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COST-EFFECTIVE WASTE ENERGY UTILIZATION

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It does not seem likely that we will ever return to an era of low-cost energy. From now on, we will be paying an ever increasing fraction of our income for energy needs, and hence, at a fixed rate of productivity, our standard of living will be declining. Can we arrest this fraction at some new plateau without depriving ourselves of the beneficial effects of energy uses? No one can give a sure answer to this question. We believe, however, that a combination of efforts in both new energy supplies and in energy savings is the most reasonable and profitable approach to the problem. In this article we concentrate only on savings through more effective use of energy that is now wasted; i.e. improved energy productivity.

A brief overview of the pattern of recent trends in energy costs and productivity, and of the present state of waste energy utilization, is an appropriate introduction to a review of generic technologies for waste energy utilization, their specific applications, and potential benefits and drawbacks.

OVERVIEW

Energy Costs and Prices

In the 1970s, energy prices began spiraling upward, a trend that is likely to continue for years to come. The reasons are the exhaustion of our finite store of easily recoverable fuels, especially the liquid and gaseous forms, the

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high cost of possible replacements, and the long lead times required to bring new fuel supplies to the market and to improve our energy consumption habits without destroying our economic and social well-being. To resolve the energy predicament, we must invest in both increased energy supply and reduced demand. As with all capital outlays, investments in energy production and energy productivity require that some of today's benefits be deferred in favor of future returns.

Since the end of the second World War and up to the mid-1970s, energy consumption had been accelerating, especially oil and gas usage. Such growth was justified because fuels were being discovered at rates higher than production, and at relatively low cost. Reserves were doubling every 5 years, whereas extraction was doubling only every 10 years. The cost of extraction of a barrel of oil was as little as a fraction of a dollar. Exploitation methods and conversion processes were continuously improving. Thus, the economies of most industrialized nations were expanding rapidly, fueled by readily accessible cheap energy.

Around 1970, however, the availability of cheap oil and gas began to take a dramatic downturn. In the United States, discoveries of new reserves were not coming on stream as fast as the growing production required. In the 1950s, 1¼ barrels of oil were being discovered for each barrel extracted, but by the mid-1970s this had dropped to only about ½ barrel. Moreover, capital investment requirements for new finds were becoming much larger than in the past. The investment in North Sea oil, for example, was about $10,000 per daily barrel of capacity compared with investments in the Middle East of only a few hundred dollars for the same capacity. Projected costs of alternatives to oil, such as synthetic fuels, were more than five times those of the North Sea. No major energy supply could be brought to the market fast enough to effectively compete with oil. For the first time in our history, the replacement cost of all energy sources rose above the average price paid by consumers.

Electricity costs followed the same pattern as replacement oil costs, due in part to safety, environmental, and regulatory requirements. In 1968, the average cost of two 1200-MW nuclear plants for 1976–78 operation was $230 per kW. The cost of three 800-MW coal-fired units for 1976–78 operation was $180 per kW. The corresponding costs of electricity were 0.8 and 1.1 ¢ per k Wh. In the early 1980s, the estimated costs for both nuclear and coal-fired plants are in the thousands of dollars per kilowatt, and the corresponding electricity costs are over 10 ¢ per kWh.

Energy Productivity

For each component of the economy, resources should be allocated so as to maximize benefits. For example, energy and other inputs should be used in such proportions as to achieve a given level of products and services at the lowest cost. Because fuels are so important both to our economy and to our national security, the question arises: "Is it possible to reoptimize energy end uses so as to satisfy the same societal needs at equal or lower cost while consuming less energy?" Asked differently: "Is it possible to achieve cost-effective energy productivity?" A positive answer to this question depends on satisfactory results from three concurrent considerations: economic, scientific, and technical.

During the past decade of rampant inflation, all prices have been rising. But energy prices have been rising faster than those of labor, capital goods, and materials. This point is illustrated in Figure 1. As a result, a sizeable reduction in the energy required to produce each unit of economic output has been achieved. There were improvements in all sectors of the economy; greater energy productivity in industrial processes, as well as increased operating efficiency in end-products such as appliances and automobiles. Also, there have been shifts in the mix of output from more- to less-energy-intensive products. As we will see, however, the opportunities for much larger fuel savings have not been exhausted.

Some improvements in industrial processes have been achieved through investments in more-energy-efficient equipment. These investments, however, have not been as numerous as warranted by the large relative differences between energy and capital equipment prices, because of the concurrent and unprecedented rise in the cost of capital (Figure 1). Though the outlook for the future is uncertain, we can expect the trend of energy prices outpacing those of other factors of production to continue, especially in the United States. We base this judgment on the following reasons.

With regard to oil, relative price stability may prevail in the near term

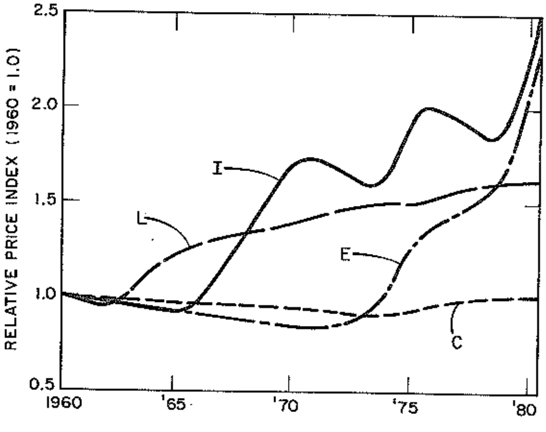


Figure 1 Price trends for energy, capital equipment, cost of capital, and labor. E, energy price divided by GNP deflator; C, capital equipment price divided by GNP deflator; I, interest rate on baa bonds; L, labor costs divided by GNP deflator.

because the major oil-consuming nations are in an economic recession. Energy costs for the manufacturing industries in the United States will continue to rise, however, even if oil prices remain flat. Petroleum represents under 20% of energy costs to manufacturers, whereas electricity and gas account for 70%. In the 1960s, gas fuels were being sold at extremely low prices—as low as $0.20 to $0.40 per million Btu—because of the enormous gas surpluses associated with oil production. As a result, much of the nation's industry was built around the availability of cheap natural gas. In the 1970s, gas shortages began to occur as supplies declined in response to continued federal price controls, which prevented development of the more expensive reserves in deep basins and tight rock formations.

Although gas prices have already quadrupled in real terms since 1972, deregulation will create even higher prices. Natural gas still sells for an average $2.90 per million Btu to industrial customers. By comparison, residual and distillate petroleum products cost $4.70 and $6.60 per million Btu, respectively. The versatility and low combustion emissions of natural gas will continue to make this fuel attractive for many industrial processes. With deregulation, the prospects for adequate gas supply are much improved, because of greatly expanded drilling and exploration throughout North America.

Electricity alone represents over 40% of energy costs for manufacturers. The price of electricity can be expected to rise even faster in the future than the price of oil and gas. Electricity prices initially respond more slowly to higher costs because expensive new generating capacity must be "rolled-in" with existing plants to arrive at an average cost per kilowatt hour, and because of delays in obtaining rate increases from utility regulatory agencies. As time goes on, however, these factors become less and less effective, and electricity prices will reflect the high marginal costs of new capacity.

Thus, we conclude that the economic opportunity for increased energy productivity will continue to exist for many years ahead, and turn to the scientific consideration.

Potential Fuel Savings

In establishing patterns of energy consumption, it is customary to find the total amount of energy used in each task in the economy and, thus, to determine the needs for different fuels. The term energy in this connection is ambiguous. For example, the heat required in an industrial process may be added to the electrical work required or to the "heating value" of the fuel consumed in producing the electrical work required. None of these quantities represents energy consumed in the process, because it is known from the laws of thermodynamics that energy, rather than being consumed in any process, is always conserved. When opportunities for fuel savings are to be assessed, it becomes necessary to use a measure other than energy (1).

Every engineer knows that a Btu of enthalpy in the circulating water of a powerplant is less marketable and less valuable than a Btu of enthalpy in a steam main. It is also apparent that a cold battery that is charged is more valuable and useful than a discharged battery having the same energy by virtue of being hot.

Typical conditions of process steam used in industry, for example, are 270° F temperature and 45 pounds per square inch (psi) pressure. The heat required to change water from ambient conditions (55° F) into typical process steam conditions is 1150 Btu per pound of steam. Accordingly, since the typical heating value of hydrocarbon fuels is about 20,000 Btu per pound of fuel, it is often concluded that at least 0.057 pounds of fuel per pound of process steam is needed. If this amount of fuel were used, then, according to the customary definition, the effectiveness of fuel utilization would be 100%. By virtue of the laws of thermodynamics, on the other hand, it can be shown that the minimum amount of fuel required to accomplish the task just cited, is only 0.015 pounds of fuel per pound of steam and, therefore, only when this minimum amount is consumed is the process 100% effective. Conversely, if 0.057 pounds of fuel per pound of steam is consumed, the effectiveness of fuel utilization is only 0.015/0.057, which equals 26%.

The preceding simple examples illustrate the necessity for using a yardstick other than energy for assessment of fuel needs and of effectiveness of fuel utilization. The laws of thermodynamics indicate that neither energy, nor heat, nor enthalpy, nor Gibbs free energy are, in general, satisfactory yardsticks. The relevant quantity is a property called availability that is in turn uniquely related to another important property of matter called entropy. A brief summary of the thermodynamic considerations of availability and its application as the measure of fuel needs is given in the section on thermodynamic effectiveness.

Using availability as a yardstick, we find that the effectiveness of fuel use in some commonly required societal tasks are (2, 3):

- Residential and commercial space heating: 6%
- Residential and commercial water heating: 3%
- Air-conditioning and refrigeration: 5%
- Automobile propulsion: 10%
- Steel production: 21%
- Petroleum refining: 9%
- Cement manufacturing: 10%
- Paper production: less than 1%

The average effectiveness for all tasks in our economy is about 10%, found by weighing each partial effectiveness by the amount of fuel used for the task. From these results we see that the theoretical potential for improvement is enormous. Of course, energy end-use effectiveness will never approach 100% for real processes and devices, even in the remote future. But the present low values emphasize the opportunity for savings and the fact that no fundamental scientific barriers exist to prevent substantial improvements.

The shift toward greater energy efficiency has already begun to show results. In the United States, for example, we now use about 10% less energy per unit of real GNP than we did a decade ago. The average fuel economy of new automobiles, for example, has risen more than 70% since 1973. The industrial sector, which has seen fuel prices rise three times faster than the general rate of inflation over the past eight years, has cut energy use per unit of production by over 12%.

Despite the progress made to date, however, the process of restructuring our economy around high cost energy is still very young. How rapidly we proceed with reducing waste will depend to a large extent upon the economics of energy conservation. High energy prices, alone, do not guarantee that energy-saving measures will become attractive investments.

For example, the period immediately following the oil embargo was characterized by high rates of inflation, a worldwide slowdown in economic activity, and high cost of capital. Little progress was made in improving energy productivity until economic recovery began. Then, energy prices were still rising, but only slightly in constant dollars. Moreover, declining interest rates and relatively stable capital goods prices combined to create a very favorable climate for investing in energy-efficient equipment. Rapid gains in output per unit of energy consumption were recorded throughout this second period, but the trend came to an abrupt halt with the advent of the next round of oil price hikes in 1978. Once again, inflation accelerated and the cost of capital rose to unprecedented heights, thereby severely reducing the incentive for energy-productivity investments.

Waste Energy Sources

By rigorous and careful analysis of each process, engineers can accurately determine the steps in the process that waste energy and the causes of such waste. By using cost-effective new devices and system configurations, they can then reduce the waste and thus increase the effectiveness of energy utilization. It is clear that any cause of energy waste is, therefore, a potential waste energy source.

What are some of the major causes of energy waste? An obvious one is the rejection of a stream at either high temperature or high pressure or both to the atmosphere, because then the ability of the stream to perform a useful task is forever lost. Another is the transfer of energy from a high-temperature source to a medium at lower temperature because then the initial high quality of the energy is degraded to a low quality without extracting any benefit. A third example is the throttling of the pressure of a stream to a lower value without extracting the mechanical work that the stream could have performed. Finally, another example is waste materials that are disposed of without further use or recycling. Some of these wastes can be either burned as fuels, such as sawdust from lumber mills, or reprocessed with much less fuel consumption, such as aluminum scrap.

Many cost-effective technologies exist for waste energy utilization. Any such technology is cost effective if its cost is less than the benefit derived from the fuel savings. The cost-benefit analyses of fuel savings expenditures involve many factors such as tax laws, depreciation schedules, availability and cost of capital, return on assets, and discount rates. For our purposes, we will use a simple criterion based on the payback period. The payback period is defined as the ratio of the total investment for waste energy utilization over the annual savings achieved by the reduced energy consumption. When this ratio is less than 3–4 years then we will consider the technology as cost effective.

TECHNOLOGIES FOR WASTE ENERGY UTILIZATION

There exists today a broad spectrum of proven energy-saving technologies that can be employed in all sectors of society with attractive economic payback. This section describes some of the more important of these in terms of their cost and operating characteristics. The importance of opportunities to save energy has been emphasized in many reviews and studies of the energy problem (2–13).

Cogeneration

Cogeneration is the concurrent generation of motive power and process heat or steam (1, 14–16). It saves fuel because either waste energy from a heating process is used for the generation of motive power, or waste energy from a power plant is used for heating applications. Two cogeneration schemes are shown schematically in Figures 2 and 3.

Cogeneration affords one of the largest opportunities for saving fuel because many common processes have sizeable waste energies suitable for this technology. It encompasses many different energy recovery and energy conversion devices. Some of the energy conversion devices, such as steam turbines and reciprocating diesel and spark-ignition engines, have been in common use for decades. Others, such as turbines with an organic material as a working fluid and thermionic converters, are just now being commercialized or are still undergoing testing. The various conversion technologies

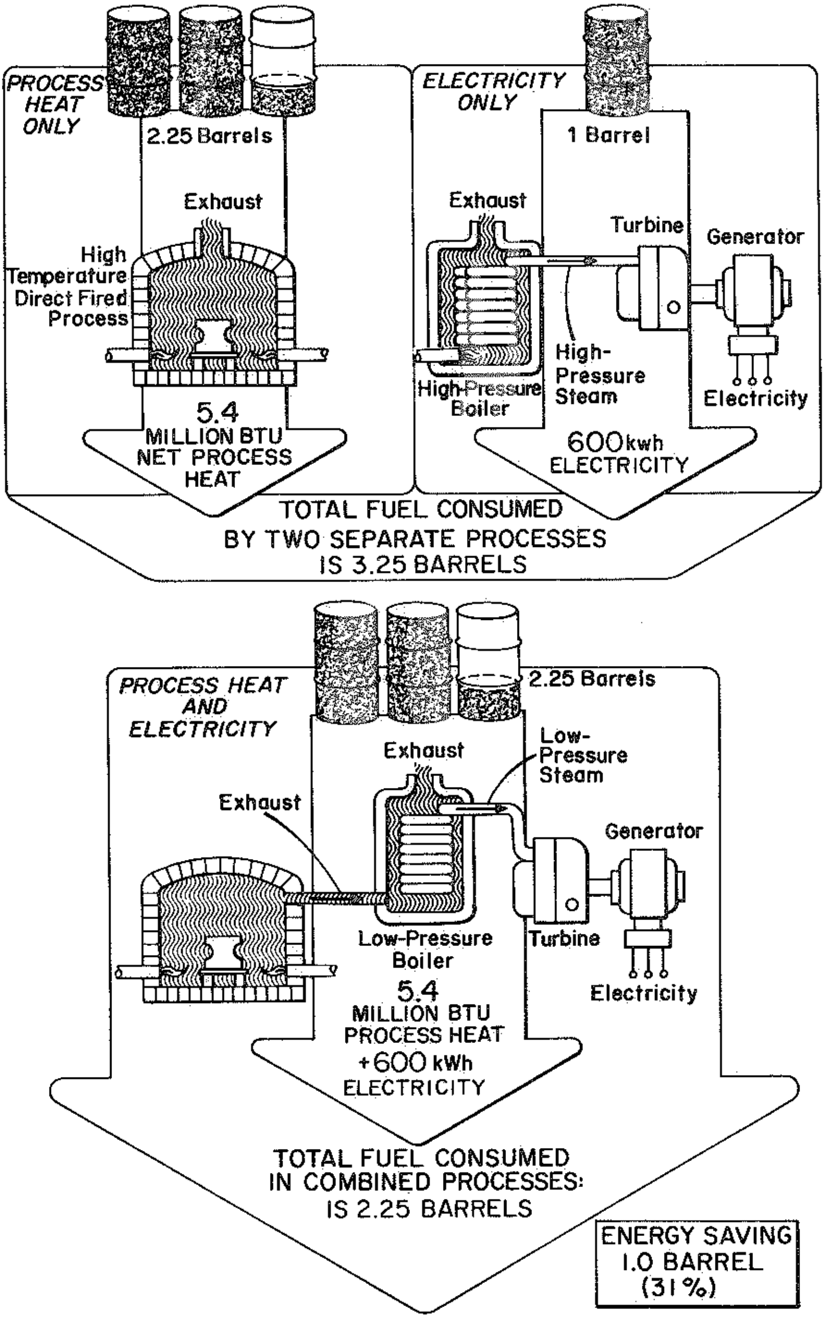


Figure 2 Bottoming cycle cogeneration.

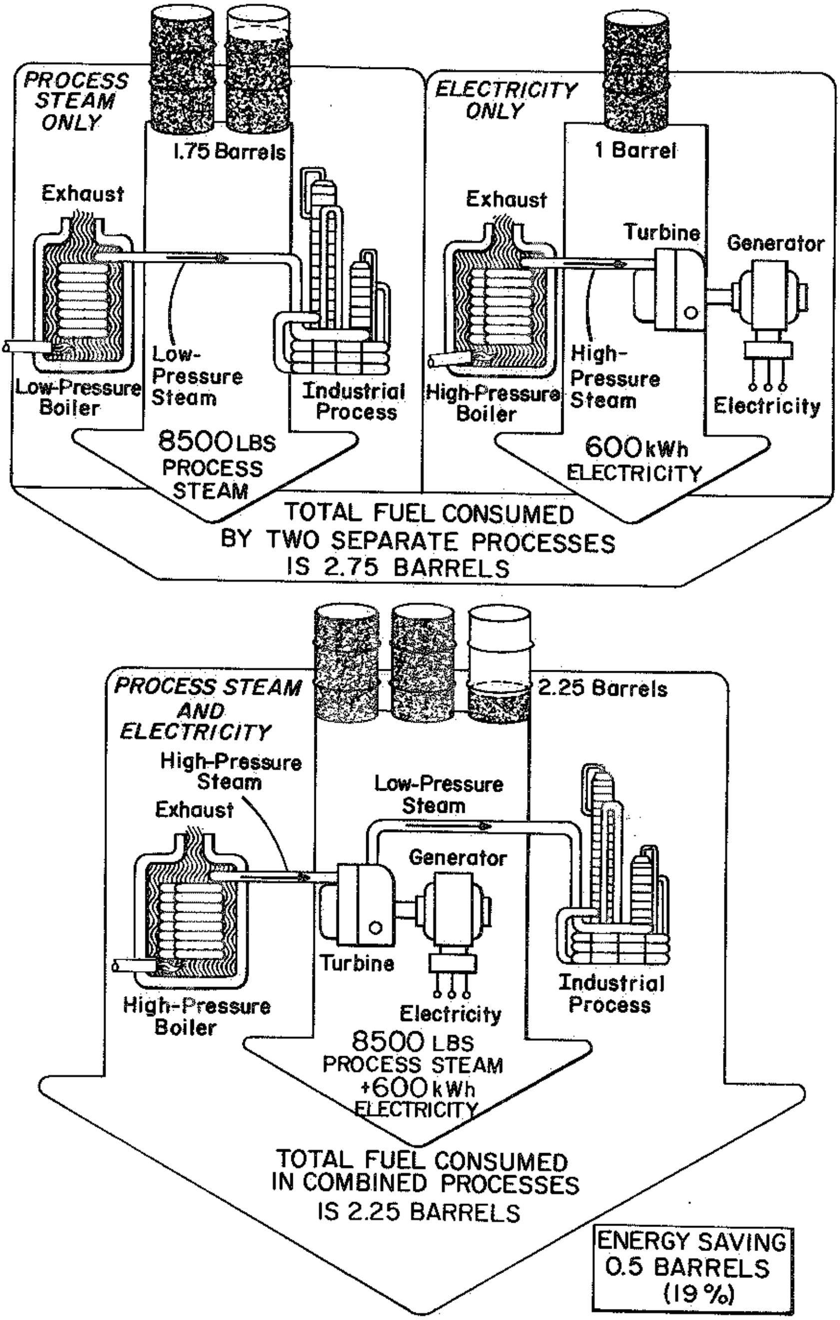


Figure 3 Topping cycle cogeneration.

currently available and those soon to enter the marketplace provide power system designers with an unprecedented opportunity to save not only energy but scarce capital as well.

Small-scale cogeneration facilities save capital because the equipment is built in a manufacturing plant rather than at the site of the facility, and in a much shorter time than that required for a large central electric power station. This latter feature is an invaluable tool for electric utility planners who have had to predict under conditions of great uncertainty electricity demands a decade before a new large powerplant would finally come into service.

Power devices for cogeneration fall into two distinct classes: topping units and bottoming units. Topping units take advantage of the fact that many low-temperature direct-fired processes such as drying, curing, baking, space heating, and washing are thermodynamically inefficient because they consume directly the high-quality energy of high-temperature combustion products for tasks that actually require only low-quality energy. The effectiveness of fuel use in such processes can be increased substantially by first using the high-quality energy of fuel combustion in a diesel engine, gas turbine, or steam turbine to drive an electric generator, and then recovering the exhaust energy of the unit to perform heating tasks needing temperatures of only 150°–600° F.

Bottoming units are applicable to high-temperature processes such as the production of metals and ceramics in furnaces and kilns operating at 1000°F and above. Waste energy from the process is directed to a power conversion device driving an electrical generator. In a typical application, furnace exhaust gas, still containing a large quantity of high-quality energy, is directed to a boiler where steam is generated. The steam drives a turbine-generator engine and produces electricity. The combined system uses about 30% less energy than when the furnace heat and electricity are produced seaparately. Cogeneration by means of waste energy recovery with a bottoming engine is particularly attractive because it produces electricity with no incremental consumption of fuel and often can be installed in existing facilities.

The major energy conversion technologies used in cogeneration are described briefly below.

STEAM TURBINES Steam turbines have been used for both cogeneration and conventional power generation throughout much of this century. In a paper mill, for example, a high-pressure topping turbine extracts part of the energy from a high-pressure steam flow. The remaining energy in the exhaust steam, at pressures of 50–200 pounds per square inch, is used to operate paper mill machinery such as digesters, blenders, and dryers. A typical electrical output would be about 50 kWh per million Btu of steam energy delivered to the mill machinery.

In a district heating installation, waste energy from a powerplant is fed, either in the form of low-pressure steam or hot water, to a network that supplies the heating needs of a city or a residential and commercial complex of buildings.

Low-pressure steam turbines are used as bottoming units. They recover waste energy from relatively high-temperature exhaust gases of a process by means of a waste heat boiler, or from the spent steam of intermediate-temperature industrial processes.

Steam topping and bottoming turbines are feasible from about 2000 kW up to 50,000 kW with presently available hardware. Capital and installation costs for such units range from about $1000 to $2000 per kilowatt, depending upon system size, waste energy temperature, type of fuel, and specific interface requirements and site constraints for the cogeneration system.

For district heating applications, the powerplant rating can be much larger and the capital and installation costs are dictated by the type of plant under consideration and the costs of the district heating network.

DIESEL ENGINES Diesel engines are applicable as topping units of cogeneration systems when a high ratio of electrical output to process heat is required—up to 400 kWh per million Btu of heat delivered to the process. Process steam and hot water are produced by recovery boilers coupled to the exhaust stack and to the cooling water of the engine. Systems from as little as 100 kW to several thousand kilowatts can be built. However, these systems are based upon medium-speed and high-speed diesel engines, the type generally used in trucks, construction equipment, and rail locomotives. Such engines are limited to the burning of high-grade distillate petroleum, a product that is likely to be expensive and often in short supply in years to come.

A more versatile diesel engine for topping large cogeneration systems, from several thousand kilowatts up to about 30,000 kW, is the large slow-speed, two-stroke diesel engine. This engine, often used for propulsion of large ships, is capable of burning very-low-grade fuels such as high-sulfur crude or heavy residual oil. Recent experiments have shown that it may even be capable of burning a powdered coal-water slurry. System costs, including heat recovery boilers, range from about $1200 to $1800 per kW.

COMBUSTION GAS TURBINES Combustion gas turbines are well suited as topping units for large-scale systems, particularly where natural gas or clean-burning byproduct fuels such as refinery gas are available. Gas turbine systems offer low capital cost, about $500–$1000 per kilowatt, particularly in large systems of 10,000–150,000 kW. Also, the high exhaust gas temperature of gas turbines permits their integration with a great variety of industrial processes.

SPARK-IGNITION ENGINES Spark-ignition engines that burn natural gas can also be used as topping units. A relatively new concept for achieving very low capital cost, about $500 per kW, is based upon derated automobile engines converted for use in small cogeneration modules of about 60 kW output. Each module produces about 500,000 Btu per hour of process heat in the form of low-pressure steam and hot water. One to ten modules could be used in applications such as shopping centers, hospitals, apartment buildings, and light industrial sites, to supply all on-site electrical and process heat needs.

ORGANIC RANKINE TURBINES An organic Rankine turbine is an advanced type of bottoming unit (17). It uses an organic material as a working fluid and is capable of recovering efficiently the energy from low-temperature (300°–600° F) waste streams. It can be built in a wide range of sizes, from as small as 50 kW to 30,000 kW or more. Output per unit of waste energy input will generally be 20–30% greater than that obtainable with steam-turbine bottoming units. Commercialization of organic Rankine turbines is just beginning.

The various technologies described above provide the basis for virtually all cogeneration systems. Other technologies now in the research and development stage, such as thermionic converters and Stirling cycle engines, may also play a role in future cogeneration systems.

In its most elementary form, a thermionic converter (18) consists of one electrode connected to a high-temperature energy source (about 3000° F), a second electrode connected to a low-temperature energy sink (about 1000° F) and separated from the first by an intervening evacuated space, and leads connecting the two electrodes to an electrical load. Electrons boil off the hot electrode by the process of thermionic emission, condense on the colder electrode, and return to the hot electrode via the load. Thermionic converters may eventually be used as topping units for gas turbines and high-temperature industrial furnaces.

Heat Pumps

The term heat pump (19) describes a system that uses either mechanical work (electricity) or high thermodynamic availability heat to transfer energy from a low-temperature source to a system at higher temperature. Under suitable conditions of operation, it saves fuel because either the energy transferred to the hot medium is larger than that used to produce the mechanical work and the low-temperature source is a waste stream, or the entire heating is accomplished by using waste energy sources.

A heat pump works in the same way as a household refrigerator, which uses electricity to pump energy from the cold inner space of the refrigerator to the hotter environment. The difference is that, when used as a heat pump rather than a refrigerator unit, the task of the system is to heat rather than cool a medium.

Heat pumps can be used in a great variety of applications to pump low-quality waste heat or other energy (such as low-temperature solar energy) to the temperatures required for process conditions without a commensurate consumption of fuel. Some applications are heating or cooling of residential and commercial buildings, waste energy upgrading in distillation columns of chemical plants, waste energy upgrading in industrial drying processes, and process steam raising by solar energy.

Expanders

An expander is a turbine or other prime mover that extracts mechanical work out of a moderate- or high-pressure liquid or gaseous waste stream. Many industrial plants have such streams and their ability to do work would be wasted if not captured by an expander. For example, many hydrogen processing schemes, such as hydrocrackers, require the reaction of liquid streams with hydrogen at pressures well over 1000 pounds per square inch. After reaction, the high-pressure liquid stream can power a hydraulic turbine to recover mechanical work. Again, refineries have many gaseous streams at pressures 30–50 pounds per square inch. The quantity of gases available, even at such low pressures, is so large that large amounts of work can be produced and, thus, enormous fuel savings can be achieved. Expanders have been used for many decades in industrial processes.

Heat Exchangers

A heat exchanger (20) is a device that transfers energy from a hot stream, gaseous or liquid, to a colder stream, gaseous or liquid. During such a transfer, the hot stream is cooled and the cold stream is heated.

Heat exchangers can be used in many different ways to recover waste energy and save fuel and reduce other expenditures. For example, networks of heat exchangers can be used in chemical plants to couple hot streams that need to be cooled to cold streams that need to be heated thus saving the expenditures for both cooling water and heating fuel. Again, they can be used to capture waste energy from stack gases to preheat combustion air, processed parts, or boiler feedwater, or to generate steam.

A heat exchanger if used to preheat combustion air is called a preheater or a recuperator, if used to preheat boiler feedwater an economizer, and if used to generate steam a waste heat boiler.

Heat exchangers come in many different categories, such as shell and tube heat exchangers, metallic radiation recuperators, finned-tube economizers, and counterflow heat exchangers, depending on the application, the materials used, the modes by which energy is transferred from one stream to the other, and the flow patterns of the streams.

In general, heat exchangers are inexpensive pieces of equipment that save significant amounts of fuel. Their payback periods are often less than one year.

Regenerators and Heat Wheels

An alternative method of exchanging energy from a hot to a cold stream is by first heating a material body by the hot stream and subsequently transferring the energy stored in the body to the cold stream (20). The material can be stationary with the passage of the hot and cold streams over it alternating. Then we say that the energy exchange device is a regenerator. The material can rotate within two ducts, part of it being heated by the hot stream while the other part is being cooled by the cold stream. Then the device is called a heat wheel.

Regenerators and heat wheels can be cost-effectively used to recover waste energy in a great variety of industrial and commercial applications.

Heat Pipes

A heat pipe (20) is a device that transfers heat from one place to another with practically no temperature difference between the two places and no mechanical pumps. It saves fuel because it eliminates the ineffectiveness—increase of entropy—involved in any heat transfer across a finite temperature difference.

A heat pipe is a hollow chamber, not necessarily cylindrical, whose walls include a capillary structure. After being evacuated and sealed, the chamber is filled with a substance—water, organic compound, or liquid metal—which is in liquid-vapor equilibrium at the operating temperature of the heat pipe. When heated at one end, the liquid vaporizes and its pressure is raised. The resultant pressure drives the vapor to the other end of the heat pipe, which is being cooled. There the vapor condenses and releases the heat which was absorbed at the heat-input end. Thus, heat is carried from one end of the heat pipe to the other via vapor. The condensed liquid is then returned to the heat-input end of the pipe by the capillary forces developed in the capillary structure, which functions much as the wick in an oil lamp, and the cycle is repeated. The result of this process is that large quantities of heat can be transferred from one place to another with very little decrease in temperature, and without any external equipment.

A heat pipe can be thought of as a heat conductor with an effective thermal conductivity thousands of times greater than that of most highly conductive metals such as copper or aluminum. Because of this high effective thermal conductivity, it can replace many conventional fluid heat transfer systems that require large temperature differences and electromechanical pumps for fluid return.

Heat pipes have been developed for various heat transfer and thermal control applications. These include high-temperature lithium, sodium, and potassium heat pipes for industrial heat transfer devices; and ammonia, water, and organic working fluid heat pipes for commercial cooking appliances, domestic water heaters, and deicing of ships at sea.

Table 1 Energy content and densities of common industrial waste (21)

Name	Heating Value (Btu/lb)	Density (lb/cu yd)
Bitumen waste	16,570	1,500
Brown paper	7,250	135
Cardboard	6,810	180
Cork	11,340	320
Corn cobs	8,000	300
Corrugated paper (loose)	7,040	100
Grass (green)	2,058	75
Hardboard	8,170	900
Latex	10,000	1,200
Magazines	5,250	945
Meat scraps	7,623	400
Milk cartons (coated)	11,330	80
Nylon	13,620	200
Paraffin	18,621	1,400
Plastic-coated paper	7,340	135
Polyethylene film	19,780	20
Polypropylene	19,860	100
Polystyrene	17,700	175
Polyurethane (foamed)	17,580	55
Resin-bonded fiberglass	19,500	990
Rubber (synthetic)	14,610	1,200
Shoe leather	7,240	540
Tar paper	11,500	450
Textile waste (nonsynthetic)	8,000	280
Textile waste (synthetic)	15,000	240
Vegetable food waste	1,795	375
Wax paper	11,500	150
Wood	9,000	300

[1] The prospect for major increases in domestic energy supplies of oil, gas, coal, and nuclear energy is bleak. Energy supply from these four sources is equivalent to approximately 27 million barrels per day (mb/d) at present. This might be expanded to 32 mb/d; however, the DOE forecast for demand in 1990 is 51 mb/d, which leaves a 19 mb/d shortfall which must be made up by imports, or solar energy, or conservation.

Waste Materials

Many waste materials have large heating values (Table 1) and can be used as substitutes for valuable fuels (21). Solid waste can be burned by incineration or pyrolysis. In contrast to incineration, pyrolysis involves the degradation of waste by heating in an oxygen-lean atmosphere and, thus, producing combustible gases and a carbon-rich char. The gases are then used as fuel in conventional combustion processes for generation of heat or work.

An example of waste material combustion is the use of sawdust in brick-firing ovens instead of natural gas. A side effect of this fuel-saving substitution is that bricks come out somewhat blackened. This problem, however, can be readily solved by selling sawdust-fired bricks as antiques!

Other waste materials can be reprocessed or recycled to produce finished products at a cost less than that involved in production from raw materials. For example, reprocessing scrap aluminum consumes only 5% of the fuel required to produce aluminum from bauxite. Of course, recycling involves energy and other costs in addition to the energy required for reprocessing.

Process Controllers

A controller is a system that monitors key parameters of a process, such as temperature, pressure, and composition, adjusts other parameters such as flow rate and feedstock composition, and achieves the desired quantity and quality of the product of the process.

The great advances that have been made since World War II in sensors, signal converters and processors, computer costs, and control theory provide engineers with invaluable tools to design inexpensive process controllers that reduce waste energy in practically every fuel-consuming application (22). In some applications, fuel savings are achieved by controlling combustion and steam flows. In others, the savings occur by controlling the quality of product and thus achieving the best output for a given fuel input.

APPLICATIONS

This section presents specific applications of waste energy utilization technologies. The examples illustrate typical performances and economic characteristics of such technologies in actual practice.

Diesel Cogeneration System

A diesel topping unit cogeneration system is shown schematically in Figure 4. Installed in a large chemical plant, it provides 24,000 kW of electricity, 170,000 pounds per hour of process steam, and 500 gallons per minute of hot water. The system is connected to a regional utility to which it sells surplus electricity and from which it buys supplementary electrical service, as the needs of the chemical plant vary below and above 24,000 kW respectively.

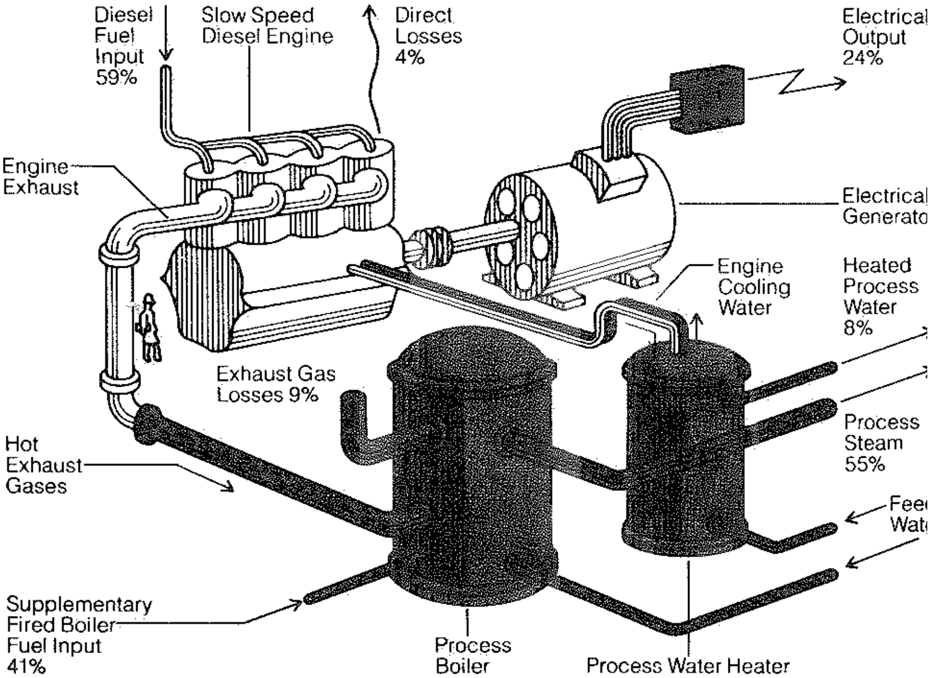


Figure 4 Diesel topping cycle cogeneration system schematic.

Low-grade residual fuel oil is burned directly in the cylinders of a large, 120 revolutions per minute, 2-stroke cycle diesel engine to produce shaft power that drives an electrical generator.

Heat exchangers recover a portion of the waste energy that would normally be lost from the power generation process. The exhaust gas from the diesel is used to preheat combustion air for the supplementary fired boiler, which produces process steam at a pressure of 225 pounds per square inch. The cooling water from the diesel is used to heat process water to 170° F.

Overall, the system utilizes 87% of the total heating value of the input fuel—24% as electricity, 55% as process steam, and 8% as process hot water. Waste energy recovery displaces over 450 barrels of oil per day that would have otherwise been consumed in conventional process boilers and water heaters to satisfy the thermal needs. The cost of the facility was $25 million and at the then prevailing electricity and residual fuel oil costs the payback period was about 3 years.

Total Energy System

A major proportion of the fuel supplied by gas utilities to residential, commercial, and small industrial customers is used for water heating and space heating of buildings. Because of the low temperature required by these end uses, the thermodynamic effectiveness of the process is less than 5%, i.e. 95% of the availability of the fuel is wasted. The effectiveness can be improved by use of cogeneration. For small power rating installations, the cogeneration unit is called a total energy system. An on-site total energy system uses about ⅓ less fuel than that consumed without such a system for the same electrical and heating needs.

For on-site total energy systems, market studies indicate an optimum installation size of 40–60 kW. This power rating happens to coincide closely with the output obtainable from typical American automobile and light truck spark-ignition engines operating at 1800 revolutions per minute on natural gas. A schematic of a total energy system using a 454-cubic inch V-8 engine block is shown in Figure 5. This unit employs an induction alternator and a series of heat exchangers to produce 60 kW of electrical power and 520,000 Btu per hour of process water heated to 180° and 260° F. Fuel consumption at rated output is 740 standard cubic feet of natural gas per hour.

The installed cost of the complete system is $500 to $600 per kW. Based upon current fuel and electricity prices, the system can have a payback period of 1–2 years in those regions of the country where electric utilities are experiencing low reserve margins and are confronted with severe difficulties in the siting and financing of new powerplants, such as Southern California.

The induction alternator of the gas total energy system would be connected to the electric utility grid. This allows the system to be operated in response to the on-site thermal demand. Excess (or deficit) electricity is sold to (or bought from) the electric utility. Alternatively, the total energy system might be sized to provide only the baseload thermal needs, with supplemental heat to match peak requirements supplied by a separate gas-fueled water heater or boiler. With sophisticated controls, the units could also be dispatched by the electric utility to provide additional capacity when the demand on the grid exceeds the utility's conventional capacity. Surplus process heat would be dumped during such periods.

The most economical applications for total energy systems are in those commercial or light industrial facilities that have a need for either process heat or space heat or both over a substantial fraction of the year. For example, hospitals, laundries, hotels and, in some areas, large apartment buildings can afford the necessary scale and the appropriate match between electrical load and heat demand needed to justify an on-site total energy system.

Total energy systems, using relatively large and costly special-purpose spark-ignition engines as prime movers, have been installed in several US cities over the past decade.

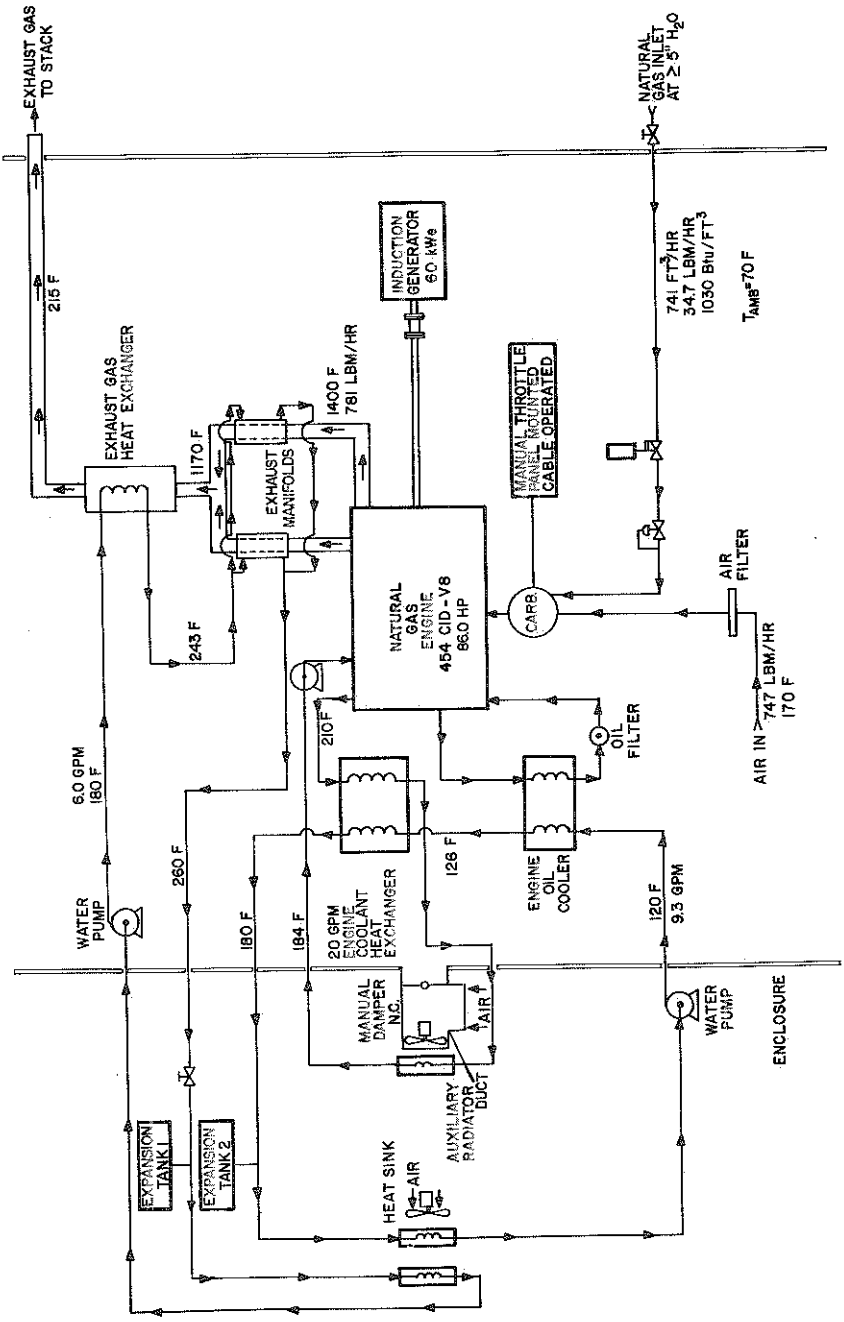


Figure 5 Gas total energy system schematic.

Organic Bottoming Unit for a Truck Diesel

The organic Rankine turbine is a power conversion system similar in principle to the commonly known steam engine. Instead of water, however, the system uses a hydrocarbon-based liquid as the working fluid within the hermetically sealed engine. By appropriate matching of specific working fluids, turbines, pumps, and heat exchangers, it is possible to tailor organic Rankine turbines to a wide spectrum of waste energy recovery applications. No other practical power conversion device can match the efficiency of the organic Rankine turbine for recovering waste energy in the temperature range from about 400° to 750° F, a range corresponding to both the waste energy temperature of many industrial processes and the exhaust of most internal combustion engines.

The organic Rankine turbine technology has been under development for about 15 years. During that period effort has been applied to working fluid studies, component development, system design, applications engineering, and full-scale testing of complete power systems, ranging in size from a few horsepower to thousands of horsepower.

One potential application of this technology is by long-haul diesel trucks (23). The organic turbine can be used as a bottoming unit to produce additional shaft power from the waste energy of the exhaust gas of the diesel. In a typical installation, up to 40 additional net horsepower can be extracted from the exhaust gas of a 285-horsepower diesel engine. The additional power, transmitted by gears to the diesel engine's output shaft, can provide about 15% lower fuel consumption over the average driving profile of a heavy-duty tractor-trailer combination.

The mode of operation of the bottoming unit is outlined in the system flow schematic in Figure 6. Hot exhaust gas, approximately at 950° F at full power when the diesel runs at 2100 rpm, passes through a boiler (vapor generator) where the organic working fluid is transformed to a vapor at 600° F temperature and 800 pounds per square inch pressure. The vapor expands through a small single-stage turbine in the power conversion module, delivering supplemental power to the engine output shaft through a set of reduction gears. Part of the availability in the turbine exhaust vapor is recovered in a regenerator mounted on the power conversion module, and the remaining low-quality heat is transferred to cooling water in the condenser. Waste heat is rejected to the atmosphere by means of a separate radiator core mounted integrally with the diesel engine coolant radiator. After leaving the condenser, the organic working fluid passes through a feedpump. The high-pressure liquid then regains part of the energy transferred to the regenerator prior to entering the vapor generator to complete the cycle.

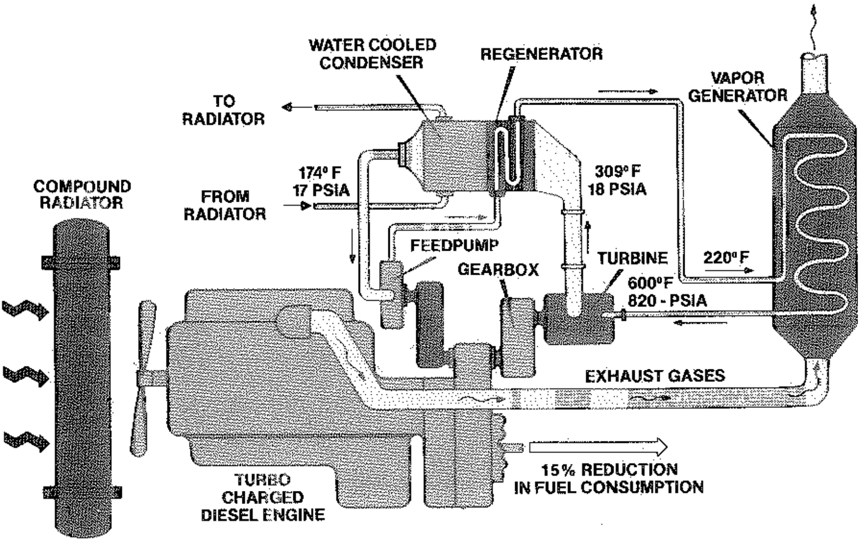


Figure 6 Organic Rankine bottoming cycle for truck diesel engine.

Prototype performance tests and 1000-hour endurance tests of a diesel plus organic Rankine turbine combination have demonstrated a minimum specific fuel consumption rate of 0.288 pounds per horsepower hour—the lowest fuel rate ever recorded by any vehicle powerplant. First generation engine systems have also completed over 40,000 miles of highway and proving ground testing in a tractor-trailer of 70,000 pounds gross combination weight. In a 3000-mile comparative test run, a prototype engine system resulted in actual fuel savings of 12.5% compared to an identical "diesel-only" tractor-trailer driven simultaneously over the same standard mountain and level highway course. A second generation prototype system raises the fuel savings to 15%.

The bottoming unit system will add approximately $10,000 to the cost of a typical $50,000 Class 8 highway tractor. However, the projected fuel savings should return this incremental investment in about 2 years. For the truck fleet operator, the impact of fuel costs has become so great that a 15% improvement in miles per gallon will translate into 30% higher net profit margins.

Chemical Plant Process Controller

Some of the fastest payback investments available today are found in the application of advanced control systems to energy-intensive processes. An improved sensor and control system installed at a fertilizer plant yielded full recovery of its cost in 26 days of operation of the plant.

The fertilizer plant is shown schematically in Figure 7. Fertilizer is made from natural gas feedstocks by means of an ammonia-urea process. The gas feedstock, used as a raw material for the fertilizer and not as fuel, comes from two different sources, one having a heating value of about 1050 Btu per standard cubic foot (SCF) and the other of about 930 Btu per SCF. These two gases are also very different in chemical composition. The natural gas supply switched frequently and abruptly from one gas source to another without warning, which resulted in expensive process upsets that caused the plant to operate below its intended capacity of 250 tons per day.

Orginally, the process was controlled by a gas chromatograph which provided feedback information (Figure 7) to regulate the ratio of nitrogen to hydrogen in the ammonia process. The hydrogen comes from the natural gas. However, the time response of this control scheme was about 10 min, thus any abrupt change in the composition of the natural gas affected the ammonia process before any action could be taken. As a result, substantial product loss occurred.

A new control scheme was installed (Figure 8) based on a real-time gas composition analyzer with feed-forward commands. The new controller detects changes in gas composition and automatically adjusts the nitrogen feed rate to compensate for the changes before the ammonia process can be affected. As a result, the use of natural gas has been reduced by 3%, i.e. 3% less feedstock per unit weight of fertilizer. That advantage alone is

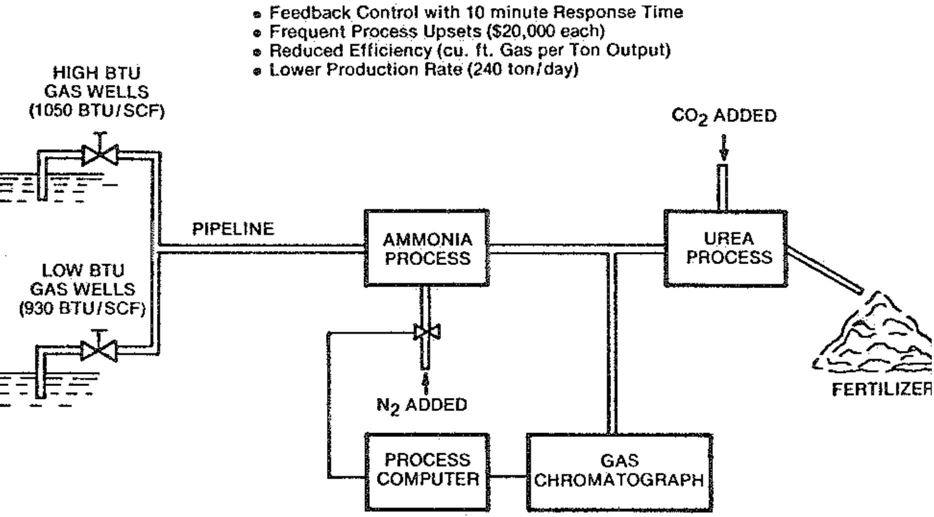


Figure 7 Conventional process control.

worth around $350 a day. Because of better control, the plant is also able to increase capacity, not only under routine processing, but also during upset conditions. That benefit averages about $550 a day. The cost of the gas analyzer, including installation was $23,500 and, therefore, the payback was 26 days.

Paper Machine Dryers

An advanced dryer system for a paper machine produces 190 tons of two-ply bathroom tissue per day. In order to achieve this production rate, 28,000 pounds of water per hour must be continuously evaporated from a 210-inch wide wet sheet at speeds exceeding 60 miles per hour. The wet sheet is dried as it passes over a rotating 16-foot diameter cast-iron drying cylinder.

Part of the evaporation is achieved by heating the inside of the cast-iron cylinder with steam at a pressure of 165 pounds per square inch. The balance of the evaporation is provided by hot air at 900° F impinging against the wet sheet on the outside of the cylinder. The steam and hot air systems and their controls are combined in an integrated unit. This combination allows not only the maintenance of air and steam conditions within desired limits for maximum drying efficiency but also extensive use of energy recovery techniques. In this system, compressors are used to recycle 40% of the cylinder exhaust steam, and economizers and heat exchangers

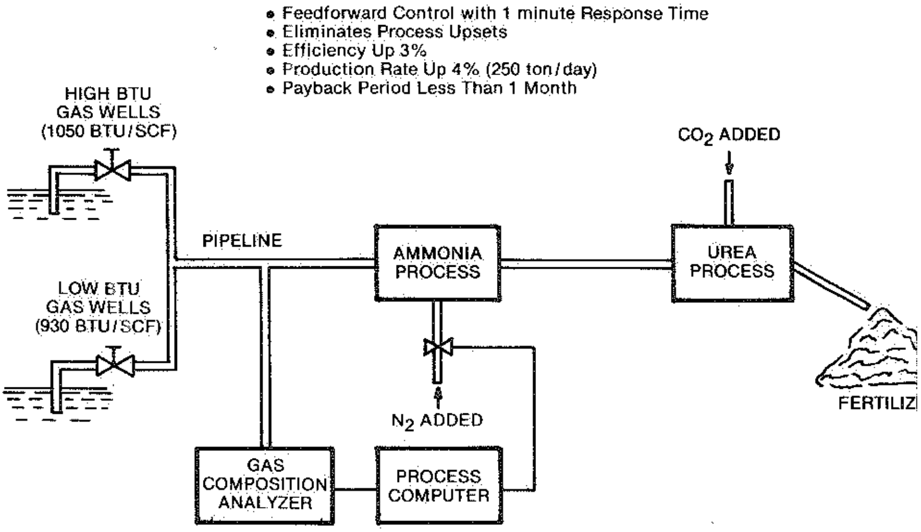


Figure 8 Feedstock composition analyzer control.

are employed to utilize flash steam from the condensate system and exhaust air from the drying system to heat large quantities of mill process water. This water is utilized in showers that clean the paper machine felts and for preheating paper stock. (See Figure 9).

The integrated energy system approach used for this installation yields savings of 25 million Btu per hour, equivalent to 100 barrels of oil per day, over systems without waste energy utilization.

Another example illustrates the economic benefits of better process control. Here, the integrated dryer processes 150 tons of paper products per day. It operates 8000 hours per year and consumes natural gas fuel costing $3.50 per million Btu. Without a moisture controller, the dryer operators frequently overdry the paper, to be on the safe side, using excessive quantities of fresh air and, thus, excessive fuel. As a result, the moisture content of the air circulating in the dryer after leaving the drying zone is too low. The inefficiency was eliminated by use of a controller, which measures the moisture content of the air and adjusts the air flows in the dryer so as to maintain a value of about 0.4 pounds of water per pound of air, rather than the typical 0.2 value found in standard dryer operations. The total cost of the controller was $440,000, and annual fuel savings $224,000, i.e. a payback period of less than 6 months.

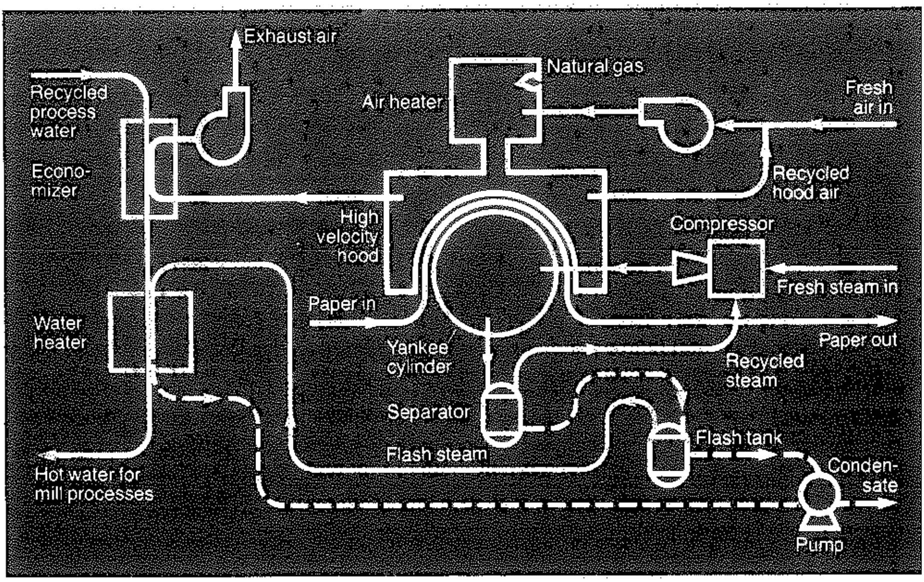


Figure 9 Energy recovery system for paper dryer.

Industrial Furnace Recuperator

Recuperators afford a highly cost effective means for saving fuel in a variety of high-temperature industrial furnaces. The amount of waste energy in furnace flue gases is directly related to the processing temperature. For example, exhaust gases leaving a furnace at 1700° F contain almost half of the total heating value of the fuel, and about half of this waste energy can be saved with recuperators.

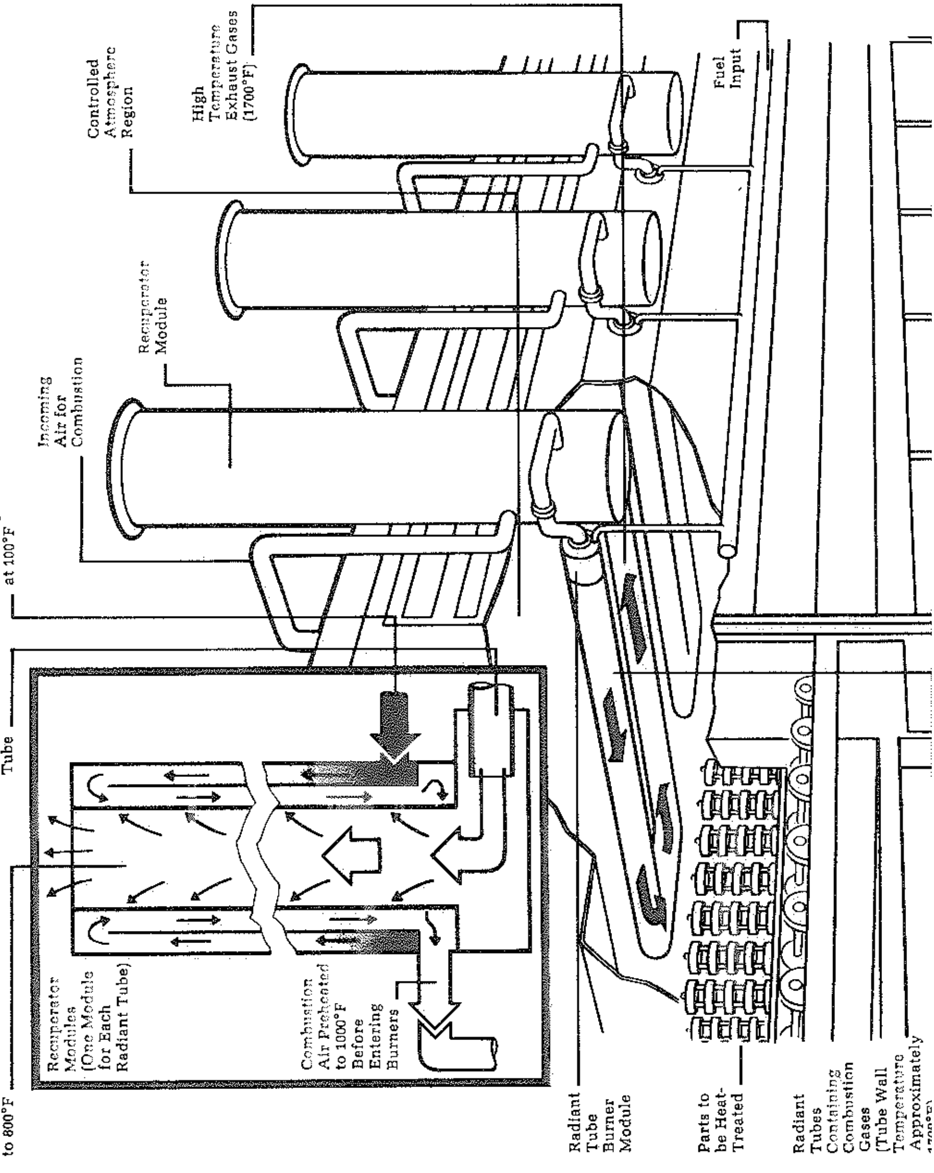
As already discussed above, a recuperator is a heat exchanger that transfers energy from the high-temperature flue gases to the lower-temperature air used for combusting the fuel. Thus, less energy is needed to raise the air-fuel mixture to processing temperature and, therefore, less fuel is consumed. Recuperators have payback periods of about 6 months.

Design of a recuperator requires an efficient balance between heat transfer and flow velocity. Although high flow velocities can increase the heat transfer coefficient, they also cause excessive pressure drops. With a low-pressure drop design, furnaces operate efficiently without the need for high-pressure air blowers or excessive furnace pressures.

A typical recuperator design for radiant-tube heat-treating furnaces is shown in Figure 10. The unit consists of three concentric cylinders. The hot exhaust gases flow upward through the inner cylinder, or flue. Cold combustion air enters at the bottom of the outer cylinder, flows upward and then down through the middle cylinder, and exits from the bottom of the middle cylinder. The double pass air flow pattern improves the heat transfer efficiency, reduces exterior heat losses, and simplifies the air piping. Waste energy from the exhaust gases is transferred through the inner cylinder wall to the combustion air by the combination of convection and radiation heat transfer. The net effect is preheated air temperatures as high as 1000° F, with inlet exhaust gases entering at 2000° F and exiting at 1300° F.

An automobile manufacturer, after fitting recuperators to an existing radiant tube heat-treating furnace several years ago, ran comparison fuel consumption tests against an identical furnace without recuperators. These batch-loaded furnaces operated at 1525° F and processed 500 pounds of alloy steel parts at each furnace cycle. The heating time required was 33 min for the unrecuperated furnace and 34 min for the furnace equipped with recuperators. The heat-treating cycle time, including the soaking period, was 92 min for both furnaces.

The amount of fuel saved depended on furnace conditions. For example, when the furnace was at full fire, the recuperator saved 29%, but when the furnace was idling, the saving was only 14%. Based on a 6-day week operation and 12 one and a half hour cycles per day, and the remaining time at idle, without recuperation the batch furnace consumed 4.5 million cubic


Controlled Atmosphere Region
High Temperature Exhaust Gases (1700°F)
Recuperator Module
Incoming Air for Combustion
at 100°F
Tube
to 800°F
Fuel Input
Recuperator Modules (One Module for Each Radiant Tube)
Combustion Air Preheated to 1000°F Before Entering Burners
Radiant Tube Burner Module
Parts to be Heat-Treated
Radiant Tubes Containing Combustion Gases (Tube Wall Temperature Approximately

feet of gas per year. With recuperation, however, the fuel consumption was 19% less.

In some special instances, such as open-type radiant tube burners using eductors, the fuel savings with recuperators and sealed-head burners is as high as 35%. This is due to the inherently low efficiency of the eductor-burner system design and, therefore, the greater opportunity for fuel savings.

Heat-Pipe Water Heater

An improved water heater with reduced heat loss has been designed around the unique properties of the heat pipe. Contemporary gas-fired storage water heaters are normally constructed with glass-lined steel tanks protected from corrosion by a sacrificial magnesium anode. The residential models include a flue, usually from 3–4 inches in diameter, extending through the tank and terminating in a vent hood connection at the top. A combustion chamber is attached to the bottom of the tank, the tank is insulated, an outer enameled steel jacket is added, and an atmospheric-type gas burner and control system are installed. Commercial heaters differ in that they either use a larger number of internal flues (as many as 12), or pass the flue gases around the outside of the tank in a "floater" design in order to accomplish the higher heat transfer required in commercial installations.

Both the center flue and floater designs result in a continuous heat loss from the stored water when the burner is not operating. The flue is at essentially stored water temperature and promotes a thermal circulation of air through the flue and out the vent system. This can result in an overall utilization of less than 40% of the heating value of the fuel, even though during burning the flue gas carries less than 30% of that value. A heat pipe can significantly improve this utilization.

The heat-pipe water heater concept is illustrated in Figure 11. The water heater consists of a plastic, 40-gallon storage tank with a conventional plastic cold water dip tube, a drain valve, and an immersion thermostat. The tank rests on a cylindrical base that contains the combustion system and heat-pipe assembly. The combustion system consists of a 40,000 Btu/h forced draft burner, which directs hot flue products across the evaporator surface of a heat pipe. The flue gases are then collected and exhausted through a small diameter vent pipe.

Since the heat pipe only transmits heat into the tank when the burner is fired, and resists heat transfer out of the tank during standby conditions, overall losses are greatly reduced. Overall utilization of the heating value of the fuel exceeds 60%, or 1.5 times that of the conventional water heater.

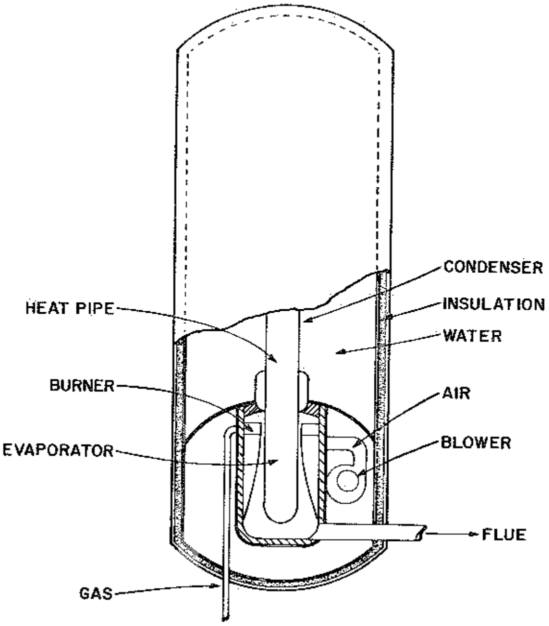


Figure 11 Heat pipe application to home water heater.

The payback period for a typical residential installation is 3 to 5 years at current gas prices.

Steam Heat Pump

In many industrial processes, large quantities of energy are discharged in the form of low-pressure waste steam and low-grade waste heat. Economical energy recovery is limited by the low temperature levels and in some cases by contamination of the steam. In industrial processes that utilize steam directly or as a mode of energy transport, such waste energy can be efficiently upgraded to high-pressure steam by means of an open-cycle steam heat pump system.

Such a system (Figure 12) compresses low-pressure waste steam to the desired pressure level for process use. The compressor is driven by a gas-fired prime mover such as a gas turbine or reciprocating engine. To maximize efficiency, the prime mover's exhaust and cooling water waste energies are also recovered to generate additional process steam or hot water.

The steam compressor is analogous to a heat pump where mechanical work is used to upgrade energy from a low- to a higher-temperature level. Fuel consumption can be as little as 30% of that needed for a direct-fired boiler, because the major fraction of the energy in the steam is already

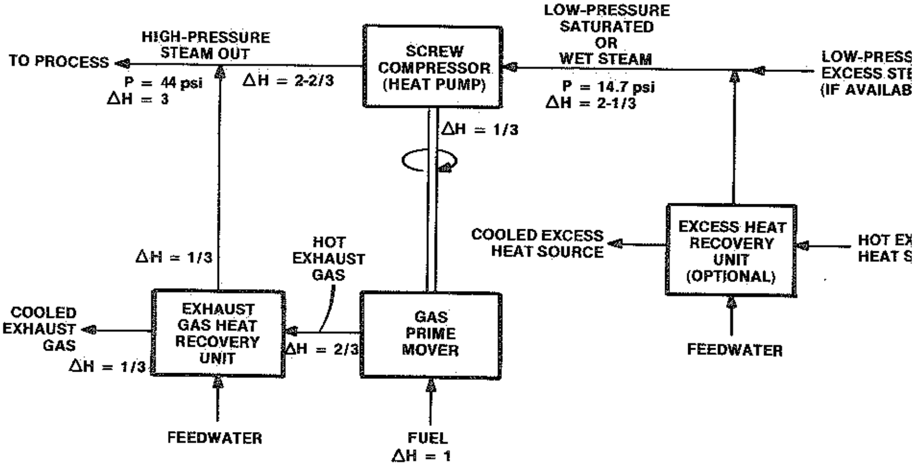


Figure 12 Steam heat pump schematic.

available to the compressor as latent heat. Thus, only a small fraction of additional energy is required to raise the pressure. Depending on the nature of the waste energy or steam source, the steam flow rate and pressure ratio, and fuel prices, the payback period of a steam heat pump is between one and three years.

A demonstration system has been built and is currently undergoing performance testing (24). The test unit is based on a 220 cubic feet per minute screw compressor driven by a 500-horsepower industrial gas engine. Nominal steam flow rate is 10,000 pounds per hour at an inlet pressure of 30 pounds per square inch and an outlet pressure of 90 pounds per square inch. After testing of the operational and control features under controlled laboratory conditions, the unit will be installed in an industrial site for long-term demonstration.

Fume Incinerator

The recovery and utilization of energy from combustible waste material is illustrated by a fume incinerator applied to a curing and drying process. The waste energy recovery features of this system reduce process energy consumption from 54 million Btu per hour to 32.7 million Btu per hour, a decrease of 40%. This represents a savings in fuel costs of approximately $400,000 per year. Since the heat recovery components cost only $250,000, the payback period is less than 1 year.

The overall curing and drying installation system integrates four separate technologies into a single energy-efficient system. This includes through-drying of a fiberglass mat, curing of the binders in the mat, pollution abatement through incineration of the process exhaust fumes, and efficient recovery of waste energy from the exiting streams. Energy from the exiting zones of the through-dryer is recovered and transferred to the processed stream at the entering zones, thereby reducing the total energy requirements of the drying process. Exhaust from the dryer is delivered to the pollution control equipment, where contaminants in the air stream are thermally oxidized, which produces a harmless effluent consisting of carbon dioxide and water vapor. The heat of oxidation is recovered and used for the through-drying process. The total cost of this unit is $1.3 million of which only $250,000 are attributable to the waste utilization components.

Another similar installation provided fuel savings of $120,000 per year. The system cost was $300,000 of which $40,000 represented the added cost of the waste energy utilization equipment. Thus, payback for the energy saving features was only 4 months.

POTENTIAL BENEFITS AND BARRIERS

In the preceding sections we have shown that from the points of view of both sound economics and basic thermodynamics it is possible to become more efficient in our end uses of energy. We have given many examples of proven, reliable, and cost effective technologies that can accomplish this objective.

How much fuel can be saved through cost effective use of waste energy during the 1980s? As pointed out by physicist Niels Bohr "It is difficult to make predictions, especially about the future." The failures of numerous forecasts about energy supply and demand during the 1970s is a sobering proof of Bohr's belief. Nevertheless, we tentatively believe that during the 1980s it is possible to increase the goods and services in the US economy by about 25% and yet consume energy at about the present annual rate. By doing so, the nation will invest less scarce capital in the energy services sector and the consumer will be paying less for these services. Thus making use of waste energy can satisfy our needs.

Though profitable, investments in energy productivity encounter a number of barriers. Some barriers are practical, such as there not being enough space in an existing plant to retrofit the required waste energy utilization equipment; some are environmental, such as regulations that do not permit the use of a particular fuel in a specific cogeneration site; some are traditional, such as a manufacturer not being willing to become involved in the energy business because it differs from his own; some are inertial, such as lack of confidence in a technology that is not widely used by others; and, finally but most importantly, some are financial, such as lack of capital.

Even some of the larger US industries, such as steelmaking, have virtually no access to capital, except for very limited retained earnings, because their stocks sell at very low price-to-earnings ratios and their debt has reached the limit allowed by creditors. Limited availability of capital is even more pronounced in the residential and commerical sectors.

Despite these barriers, we sense that waste energy utilization is continuously gaining momentum and that substantial gains will be made in the next 10 years.

THERMODYNAMIC EFFECTIVENESS

Thermodynamic Availability of Bulk Flow Processes

Several approaches exist for establishing that availability change and not change in any other property represents the optimum (minimum or maximum) work requirement (input or output) of a process. One approach that results in the concept of availability is based on a combination of the energy and entropy balances.

The laws of thermodynamics imply the existence of two properties of any system in any state: energy and entropy (25). These properties are such that: (*a*) the energy of all the systems involved in a process is conserved, i.e. the energy of all the systems at the end of the process is equal to the energy at the beginning of the process, or the energy must be balanced; and (*b*) the entropy of all systems involved in a process either increases or remains invariant, i.e. the entropy of all the systems at the end of the process must be equal to or greater than the entropy at the beginning of the process. The statement regarding entropy can be written as an entropy balance by adding to the initial total entropy a nonnegative amount of entropy and saying that this amount is generated by irreversibility. If the process is reversible, namely, the best possible, the irreversibility is equal to zero. If the process is irreversible, namely, not the best possible, the amount of entropy generated by irreversibility is greater than zero. The more the process deviates from the best the larger the irreversibility. The energy and entropy balances are essential to any thermodynamic analysis.

The analytical expressions used to account for energy and entropy in the two balances just cited depend on the systems involved in the process, their initial and final states, and the types of interactions that they experience. Each set of circumstances leads to different expressions for the two balances. For example, if the systems involved in the process are simple and closed then internal energy of each system enters the energy balance equation.

We illustrate the two balances by considering a bulk flow, steady-state process (Figure 13) in a system with a fixed volume, and in which all

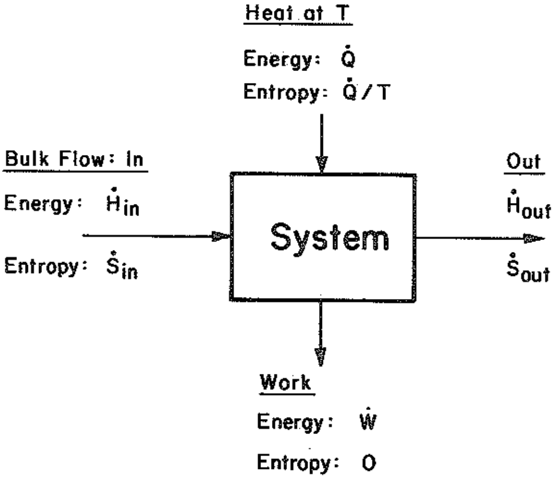


Figure 13 Energy and entropy rates in a bulk flow process.

potential and kinetic energy changes are negligible compared to enthalpic changes (ΔH) of the flowing stream. Many practical processes can be approximated as steady-state bulk flow processes.

A bulk flow stream supplies to the system energy and entropy at the steady rates $\dot{H}_{in}$ and $\dot{S}_{in}$, and carries away from the system energy and entropy at the steady rates $\dot{H}_{out}$ and $\dot{S}_{out}$, respectively. In addition, energy is supplied to the system in the form of work at the rate $\dot{W}$, and in the form of heat from a heat source at temperature T at the rate $\dot{Q}$. By definition, heat implies that the system receives entropy at the rate $\dot{Q}/T$.

The process in Figure 13 can be thought of as accomplishing one of two tasks: (*a*) the change in the state of the stream from input to output produces work and heat; (*b*) the change of the stream from input to output is accomplished by using work and heat.

Since the system is in steady state, the energy and entropy rate balances are:

Energy rate balance

$$\dot{H}_{in} - \dot{H}_{out} + \dot{Q} - \dot{W} = 0 \qquad 1.$$

Entropy rate balance

$$\dot{S}_{in} - \dot{S}_{out} + \frac{\dot{Q}}{T} + \dot{S}_{irr} = 0 \qquad 2.$$

where $\dot{S}_{irr}$ denotes the positive entropy rate due to irreversibility.

Multiplying Equation 2 by T_0, the temperature of the environment in which the process occurs, and subtracting the result from Equation 1 we find

$$\dot{W} - \frac{T - T_0}{T}\,\dot{Q} = [(\dot{H}_{\text{in}} - T_0\,\dot{S}_{\text{in}}) - (\dot{H}_{\text{out}} - T_0\,\dot{S}_{\text{out}})] - T_0\,\dot{S}_{\text{irr}} \qquad 3.$$

The term $[(T - T_0)\,/T]\,\dot{Q}$ is the work rate equivalent obtainable from a heat source at temperature T with respect to the environment at temperature T_0. Therefore, the left-hand side of Equation 3 is the work rate equivalent associated with the change of state of the stream. This work rate is optimum (minimum in, maximum out) if the process is reversible, i.e. $\dot{S}_{\text{irr}} = 0$, and the entropy change, $\dot{S}_{\text{out}} - \dot{S}_{\text{in}}$, is supplied by the heat source only (Equation 2). The only zero-cost heat source available is the environment at temperature $T = T_0$. By using the environment as the entropy source for the reversible process we find

$$(\dot{W})_{\text{optimum}} = (\dot{H}_{\text{in}} - T_0\,\dot{S}_{\text{in}}) - (\dot{H}_{\text{out}} - T_0\,\dot{S}_{\text{out}}). \qquad 4.$$

When the right-hand side of Equation 4 is positive, it represents the maximum work rate that can be done by the change of state of the stream from input to output, and when it is negative the minimum work rate required to change the stream from input to output.

The expression $\dot{H} - T_0\,\dot{S}$ is a characteristic of the state of a flowing stream and the environment. It is called an availability rate function. Its usefulness lies in the fact that its change from state to state yields the optimum work rate required by the specified change of state. Other availability expressions result for other circumstances, but changes of each of them from state to state relate to optimum work.

Effectiveness

Associated with each task in our economy is a minimum amount of work needed to accomplish the task out of materials in our environment. Similarly, associated with each unit of fuel or energy source is a maximum amount of work that we can extract. We can express each amount of work as a change in the appropriate availability function.

If a task requires an amount of work W_{minimum} for its accomplishment, but consumes an amount of fuel that could have produced an amount of work W_{maximum} if used under perfect conditions, then the effectiveness with which fuel was used in the task is given by the relation

$$\eta_e = \frac{W_{\text{min}}}{W_{\text{max}}}.$$

In a perfect (reversible) process, $W_{\min} = W_{\max}$ and $\eta_e = 1$. To the extent that the process deviates from perfection (irreversible process), $W_{\min} < W_{\max}$ and $\eta_e < 1$.

In general, availability analysis (as well as other analyses) requires specifying the task to be performed, and evaluating availability changes of feedstocks and energy sources. Because of practical limitations, specifying a task is more often than not relative and not absolute and, therefore, availability analyses yield results that are relative to existing knowledge and technology.

For example, a common process encountered in industry is the heat treating of alloy steel parts to produce a locally hard surface (e.g. bearing or gear tooth wear surface). Though only a very small fraction of the material actually needs to be hardened, conventional technology has required that the entire part be heated to about 1650° F, then quenched at 350° F in oil to produce a hard martensite structure in the steel.

One way of specifying the task is to say that the total mass of the part must be heated to 1650° F. Another way is to specify that only a small fraction near the surface of the material need be hardened. The availability change required by the first task is substantially different from that required by the second. The results of the two availability analyses, however, are not comparable to each other, because the tasks are different. They cannot be compared to each other, just as the task of making pig iron in a blast furnace cannot be compared to that of making aluminum in an electrolytic cell.

In the example of steel hardening, the second specification of the task has, of course, little practical significance. However, the lower availability change required by the second task can provide useful guidance for innovative approaches to the problem of metal hardening. In fact, recent developments in high-power lasers and electron beam accelerators have led to the development of practical processes for localized heat treating. In one carburizing application, for example, electron beam heat treating has reduced total energy needed for a particular part from 3700 Btu to only 80 Btu. Thus, by redefining the task, the required availability was lowered well below the level previously thought to be ideal.

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