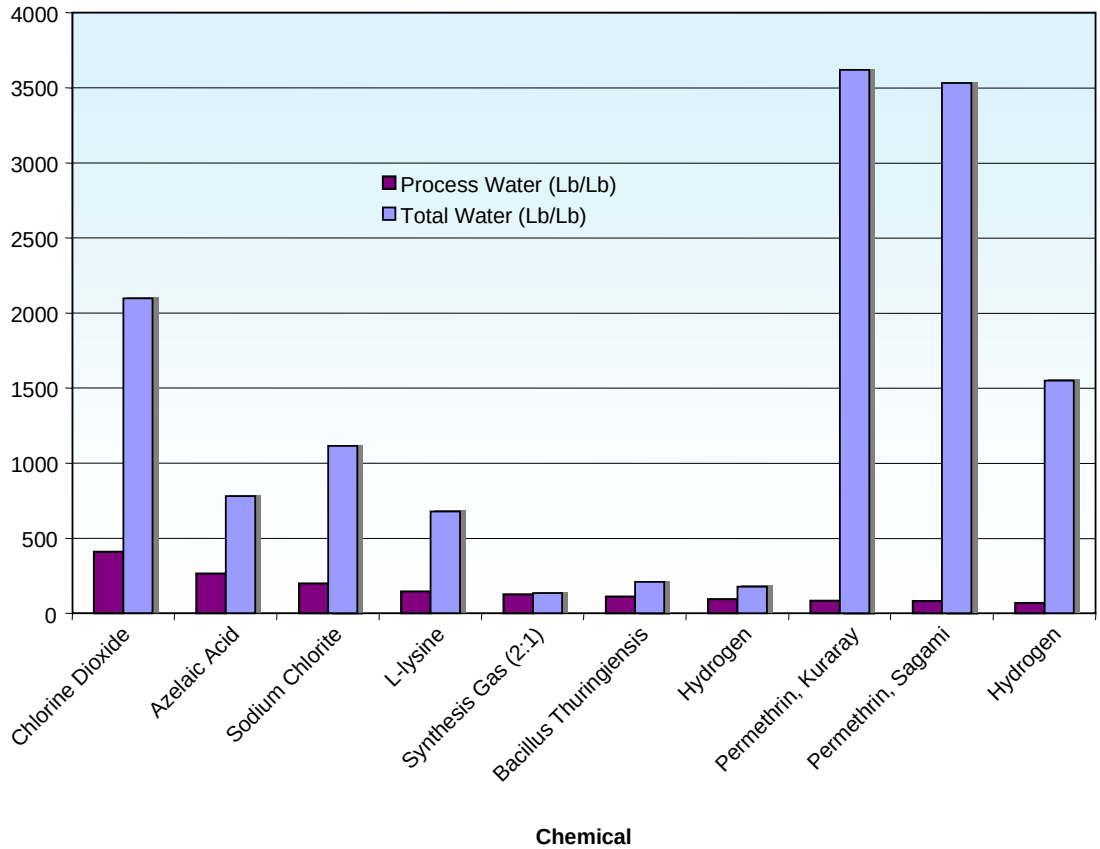

FIGURE 4.1-2
Most Intensive Process Water Users

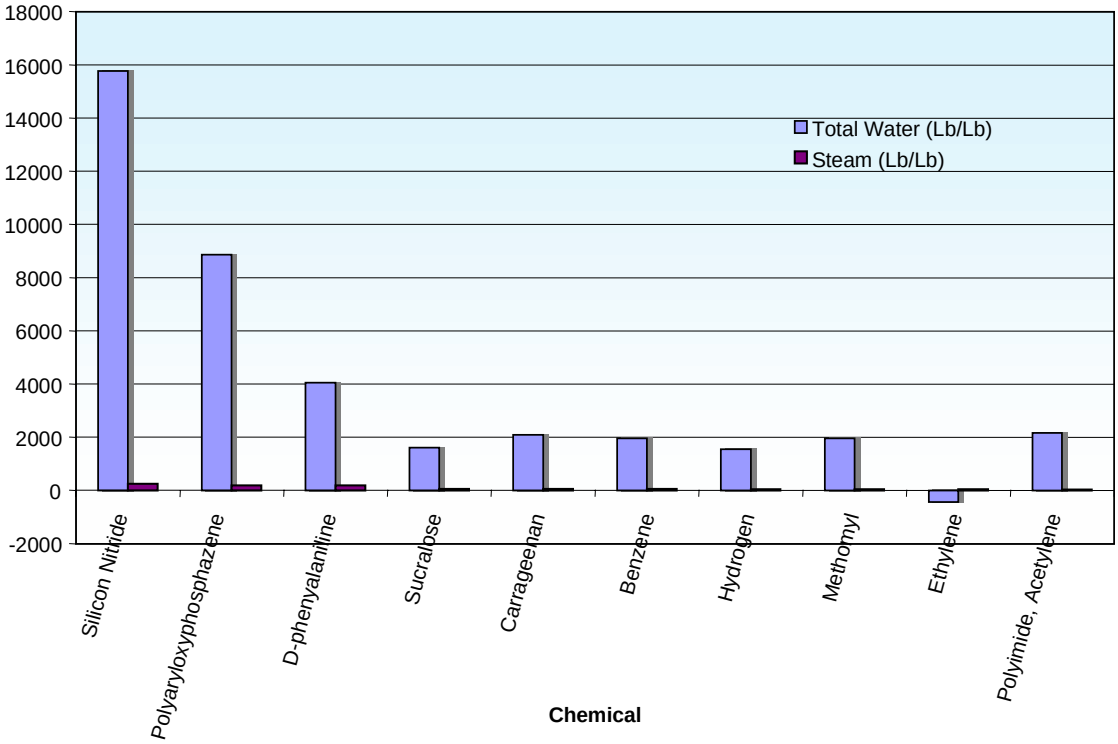

FIGURE 4.1-3
Most Steam Intensive Processes

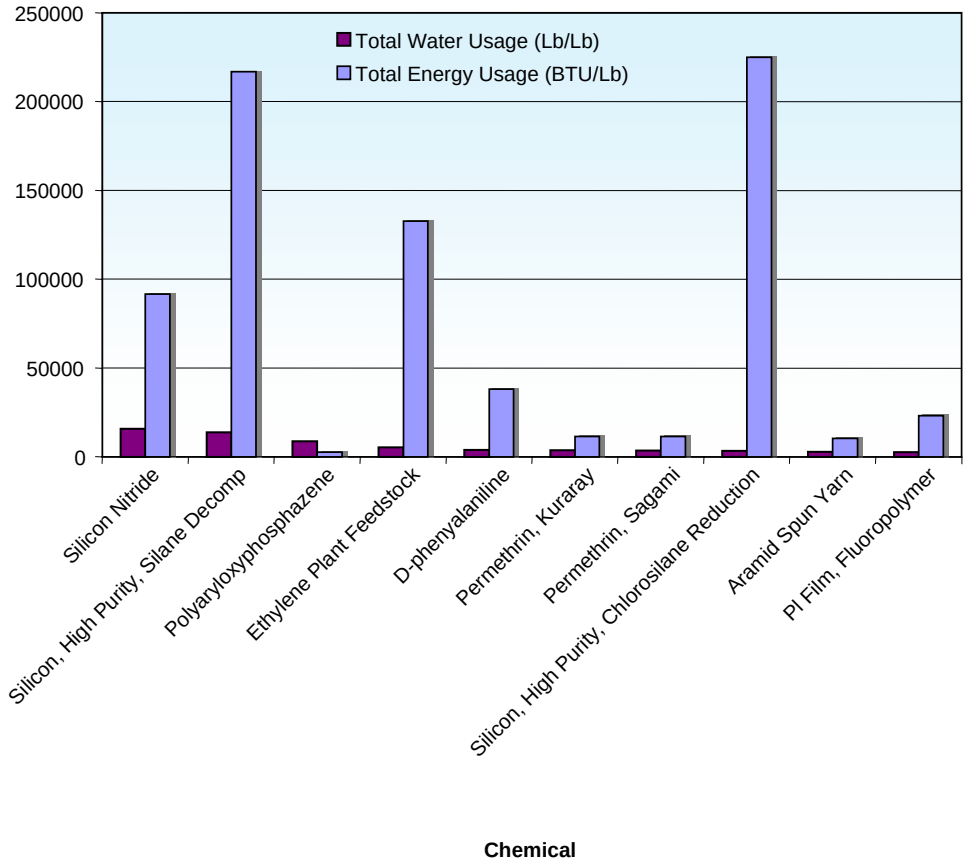

FIGURE 4.1-4
Energy Usage of Highest Per Pound Water Users

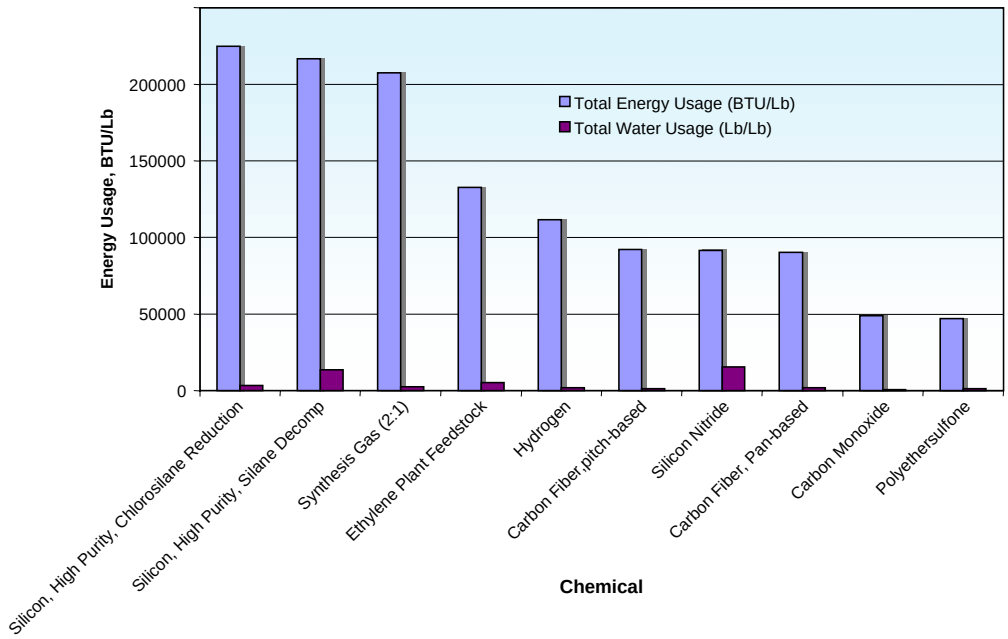

FIGURE 4.1-5
Highest Per Pound Energy Users

4.1.5 Water Reuse Practices and Challenges in the Chemical Industry

Like water use, water reuse has not been widely documented in the chemical industry. The majority of known cases involve the tertiary treatment of wastewater, e.g., contact water. For example, industrial facilities that already operate a wastewater treatment plant might select to add unit processes such as carbon adsorption, sand filtration, ion exchange, and/or membrane processes to facilitate return of the treated wastewater to upstream processes. A number of plants are leading the industry by exploring increasingly popular zero water discharge options. Recent attention to the water limitations listed in the Introduction of this chapter make water reuse far more attractive than it was only a few years ago. Chemical industry contacts are more commonly naming water needs as among their greatest environmental challenges. Therefore, the trend of process water reuse is expected to continue to increase in popularity.

However, it is clear from the design data presented in this chapter that the highest potential for water conservation lies in the reduction of cooling water usage. A number of the water intensive processes are also energy intensive and vise versa. Given the unquantified energy losses associated with cooling water, it is likely that water use reduction may be coupled with a reduction in energy use.

To further define the challenges of water reuse and conservation, the following are recommended for individual chemical processes:

- **Institute a rigorous system of water use measurement**. Although the instrumentation need not be sophisticated, it should be reliable, and all significant water uses should be measured and recorded.
- **Quantify the energy losses from the use of cooling water.** Given the increasingly short supply of water, it could be that for some processes cooling is no longer best accomplished using water. A comprehensive evaluation of energy usage should be performed.
- **Reduce the practice of once-through cooling water.** Cooling towers should be utilized wherever possible to decrease energy consumption and reuse as much cooling water as possible.
- **Educate employees and the public on the importance of water conservation.** Employees generally respond to issues on which they're well informed and on which management attention is focused, as indicated by training and other emphases.
- **Eliminate leaks and other inefficiencies.** Although a number of facilities have implemented housekeeping and/or water conservation programs, leaks in sewer systems and other piping continue to waste water.
- **Identify water reuse opportunities that also reduce energy consumption.** The chemical industry has often failed to explore water reuse because of its extensive infrastructure investments. As water and energy costs escalate, the drivers for water reuse increase, and the opportunities for associated energy reductions are numerous.
- **Continue research and development efforts focused at low energy, low water processes.** Several chemical companies report impressive advances in processes that were previously thought impractical. Technology is likely to be integral in realizing even greater gains in the challenge of water and energy minimization.

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