ENERGY MANAGEMENT

1. Introduction

The chemical industry is inherently energy intensive, and in the U.S. energy costs for the industry are equivalent to ~5% of the value of shipments, although this percentage is typically higher for bulk chemicals. Effective energy management is therefore an important factor in ensuring profitability.

Energy management has many dimensions. Its overall goal is to provide, at minimum cost, the heat and power needed to operate a chemical facility. However, in pursuing that goal the energy manager needs to understand the basic physics and chemistry, as well as the commercial aspects, of providing energy. Reliability, environmental impacts, and selection of utility systems and process equipment are also important issues. Finally, energy management often includes organizing and implementing energy efficiency programs, which are usually focused on improving the operation of existing facilities.

These different dimensions are reflected in the sections that follow in this article. The section Energy and the Chemical Industry provides an overview of energy use in the industry, including fuels and power, and environmental issues. In the section Energy Technology, we look at energy technology, which focuses on the thermodynamic basis for energy management, as well as discussing the basic systems and equipment items used to deliver heat and power in chemical facilities. The section Design of Utility Systems deals with utility systems, of which the most prominent are steam and electric power. Other utility systems (including cooling water, compressed air, and refrigeration) are also covered. The section Key Process Equipment Items looks at the types of process equipment that consume the largest amounts of energy, with an emphasis on ways of improving their efficiency. Finally, in the section Energy Efficiency Programs and Activities we explore different approaches that are currently being taken in energy efficiency programs across the industry.

2. Energy and the Chemical Industry

The chemical industry uses energy to supply heat and power for plant operations. In addition, hydrocarbons are used as a raw material for the production of petrochemicals, plastics, and synthetic fibers, and these are customarily reported in energy-equivalent terms.

The U.S. chemical industry is the second largest consumer of energy in manufacturing after petroleum refining. In 1998 (the most recent year for which data is available at the time of writing), the U.S. chemical sector consumed ~6.4 EJ [6.1 quads (quadrillion Btu, or 10^{15} Btu)] of energy (1). This represents ~6% of domestic energy use and ~25% of all U.S. manufacturing energy use. Energy purchases cost the industry ~$22 billion in 1998, or roughly 5% of the value of shipments that year. Table 1 shows the energy consumption of the U.S. chemical industry from 1985 to 1998.

Excluding hydrocarbon feedstocks, most of the energy use in chemical processing falls into one of two categories:

- Thermal energy (heating and cooling), which is used primarily to drive reaction and separation processes.
- Mechanical energy (often derived from electrical power), which is used primarily to move materials, most commonly using pumps and compressors.

Some processes have very specialized uses for energy, such as electrolysis in chloralkali production.

Table 1. **United States Chemical Industry Total Energy Consumption**[a]

Year	Energy consumption, No Feedstocks[d,e]	Feedstocks	Energy consumption, EJ [b,c], Total energy consumption
1985	2.33	1.43	3.75
1988	2.82	1.77	4.59
1991	2.83	2.48	5.32
1994	3.02	2.59	5.61
1998	3.46	2.92	6.38

[a]Ref. 1.
[b]The primary component is energy used for heat and power.
[c]Years prior to 1994 do not include adjustments for energy shipped off-site.
[d]$1\ \mathrm{EJ} = 1 \times 10^{18}$ J.
[e]To convert Joules to Btu, multiply by 0.95×10^{-3}.

Within the industry there are also significant uses of energy that are common to all commercial and industrial sectors, such as lighting and heating, and ventilation and air conditioning for buildings. However, in this article our main focus is on energy uses that are specific to the chemical and allied industries, rather than these generic uses.

Most energy is supplied to processing facilities either as imported fuel or electricity. Steam is often used as a medium for transporting energy, and in many cases steam turbines or gas turbines drive individual pumps or compressors, rather than using electricity. Electric power is also often generated within the chemical plant or by a third-party cogenerating facility, to reduce dependence on imported electric power.

2.1. By-Product Energy. In a number of commercially important chemical processes, by-product energy from feedstock oxidation dominates purchased fuel and electricity. A classic example is the manufacture of nitric acid (qv), HNO_3. Ammonia (qv), NH_3, is burned in air on a catalyst. Typical operating conditions are ~1 MPa (10 atm) and >900°C (2). The simplified diagram in Figure 1 shows that the process is built around the heat and power recovery from this reaction, including the integration of the power recovery turbine and the air compressor. Another example is the reaction of propylene (qv), C_3H_6, and ammonia to make acrylonitrile (qv), C_3H_3N. Here, two-thirds of the hydrogen is combusted just to satisfy stoichiometry. In addition, CO and CO_2 formation consumes ~15% of the feed propylene.

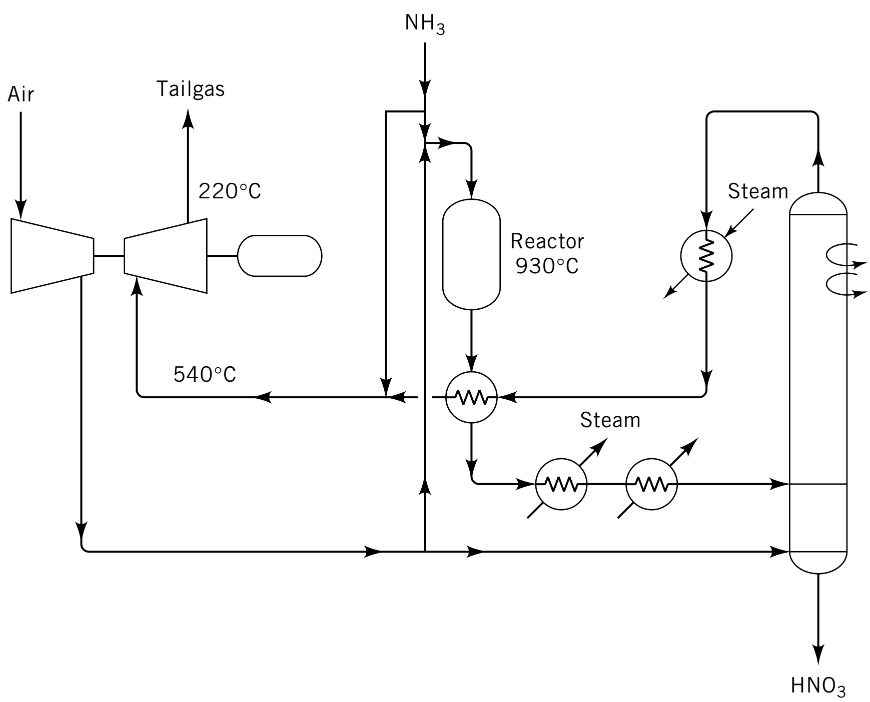

Fig. 1. Schematic of nitric acid from ammonia showing integration of reactor heat recovery, power recovery from tailgas, and air compression (2).

Table 2. **United States Chemical Industry Energy Consumption by Fuel Type—1998**[a]

Energy source	Consumption, EJ[b,c]
natural gas	2.85
LPG & NGL	1.89
electricity losses[d]	1.26
net electricity	0.61
coal	0.32
fuel oil	0.11
other	0.72
total	*7.76*

[a]Ref. 1.
[b]$1\ \mathrm{EJ} = 1 \times 10^{18}$ J.
[c]To convert Joules to Btu, multiply by 0.95×10^{-3}.
[d]Losses incurred during transmission, distribution and generation of electricity (conversion factor used: 10,500 Btu/kWh).

2.2. Fuels. Table 2 shows the variety of fuel sources used by the US chemical industry (1). Based on 1998 data, the industry is the largest single consumer of natural gas (>26% of the domestic manufacturing total) and uses virtually all the liquefied petroleum gas (LPG) consumed in U.S. manufacturing. Nearly all LPG and about one-fourth of natural gas are used as feedstocks. Other energy sources include by-products produced onsite (eg, off-gases from the acrylonitrile process discussed in the section By-Product Energy), hot water, and purchased steam.

2.3. Electricity. Electricity, including the losses associated with production, represents 24% of the total energy used by the chemical industry (Table 2). Increases in electrical costs have provided the driving force for increased cogeneration, ie, the recovery of power as a by-product of other process plant operations. In 1998, cogeneration in the U.S. chemical industry amounted to nearly 43.5 million kWh (3). The historic cogeneration example is the steam turbine associated with the boiler plant. The relatively high cost of electricity has also led designers to focus on the efficiency of rotating equipment, and has motivated a closer look at how processes can be controlled to reduce power, using such innovations as variable frequency motor drives.

2.4. Energy Efficiency Improvements. Fuel and power energy consumption per unit of output in the U.S. chemical industry declined by >39% between 1974 and 1995. Two major forces are largely responsible for these improvements: technological progress and cost optimization. Technological progress is a long-term trend that yields improved designs (eg, more efficient designs for distillation and new catalysts) that reduce the inherent demand for energy in chemical processes. Cost optimization is a short-term trend that responds to price swings: the tradeoff of increased capital and maintenance costs for reduced energy use.

The greater part of the improvement between 1974 and 1995 was the result of cost optimization: aggressive energy management and housekeeping programs instituted after the 1973 oil crisis. The increased adoption of energy-efficient practices like cogeneration, waste-heat recovery and heat integration have also helped to reduce overall energy intensity (1).

Whereas energy conservation is an important component of cost reduction for the chemical industry, conservation is rarely the only driving force for technological change. Much of the increased energy efficiency comes as a by-product of changes made for other reasons such as higher quality, increased product yield, lower pollution, increased safety, and lower capital. For example, process heat integration in design saves energy as well as capital; substitution of variable speed drives on motors for control valves saves energy while also improving control; and the use of gas turbines in cogeneration saves energy as well as capital in the supply of power. One of the roles of energy management is to be sure energy use reduction is considered whenever processes are changed.

The refinement of processes, such as the improvements in the production of low density polyethylene that lowered operating pressures from >100 MPa (1000 atm) to ~ 2 MPa (20 atm), is likely to continue, albeit at a slower pace than in the past. The introduction of biotechnology-derived processes is expected to cause a shift to lower temperature and lower pressure processing in the chemical industry, but up to the time of this writing the impact on energy use in the industry has been small.

2.5. Energy and the Environment. The impact of energy usage on gaseous emissions is an important environmental issue, and regulatory action has required emission reductions in NO_x and SO_2 (see Air pollution; Air pollution control methods; Exhaust control, industrial). The best way to reduce NO_x emissions is by improving energy efficiency and thus eliminating the need to fire fuel [eg, by heat integration (4)]. Where the fired heating cannot be eliminated, generation of NO_x can be reduced by lowering the temperature of combustion and limiting excess oxygen. Technologies such as low NO_x burners (and now "Ultra-low NO_x" burners) and flue gas recirculation are typically used. Alternatively, NO_x emissions can be reduced after the combustion process using either selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR). These processes use a reducing agent (typically ammonia) to eliminate the NO_x.

As in the case of NO_x emissions, the most desirable way to reduce SO_2 emissions is by eliminating the need to fire fuel. Where this is not possible, SO_2 can be controlled either by changing to a low sulfur fuel or by flue gas scrubbing. The need to minimize SO_2 emissions partly explains the predominance of low sulfur natural gas as the preferred fuel of the chemical industry.

Industry around the world has been placed under pressure to reduce greenhouse gas emissions (most notably CO_2) by proposed global agreements such as the Kyoto Accord (5) of 1997, which calls on nations to reduce their overall emissions of greenhouse gases to at least 5% below 1990 levels in the commitment period 2008–2012. Regulations at the national, state, and local levels also require industry to reduce emissions. Energy conservation directly reduces hydrocarbon combustion, and therefore has an important role to play in reducing CO_2 emissions (6). The elimination of fugitive hydrocarbon emissions as a result of improved maintenance procedures is also a tangible step that the industry is taking to minimize greenhouse gases.

3. Energy Technology

Energy management requires the merging of such technologies as thermodynamics, process synthesis, heat transfer, combustion chemistry, and mechanical engineering (see also COMBUSTION SCIENCE AND TECHNOLOGY; HEAT PIPES; THERMODYNAMICS).

3.1. Thermodynamics. The first law of thermodynamics, which states that energy can neither be created nor destroyed, dictates that the total energy entering an industrial plant equals the total of all of the energy that exits. Feedstock, fuel, and electricity count equally, and a plant should always be able to close its energy balance to within 10%. If the energy balance does not close, there probably is a big opportunity for saving.

The second law of thermodynamics focuses on the quality, or value, of energy. The measure of quality is the fraction of a given quantity of energy that can be converted to work. What is valued is the ability to do work. Electricity, eg, can be totally converted to work, whereas only a small fraction of the heat rejected to a cooling tower can make this transition. As a result, electricity is a much more valuable and more costly commodity.

The Carnot cycle is the most efficient heat engine cycle. This operates reversibly between an isothermal heat source at absolute temperature T_{h} and an isothermal heat sink at absolute temperature T_{c}. The fraction of the heat entering the Carnot cycle that can be converted to work is defined by the efficiency, $e_{\mathrm{th}} = 1 - T_{\mathrm{c}}/T_{\mathrm{h}}$. This sets an upper bound on the amount of work that can be obtained from a given amount of heat available in any heat engine cycle that operates between any two given temperatures.

Unlike the conservation guaranteed by the first law, the second law states that every operation involves some loss of work potential, or exergy. The second law is a very powerful tool for process analysis, because this law tells what is theoretically possible, and pinpoints the quantitative loss in work potential at different points in a process.

Typically, the biggest lost that occurs in chemical processes is in the combustion step (7). One-third of the work potential of natural gas is lost when it is burned with unpreheated air. Figure 2 shows a conventional and a second-law heat balance. The conventional analysis only points to recovery of heat from the stack as an energy improvement. Second-law analysis shows that other losses are much greater.

The second law can also suggest appropriate corrective action. For example, in combustion, preheating the air or firing at high pressure in a gas turbine, as is sometimes done for an ethylene (qv) cracking furnace (8), improves energy efficiency by reducing the lost work of combustion (Fig. 3).

There has been a historic bias in the chemical industry to think of energy use in terms of fuel and steam (qv) systems. However, when we look at work potential, as illustrated above, we gain a more fundamental understanding of the factors that affect energy efficiency and cost.

Waste heat tends to be very visible. It can be seen directly in steam plumes and is easily measured by determining the temperature of the discharges. The loss of work potential or excess use of work is much harder to spot, but often

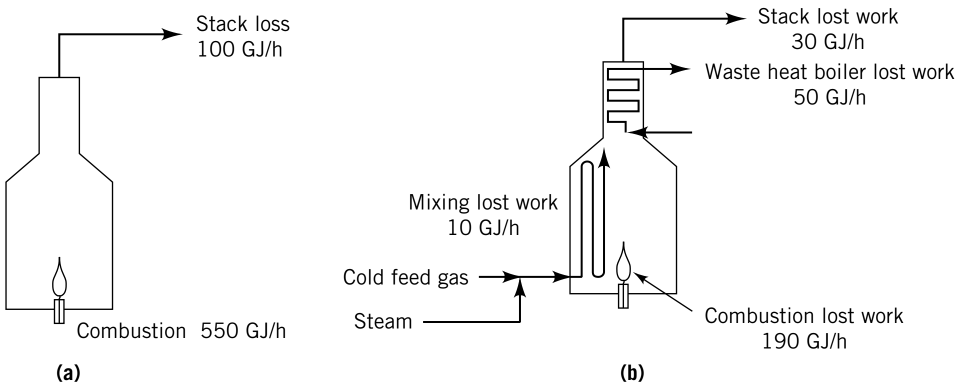

Fig. 2. (**a**) A conventional heat balance, and (**b**) a balance employing the second law of thermodynamics. To convert J/h to Btu/h, multiply by 0.95×10^{-3}.

is larger and more easily corrected. Examples of lost work potential include small inefficient turbines, oversized pumps, rewound motors having efficiency far below design, higher than optimum temperature differences that lead to below optimum power recovery, organics discharged in wastewater, and pressure drops taken across control valves.

3.2. Steam Systems and Power Recovery. *Cogeneration in a Steam System.* Steam is the most common medium for distributing energy within

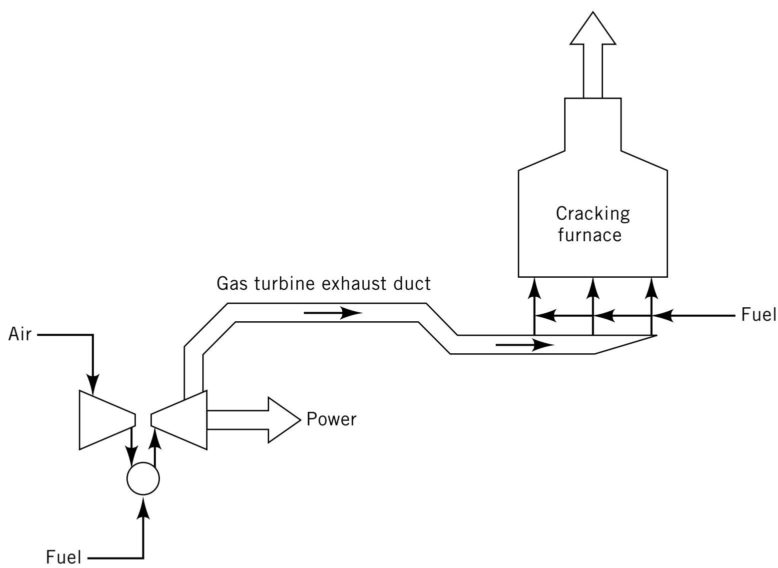

Fig. 3. Use of gas turbine air preheat for ethylene cracking furnace. The gas turbine exhaust duct contains 17% oxygen at 400°C.

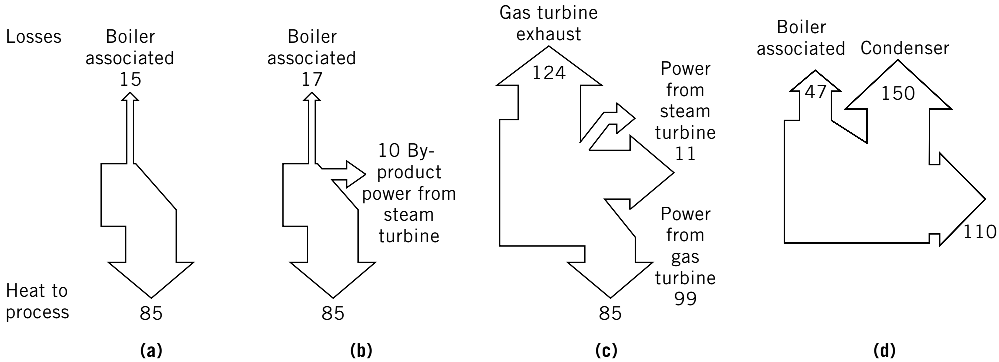

Fig. 4. Relative energy flows showing power generation and heat losses in GJ/h for (**a**), boiler only; (**b**), boiler + steam turbine; (**c**) combined cycle employing gas turbine; and (**d**), condensing steam for power only. To convert J/h to Btu/h, multiply by 0.95×10^{-3}.

chemical complexes. The value of energy in a process stream can always be estimated from the theoretical work potential defined by the Carnot cycle efficiency. However, in a steam system a more tangible approach is possible, because steam at high pressure can be let down through a turbine for power. The shaft work developed by the turbine is sometimes referred to as by-product power, and the process is referred to as cogeneration.

Four different types of steam system are illustrated in Figure 4**a–d**. Figure 4**a** shows a typical distribution of heat to process and to waste from a stand-alone boiler. Figure 4**b–d** illustrate the corresponding energy distributions with three different types of systems that include power generation. Key parameters for the different systems are given in Table 3. Figure 5 shows principal equipment components.

By-product power from a steam turbine typically takes only 40% as much incremental energy to produce as on-purpose firing for power only. A comparison of Figure 4**a**, **b** and **d**, together with the data in Table 3, illustrate this point: The incremental energy to generate 10 GJ/h of by-product power in a steam turbine is 12 GJ/h (compare Fig. 4**a** and **b**); whereas the energy needed to generate 110 GJ/h in a power only system is 307 GJ/h (Fig. 4**d**).

If a back-pressure steam turbine can be directly coupled to a power consumer such as a compressor, we eliminate the need for a generator to convert mechanical power to electricity and a motor to convert electricity back to mechanical power, as well as associated power lines and transformers. This

Table 3. **Key Parameters for Typical Steam Systems in Figures 4 and 5**

Parameter	(a)	(b)	(c)	(d)
fuel	100	112	319	307
incremental fuel	0	12	219	307
power	0	10	110	110
power/incremental fuel		0.85	0.5	0.36
power/heat to process	0	0.12	1.29	

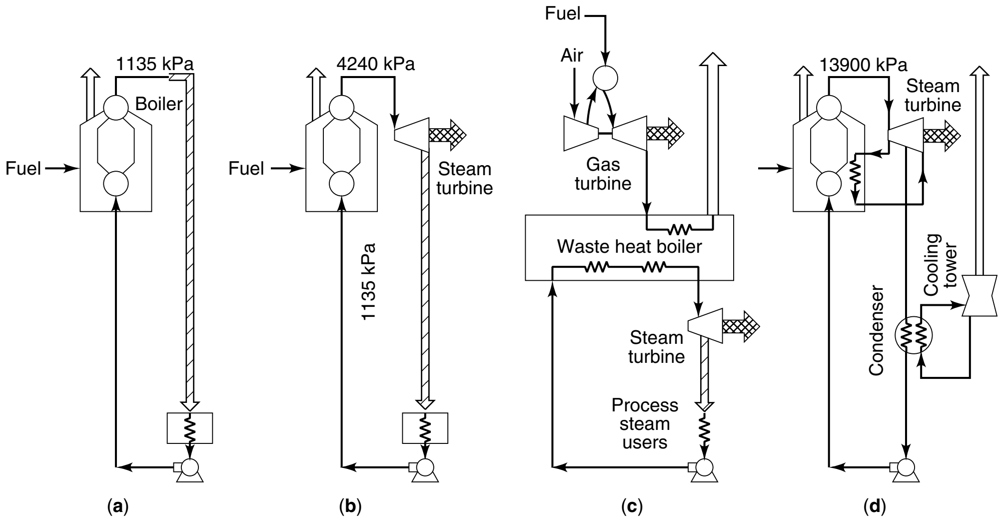

Fig. 5. Schematics showing the principal equipment components for the energy systems shown in Figure 4. ((**a**)–(**d**) correspond to Figure 4**a**–4**d**, respectively. To convert kPa to psi, multiply by 0.145).

eliminates many of the capital costs and power losses associates with energy conversion and transmission, so in these situations by-product power is particularly advantageous compared to power purchased as electricity.

However, the scope for generating by-product power is limited by the demand for process heating, and for large process operations the demand for power is usually far greater than the simple steam cycle can produce. Many steam system design decisions fall back to the question of how to raise the ratio of by-product power to process heat. One simple approach, which allows a modest increase in power generation, is to limit the turbines that are used to extract power to large sizes, where high efficiency can be obtained.

Another way to raise the power/heat ratio is by raising the pressure of the steam system. An increase in pressure from 4.2 to 10.1 MPa (600 to 1500 psi) almost doubles the power associated with a given steam load. (Power/heat ratio increases from 0.12 to 0.20.) This, however, comes at appreciable capital cost for alloy materials of construction in the boiler, piping, and turbines. It also requires a substantially higher cost treatment system for the boiler feedwater, and mandates a relatively high recovery factor for condensate. However, in general we can lower the specific capital cost ($/kWe) by raising the steam pressure.

The back-pressure steam turbine cycle is the most energy efficient use of the fuel providing the power is matched to the steam demand. However, by-product power does not give enough power to match the demand for many processes such as ammonia synthesis, and designs have historically incorporated condensing turbines for incremental power with heat rejection to cooling water. A more effective response is use of the gas turbine combined cycle shown by Figure 4**c** and 5**c**.

Gas Turbines and the Combined Cycle. The combined cycle first fires fuel into a gas turbine and greatly increases the power extracted per unit of steam produced (9). As the numbers in Figure 4 and Table 3 show, the simple steam turbine gives by-product power at the lowest incremental energy use. The combined cycle shown in Figure 4**c** is intermediate between Figure 4**b** and **d** in incremental energy per unit of power. Systems of this type have allowed many petrochemical plants to become exporters of cogenerated power to utilities.

The big advantage of the gas turbine in cogeneration is that it permits a much higher ratio of power to heat-to-process. This ratio, which is routinely >0.8, gets bigger as the unit size of the turbine increases. The gas turbine also has advantages that are firmly rooted in thermodynamics. It utilizes energy directly at a high temperature level, without large driving forces for pressure drop and temperature difference.

The ratio of power output to heat input is larger for aero-derivative systems, which are basically jet engines exhausting into power recovery turbines. Because the original design assumed only a gas cycle, ie, no waste heat boiler, the aero-derivative was designed for a higher compression ratio, resulting in a cooler (500°C) gas turbine exhaust. Cooler exhaust means less heat to surrender, and hence a higher power/heat ratio. The most efficient gas turbines convert 40% of input fuel energy to power. The heavy-duty machines of comparable vintage run discharge temperatures ~100°C higher. The aero-derivatives are also lighter in weight, giving a second advantage for a process operation because the light weight permits very fast plug-out/plug-in maintenance using spare rotating assemblies. Standardized equipment and prepackaged skid mounted components provide additional advantages for these systems.

In contrast, the heavy-duty gas turbines, designed with capital cost per kilowatt and combined cycle efficiency as key criteria, cost less for the same power output and come in much larger sizes than the aero-derivatives. This means that very large (>100 MW) installations invariably use the heavy-duty type. Heavy-duty turbines have benefited from such technology developments of the aero-derivatives as increased firing temperatures permitted by use of high temperature alloys (qv) and internal cooling of the blading. These developments have been a factor in continuing increased efficiency and increased output from a given frame size.

Gas turbine cogeneration is typically higher cost in capital for power delivered ($/kWe) than steam turbine systems, but has inherently low comparative costs for heat delivered ($/kWth). Rising natural gas prices have driven the need for higher efficiencies in both power generation and heat recovery from gas turbine exhausts.

Most gas turbine applications in the chemical industry are tied to the steam cycle, but gas turbines can be integrated anywhere in the process where there is a large requirement for fired fuel. An example is the use of the heat innthe gas turbine exhaust as preheated air for ethylene cracking furnaces (8) as shown in Figure 3.

The combined cycle is also applicable to dedicated power production. When the steam from the waste heat boiler is fed to a condensing turbine, overall conversion efficiencies of fuel to electricity in excess of 50% can be achieved. This cycle is becoming increasingly popular with utilities and independent power producers (IPPs) for power generation throughout the world due to significant benefits of fast build times (resulting from the use of standard power plant modules), high thermal efficiency and environmental performance.

Power Recovery in Other Systems. Steam turbines offer by far the largest opportunity for power recovery from pressure letdown in chemical plants. However, there are opportunities to recover power using expanders on various process vapor streams, such as tailgas in nitric acid plants (Fig. 1) and on catalytic crackers.

It is also sometimes possible to recover power in liquid systems. One example is the letdown of the high pressure rich absorbent used for H_2S/CO_2 removal in NH_3 plants. Letdown can occur in a turbine directly coupled to the pump used to boost the lean absorbent back to the absorber pressure. Similar systems are also used on high pressure hydrocarbon streams, eg, hydrocracker liquids from a high pressure separator.

3.3. Energy Balances and Heat Recovery. *Energy Balances.* An energy balance is a summary of all of the energy sources and all of the energy sinks for a unit operation, a process unit, or an entire manufacturing plant. As an example, Table 4 gives an energy balance for a simple propane-fired product dryer.

The energy balance is the basic tool for analyzing an operation for energy conservation opportunities such as operational changes, system reconfiguration, and equipment alterations. Development of an energy balance is therefore

Table 4. **Product Dryer Analysis Heat Balance**

Material	Mass, kg/h	Energy, MJ/h[a]
	Inputs	
fuel, C_3H_8	130	6,553
air		
combustion	6,817	106
secondary	14,846	232
in-leakage	4,289	67
water with product	1,731	354
dry product solids	4,478	249
Totals in	*32,291*	*7,561*
	Outputs	
water vapor		
from product	1,445	3,808
from combustion of H_2	212	560
air and combustion products	25,870	1,933
dry product solids	4,478	458
water with product out	286	146
heat losses		656
Totals out	*32,291*	
7,561		

[a]To convert J/h to Btu/h, multiply by 0.95×10^{-3}.

an essential step in any meaningful energy efficiency program. Ideally, energy balances should be generated using process simulation software. However, in many cases it is cheaper and quicker (though generally less accurate) to develop energy balances directly from process operating data and design data.

Heat Recovery. The goal of heat recovery is to ensure that energy does the maximum useful work as it cascades to ambient. Wherever process streams require heating and cooling there is the potential to recover the heat that is rejected by streams that are being cooled in other streams that require heating. In this way we minimize the need for external heating and cooling.

There are several standard forms of heat recovery that are common in chemical plants (eg, waste heat boilers and product-to-feed heat interchangers), and these are discussed below. However, the optimum form for a heat recovery system is not always obvious. In such cases pinch analysis (see THE SECTION IDENTIFYING ECONOMIC INVESTMENT OPPORTUNITIES) is now established as the most appropriate way to develop suitable heat exchanger networks.

Waste-Heat Boilers. In most chemical process plants, the steam system is the integrating energy system. Recovering waste heat by generating steam makes the heat usable in any part of the plant served by the steam system. Many waste-heat recovery boilers are unique and adapted to fit a particular process. There is a long history of process waste-heat boiler failure resulting from inadequate attention to detail in design and failure to maintain water quality (10). The high heat-transfer coefficients of boiling water are dependent on clean surfaces. Designers should match the hardware as closely as possible to demonstrated designs, and operators should ensure that water treatment is monitored.

Incinerators (qv) and gas turbines are also often coupled with heat recovery boilers. Here, a number of fairly standard designs have evolved (11).

Product-to-Feed Heat Interchange. Heat exchange is commonly used to cool the product of a thermal process by preheating the feed to that process, thus providing a natural stabilizing, feed forward type of process integration. Product-to-feed interchange is common on reactors as well as distillation (qv) trains.

Combustion Air Preheat. Flue gas to air exchange, a type of product-to-feed heat exchange, is extremely important because of the large loss associated with the combustion of unpreheated air. This exchange process has generated fairly unique types of hardware such as the Ljungstrom or rotary wheel regenerator shown in Figure 6**a;** the brick checkerwork regenerators used in metallurgical furnaces, hot oil, or hot water belts (also called "liquid runarounds") (Fig. 6**b**); and heat pipes (Fig. 7). Liquid runaround systems make it practical to use finned surface on both gas exchange surfaces. These are particularly useful for retrofits because of the ability to move the heat to physically separated units.

The heat pipe exchanger is a variant on the liquid runaround system where each tube (pipe) is sealed on both ends and filled with a vaporizing–condensing heat-transfer medium. At the hot end of the pipe, liquid is vaporized and moves to the cold end. At the cold end, vapor condenses and returns to the heat intake end. The flows are driven by gravity and capillary wicking. The heat pipe is particularly useful because it permits very compact, side by side ducting arrangements with countercurrent flow, as shown in Figure 7 (see HEAT PIPES).

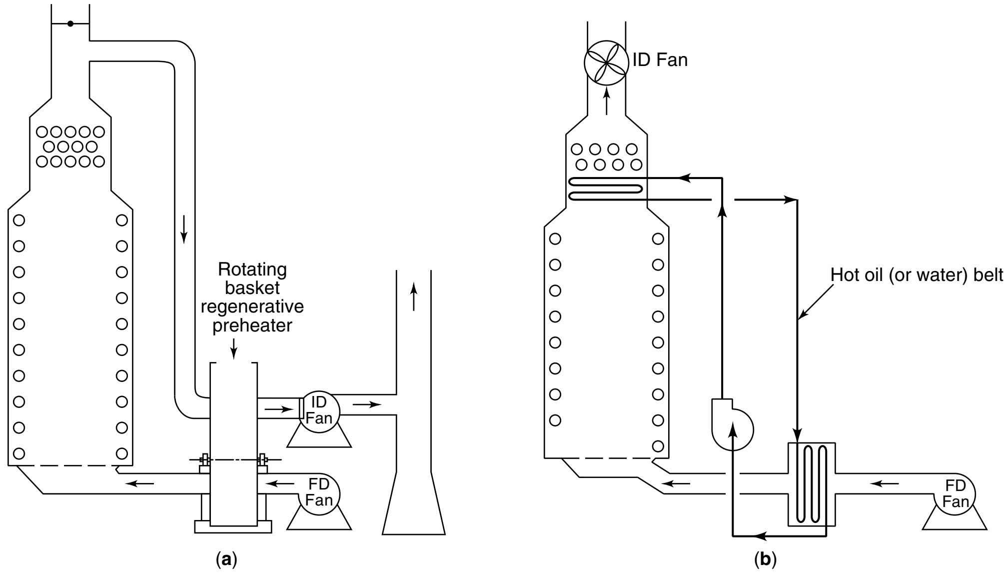

Fig. 6. Air preheaters where ID = induced draft and FD = forced draft fan. (**a**) Rotating metal basket or Ljungstrom regenerative preheater, and (**b**) hot oil or water belt (liquid runaround) used to move convection section heat to air preheater in furnace retrofit.

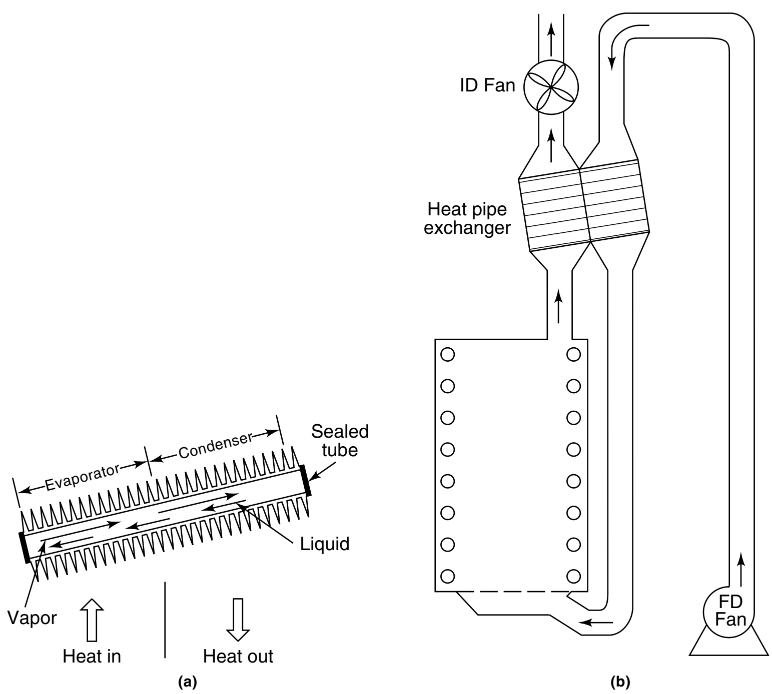

Fig. 7. (**a**) Heat pipe showing the use of finned tubing for both heating and cooling and (**b**) heat pipe exchanger air heater system, where ID = induced draft and FD = forced draft fan.

Boiler Economizers. Heat exchangers that use boiler flue gases to preheat the boiler feedwater are termed boiler economizers.

Heat Pumps. Heat pumps use a compressor to boost the temperature level of rejected heat, which can be accomplished in several different ways (eg, mechanical compression of a vapor or absorption cycles).

Heat pumps can be a very effective means of recovering heat and making it reusable, especially in small plants where there are few opportunities for conventional heat interchange. However, heat pumps are typically expensive, both in terms of capital cost and operating expense; and in large facilities a closer look usually shows simpler, more cost-effective, alternatives for recovering heat.

4. Design of Utility Systems

4.1. Steam. The steam system serves as the integrating energy system in most chemical process plants. Steam holds this unique position because it is an excellent heat-transfer medium over a wide range of temperatures. Water gives high heat-transfer coefficients whether in liquid phase, boiling, or in condensation. In addition, water is safe, nonpolluting, inexpensive and, if proper water treatment is maintained, noncorrosive to carbon steel.

Steam Balances. The steam balance is usually the most important plant-wide energy balance. A complete balance should show each service requirement, including the use of steam as a working fluid to develop power.

Steam balance data can be presented schematically or in tabular form. For both presentation types, a balance is made at each pressure level. In a schematic balance (sometimes called a “ladder diagram”), such as that shown in Figure 8, horizontal lines are drawn for each pressure. The equipment items that use the steam (eg, steam turbines, vacuum jets and reboilers) are shown between or below the horizontal lines, and individual flows are shown vertically. Table 5 contains the same data as shown in Figure 8. In both cases the steam balance has been simplified to show only mass flows. A separate balance should be developed that identifies energy flows, including heat losses and power extraction from the turbines. Computerized modeling methods are generally used to generate both the mass flow and energy balances. This subject is discussed in more detail, together with uses of steam balances in energy efficiency improvement programs, in the section Identifying Economic Investment Opportunities.

4.2. Steam Turbines. Historically, back-pressure steam turbines were used as drives throughout processes to increase reliability and cover electrical power failures. A typical turbine would be a single-stage 375-kW machine having throttle steam at 4240 kPa (600 psig) and exhaust at 1135 kPa (150 psig). The turbine would be controlled by a centrifugal fly-weight governor operating a single throttle valve. The efficiency would be $\sim$40% when operated at rated conditions; ie, for the amount of steam passing through the turbine, it would develop 40% of the power that could be developed by an ideal turbine, expanding the steam isentropically. The efficiency was substantially lower when the machine was operated at part load, because a large portion of the pressure drop at part load was lost across the throttling valve, producing no work.

Because of increased emphasis on maximizing cogenerated power, newer plants typically utilize back-pressure turbines only in applications where

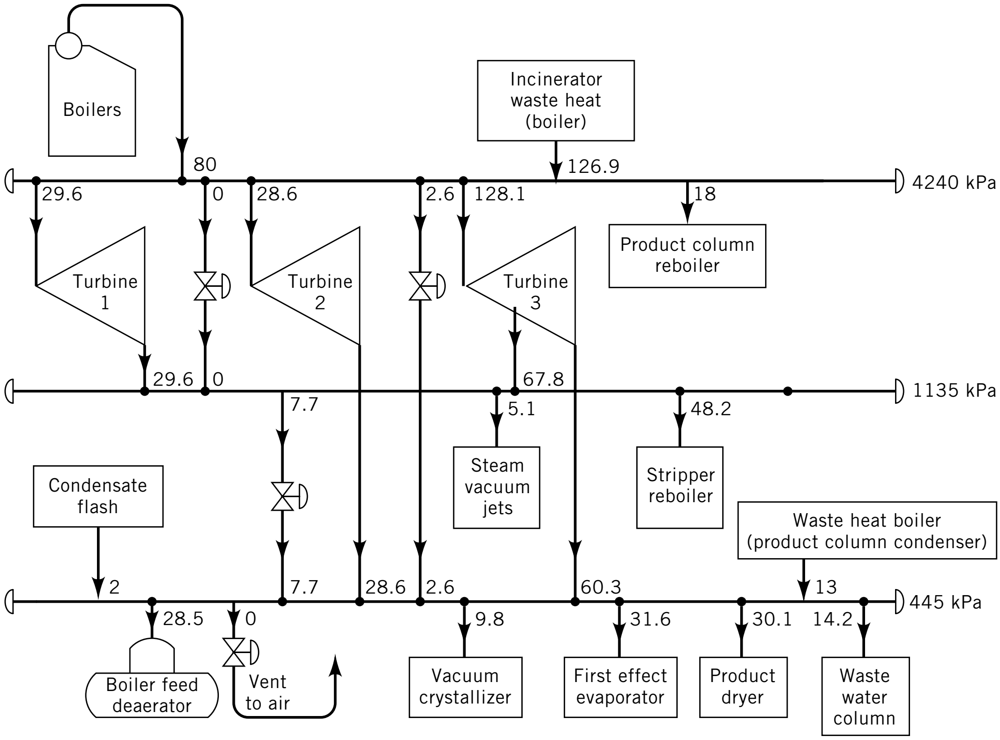

Fig. 8. Schematic steam balance where the numbers represent steam flows in metric tons per hour. See Table 5.

efficiencies >70% can be attained. This generally means limiting the applications to large (>1000 kW) drives, and using small machines only where they are necessary for the safe shutdown of the unit. Multistage turbines are used even on the smaller loads.

Many large plants also have some condensing turbines to handle process and seasonal swings and provide some flexibility to the steam balance. For large (>15,000 kW) applications, condensing turbines can sometimes compete with purchased electricity. For small applications, power can usually be provided at much lower cost by motors. Condensing turbines generally have high reliability, and are also used where the costs of electrical power failure, in process downtime, are high. Public utility plants usually have condensing turbines at the bottom of a power cycle as shown by Figure 5**d**.

Condensate Return Systems. Condensate recovery is important in the economics of steam systems. By recovering condensate we reduce the amount of fresh water that must be treated for make-up to the steam system, and so minimize the cost of water treatment facilities. In addition, most condensate is hot, and the heat also has value. Typically ~60% of the steam condensate produced in a chemical plant is recoverable, but this varies with the types of operation on the facility. Steam that mixes with process streams (eg, in stripping operations or ejectors), and low pressure steam that is likely to be contaminated when condensing against a higher pressure process stream in a reboiler, is typically not recovered.

Table 5. **Steam Balance, Flows in Metric Tons per Hour**[a]

	4240 kPa[b]		1335 kPa[b]		445 kPa[b]	
Equipment	Supply	Use	Supply	Use	Supply	Use
boilers	80.0					
incinerator waste heat	126.9					
turbine 1		29.6	29.6			
turbine 2		28.6			28.6	
turbine 3		128.1	67.8		60.3	
pressure reducing valve		0	0			
pressure reducing valve		2.6			2.6	
pressure reducing valve				7.7	7.7	
product column reboiler		18.0				
steam vacuum jets				5.1		
stripper reboiler				48.2		
finishing column reboiler				36.4		
condensate flash					2.0	
product column condenser						
waste-heat boiler					13.0	
vacuum crystallizer						9.8
1st effect evaporator						31.6
product dryer						30.1
wastewater column						14.2
boiler feed deaerator						28.5
Total	*206.9*	*206.9*	*97.4*	*97.4*	*114.2*	*114.2*

[a]See Figure 8.
[b]To convert kPa to psi, multiply by 0.145.

In a process plant, various condensate drainage devices can be used to recover and return condensate. These devices include steam traps, combination pump/traps, level pots and condensate pumps. Proper selection and installation of these products is required to ensure the system operates with maximum energy efficiency and operating productivity.

It is essential to account for the pressure profile of the condensate under various stages of load turndown. Equipment oversurfacing can lead to significant pressure drops and cause the condensate to "stall" (ie, equipment outlet steam pressure is less than condensate return back pressure, thereby stopping condensate flow). When stall is an issue, it is generally best to control by throttling the inlet steam rather than placing a control valve on the condensate, and using a combination pump/trap (eg, PowerTrap from TLV Corporation) to drain the condensate. This approach will generally provide improvements in control, operation, and energy performance (12).

Preheating Feed Water. Most steam systems use deaeration to keep noncondensables out of the steam. Usually, this uses low pressure steam to strip air out of the boiler feed water in a thermal deaerator. However, in many cases the water fed to the deaerator is cold, and large amounts of steam are consumed simply heating it to the deaerator's operating temperature. The steam demand can be greatly reduced by preheating the deaerator feed water with waste heat recovered either from process sources or boiler blowdown. In some cases it is also possible to use waste heat to preheat the boiler feed water downstream of the deaerator and thus save energy in the boilers.

4.3. Electrical. The electrical system consists of the utility company's entry substation, any in-plant generating equipment, primary distribution feeders, secondary substations and transformers, final distribution cables, and various items of switch-gear, protective relays, redundant systems, motor starters, motors, lighting control panels, and capacitors to adjust power factor.

By far the largest single opportunity for improving overall energy efficiency in the chemical industry is cogeneration (see THE SECTION STEAM SYSTEMS AND POWER RECOVERY). This expedient reduces the amount of power imported from the utility company, and in some cases turns the chemical plant into an electricity exporter. Deregulation of the power industry in the United States has made it easier for chemical companies to exploit this opportunity. Another important consideration is the rate structure for imported electricity (see THE SECTION BEST PRACTICES IN OPERATION AND MAINTENANCE).

There are also opportunities to reduce electricity costs associated with facilities improvements, such as the following.

Electric Motors. Except for electrolytic, eg, chlorine production (see CHLORINE; ELECTROCHEMICAL PROCESSING, INTRODUCTION) or electric furnace processes, eg, phosphorus, typically 95% of the electricity used in a chemical plant is for electric motor drives. Induction electric motors in general use in chemical process plants range in efficiency from 90 to 95% depending primarily on size. The larger motors are generally more efficient. For any size, a range of efficiencies is available and high efficiency motors are somewhat more expensive than standard ones as shown in Figure 9. This price increment is normally justified in chemical process plants because of the high number of annual operating hours (13). For heating and ventilating operations, the lower operating hours sometimes make lower efficiency units the cost-effective choice.

Variable Frequency Drives. An important energy by-product of solid-state electronics is the relatively low cost variable speed drive. These electronic devices adjust the frequency of current to control motor speed such that a pump can be controlled directly to deliver the right flow without the need for a control valve and its inherent pressure drop. Figure 10 shows that at rated load the variable speed drive uses only ~70% as much power as a standard throttle control valve system, and at half-load, it uses only ~25% as much power.

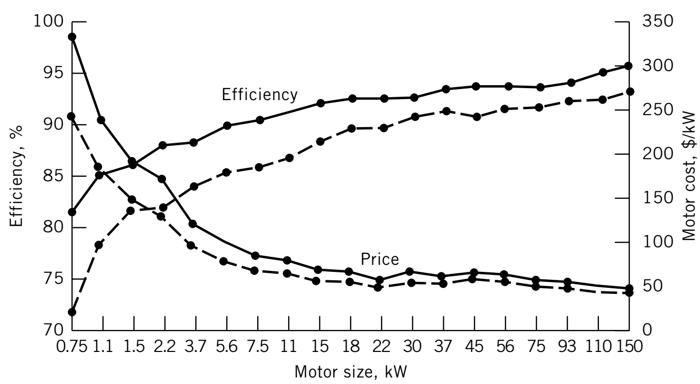

Fig. 9. Full-load efficiencies and wholesale prices (in 2003 U.S. dollars) of (– – –) standard and (—) energy efficient (EEM) three-phase motors (13, with costs updated).

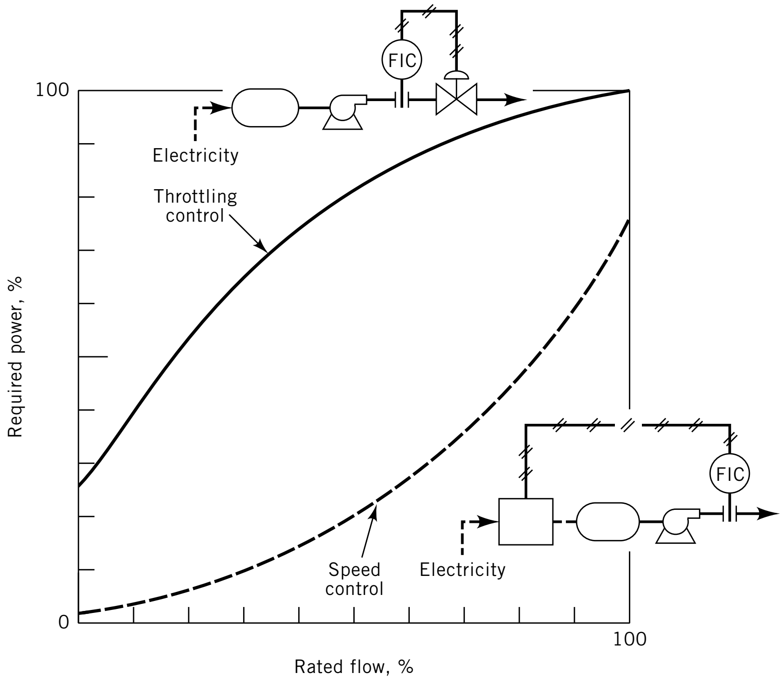

Fig. 10. Power saving for variable speed drives. Power input for variable speed adjusts with flow to naturally match the frictional losses. FIC = flow indicating controller.

In addition to energy conservation, variable speed drives offer better control because of a faster response, ie, reduced dead band. They are also sometimes chosen for safety reasons because of elimination of the control station and accompanying valving. The capital saved by use of a smaller motor and elimination of the control valve partially compensates for the cost of the drive.

4.4. Other Energy Systems. Chemical plants usually require cooling water, compressed air, and fuel distribution systems. Refrigeration, pressurized hot water, or specialized heat-transfer fluids such as Therminol liquid or condensing vapor are sometimes also needed. Each of these systems serves the process and reliability is the most important characteristic.

Cooling Water. The primary reliability concern is that water chemistry must be maintained in a low fouling, noncorroding regime. In addition, water flow velocity must be maintained above a certain threshold (~0.5 m/s in tube-side flow) to avoid fouling and corrosion.

The principal energy cost is pumping, which can be minimized by

1. Ensuring that the water flow does not greatly exceed the need.
2. Avoiding excessive pressure drop by increasing pipe diameters and eliminating unnecessary valves and fittings.

Care should be taken in design to ensure that the system is balanced, and all heat exchangers utilize available pressure drop with the design flow. Every user should have a thermowell in the cooling water outlet to monitor temperature rise, and enough flow and temperature measuring elements should be provided to check the overall heat balances (see TEMPERATURE MEASUREMENT).

Modern cooling towers are typically supplied with high-efficiency fills, which typically allow an approach of ~7 or 8°F to wet bulb temperature. The performance of older towers can generally be improved cost-effectively by upgrading to a high efficiency fill, with benefits both in reduced energy costs and improved plant throughput or product yield.

One other area in which cooling tower costs can be optimized is the air/water ratio, and the associated fan horsepower requirements. When the demands on a cooling tower are reduced, it may be cost-effective to reduce the size of the fan motor.

Compressed Air. A key question for compressed air systems is the discharge pressure. Dropping pressure from 790 kPa (100 psig) to 650 kPa (80 psig) reduces the required power 12%, and reduces the driving force for air leakage losses by 20%. Controls such as inlet guide vanes on the air compressor can be provided to trim pressure to the required level. Another action that lowers energy use is lowering inlet and interstage temperatures by adding coolers. A drop from 30 to 20°C typically reduces power by 3%.

Refrigeration. In processes such as olefin separations refrigeration is of great importance. Improvements in refrigeration systems can reduce energy costs, but in some cases they provide even greater benefits in enhanced product yields.

Refrigeration is an extremely costly utility because of the work required to raise heat to ambient temperature. Its cost goes up directly as the temperature gap between ambient and use level goes up. For example, refrigeration at −25°C typically costs approximately as much as heat at 250°C, but refrigeration at −75°C costs twice as much. Energy costs are cut if cooling water can be used directly or used for part of the year or for part of the load. An energy saving can also be realized if a higher refrigeration temperature can be used. If the refrigeration need is >5°C, and there is waste heat available >90°C, absorption or adsorption refrigeration systems may be viable.

Another option that can sometimes be used is a heat pump or mechanical vapor recompression arrangement (eg, taking overhead vapor from a low temperature distillation column, compressing it, and condensing the compressed vapors against the reboiler). This not only provides refrigeration, but also makes use of the heat rejected from the refrigeration system. It is used, eg, in propane/propylene separations.

The optimization of heat-transfer surfaces also plays a role in minimizing refrigeration costs. Additionally, condensation on insulation is a sign of questionable insulation (see INSULATION, THERMAL). Frost is a certain signal that insulation can be improved.

Condensing Organic Vapor. Many specialized organic heat-transfer fluids are now available from a number of vendors. Depending on the temperature range and the application, these may be used in either the vapor or liquid phase.

The eutectic mixture of biphenyl and diphenyl oxide is an excellent vapor medium for precise temperature control at temperatures higher than those practical using steam. This mixture can achieve 315°C while holding pressure at 304 kPa (3 atm) absolute. In contrast, steam would require 10.6-MPa (105 atm) pressure.

These systems, commercially known as Therminol VP-1 or Dowtherm A, differ from steam in some key areas which can result in operating problems unless handled properly in design (14). The low pressure–high temperature operation means that the $\Delta T/\Delta P$ ratio at saturation is quite high; eg, at 315°C the ratio is 25 times that of steam. This means that a pressure drop that would be nominal in a steam system [10 kPa (0.1 atm)] cannot be tolerated if precise temperature control is needed.

Another difference is that molecular weight is much higher than that of the common noncondensables, and hence the noncondensables are harder to purge. In contrast, in a steam system almost all noncondensables are heavier than steam and tend to flush out with the condensate.

5. Key Process Equipment Items

Virtually all chemical processing is energy driven, but in separations such as distillation, drying (qv), and evaporation (qv), this is particularly clear. All three of these processes are simple thermal operations that involve separation through vaporization, and only a minor change in the chemical energy of the products. Energy, this time in the form of mechanical work, is also central to compression and pumping—operations that physically move materials. Boilers and furnaces are the main unit operations for obtaining heat from fuel, and heat exchangers transfer heat between process streams, so they are also considered key process equipment items for energy management.

A major concern is to design and operate these equipment items, together with their ancillaries, at the highest possible energy efficiency. However, in almost all cases there is a balance between capital and energy costs, and typically one is traded against the other to achieve the lowest overall cost (15).

5.1. Distillation. The optimum reflux rate for a distillation column depends on the value of energy, but is generally between 1.05 and 1.25 times the minimum reflux rate that could be used with infinite trays. At this level, excess reflux is a secondary contributor to column inefficiency. However, when designing to this tolerance, correct vapor-liquid equilibrium data and adequate controls are essential.

The energy savings that can be achieved through improved control are surprisingly high, because advanced control schemes, based on process computers and on-line analyzers, permit a reduction in the margin of safety that the operators use to handle changes in feed conditions. One key element is the use of feed-forward capability, which automatically handles changes in feed flow and composition. Applications using dynamic matrix control (DMC) and real-time optimization (RTO) are now further improving distillation column performance. An important new dimension that these systems allow in some cases is quantification of the trade-off between energy use and product yield, which drives operations toward maximum overall profitability rather than simply minimum energy use.

The real work used in a distillation column varies with the temperature difference between the heating medium and the cooling medium. Part of this differential is the difference in boiling points between the overhead stream and the bottom stream. However, a larger portion often results from the temperature difference between process and utility in the reboiler and condenser. The optimum differential is generally under 20°C, and if refrigeration is used, the optimum can be as small as 3°C. A signal that an excessive temperature difference may exist is a condenser or reboiler having a shell diameter less than one-third the diameter of the column.

One way of reducing temperature differentials in many existing reboilers is by installing enhanced heat transfer tubing (eg, UOP's HIGH FLUX tubes). These can increase the overall heat transfer coefficient in a given shell by a factor of between 2 and 4. This may allow the use of a lower temperature heat source (eg, low pressure steam rather than medium pressure steam), with associated cost savings.

In conventional distillation columns all the utility heat enters through a reboiler at the bottom of the tower, and leaves through a condenser on the tower overheads. This means that all the utility heat must be supplied at a temperature higher than any process temperature in the tower, and all utility cooling must be at a temperature lower than any process temperature in the tower. It is sometimes attractive to introduce a side-reboiler part way up the tower, where the process temperature is lower than at the bottom of the tower. This allows us to use a lower temperature heating medium (eg, low pressure steam rather than high pressure steam) for part of the reboiler duty, especially when there is a large temperature differential across the tower. Similar, there are situations where heat can be removed from distillation towers in either side-condensers or pumparound circuits, allowing the use of higher temperature cooling media—sometimes even permitting steam generation from recovered heat.

An important factor that sets the temperature differential across a distillation column is the pressure drop in the column and its auxiliaries. One way to reduce this is by using special structured packings (see DISTILLATION), which give extremely low (10% of an equivalent column with trays) pressure drop. This energy benefit can show up in an overhead temperature high enough to permit generation of by-product steam. It can also show up in a variety of other ways including lower bottoms temperature, yielding less fouling and product degradation to by-products, as in the styrene–ethylbenzene separation.

One way to reduce energy use in distillation is by means of double-effect distillation, which uses the overhead vapor from one column as the heat source for another column such that the second column's reboiler becomes the first column's condenser. This reduces the energy requirement by roughly one-half, because external heat is supplied to only one of the units.

Several new complex column configurations are now also being developed to reduce energy use, notably several variants of the Petlyuk (dividing wall) design.

Each distillation column should be examined in context with the rest of the process as well as by itself. For example, we may be able to save energy by reducing process recycles via a purer overhead or bottoms stream. Lowering or raising column pressure to facilitate heat interchange with other parts of the process is another possible opportunity.

5.2. Drying. The typical dryer mass and energy balance shown earlier (Table 4) shows that the heat loss is 10% of the fuel input. Improving insulation is one of the simplest ways to reduce energy input. Another simple way to reduce energy input is improving the dewatering (qv) of the feed. There is a great difference in energy input for dewatering as compared to the subsequent drying step, as shown by Figure 11.

Some of the other energy conservation approaches applicable to dryers are heat interchange between the stack vapor and the incoming dryer air; recovering sensible heat from the product; use of waste heat from another operation for air preheat; and using less, but hotter drying air. This last is limited to non-heat-sensitive materials.

5.3. Evaporation. In most chemical industry evaporation systems, the objective is product recovery, although occasionally the objective is concentration of an organic waste from an aqueous solution, to facilitate disposal. Similar equipment is used extensively for desalination of salt or brackish water (see also WATER, SUPPLY AND DESALINATION).

A single-effect evaporator produces slightly less than a kilogram of water vapor per kilogram of steam. By using the vapor produced by the first-effect as the heat source for a second-effect evaporator, steam use can be essentially halved. The performance can be improved almost in proportion to the number of effects employed. Six- and seven-effect evaporators are common in the wood pulp (qv) industry for concentration of black liquor. However, as the number of effects goes up, the temperature driving force is spread over the additional units and the capital cost increases almost in direct proportion to the number of effects. As a consequence, high alloy systems are often limited to single- or double-effect.

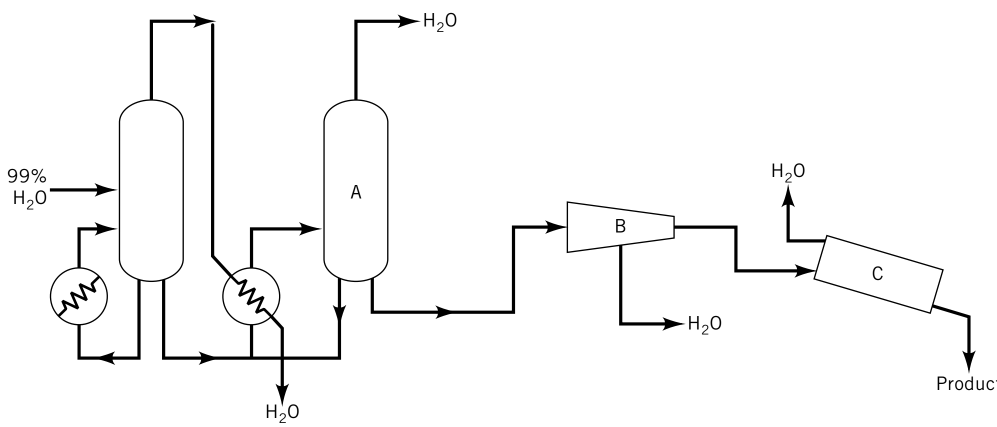

Fig. 11. The relative energy input for removal of 1 kg of water relative to heat of vaporization is 0.7 in A, the double-effect crystallizer; 0.015 in B, the dewatering centrifuge; and 5 in C, the rotary dryer.

In some cases reverse osmosis can be a viable alternative to process evaporation. It can be used in desalination applications, and is particularly attractive where the inlet stream is >99% water.

5.4. Compressors. Compression equipment accounts for a large fraction of power use as well as a large fraction of installed capital in many chemical plants. Usually, the energy bill for a compressor is large enough to warrant a very visible monitor of the driver, such as a control room electric meter. Testing programs to ensure operation of the compressor and its driver at peak energy efficiency are also justified. Temperature rise across a compressor is a simple and effective way to monitor efficiency.

Compressors are precision machines, and generally require more care in specification and maintenance than any other part of the process. The largest process compressors (for high flow, low head) are axial flow machines. Centrifugal machines can also handle large volumes and are used, eg, as the cracked gas compressors in ethylene plants. Centrifugal machines are a bit less efficient, but are more rugged and tolerant of fouling service. Smaller volume compressors are usually reciprocating or rotary designs.

Energy consumption is but one of the selection criteria. For example, a reciprocating compressor usually delivers 5–25% higher efficiency than a centrifugal machine, although its efficiency decays over time due to degradation of wearing parts. In the size range where a single unit compressor can handle the flow, the higher efficiency of the reciprocating machine usually pays for increased maintenance, but it rarely justifies the increased capital of parallel units in competition with a larger single-train centrifugal.

A compressor is typically a specially designed device, and comes with far less surplus capacity than other process components. As a result compressors merit great care in specification of flow, inlet pressure, and discharge pressure. Similarly, the control system and equipment need to be carefully matched to provide turndown with maximum efficiency. High speed motors, variable frequency drives (VFDs), and speed increasing gearbox designs are being utilized as an alternative to control valves to increase the efficiency of the centrifugal option. The American Petroleum Institute (API) recently added the integrally geared compressor to recognized API process gas compressors within the API 617 specification.

Because of the large volumetric flow inherent in gases, the cost of power for incremental pressure drop is high. To a first approximation, incremental power is proportional to the volumetric flow of suction or discharge, multiplied by incremental pressure drop. Pressure drop optimization for the associated piping and heat exchangers is therefore very important. Volumetric flow also varies with the absolute value of temperature, so it is important to keep temperatures down. Suction cooling is one way to do this. The drive for lower temperatures also provides the incentive for adding compression stages, with interstage cooling between stages.

5.5. Pumps. Energy use for pumps can best be controlled by design for the proper flow and discharge pressure. Constant speed electric motor driven pumps, having a large margin of safety on flow, are particularly wasteful. The fluid flow rate is inefficiently controlled in many centrifugal pumping systems by the use of throttling or bypass valves. For constant flow applications, the operating unit's impellers can be trimmed to reduce the flow rate and energy consumption. For variable flow applications, adding a variable speed drive to the system can often reduce energy costs substantially, while simultaneously improving process control and system reliability. A variable speed drive may not be appropriate for systems with high static head pressure, however, so a proper design analysis is recommended.

Several other opportunities often exist to improve pumping system performance. In new system design, frictional losses in the distribution system can be minimized by using proper distribution design techniques, especially near the pump intake and outlet. Unnecessary valves should be avoided, and larger diameter piping installed. Installing multiple parallel pumps allows units to be energized individually as necessary to match system demand.

In oversized existing systems, several optimization strategies are possible with minimal capital outlay. Options include installing a smaller pump casing and impeller, installing a slower or smaller motor, installing a premium efficiency motor, or adding a smaller pump to the system to operate during periods of reduced demand.

5.6. Vacuum Systems. Vacuum systems in chemical facilities are most often encountered in distillation, evaporation, drying and filtration applications. Steam ejectors are most commonly used to produce the vacuum. These achieve compression by fluid momentum transfer, and their great advantage is that they have no moving parts. However, they are also notoriously inefficient. Greater efficiencies and lower effluent volumes can be achieved with various types of mechanical vacuum pumps (eg, liquid ring pumps).

Due to the absence of reliable methods for estimating inert loading, many vacuum systems are overspecified. It is therefore often possible to achieve significant energy savings with little or no adverse impact on process operations by derating the vacuum system (eg, by shutting down surplus steam ejectors in a system that includes ejectors in parallel). This has the added benefit of reducing the amount of effluent that has to be treated.

5.7. Boilers and Process Furnaces. Boilers and process fired heaters are the entry point for the energy released from burning fuel. Fuel combustion is irreversible, and fired heaters are typically the principal loss point for work potential (7). The high irreversibility results from taking the chemical energy of fuel and degrading it to heat. Air preheat cuts energy losses by reducing fuel firing and increasing the flame burst temperature.

A more obvious energy loss is the heat to the stack flue gases. The sensible heat losses can be minimized by reduced total air flow, ie, low excess air operation. Lowering the discharge temperature via increased heat recovery in economizers or air preheaters also minimizes flue gas losses. When fuels containing sulfur are burned, the final exit flue gas temperature is usually not permitted to go below $\sim 150^{\circ}C$ because of severe problems relating to sulfuric acid corrosion. Special economizers having Teflon-coated tubes permit lower temperatures but are not commonly used.

Inadequate mixing of air and fuel can result in unburned combustibles in the flue gases. These result in energy losses, environmental problems, and damage from afterburning in the convection section. Heat leakage through refractories (qv) constitutes still another type of energy loss from combustion equipment. Because of the high temperature, the heat leakage is higher than on most equipment and can be as much as 3 or even 5% of fired fuel. On newer designs this value is typically between to 1.5 and 2.5%.

5.8. Heat Recovery Equipment. Factors that limit heat recovery applications are corrosion, fouling, safety, and cost of heat-exchange surface. Most heat interchange utilizes shell and tube-type units because of the rugged construction, ease of mechanical cleaning, and ease of fabrication in a variety of materials. However, there is a rich assortment of other heat exchangers. Examples found in chemical plants in special applications include the following:

- Plate heat exchangers are made by sandwiching thin sheets of metal that have a corrugated pattern pressed into them. The corrugations provide mechanical support where the sheets contact each other, permitting compact, low cost construction and generating high turbulence and high heat-transfer coefficients. These plates are normally separated by gaskets, and are particularly useful in food processing (qv), where cleaning is facilitated. However, the gaskets are the mechanical weak link. In order to overcome this welded plate exchangers are now available, extending the service range to 30 barg, 250°C and beyond.
- Brazed-fin aluminum cores are made of aluminum sheets having corrugated, cut layers sandwiched between flat sheets. The package is brazed together to form a very compact unit. The cut corrugated layers act as fins for both sides of the exchanger. The brazed aluminum construction needs to be protected from fire by special insulation or a coldbox filled with perlite. These units are used almost exclusively for very clean, cryogenic services such as air separation or hydrogen purification.
- In spiral plate construction, two plates are welded together and rolled into a jelly-roll shape. The prime advantage is that there is a single flow passage. Any plugging generates a high local pressure drop and tends to erode the deposit. Thus the unit is less subject to plugging than in the other constructions having parallel flow paths.

An important approach that has gained acceptance for improving the cost-effectiveness of energy efficiency revamps is the addition of proprietary heat transfer enhancing technologies in shell and tube heat exchangers. In these applications an existing shell is kept in place, but the internals are either modified or replaced to increase effective area or increase heat transfer coefficient, or both. Examples include twisted tube bundles, helical baffles, tube coatings that improve nucleation in boiling applications (eg, HIGH FLUX tubing) and wire inserts in tubes (eg, HiTRAN or Spirelf) to increase turbulence and reduce fouling.

5.9. Insulation. A surprisingly important capital element of energy management is insulation. On large projects the capital cost of insulation is in the same range as that for heat exchangers or distillation towers and trays. At the optimum insulation thickness, the lifetime value of the insulation approximates the lifetime value of the heat loss; ie, insulation is as costly as the heat loss that it prevents. Uninsulated flanges, when they exist, are a particularly severe loss point, and when flanges need to be opened periodically, insulation via removable blankets is usually justified.

Insulation provides other functions in addition to energy conservation. A key role for insulation is safety. It protects personnel from burns and minimizes hot surfaces that could ignite inflammables. It also protects equipment, piping, and contents in event of fire. Thus materials such as mineral wool are sometimes used despite relatively poor thermal qualities.

Corrosion under insulation is also a concern, particularly in refrigeration systems.

6. Energy Efficiency Programs And Activities

6.1. Reasons for Action. Energy is essential to all chemical processes, and in many cases profitability increases as we use more energy (eg, by using more energy we may increase throughput or improve product yields). The goal of effective energy management, therefore, is not the blind pursuit of minimum energy consumption. Rather, it is the efficient use of energy (ie, the minimum use of energy subject to production requirements, environmental considerations, and other constraints).

The most obvious reason for pursuing energy efficiency is cost reduction. However, when assessing the benefits of energy savings we must be careful to identify the actual credit based on imported energy streams at the plant gate. This may be very different to the credits assigned by the plant's accounting system. For example, each plant typically assigns a fixed value per unit of steam use. However, for a particular project the incremental value of steam may be near zero because the site vents excess low pressure steam from waste heat boilers. In this situation, there may be virtually no change in fuel use as the steam demand varies over a certain range. Prudent planning credits a steam saving project based on the probable plant energy balance during the project's operation rather than on current allocated cost.

A second reason for pursuing energy efficiency is good stewardship of resources, which is closely linked to sustainable development, waste minimization and pollution prevention. Environmental standards have risen and continue to rise; it is no longer socially, politically or legally acceptable for companies to be seen as polluters, and this includes the pollution associated with inefficient energy use. Not surprisingly, many energy efficiency activities are linked to pollution prevention programs (16).

6.2. Industry Response. About 49% of the chemical industry population reported engaging in at least one energy-management activity in 1998. The scope and technical approach of these activities vary considerably, ranging from very limited programs focusing on individual equipment items to comprehensive management systems that attempt to address a wide range of energy issues across large corporations.

The top four reported activities to improve the efficiency of energy use (1) were energy audits, electricity load controls, equipment or facilities modification to improve direct machine drives, and purchase of electricity under special electricity rate schedules (eg, interruptible or time-of-use rates). Funding by government agencies and other entities (eg, utility companies) assisted a number of these activities. Several companies have published information on their energy efficiency activities [eg, Rohm & Haas (17), ExxonMobil (18), and Dow Chemical (19)].

In general, there are three main dimensions to energy efficiency activities in the industry, some or all of which are included in each of the various programs that have been reported:

1. Operate existing facilities optimally and efficiently through applications of best practices.
2. Identify economic investment opportunities for step-change improvements.
3. Implement strong management systems to sustain progress and drive continuous improvement.

The main elements in each of these three areas are discussed in the sections that follow. There is inevitably some overlap between areas (eg, studies intended to identify investment opportunities often highlight opportunities to improve operating practices as well).

6.3. Best Practices in Operation and Maintenance. Significant energy savings are often possible with no capital investment simply by operating and maintaining existing equipment properly, or by improving commercial arrangements. Additional benefits can sometimes be obtained with minor projects to upgrade equipment at low cost.

Six areas that typically yield substantial savings through improved operation and maintenance programs and commercial arrangements are electric supply, steam systems, compressed air, heat exchangers, fired heaters and process equipment. These are discussed below.

Electric Supply. Electricity supply contracts are often complex. It is often possible to achieve large savings by operating chemical plants in ways that take advantage of contract terms, or by negotiating new contracts that are more beneficial.

Utility companies often charge for peak load and time-of-use, as well as the total amount of power consumed. These terms in the rate structure can have a significant impact on how chemical plants use electric power (eg, there may be significant savings in operating power-intensive equipment only during periods when time-of-use rates are low). It may also be desirable to schedule operations that create an upward spike in electric load for times when base loading is low, to avoid creating a high peak load.

Many utility companies offer a variety of rate structures. Contracts for interruptible power (where the user may be required to reduce power load at short notice), eg, are fairly common, and offer large savings to those who can take advantage of them. There may be significant savings through selecting or negotiating the most favorable rate structure for any given facility.

Steam System Maintenance. Effective correction of steam system leaks and maintenance of the plant's drip and tracer steam trap population is an important step in energy management. External leaks from the steam system are sometimes left unattended, but even a single steam leak to atmosphere can cost in excess of $90,000/year. Potentially worse instances occur when bleed lines are intentionally left open, such as on turbine inlets, where a single 1 inch bleed can cost over $100,000 annually, or on bypass lines around process equipment, where losses on a 2 inch bypass can *well exceed* $250,000 annually for large process applications (see Table 6).

Unlike the known losses from external pipe leaks, which will generally be marked for repair, intentional steam bleeds or opened bypasses are often considered necessary for plant operations and there is usually no plan to prevent them. The losses due to such leakage can be enormous, and the goal should be to prevent steam bleeds and bypasses wherever possible.

The losses through a steam trap can vary with plant conditions and trap type; typical losses are illustrated in Table 6. Plants without a consistent and proactive trap management program typically see a 40% failure rate *or higher* when the trap population is left unattended. This equates to losses up to $1,000,000/year in plants with trap populations of 7000–8000. However, managed improvement in the trap population can quickly recover most of these losses. First year net return ratios are often between 8:1 and 2.5:1.

A typical program entails annual or semiannual testing of the traps, using a diagnostic instrument such as TrapMan from TLV Corporation. The TrapMan probe records high frequency ultrasonic signals, filters contaminant noise, and measures temperature—all in a 15 second test interval. The combined readings are compiled to a reference database to determine the trap's operational status. The data from TrapMan is imported into TrapManager software

Table 6. **Steam and Condensate Value Estimates External Leaks, Bleeds, Bypasses, Trap Leaks, Dumped Condensate**[a,b]

Loss condition	600 psig steam $7.50/ 1000 No; valuation	150 psig steam $6.00/ 1000 No. valuation
0.125″ pipe steam leak to atmosphere	>$20,000	>$5,000
0.250″ pipe steam leak to atmosphere	>$90,000	>$20,000
0.5″ steam bleed on inlet supply to turbine	>$100,000	>$50,000
2″ open steam bypass line around process	Not Available	>$250,000
"blowing" steam trap	$7,300	$5,400
"large leak" steam trap	$5,800	$4,700
"medium leak" steam trap	$3,600	$3,000
"small leak" steam trap	$1,500	$1,200
20,000 #/h condensate @ $0.59/1000 psig		>$100,000.

[a]Ref. 12.
[b]Steam leakage calculations derived from TLV SE1 software using discharge coefficient (DC) of 0.7 on open leaks, 0.3 on enclosed leaks. Steam trap leak calculations derived from TrapManager(tm) software and actual test results. A Pocket PC version of SE1 software is available for free download at www.tlv.com under the "download" section.

where failure reports are compiled and printed, and based on these reports maintenance resources are mobilized to replace defective traps and capture the losses.

Compressed Air Systems. Compressed air is often unmetered; thus there is little motivation to reduce use. A large fraction is often lost through leakage at fittings. Improved flow measurement and accounting is therefore key to reducing compressed air costs.

Typical leaks occur from fittings, but the largest leaks are often from open drain points where the drainage device has failed and a valve is left open or cracked to drain condensate. Since the air loss is not visible (like a steam leak), it is often a substantial flow. Leaks of this type can lead to a plant needing portable compressors to meet the excess air demand.

Heat Exchanger Cleaning Cycles. Typically the performance of heat exchangers decays over time as fouling or scaling increases resistance to heat transfer. The rate of decay depends on the type of service and the design of the heat exchanger. Periodic cleaning is therefore required for many heat exchangers.

In many cases heat exchangers are only cleaned when fouling cause blockages that create hydraulic limits. However, it is often economic to clean them long before this happens, in order to recover energy. The first step in setting up a heat exchanger cleaning program, therefore, is to determine which heat exchangers have the largest impact on energy efficiency.

A reduction in heat-transfer coefficient may or may not have a significant effect on energy efficiency, depending on how the heat exchanger is being used. For example, many heat exchangers that are used as steam heaters or cooling water coolers include overdesign factors that ensure they can meet process requirements even when they are moderately fouled. However, a loss of heat transfer in heat exchangers in other services (eg, feed/effluent heat recovery) has a direct impact on energy efficiency.

The optimum cleaning frequency depends on the cost of energy losses due to the fouled condition of the heat exchanger and the costs (including process debits) associated with cleaning. This trade-off can be evaluated fairly easily for single heat exchangers (20). For complex preheat trains, the sensitivity of heat recovery to fouling of individual heat exchangers is often difficult to determine, and specialized computational tools should be used (eg, Persimmon, a spreadsheet tool from Veritech, Inc.).

The energy savings from optimizing the cleaning of individual energy critical heat exchangers are typically several tens of thousands of dollars per year. Optimizing the cleaning of complex preheat trains can save hundreds of thousands of dollars per year.

Frequent cleaning typically requires the ability to isolate individual heat exchangers while the process is running. If facilities are not available to do this, it may be necessary to invest in additional valves, bypasses, etc, in order to secure these savings.

Fired Heaters. The performance of many boilers and furnaces can be improved markedly through proper operation and maintenance (21). The key measurements are stack temperature and excess oxygen. If these parameters deviate significantly from design values, it is generally possible achieve improvements by one or more of the following:

- Better damper control. The main goal is to reduce excess air. In addition to energy efficiency improvements this can also reduce NO_x emissions. The improvements may simply be a matter of operator training or repair of damaged equipment, or they may require an upgrade of the control facilities (eg, installation of an O_2 analyzer or a CO analyzer).
- Leak repair. Damaged ducting or furnace walls can cause significant losses. If the equipment is under vacuum air will be sucked in, producing misleading excess air measurements.
- Cleaning of convection banks. Cleaning can significantly lower stack temperatures. In some cases it is economic to add rows of tubes to existing convection banks, or even to install entirely new air preheaters or economizers.

Process Equipment. Poor operation of process equipment items can be a major cause of energy loss. One of the most frequent inefficiencies encountered is the unnecessary cooling and subsequent reheating of process streams. This can sometimes be rectified by simply bypassing coolers, although process constraints often demand more complex solutions. Improved process control and operator training, resulting in operating with lower tolerances, can also result in significant savings. There are also many additional opportunities that are appropriate to certain types of processes and equipment. Exploitation of these opportunities generally requires expertise specific to the process or equipment in question.

6.4. Identifying Economic Investment Opportunities. Improvements in infrastructure and processes can result in significant reductions in energy costs. The types of changes range from modifications of single equipment items to construction of entire new process units. Specific opportunities include upgrades of equipment (eg, installing a new catalyst) and control systems, additions of equipment items (eg, new heat exchangers), reconfigurations of process equipment (eg, resequencing of distillation columns or reactor trains), and resource-sharing projects (eg, sharing energy and by-products across traditional boundaries).

The opportunities are generally site-specific, and the first step is identifying the opportunities are applicable at any given facility. Five approaches (employee contests, process reviews, pinch analysis, steam system rebalancing and by-product synergies) are discussed below. Once a range of opportunities has been determined, conventional engineering techniques can be used to evaluate the costs and benefits of each option. This results in a short-list of projects that meet the company's investment criteria.

Employee Contests. A number of companies have used employee contests as a means of generating energy efficiency projects. One of the best-documented programs comes from the Louisiana Division of Dow Chemical Company (16). Their annual contest started in 1981. The initial focus was strictly capital projects for energy conservation, but over time this was extended to expensed projects, maintenance programs and work process improvements, affecting not just energy, but waste reduction in general. Between 1981 and 1993 the contest achieved audited savings of >$110,000,000.

The Dow contest was originally intended for engineers, but over time increasing numbers of nontechnical personnel also participated. In this way the observations and experience of a wide range of people familiar with different aspects of the site's processes were able to contribute ideas. Factors that have been cited as contributing to the success of the program include the following:

- Simple paperwork.
- Sustained management support.
- Grassroots support.
- Winners received recognition rather than cash.
- Worked through existing line organization.

Process Reviews. There are similarities between chemical processes, even when they make different products or are at different locations, and there are also similarities between utility systems. It follows that ideas that work at one plant are often transferable to others. This concept forms the basis of the process review approach.

Process reviews can take various forms, but typically they are structured brainstorming sessions where process flow diagrams are examined and compared against a list of possible process improvement options. Material from Sections 2–4 of this article could be used as the basis for such a list, and various other lists exist in the open literature (eg, Ref. 22). Ideas that appear to be applicable to the process under review are documented and then evaluated to determine their viability. This procedure will typically generate options for equipment upgrades, rerouting process streams, and improving control schemes, although many other types of improvements may be identified.

Pinch Analysis. Pinch analysis is a systematic technique for analyzing heat flows through an industrial process, based on fundamental thermodynamics. This enables easy identification of inefficiencies in existing heat recovery systems and facilitates the design of new, more optimal heat exchanger networks (see HEAT-EXCHANGE TECHNOLOGY; NETWORK SYNTHESIS). The trade-off between energy consumption and capital investment can be incorporated in the analysis, as well as the pressure drop implications of heat recovery. Pinch techniques can also be applied to distillation column optimization and other aspects of energy optimization (23). There are also applications in water and wastewater minimization, as well as hydrogen management and other mass transfer problems.

In energy efficiency studies at existing facilities, pinch analysis is typically applied to processes with large heating and cooling duties and complex heat integration schemes, with the objective of recovering additional heat and reducing the demand for imported energy. The types of projects that commonly result from this analysis are realignments of existing heat exchangers, addition of new heat exchangers, and incorporation of enhanced heat-transfer technologies in existing heat exchanger shells. Pinch analysis is also commonly used to improve heat integration schemes in new process designs—to reduce either capital cost or energy demand, or both.

Steam System Rebalancing. There is a general introduction to steam balances in the section Steam, and a "ladder diagram" of a simple steam system is shown in Figure 8.

A steam balance depicts the steam flows at a given point in time or as an average over some period. However, the steam flow on a cold weekday morning in winter is quite different from that on a Sunday in summer, and neither matches the annual average steam balance. Startup flows are also usually far different and merit their own special balance. It is also wise to prepare a balance for the beginning and the end of the cycle between unit shutdowns. For example, the power required by a turbine driving a compressor rises as the compressor efficiency falls, and process heating requirements rise as interchangers foul. By analyzing steam balances, and noting how they vary with time of day, season and on-stream cycle, we can often identify inefficiencies and lost opportunities, and thus generate options for system improvements.

Computer-based models make it fairly easy to examine steam balances and screen option for improving them. Simple balances can be assembled using spreadsheets without any special features. Several commercial software packages are available for more rigorous steam balances. These packages incorporate physical properties for steam and water, as well as model elements for deaerators, steam headers, steam turbines, letdown valves and other steam system components. Some of these packages are "add-ins" for spreadsheets (eg, ESteam from Veritech and ProSteam from KBC/Linnhoff March); others are stand-alone programs.

Whichever modeling system is used, the overall approach is to construct a model of the existing steam balance, with submodels showing significant variations (eg, summer and winter cases). As far as possible the models are reconciled with actual plant measurements. The models are then examined to identify inefficiencies, which usually take one of the following forms:

- Pressure letdowns across valves (rather than through steam turbines, where we can generate power).
- Vents (implying excess steam in a particular header, often caused by excessive use of low efficiency steam turbines exhausting to a low pressure header).
- Excessive use of steam in deaeration (usually the result of inadequate preheating of feed water).

The model can now be used to test options for eliminating the inefficiencies (eg, adding steam turbines to eliminate letdowns; replacing low efficiency turbines either with electric drives or higher efficiency turbines to eliminate vents; adding preheaters for deaerator feed water to reduce deaerator steam demand).

Steam models of this kind can also be used as an operating tool, to optimize the steam system in real time. The plant data logging system acquires steam demand and power data for all users on the site, and feeds this to the model. Using a mathematical optimizer, the steam model determines the most cost-effective way of meeting the resulting steam and power demand (ie, which boilers should be loaded or unloaded, which discretionary steam turbines should be used). Optimization systems of this type can also be used to assist in determining how to take advantage of electric power contracts (see the section Best Practices in Operation and Maintenance) in real time.

By-Product Synergies. There are many situations in which by-product synergies result in energy efficiency improvements (eg, many petrochemical facilities recover light ends material that would otherwise be flared from refineries; and there are a number of industrial parks where waste heat is exported from certain companies and imported by others through a parkwide heat grid).

There is now a growing trend, arising from the focus on sustainable development, to seek out by-product synergies in a more systematic way. A number of recent projects have built on this concept. The underlying premise is that all "wastes" from any given process can be considered as raw materials for other processes. Of course, many plants have historically been built to produce intermediates that are fed to other processes, and many processes generate by-products that are considered valuable. However, the "100% product" philosophy challenges the industry to consider all streams that leave a process (other than the main product) as potentially valuable byproducts. Quite apart from the by-product value that this generates there are often significant energy benefits as a result of reducing or eliminating the processing of the raw materials that are replaced by the recovered "waste materials".

In order to generate projects that build on this approach it is necessary to develop a philosophy of resource sharing. This requires a culture change, enabling individuals and organizations to cross traditional barriers not only within their own organizations, but also between organizations, developing inter-organizational collaborations. With this culture in place, it is possible to identify and compare process inputs, outputs and byproducts across the participating facilities, and look for possible synergies. This requires brainstorming procedures similar to those discussed under process reviews in the section Best Practices in Operation and Maintenance. In addition, some projects have used the Six Sigma statistical methodology (24) to assist in identifying and evaluating opportunities.

One example of this approach is the By-Product Synergy (BPS) process developed in the mid-1990s by the United States Business Council for Sustainable Development. In a report outlining the value of the BPS process (19), the following annual benefits were reported from implemented synergies across various industrial sites in Texas:

- CemStar—130,000 tons of steel slag used in place of lime. 65,000 tons CO_2, 800 tons NOx eliminated. $10,000,000/year.
- ASR—120,000 tons of Auto Shredder Residue mined for 18,000 tons of additional metal reclamation and possible fuel. 151,000 tons CO_2 avoided. $10,000,000/year.
- Graphite/Copper Sludge—37,500 lbs graphite/copper sludge not land-filled.
- Spent Caustic—438 tons spent caustic in place of virgin material. $2,000,000/year.
- Sodium Sulfate—680 tons of spent sodium sulfate used in place of virgin material.

Results of a By-Product Synergy project involving six chemical sites in Texas and Louisiana included potential energy savings of 900 billion Btu/year if all nonchlorinated wastes across the participating sites are recovered and converted to products.

6.5. Management Systems to Sustain Progress. Many energy efficiency programs fail through lack of follow through. After options for improving energy efficiency have been identified it is essential to put systems in place to capture the savings—not just in the short term, but also for years to come.

Most chemical facilities now have real-time data acquisition and plant data historian systems. This infrastructure makes data more accessible, which greatly enhances process management. “If you can’t measure it, you can’t manage it!”.

Accessibility of data also provides a basis for many sustainment activities. One of the most important is monitoring and targeting (M&T). This is a technique in which historical plant data is analyzed statistically to establish challenging but achievable performance targets (eg, Btu/lb of product). When plant performance deviates from target operators are alerted, and can take corrective action. Further technical analysis of M&T output can also be used to generate energy-saving projects. Utility cost savings of between 5 and 15% have been claimed from M&T systems.

Some companies implement their own M&T applications within an existing plant data historian environment. There are also customized commercial M&T packages available (eg, Montage, from Enviros Consulting Limited, www.enviros.com/montage). Invensys Process Systems (http://www.simsci-esscor.com/products/ARPM.stm) offers ARPM (Automated Rigorous Performance Modeling), which combines monitoring of performance data for key equipment with rigorous process modeling to identify maintenance needs—a variant of the M&T concept.

Sustainment requires more than computer systems, however. Additional areas that need to be addressed include:

- Training personnel and ensuring awareness of energy issues.
- Providing an adequate budget for energy efficiency efforts.
- Retaining human resources for energy-related activities (eg, dedicated personnel for steam system maintenance).

These needs are typically addressed through modifications of existing management systems.

The preceding discussion relates predominantly to reducing energy use at existing facilities. Many companies also incorporate energy efficiency requirements into their design practices for new processes (eg, some require pinch analyses for all new process designs).

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BIBLIOGRAPHY

"Energy Management" in *ECT* 3rd ed., Vol. 9, pp. 21–45, by A. F. Waterland, Waterland, Viar & Associates, Inc.; in *ECT* 4th ed., Vol. 9, pp. 438–462, by Dan Steinmeyer, Monsanto Corporation; "Energy Management" in *ECT* (online), posting date: December 4, 2000, by Dan Steinmeyer, Monsanto Corporation.

CITED PUBLICATIONS

1. *Chemicals Industry Analysis Brief*, U.S. Department of Energy, Energy Information Administration. Accessed 12 April 2004 at: http://www.eia.doe.gov/emeu/mecs/iab98/chemicals/.
2. W. M. Weiss (personal communication), Monsanto Enviro-Chem Systems Inc., St. Louis, Mo., 1991.
3. *Manufacturing Energy Consumption Survey: 1998*, U.S. Department of Energy, Washington, D.C., 2001.
4. A. P. Rossiter, J. D. Kumana, and M. K. Ozima, "Ranking Options for Pollution Prevention and Pollution Control Using Graphical Methods," in *Waste Minimization through Process Design*, A. P. Rossiter, ed., McGraw-Hill, New York, 1995, p. 245.
5. *Kyoto Protocol To The United Nations Framework Convention On Climate Change*, Kyoto, 1–10 December, 1997. Accessed 03/19/2004 at: http://www.carleton.ca/~tpatters/teaching/climatechange/kyoto/kyoto1.html.
6. R. D. Sung, J. D. Kumana, and A. P. Rossiter, "Southern California Edison's CTAP: Saving Energy and Reducing Pollution for Industrial Customers," in *Waste Minimization through Process Design*, A. P. Rossiter, ed., McGraw-Hill, New York, 1995, p. 335.
7. W. F. Kenney, *Energy Conservation in the Process Industries*, Academic Press, Inc., New York, 1984.
8. W. F. Kenney, "Combustion Air Preheat on Steam Cracker Furnaces," *Proceedings, 1985 Industrial Energy Conservation Technology Conference*, Texas Industrial Commission, p. 595.
9. R. Kehlhofer, J. Warner, H. Nielsen, and R. Bachmann, *Combined-Cycle Gas and Steam Turbine Power Plants*, PennWell, Tulsa, Oka., 1999.
10. P. S. Gupton and A. S. Krisher, "Waste Heat Boiler Failures," *Chem. Eng. Prog.* **69**(1), 47 (Jan. 1973).
11. V. Ganapathy, *Waste Heat Boiler Deskbook*, Prentice Hall, Inc., Englewood Cliffs, N.J., 1991.
12. S. M. Garrett and J. R. Risko, *Value Opportunities Abound in Steam Systems*, TLV Technical Paper, TLV Corporation, Charlotte, N.C., 2004.
13. E. D. Larson and L. J. Nilsson, *ASHRAE Trans.* **97**(2), 363 (1991).
14. D. R. Frikken, K. S. Rosenberg, and D. E. Steinmeyer, "Understanding Vapor Phase Heat Transfer Media," *Chem. Eng.* **82**(12), 86 (June 9, 1975).
15. D. E. Steinmeyer, "Take your pick: capital or energy," *CHEMTECH* **12**(3), 188 (Mar. 1982).

16. K. E. Nelson, "Dow's Energy/WRAP Contest: A 12-Year Energy and Waste Reduction Success Story," in *Waste Minimization through Process Design*, A. P. Rossiter, ed., McGraw-Hill, New York, 1995, p. 317.
17. J. Hackworth, "Plant Energy Management Program," *Proceedings of the 2003 Texas Technology Showcase*, March 17, 2003.
18. K. Trivedi, "Global Energy Management System," *Proceedings of the AIChE Spring National Meeting*, April 25–29, 2004.
19. T. Welch, "Gulf Coast By-Product Synergy Project," *2nd Texas Industrial Energy Management Forum*, March 4, 2004.
20. B. R. O'Donnell, B. A. Barna, and C. D. Gosling, "Optimize Heat Exchanger Cleaning Schedules," *Chem. Eng. Prog.* **97**(6), 56 (June 2001).
21. A. Garg, "Optimize Fired Heater Operations to Save Money," *Hydroc. Proc.* **76**(6), 97 (June 1997).
22. K. E. Nelson, "Process Modifications That Save Energy, Improve Yields, and Reduce Waste," in *Waste Minimization through Process Design*, A. P. Rossiter, ed., McGraw-Hill, New York, 1995, p. 119.
23. A. P. Rossiter, "Succeed at Process Integration," *Chem. Eng. Prog.* **100**(1), 58 (Jan. 2004).
24. *Six Sigma—What is Six Sigma?* Accessed 1 July 2004 at: http://www.isixsigma.com/sixsigma/six_sigma.asp.

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