93

4

Availability Analysis: The Combined Energy and Entropy Balance

ELIAS P. GYFTOPOULOS
Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139
THOMAS F. WIDMER
Thermo Electron Corporation, 101 First Ave., Waltham, MA 02154

The Measure of Efficiency

Availability analysis, i.e., the combined energy and entropy balance, has long been recognized as the most appropriate method for evaluating losses in, and efficiency of, processes. Despite this recognition, the use of availability for routine analyses of efficiency is far from commonplace. Apart from the power conversion field, in fact, many engineers still rely upon simple energy balances in their consideration of equipment and process design tradeoffs.

With rising energy prices and curtailment of supplies for certain high-quality fuels, there is a need to promote wider use of the concept of availability for all types of energy end-use assessments, both because it provides a better measure of the margin for improvement and because it discloses the real sources of inefficiency.

Currently, there is an enormous disparity between the most efficient and the least efficient processes and products in use today. A review of selected process and equipment efficiencies can provide a useful guide for establishing research and development priorities.

In general, availability analysis (as well as energy analysis) 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 (about 2% of the volume) of the material need be hardened. The availability change required by the first task is substantially different than that 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 the task 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 to R&D planners looking 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 (1). 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.

With regard to evaluations of availability changes (of either feedstocks or energy sources) we note that they require knowledge of the thermophysical properties and the initial and end states of the materials involved in the task. Such evaluations can be tedious. But in some widely used processes, a change in availability can be expressed as a product of a quality factor times the appropriate energy change, where the quality factor is a simple or tabulated function of some characteristic thermodynamic variable. Thus, the absolute thermodynamic efficiency η_α can be written in the form (2)

$$\eta_\alpha = \frac{C_2 \Delta E_2}{C_1 \Delta E_1} = \frac{\text{change in availability required by the task}}{\text{change in availability consumed by the task}}$$

where

ΔE_2 = energy required by the transformation induced by the task
C_2 = quality of the required energy
ΔE_1 = total primary energy (equivalent fuel energy) consumed in the task
C_1 = quality of the consumed energy

Quality is an important characteristic of energy because, as is well known, an amount of energy at high temperature is more useful and more valuable than an equal amount at low temperature.

Of course, any change in availability can be expressed as a product of a quality factor times an energy change, and values of efficiencies can be calculated for complete processes, such as the transformation of wood into a special type of paper, or of iron ore into a special steel. The results vary widely, even for slightly different types of the same product (e.g., hardened steel versus steel ingots). But values of efficiencies can also be determined for specific stages in a process (e.g., steam raising at specified conditions, or heat treating at a given temperature). For these stages, the results are numerically simple and are almost independent of the product (i.e., uniquely related to the equipment in question and its function). Examples of tasks that fall into the category just cited are:

- Heating of stock (such as steel parts) without chemical reactions or phase changes
- Raising of steam
- Generation of motive power and electricity
- Space conditioning (heating or air conditioning)

Each of these tasks requires an amount of energy, ΔE_2, of a certain quality, C_2. For a given level of output, the energy demand, ΔE_2, can be readily calculated by means of standard procedures. Its quality, C_2, on the other hand, can be evaluated as follows:

- If the task is generation of motive power or electricity,

$$C_2 = 1.0$$

- If the task is raising of steam at specific conditions

$$C_2 = 1 - 530 \frac{\Delta s}{\Delta h}$$

where Δs and Δh are the entropy and enthalpy changes from water at environmental conditions ($T_o = 70^oF$) to steam at the desired conditions.

- If the task is heating of stock at a particular temperature T (^oF)

$$C_2 = 1 - \frac{530}{T - 70} \ln \frac{T + 460}{530} \quad .$$

This expression is essentially the same as that for steam except that here Δs and Δh are readily expressible as functions of T by using the perfect gas relations.

Values of C_2 for certain steam conditions or for heating of stock are listed in Table I.

The energy required by each of the functions in question is satisfied by consuming fuel, electricity, or recovered waste heat. For each fuel, the energy, ΔE_1, is computed by using the heating value of the fuel. For electricity, the energy is the number of kWh consumed times 10,000 Btu per kWh because most electricity is generated from fuels at a rate such that one unit of electricity requires about 3 units of primary fuel energy. For waste heat, the energy is found by considering changes in the energy content of the material that carries the waste heat.

Table I.
Quality C_2 of Energy Demand
For Raising Steam and Heating Stock

Saturated Process Steam	
Pressure psia	Quality C_2
30	0.235
50	0.26
100	0.295
200	0.33
400	0.36
600	0.38

Heating of Stock	
Temperature °F	Quality C_2
100	0.03
200	0.11
300	0.17
400	0.22
500	0.27
1000	0.42
1500	0.53
2000	0.58
3000	0.66
4000	0.71

The quality factor, C_1, for most conventional fuels can be taken to be near 1.0 (i.e., availability is almost identical to the heating value for petroleum, coal, and natural gas fuels). For other fuels, such as low-Btu gas, waste materials, lignite, etc., the term $C_1\Delta E_1$ should be calculated on a case-by-case basis. Where waste heat gases at constant pressure or steam are used as input energy to a process, C_1 is determined in the same manner as C_2 for output energy qualities (Table I).

The task-related efficiency can be evaluated either for a single piece of equipment or for several pieces collectively. It can also be applied to equipment with different types of materials (outputs) being processed and several forms of energy being supplied. The energy-quality product for each output is evaluated as discussed above and the results are additive. Moreover, the energy-quality product for each of the energies supplied is computed as above and the results are additive. The overall efficiency is the ratio of the two sums.

It is noteworthy that the ratio $\Delta E_2/\Delta E_1$ instead of $C_2\Delta E_2/C_1\Delta E_1$ is commonly used as a measure of efficiency for processes and devices. Though well defined, the ratio $\Delta E_2/\Delta E_1$ neither reveals the enormous opportunities for energy saving nor addresses the real causes of inefficiency.

Illustrative Examples

Low-Temperature Processes. A residential water heater provides a striking example of how a simplified availability analysis of efficiency can be applied. Typically, a gas- or oil-fired water heater will have an energy, or so-called "first-law" efficiency, of about 75% during operation; that is, the device will transfer about 3/4 of the fuel heating value into the enthalpy rise of the water. Due to standby losses, the overall in-service "efficiency" of the water heater is reduced to about 40%. Therefore, $\Delta E_2/\Delta E_1$ is 0.4.

Since domestic water heaters are required to deliver their output at only 140°F, the availability efficiency of such a unit is, of course, much lower than 40%. If the heater is fueled by a hydrocarbon, then $C_1 = 1.0$ and the quality, C_2, can be calculated by the expression for liquids or solids having near-constant specific heat; that is,

$$C_2 = 1 - (\frac{530}{140 - 70}) \ln \frac{140 + 460}{530} = 0.06$$

Thus, we find that the efficiency of the hydrocarbon-fired water heater is

$$\eta_\alpha = (\frac{C_2}{C_1})(\frac{\Delta E_2}{\Delta E_1}) = (\frac{0.06}{1.0})(0.4) = 2.4\%$$

If the water heater is electric, then

$$\frac{\Delta E_2}{\Delta E_1} = 0.85 = \frac{\text{enthalpy delivered to water}}{\text{electricity input}}$$

This ratio, which includes standby losses, is much higher than that for a hydrocarbon-fired unit because there is no heat leak through an exhaust flue. On the other hand, each unit of electricity input requires about 3 units of primary fuel and, therefore, with respect to the fuel consumed by the electric utility,

$$\frac{\Delta E_2}{\Delta E_1} = \frac{0.85}{3} = 0.28$$

Thus, we find that the efficiency of the electric water heater is

$$\eta_\alpha = (\frac{C_2}{C_1})(\frac{\Delta E_2}{\Delta E_1}) = (\frac{0.06}{1.0})(0.28) = 1.7\%$$

Equally small are the efficiencies of many industrial processes, particularly those involving low-temperature drying of materials such as food, textiles, or paper. This can be seen from an analysis of the efficiency of a dryer oven used to remove moisture from tobacco slurry. In this process, natural gas fuel is burned to produce hot combustion gases. These gases are then diluted with large quantities of excess air to provide drying gas at a temperature of 330°F. The drying gas impinges directly onto a moving conveyor carrying a thin sheet of tobacco-water slurry. In a typical installation, 5700 lb/hr of moisture is removed at a temperature of 130°F (or 1080 Btu/lb) by burning 15,000 ft^3/hr of natural gas (or 15.3×10^6 Btu/hr).

The "first law" efficiency of this process is

$$\frac{\Delta E_2}{\Delta E_1} = \frac{5700 \text{ lb/hr} \times 1080 \text{ Btu/lb}}{15000 \text{ ft}^3\text{/hr} \times 1020 \text{ Btu/ft}} = 0.4$$

On the other hand, considering the qualities of the energies used and required at 130°F, we find

$$C_1 = 1.0$$

$$C_2 = 1 - 530\left(\frac{\Delta s}{\Delta h}\right) = 1 - 530\left(\frac{1.8367}{1080}\right) = 0.1$$

and

$$\eta_\alpha = \left(\frac{C_2}{C_1}\right)\left(\frac{\Delta E_2}{\Delta E_1}\right) = \left(\frac{0.1}{1.0}\right)(0.4) = 4\%$$

The principal reason for this low efficiency is the availability loss caused by using high-quality fuel to perform a task that requires only low-grade energy.

The dryer example provides an excellent illustration of the opportunity that exists for both fuel substitution and fuel savings in most low-temperature industrial heating processes. It is often claimed that gas fuel is absolutely necessary for many processes requiring a clean environment in ovens, kilns, crop dryers, etc. This statement is true only for very high-temperature processes where heat exchanger problems might preclude the separation of combustion products from the stock-heating media. But for low-temperature applications, it is possible to use a separate combustion system, burning almost any type of fuel, and to heat clean air (through a heat exchanger) for delivery to a process oven or dryer. In addition, a topping engine can be installed for motive power or electricity with the required heat exchanger attached to the exhaust of the engine. In this way, the clean process environment is retained and efficiency is improved manyfold.

For the tobacco dryer system previously cited, it would be possible to provide the 15.3×10^6 Btu/hr of heated air by recovering waste heat from the exhaust gases and water jacket of a diesel engine generator set. Fuel effectiveness of the system is increased because a substantial part of the fuel availability is usefully employed to make byproduct electricity, and only low-grade exhaust heat is employed for the actual drying operation.

An energy balance of the system with the topping engine shows the following distribution of outputs (relative to fuel input):

$$\begin{aligned} \Delta E_1 &= \text{energy input} \\ \Delta E_2^{\ I} &= 0.45\Delta E_1 && = \text{energy to process air} \\ \Delta E_2^{\ II} &= (0.4)(0.45)\Delta E_1 && = \text{energy to evaporation process} \\ \Delta E_2^{\ III} &= 0.35\Delta E_1 && = \text{electricity} \\ \Delta E_2^{\ IV} &= 0.20\Delta E_1 && = \text{losses} \end{aligned}$$

Thus, the availability efficiency is

$$\eta_\alpha = \frac{C_2^{\ II}\Delta E_2^{\ II} + C_2^{\ III}\Delta E_2^{\ III}}{C_1\Delta E_1}$$

$$= \frac{(0.1)(0.4)(0.45)(\Delta E_1) + (1.0)(0.35)(\Delta E_1)}{(1.0)(\Delta E_1)} = 36.8\%$$

Total fuel consumption of the combined system will be 34 x 10^6 Btu/hr, an increase of 18.7 x 10^6 Btu/hr over conventional practice. Electricity output, however, amounts to 3500 kW, and this represents an incremental fuel rate of 18.7 x 10^6/3500 = 5340 Btu/kWh. Thus, there is a saving of at least 4000 Btu/kW relative to electricity produced by central station powerplants.

Obviously, the topping engine approach will cost far more than a simple, once-through system using only a gas burner with air dilution ports. Also, means must be found to use the byproduct electricity in other operations at the same site, or to deliver the power to a utility grid. The critical consideration from a national viewpoint, however, is the fact that this conservation measure will yield much more energy per dollar of capital invested than will comparable investments in new energy supply.

In another type of dryer, steam is used to transfer heat into large steel rolls over which paper is passed at high speed to remove moisture added in the forming process (3). Typically, the paper web temperature is held to about 170°F. Steam is introduced to the rolls at about 50 psig, with about 2.2 pounds of steam needed to remove each pound of moisture. Process boilers are commonly fired by either residual oil or coal, augmented by waste material such as wood chips and spent pulp liquors.

In a large machine, moisture is removed at a rate of about 30,000 lb/hr, necessitating a steam flow of 66,000 lb/hr. Boiler efficiency (first law) is usually about 0.88; therefore, the fuel energy requirement is

$$\Delta E_1 = 66{,}000 \text{ lb/hr} \times 1136 \text{ Btu/lb} \times \frac{1}{0.88}$$

$$= 85 \times 10^6 \text{ Btu/hr}$$

For the boiler, C_1 is approximately 1.0 and C_2 (from Table I) is 0.26 and therefore,

$$\eta_B = \frac{C_2 \Delta E_2}{C_1 \Delta E_1} = \left(\frac{0.26}{1.0}\right)(0.88) = 23\%$$

The dryer output (ΔE_3) is represented by the moisture removed.

$$\Delta E_3 = 30{,}000 \text{ lb/hr} \times 1096 \text{ Btu/lb} = 32.9 \times 10^6 \text{ Btu/hr}$$

the input steam quality factor is $C_2 = 0.26$, and the output moisture quality C_3 is given by

$$C_3 = 1 - 530 \left(\frac{1.7548}{1096}\right) = 0.15$$

Hence, dryer efficiency is

$$\eta_D = \frac{C_3 \Delta E_3}{C_2 \Delta E_2} = \frac{(0.15)(32.9 \times 10^6)}{(0.26)(85 \times 10^6 \times 0.88)} = 25.5\%$$

Overall system efficiency is the product of the boiler and dryer efficiencies:

$$\eta_\alpha = \eta_B \times \eta_D = 0.23 \times 0.255 = 5.8\%$$

Once again, the advantages of a topping cycle are obvious. In practice, many paper mills use high-pressure boilers with back-pressure steam turbines to produce about 50 kW of electricity for every 1000 lb/hr of process steam. Much greater electrical output and higher overall efficiency could be realized if a portion of the steam were supplied by using diesel engines with recovery boilers. Large two-stroke diesel engines can burn residual fuel. If used in the example shown here such engines would be able to provide as much as 26,000 kW of byproduct electricity. Overall efficiency of the process would rise from 5.8% for the simple system to 16.1% for the back-pressure turbine topping cycle, and to 35.3% for the diesel topping cycle.

Vehicle Performance. Efficiency of a vehicle can also be calculated directly from input-output considerations. As we might expect, its value depends on the definition of the task to be performed. If, for example, the task is defined as moving X passengers from point A to point B without change in elevation, then the overall efficiency of a typical automobile, based on either energy or availability changes, would be zero. Though correct, such a result is of no practical use.

Another way of defining the task might be to establish a certain mass and frontal area of vehicle needed to obtain a particular level of comfort and safety, and to set specifications for the rate of speed and acceleration desired. Then the availability required for moving X passengers from point A to point B can be calculated from the rolling resistance and drag forces and compared to the availability consumed.

A still different approach would be to use the actual figures for drag and rolling resistance of a specific vehicle (e.g., 1978 Chevrolet Sedan weighing 4200 pounds). The actual horsepower delivered to the road can then be integrated over the time of a specific driving cycle (e.g., EPA Metro-Highway program) or running at a constant speed. Dividing this actual work done by the fuel availability consumed over the test period gives an average efficiency for the vehicle.

This might be called a "machine efficiency," since it ignores any possibilities for improvement which might result from modifying the task. For example, reducing vehicle weight by using lighter materials or lowering aerodynamic drag by streamlining would not change the calculated efficiency. The figure would be affected, however, by any propulsion system improvements such as reduced engine friction, lower accessory losses, or better matching between engine and power train.

Applying the "machine-efficiency" definition to a typical automobile operating at steady 50-mph speed on level road, the only data required are the road load fuel consumption and total drag figures. For a particular Ford Galaxie weighing 4576 lb, the measured figures were 18.5 mpg at 50 mph with total drag (windage and rolling) of 157.5 lb force. On the basis of these data we find:

ΔE_2 = rate of output work

$$= \text{Drag} \times \text{Velocity} = \frac{157.5 \text{ lb} \times 50 \text{ mph} \times \left(\frac{5280}{3600}\right)}{550 \text{ ft \#/Sec hp}}$$

$$= 21 \text{ hp} = 53{,}500 \text{ Btu/hr}$$

ΔE_1 = rate of input fuel availability

$$= \frac{50 \text{ mph}}{18.5 \text{ mpg}} \times 6.1 \text{ lb/gal} \times 18{,}500 \text{ Btu/lb}$$

$$= 305{,}000 \text{ Btu/hr}$$

C_2 = 1.0 because the output is mechanical work

$C_1 = 1.0$ because the availability of gasoline is almost equal to its heating value

and

$$\eta_\alpha = \left(\frac{1.0}{1.0}\right)\left(\frac{53{,}000}{305{,}000}\right) = 17.5\%$$

This efficiency is relatively high because 50-mph road load represents a near optimum condition for the engine and transmission. In-service efficiencies will generally be lower because of both off-optimum running and losses incurred from acceleration and braking. Regenerative braking (instead of friction) is one possible method for reducing the work loss in a vehicle that must operate with frequent stops and starts.

Heavy diesel trucks have considerably higher efficiency than automobiles, due to the greater efficiency of diesel engines relative to spark ignition engines, and because of the lack of significant light-load operation during normal running.

Test data for a 72,000-lb (gross combination weight) tractor-trailer illustrate this point. The tractor is powered by a 676 in.^{3} turbo-charged and intercooled Mack diesel. When driven over a standard test route (NAPCA Control Route), the engine output as a percentage of time is that given in Table II.

Table II.
Duty Cycle for Mack Diesel Tractor-Trailer
Over NAPCA Control Route Driving Cycle

Horsepower	Percent time at given horsepower
Below 165	15.1
165 to 225	1.6
225 to 270	9.5
270 to 300	73.0

Average work delivered to the road is 261 hp over the entire cycle, with a fuel consumption rate of 104 lb/hr (an average of about 3.5 mpg). Thus, vehicle efficiency is given by

$$\eta_\alpha = \frac{C_2 \Delta E_2}{C_1 \Delta E_1} = \frac{(1.0)(261)(2546)}{(1.0)(104)(18{,}500)} = 34.5\%$$

This represents a machine efficiency roughly equal to that of central station electric power production and distribution. Even higher efficiency can be obtained with a new experimental compound engine system. Known as an organic Rankine bottoming cycle, this powerplant derives about 38 hp (at full load) from the waste heat of the truck engine. Organic fluid is vaporized in an exhaust gas boiler, expanded through a small turbine, and condensed in a heat exchanger cooled by the truck radiator. Turbine power is geared directly into the transmission and thus augments the diesel output. Laboratory tests of the complete powerplant have demonstrated an improvement of 13% in fuel economy over the simulated driving cycle and, therefore,

$$\eta_{\alpha}' = (0.345)(1.13) = 39\%$$

Applying this improvement to just the long-haul segment of the heavy truck fleet would yield savings of over 100,000 barrels of distillate fuel per day.

Chemical Processes. For complex chemical or metallurgical processes, the evaluation of availability flows requires more elaborate calculations.

The production of ammonia from natural gas (methane) provides an illustrative example. In a paper by L. Rieker (4), the common process for ammonia production is represented by the schematic of Figure 1. Material flows between process units is defined by the vertical bars, the width of the bars indicating relative magnitude of the availability.

Table III summarizes the availability values of each stream, prorated on the basis of each ton of ammonia output. The loss at each stage of the process is given in Table IV. Overall efficiency of the complete process is given by

$$\eta_{\hat{\alpha}} = \frac{\text{Availability Content of Ammonia Output}}{\text{Availability Content of Methane Input}}$$

$$= \frac{17.5 \times 10^6 \text{ Btu/ton}}{31.4 \times 10^6 \text{ Btu/ton}} = 0.56$$

Thus, well over half of all the availability contained in the methane feedstock is contained in the ammonia produced by this process. An alternative process for making ammonia from water and air, using electricity produced from coal, has an overall efficiency of only about 17%.

Another example of a process involving chemical transformation is the blast furnace used in converting iron ore (Fe_2O_3) into molten iron (5). In fact, the blast furnace is not simply a furnace but is actually a highly efficient counterflow thermochemical reactor. The enthalpy and availability figures for a typical blast furnace (Table V) show that 75% of the availability contained in feed materials is preserved in the output iron and byproduct fuel gases (principally CO).

Table III.
Availability Content of Process Stream
in Ammonia Plant

Process stream (numbers refer to Figure 1)	Availability (Btu per ton of NH_3)
(1) methane input	31.4×10^6
(2) intermediate mixtures	24.7
(3) intermediate mixtures	23.6
(4) intermediate mixtures	21.7
(5) H_2, N_2	21.4
(6) CO_2	0.16
(7) H_2, N_2	21.3
(8) purge gas	2.5
(9) NH_3 output	17.5
(10) Steam	4.46
(11) Steam	1.42
(12) Steam	0.1

Table IV.
Distribution of Losses
in Ammonia Process

Process stage	Loss of availability (Btu per ton of NH_3)	Stage Efficiency
Primary Reformer	4.79×10^6	0.85
Secondary Reformer	1.10	0.96
Shift Conversion	0.53	0.97
CO_2 Removal	0.14	0.99
Methanation	0.10	0.99
Compression Synthesis	7.08	0.74

Table V.
Enthalphy and Availability Balance
for Blast Furnace

(All Units 10^6 Btu/ton Pig Iron)

	Enthalpy	Available Useful Work
Process Fuels Consumed		
Inplant Coke	14.08	14.11
Purchased Fuels Consumed		
Merchant Coke	1.01	1.01
Injectants		
Natural Gas	0.33	0.30
Fuel Oil	0.58	0.56
Byproduct Fuels Consumed		
Injectants		
Coke Oven Gas	0.06	0.05
Tar Pitch	0.15	0.15
Blast Stove		
Blast Furnace Gas	1.61	1.50
Utilities		
Electricity	0.15	0.05
Steam	1.46	0.65
Oxygen	0.01	-
Total Fuels and Utilities	19.44	18.38
Byproduct Fuels Produced		
Blast Furnace Gas	6.57	5.9
Raw Material Output	8.25	7.85
Lost in Process	4.62	4.63
Process Effectiveness		75%

Appendix

The Combined Energy and Entropy Balance. Several approaches exist for establishing that availability change and not change in any other property represents the optimum (minimum or maximum) work requirement of a process. One of these approaches is based on a combination of the energy and entropy balances of the process.

The laws of thermodynamics imply the existence of two properties: energy and entropy. These properties are such that: (a) the energy of all systems involved in a process is conserved; i.e., the energy in any process must be balanced; and (b) the entropy of all systems involved in a process either increases or remains invariant; i.e., the entropy in any process must be balanced by considering a nonnegative amount of entropy due to irreversibility. The energy and entropy balances are essential to any thermodynamic analysis.

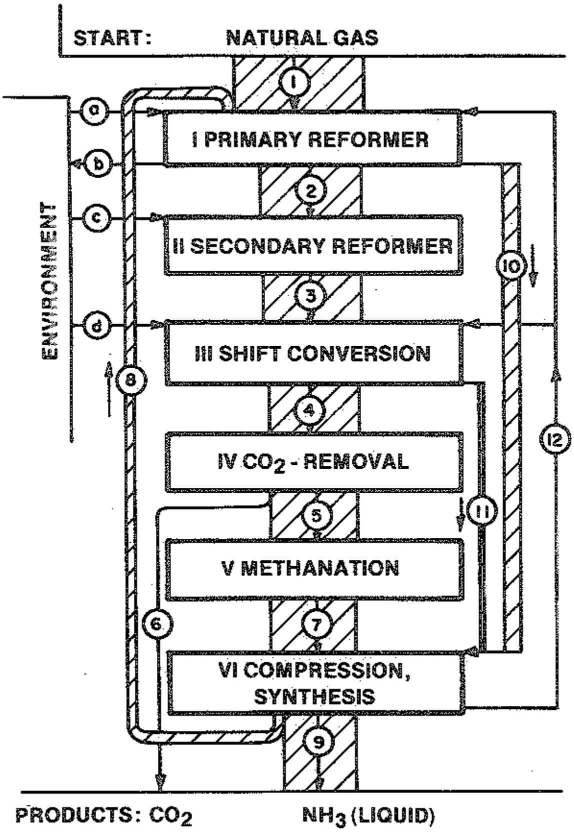

Figure 1. Process flowsheet for conversion of methane to ammonia

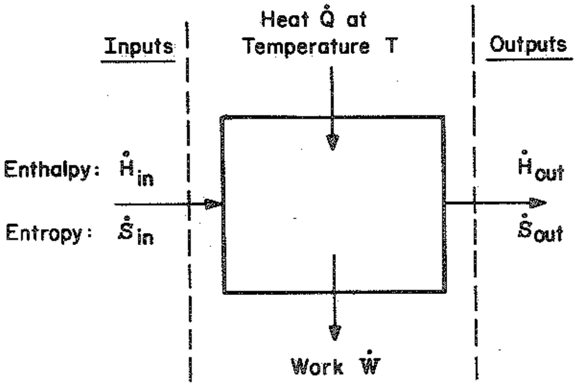

Figure 2. Energy and entropy flows in a steady-state bulk flow process

The forms of the two balances depend on the particular circumstances of the process. As an illustration, we will consider a bulk flow process in steady state (Figure 2) in a chamber with a fixed volume. The energy and entropy rate balances are:

Energy rate balance

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

Entropy rate balance

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

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

Multiplying Eq.(2) by T_o, the temperature of the environment, and subtracting the result from Eq.(1) we find

$$\dot{W} - \frac{T - T_o}{T}\dot{Q} = \left[(\dot{H}_{in} - T_o\dot{S}_{in}) - (\dot{H}_{out} - T_o\dot{S}_{out})\right] - T_o\Delta\dot{S}_{irr} \tag{3}$$

Clearly, $\left[(T - T_o)/T\right]\dot{Q}$ is the optimum work rate obtainable from a heat source at temperature T with respect to the environment at temperature T_o. The overall process will be optimum when the irreversibility is zero ($\Delta\dot{S}_{irr} = 0$) and, therefore, the optimum work rate is defined by the change in $\dot{H} - T_o\dot{S}$; i.e., the change in the availability rate of the bulk flow process.

Literature Cited

1. Obruzut, J.J., "Heat Treaters Gear Up for the New Demands," Iron Age Magazine, July 10, 1978.
2. Hatsopoulos, G.N., Gyftopoulos, E.P., Sant, R.W., and Widmer, T.F., "Capital Investment to Save Energy," Harvard Business Review, Vol. 56, No. 2, March-April 1978.
3. Villalobos, J.A., "The Effective Use of Energy in the Paper Drying Process," International Symposium on Drying, McGill University, August 3, 1978.
4. Riekert, L, "The Efficiency of Energy Utilization in Chemical Processes," Chemical Engineering Science, Vol. 29, 1974.
5. Gyftopoulos, E.P., Lazaridis, L.J., and Widmer, T.F., "Potential Fuel Effectiveness in Industry," Report to the Energy Policy Project of the Ford Foundation, Ballinger Publishing Co., 1974.

RECEIVED November 1, 1979.

Reprinted from ACS SYMPOSIUM SERIES, No. 122
THERMODYNAMICS: SECOND LAW ANALYSIS
Richard A. Gaggiolo, Editor