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Energy, Entropy, and Information

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PREFACE

This Research Memorandum contains the work done during the stay of Professor Dr.Sc. Jean Thoma, Zug, Switzerland, at IIASA in November 1976. It is based on extensive discussions with Professor Häfele and other members of the Energy Program. Although the content of this report is not yet very uniform because of the different starting points on the subject under consideration, its publication is considered a necessary step in fostering the related discussion at IIASA evolving around the problem of energy demand.

ABSTRACT

Thermodynamical considerations of energy and entropy are being pursued in order to arrive at a general starting point for relating entropy, negentropy, and information. Thus one hopes to ultimately arrive at a common denominator for quantities of a more general nature, including economic parameters. The report closes with the description of various heating applications and related efficiencies.

Such considerations are important in order to understand in greater depth the nature and composition of energy demand. This may be highlighted by the observation that it is, of course, not the energy that is consumed or demanded for but the information that goes along with it.

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ENERGY, ENTROPY, AND INFORMATION

1. INTRODUCTION

The object of this report is to clarify the relations between energy, entropy, and information on the basis of their physical principles. One application is the negentropy city project after C. Marchetti [1], where mechanical power to a city is supplied as compressed air without any net energy flux (Section 4.2 below). Further applications are the global entropy balance of the earth between incoming solar and outgoing space radiation, efficiency assessment of solar power, and description of energy degradation for heating.

The well-known limited efficiency of the conversion of thermal to mechanical or electric power will also be illustrated. Hence, if only one third of the thermal energy can be converted into electricity, this is not a waste of two thirds of the fuel as cited by A. Lovins [2]. Certain improvements can be expected, but only at the combined expense of other factors like capital and labor. Further, it is not always realized that this conversion can, at least approximately, be reversed by the known entropy (or heat) pump. This allows to make available, e.g. for room heating purposes, a thermal power flow or heat about three times the electric or mechanical energy consumed (Section 4.2 below).

Speaking about efficiency, S. Schurr et al. [3] distinguish technical (or thermal) and economic efficiency. Only the former is a physical concept, basically defined as useful energy outflux divided by energy influx. Economic efficiency refers to obtaining a maximum of outputs from a set of inputs like capital, labor, and energy. Hence, a technically efficient system can be economically inefficient if it requires much more labor and/or capital, or vice-versa.

We feel that the fundamental quantity consumed is not energy but rather negentropy or information [4]. In fact, due to universal energy conservation, all losses appear as waste heat and strictly no energy is lost. Waste heat is produced in the form of an entropy flow generated by all kinds of friction processes, which can never be eliminated entirely. Negentropy is a short word for negative entropy, whence entropy generation corresponds to negentropy consumption. This in turn corresponds to the destruction of information, or rather micro-information, which is related to the macro-information of communication theory, as will be shown (Section 2.4).

We use here a new interpretation of entropy as thermal charge [5] rather than its usual definition as an abstract (Clausius) integral. In this phenomenological sense entropy is necessarily connected with any kind of heat flux, just as electric charge flow or current is necessarily connected with electric power flux. The thermal power flux is then the product of entropy flow and of absolute temperature in the case of conduction, but for convection a form factor must be included (Section 4.1). This approach is often called network-thermodynamics according to G. Oster et al. [6], and is especially useful in chemical thermodynamics [7].

There is also the statistical interpretation of entropy as a measure of disorder according to Boltzmann, or of negentropy as order. It has been used for a theory of system complexity by L. Ferdinand [8] to derive a probability distribution for the number of defects by maximizing the entropy functional (equation 4 below). The same entropy functional is also used by S. Bagno [9] to explain economic activity, together with mathematical tools from communication theory.

2. VARIOUS ASPECTS OF ENTROPY

The concept of entropy introduced by Carnot and Clausius in the 19th century has essentially the following three aspects:

(1) phenomenological entropy governing the operation of heat engines, where it acts like a thermal charge;

(2) statistical entropy as a measure of disorder according to Boltzmann; this is a kind of theory of structure of the thermal charge;

(3) the information content of a message according to Shannon, as part of communication theory; here information is often compared to negentropy.

We feel that these are aspects of essentially the same, very fundamental quantity, as advocated first by L.M. Brillouin and more recently by J. Peters [10]. A very thorough discussion of the relation of entropy and information with a view to biological applications was made by H. Atlan [11]. However, this identification requires some qualifications and precautions since technical information and entropy appear to have different properties.

2.1 Phenomenological Entropy

Phenomenological entropy is coupled to thermal energy or heat flux $\dot{Q}$[1] by

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[1] We speak of flow when we refer to movement of charge (electric, thermal = entropy, mass, or volume), and of flux for movement of energy. The flux is then obtained from the flow by multiplication with the appropriate effort variable (voltage, absolute temperature, pressure etc.).

$$\dot{Q} = T \cdot \dot{S} , \qquad (1)$$

with T being absolute temperature, and $\dot{S}$ entropy flow.

The fundamental equation (1) defines what entropy "really" is, from which the usual, Clausius, definition can easily be derived [12]. As an aid to visualization, entropy is often compared to a gray paste. Equation (1) corresponds closely to the equation between electric power, charge flow (current), and voltage. Strictly speaking, it applies to conduction only, while for convection, i.e. entropy transport with mass flow, a form factor of about 0.5 to 1.0 must be applied both in the thermal and the electric case [7].

Entropy as thermal charge has the following properties, some of which are the same as of electric charge:

(1) Entropy is conserved in frictionless processes and machines. Such processes are reversible.

(2) Entropy is generated by various friction processes which are unavoidable in real machines. Thus friction is essentially irreversible.

As an illustration of the frictionless process, Fig. 1 shows a conversion engine working between two temperature sources with temperatures T_1 and T_2 (analogous to voltage sources in electronics, but often called heat reservoirs) to extract mechanical power. The thermal power is supplied from source T_1 with a certain entropy flow $\dot{S}_1$ according to equation (1); the entropy flow must be deposited in the low-temperature source T_2, just as an electric motor needs a return wire for the electric charge to flow out. For this a power $\dot{S}_1 T_2$ is required. Hence, the efficiency of an ideal engine defined as mechanical power outflux divided by thermal power influx is

$$\eta = \frac{T_1 - T_2}{T_1} \quad . \qquad (2)$$

Equation (2) is the celebrated Carnot formula.

An efficiency of 50 per cent of an engine working between 600 K and 300 K is then just as evident as with an ideal electric motor between 600 and 300 volt.

The ideal engine of Figure 1 is completely reversible, and can be used to pump entropy from a low-temperature source to a high-temperature source. This is the well-known heat pump, which we prefer to call entropy pump, since entropy is the characteristic thermal quantity transported. The efficiency of the entropy pump is the reciprocal of equation (2), and can become much larger than one if the temperature difference is small.

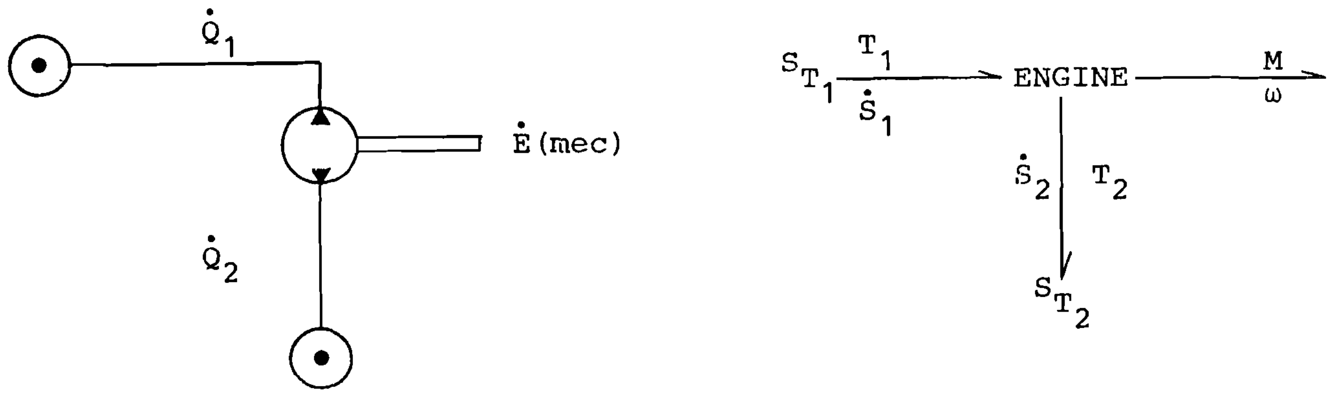

Fig. 1 Conversion of thermal energy from a source at high temperature T_1 into mechanical power. The consequent entropy flow $\dot{S}_1$ must be deposited in the (reversely driven) cold source T_2, for which the power $\dot{S}_2$ T_2 is needed. The engine is assumed to be frictionless (no losses), and thus $\dot{S}_1 = \dot{S}_2$. The figure is a double representation with internationally standarized fluid power symbols (left) and bond graph symbols (right). (Q = heat; E = energy; S = entropy; T = temperature; M = angular momentum; W = angular velocity)

The efficiency formula (2) implies that the outgoing entropy flow (heat flux) is worthless, which is the basis of the opinion that during mechanical or electric power generation two thirds of the thermal power is wasted. In fact, in many cases it is possible and "economically efficient" to use the entropy outflow for home or chemical process heat. Such an installation is called a total energy system or cogeneration system [2]. A familiar example is the private car, where part of the entropy outflow is used to heat the cabin in winter without additional fuel consumption.

For friction processes generating entropy one must use a slightly more general definition than usual, as follows:

(1) all kinds of friction like mechanical, hydraulic, electric, or chemical [7];

(2) heat conduction under definite temperature drop;

(3) mixing of fluids of different chemical species.

All these friction processes are irreversible[2], and generate entropy flow and absolute temperature equal to the dissipated power. The temperature that is reached depends on how well one

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[2]Mixing can be made entropy-conserving and reversible by semipermeable membranes.

succeeds in removing entropy, a phenomenon known from overheating of friction brakes. All real machines have some friction-generating new entropy. In the case of the conversion engine of Figure 1 it must be deposited in the low-temperature source and requires additional power, thus reducing the real efficiency.

The various properties of phenomenological entropy are conventionally all thrown together into the second law of thermodynamics. This law has then many different aspects, a fact that disturbs the understanding of phenomenological thermodynamics.

It should also be noted that, by inclusion of thermal effects or entropy production, all friction processes become power-conserving, which is the first law of thermodynamics. In this sense an electric resistor is 100 per cent efficient and converts the total electric power into heat. Clearly, conventional efficiency is not a very good indication of the performance of thermal machines, as will be discussed further in Section 4.

Heat conduction is also a power-conserving process. Entropy, and correspondingly heat, always flows from a higher temperature T_1 to a lower temperature T_2 and produces additional entropy flow according to the equation

$$\dot{S}_2 = \dot{S}_1 \frac{T_1}{T_2} \quad . \tag{3}$$

The main difference between thermal and non-thermal energy is that, with thermal friction (heat conduction), the generated entropy remains within the thermal domain. With non-thermal, e.g. electric friction, the dissipated power transfers from the electric to the thermal domain. This bias of nature towards producing entropy is an indication that entropy is really a kind of disorder or random vibration of atoms and molecules.

The logical unit for entropy is joule per kelvin (J/K), and for entropy flow watt per kelvin (W/K). Familiarity with some typical values is useful; for instance, 1 MW at 300 K corresponds to 3.3 kW/K.

The bond graph notation, developed originally for interdisciplinary dynamic control systems, is especially suitable for visualization of phenomenological thermodynamics [13].

2.2 Statistical Entropy

Entropy was explained by Boltzmann as a measure of disorder in his famous formula

$$S = k \sum_i p_i \ln p_i \quad , \tag{4}$$

where k is Boltzmann's constant equaling $1.38 \cdot 10^{-23}$ J/K, having the dimensions of entropy.

The symbol p_i denotes the probability of occupation of a microstate. Equation (4) refers to one particle, or strictly to each degree of freedom having several microstates. There can be an infinite number of microstates, but the sum over the probability p_i must converge since it equals one, corresponding to the certainty of finding the degree of freedom in some state.

For the entropy of a piece of matter, the contributions of all degrees of freedom are summed, each contributing its entropy share. The total energy of a degree of freedom is E = kT and acts as a constraint on the probability p_i, since

$$E = \sum_i \varepsilon_i p_i \quad , \tag{5}$$

with ε_i being the energy level of each microstate.

At very low temperatures some degrees of freedom freeze out and no longer contribute to thermal energy. This is necessary to prevent the incremental entropy capacity, i.e. specific heat divided by absolute temperature, from diverging. At zero temperature, all degrees of freedom are in the lowest state with a probability of one, the other probabilities being equal to zero. Hence, equation (4) gives zero entropy (S = 0), known as Nernst's heat theorem or third law of thermodynamics.

The distinction between microstates, degrees, and freedom and the entire piece of matter is important for the connection with information theory. According to equation (4) one can definitely speak of the entropy of a single degree of freedom.

2.3 Technical Information

Information according to Shannon is the irreducible content of a message of consecutive signals. Each signal occupies a certain position in the message and can assume several discrete values (or symbols), each with a probability p_i (where i runs from 1 to m, and $\sum_{i=1}^{m} p_i = 1$ is a probability normalization).

The information transported by a given symbol i is ld p_i when I know that it has appeared. The logarithm to base 2 (log dualis or ld) is chosen because a decision with 50 per cent probability gives one unit of information, customarily called a bit.

The mean information contribution by this symbol is p_i ld p_i, and the mean information per position in the message is the sum of all possible signals, the Shannon or confusion functional:

$$H = - \sum_{i=1}^{m} p_i \text{ ld } p_i \quad . \tag{6}$$

Since the probabilities are smaller than one, the minus sign assures a positive confusion functional.

In the case of binary symbols (m = 2) and with $p_1 = p$, $p_2 = 1 - p$ we have

$$H = -p \text{ ld } p - (1 - p) \text{ ld } (1 - p) \quad . \tag{7}$$

To clarify some properties of information it is helpful to look at the schematic representation of a communication system (Fig. 2). Information is stored in the elements of the trans-

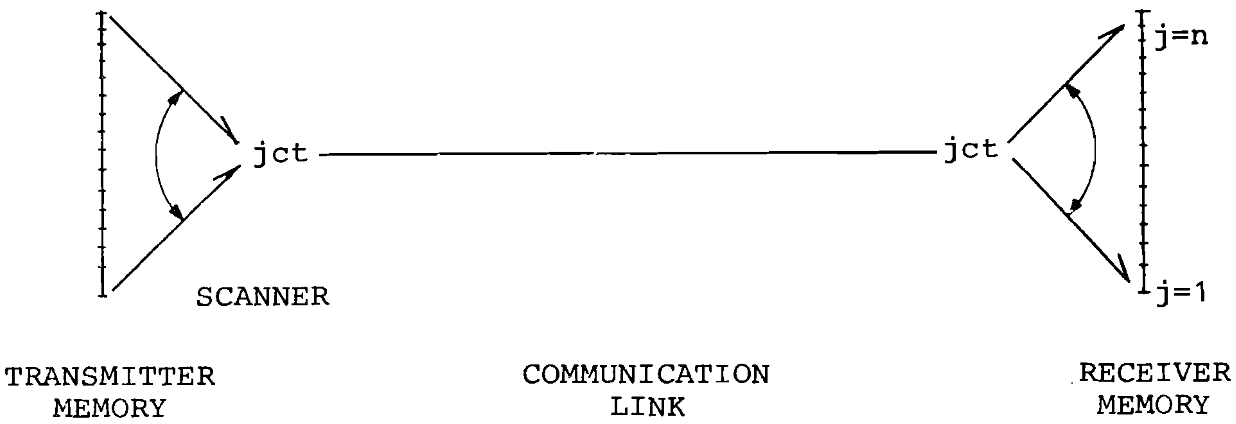

Fig. 2 Schematic representation of a communication system with transmitter memory (left), and a communication link to the receiver memory (right). The receiver memory has n elements, each corresponding to a certain question with probabilities p_i for the possible answers. The transmitted information is a measure of the changes between the best estimates of p_i before and after receiving the message, combined according to equation (8).

mitter memory, read consecutively by a scanner, and sent over a communication link such that a position in the message corresponds to each memory element. At the receiver, another scanner enters the signal of each message position into the appropriate element of the receiver memory.

In the memory of the receiver there are several elements $j = 1...n$, each corresponding to a certain question (e.g. what symbol goes into element 5?) with a range of answers $i = 1...m$, and corresponding probabilities p_i (or strictly, p_{ij}). The mean information contained in each element of the memory is given by the confusion functional

$$H = - \sum_{i=1}^{m} p_i \operatorname{ld} p_i \quad . \tag{8}$$

Before receiving the message, the receiver will have a certain idea of the set of probabilities, p_i. After the message has been received the probabilities will change in general, and the transmitted information is defined as the difference of the confusion functional before and after reception.

$$I = -(H_{after} - H_{before}) \quad . \tag{9}$$

To use a numerical example, suppose that a memory element has 1024 answers with an equal probability $p_i = 1/1024$ for each answer before the message. Then H_{before} is ten. After reception, one answer is certain (p_1) and the others have zero probability, giving $H_{after} = 0$. Hence, the information gained by the message is ten bit.

Information can be easily lost in the following ways:

(1) If the probability assessment is not changed by reception of the message, that is, if the message tells what the receiver already knows. This is redundancy or redundant information.

(2) If the message contains a signal that does not correspond to any element of the receiver's memory. In this case it answers a question that has not been asked. This is irrelevance or irrelevant information.

(3) If the scanners become desynchronized.

(4) If the signal is mutilated by noise.

Technical information has the important property that the memory of the transmitter is not erased by passage or reading of the scanner: Technical information can be multiplied at will.

It should be noted that information transport always refers to a definite set of questions or memory elements, and depends on the receiver's subjective assessment of the probabilities before and after the message. If nothing is known before the message, one can assign equal probability to all possible answers [10]. One can also admit an infinite number of answers ($m = \infty$) as long as the probabilities converge. Information theory is only based on probabilities and takes no account of the significance or subjective meaning of the meassage.

2.4 Negentropy as Micro-Information

The equality, apart from a factor k ln 2, of equations (4) and (6) has strongly suggested that statistical entropy, or rather negentropy, and information are the same. Intuitively this is clear: Statistical entropy is disorder, and information reduces it. Hence, a flow of information equals a flow of negentropy. The obstacle is the above properties of technical information, which are quite different from the semi-conservation of technical entropy.

The solution is to distinguish between micro-information and macro-information, as follows:

(1) Micro-information refers to the individual degrees of freedom of matter, where each memory element corresponds to a degree of freedom and each state of a degree of freedom to a state of the memory.

(2) Macro-information refers to macroscopically readable signs, letters, or signal values, each consisting of many molecules or degrees of freedom of the electron movement. Macro-information is multiply redundant micro-information.

Thus micro-information is equal to statistical entropy because it specifies the value of each degree of freedom:

$$S = k(\ln 2)\, H \quad , \tag{10}$$

where the factor ln 2 arises from the conversion of the binary to the natural logarithm. Reading such a memory erases it since the information is destroyed by the action of the scanner. Hence, after reading the state of the memory is indefinite. This is also the basic reason why Maxwell's demon cannot work: Measuring the velocity of a molecule disturbs it to such a degree as to nullify the gain in negentropy achieved by the demon through opening the trap door to a fast molecule. The elements of a technical memory storing macro-information consists of so many molecules that change their state in concert (for instance, from black to white) that the scanner will only disturb a very small fraction of them. Hence, macro-information can be read or reproduced at will.

Physically, entropy is a measure of the random energy of the degrees of freedom of matter or radiation. It is produced in all processes as information is lost about the precise movement of molecules, atoms, or even elementary particles. The highly definite trajectories of elementary particles and the concentrated position of the nucleus in the center of the atom contain very much information, which appears to be a new basic quantity of physics. It would be interesting to explore its properties, described above, in the atomic diameter range, on the length and energy scale of the atomic nucleus and of elementary particles. Presumably, the large size of particle accelerators is related to this high information concentration.

Any direct comparison of technical (macroscopic) and microscopic information must be done with caution, and the difference in properties due to multiple redundancy must be kept in mind.

Ferdinand [8] calls the Shannon functional defect entropy, but relates it to the macroscopic probability of having r defects in a complex system with m potential defects. He uses the maximum defect entropy to derive a coefficient of complexity σ, which is given by the expectation value of defects in the system and, through $\sigma = 1$, defines a boundary between simple and complex systems.

S. Bagno [9] also speaks about technical information and entropy. He introduces the concept of information production by work, and estimates its cost through the hourly labor rate. He uses 10 bit/sec and 1.20 $/hour to arrive at a cost of 30 kbit/$.

The biological information contained in the genetic code of DNA molecules is an interesting intermediary between macro- and micro-information. It can certainly be reproduced at will by reproduction of the entire molecules. The reason for genetic mutations is the statistical information defects on reproduction.

2.5 Transmission of Technical Information

The transmission of information depends on the assessment of the probability of each state i (of each memory element j) before and after the message, i.e. of p_{before} and p_{after} (dropping the indices i and j). It is changed by the arriving probability p_{ar}, which is made up by the content probability p_{cnt} and the reliability r

$$p_{ar} = p_{cnt} \cdot r \quad . \tag{11}$$

In most messages p_{cnt} equals one since they send a definite symbol, but occasionally they might give only 50 per cent probability to a transmitted figure. The reliability r of a message may be smaller than one due to noise or with deliberately false messages (deception). It would be interesting to explore the connections to cryptography.

Let us take a numerical example. If p_{before} is assessed as being 0.5, and the message gives a definite signal $p_{cnt} = 1$ but one attaches a reliability of only 50 per cent to it (because of noise or deception), one's after-assessment will remain 0.5. No information will have been transmitted or gained.

More generally, the after-probability will be an estimated function of the various probabilities, presumably a linear combination

$$p_{aft} = p_{bf} \cdot (1-r) + p_{cnt} \cdot r \quad . \tag{12}$$

From these probabilities, the confusion functional H is formed and summed over each state or signal i and over each memory element j, in order to obtain the total information transmitted by the message.

3. INFORMATION IN CAPITAL AND LABOR

3.1 Estimating the Information Content of Capital

Apart from its importance in physics and engineering, information has its role in capital and labor. The variable complexity of physical capital (machines and plants) can be described by its information content according to the following method. It basically refers to mechanical engineering, but extension to non-mechanical aspects seems possible.

For determining the information content, the number of specifications such as length, angles, materials, etc., of all parts are taken from detail drawings. Each specification is multiplied by its information content, i.e. the logarithm of the ratio of the specification to its tolerance range, such as length divided by the admitted length tolerance:

$$I_{cap} = \sum_{i=\text{all specs}} Ni \; ld \; q_i \; , \tag{13}$$

where

$$q_i = \frac{L}{\Delta L} \; ,$$

is the reciprocal relative tolerance.

Infocap (short for information content of capital) is correlated with price, but there are the following disturbing influences:

(1) rapid increase of cost with absolute size;

(2) scarcity of material, and machining difficulties;

(3) intricacy, complexity, and inaccessibility of specifications.

The tolerances provide an indifference range and imply a kind of macroscopic quantification: How many different cases can one construct with the tolerance of the given length? Selecting one possibility yields the information attached to this specification.

Infocap can be used to assess different technologies for a given end with the basic inference that more Infocap per size or cost implies a more advanced technology.

3.2 Information Flow from Labor

Similarly to capital, the main output of human labor can be conceived as information flow. As illustrated in Fig. 3 information originates in the human mind and its learning, both past and continuous through discussions, current inputs, etc. It is disturbed by foolish errors, which is similar to random noise generated by a noise source. This source is modulated by the care and attention devoted to the job.

Infolab (short for information flow from labor), can be measured in bits per second, but the estimates range from 10 through 40 [10] to 10,000 bit/sec [14]. The latter value seems by far too high.

The classic problem of substitution of labor by capital can be extended to Infocap and Infolab:

(1) to describe the possible substitution of Infolab by Infocap in equipment and work force required for a given job;

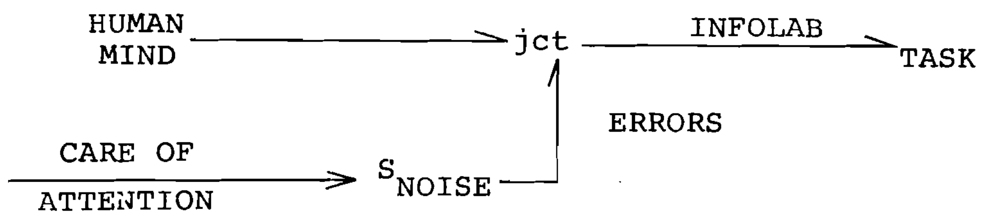

Fig. 3 Illustration of the human mind as information source. It is disturbed by a noise source representing foolish errors, which is internally controlled by the care or attention devoted to the job.

(2) again for a given job, to relate the energy saved over the life-time of the newer equipment to its Infocap.

In order to make this more convincing, it should be applied to the following examples of old and new technologies for a given job:

(1) steam and Diesel locomotives;

(2) computers with radio tubes and microelectronics;

(3) fossil-fired and nuclear power plants.

A provisional calculation of numerical parameters for steam and Diesel locomotives is made in Table 1. It results in relatively low information contents.

The above is an attempt to quantify the information content of physical capital based on the numerical indications of detail drawings and specifications. For successful manufacturing much more information is really needed. It is contained in norms and standards for parts and material apart from the knowledge of the producer's personnel, which could be called background information.

The importance of background information is the main reason for the various licence and technology transfer agreements between different countries, including developed and less developed ones. Furthermore, the higher the production rate the more elaborate are the production machines that are "economically efficient" and customarily used. One extreme example is private motor car production.

Nevertheless, it is believed that the relatively objective concept of Infocap is useful to compare different machines or equipment produced in similar numbers for the same end use (economic consumption).

Other equipment for which it would be interesting to determine Infocap includes ammonia production facilities, textile machines (weaving and spinning), and even watches.

4. POWER, NEGENTROPY FLOW, AND EFFICIENCY

4.1 Thermal Power and Convection

Thermal power flux is always connected with the flow of entropy or the outflow of negentropy. As an illustration, Fig. 4 contains the power and entropy flow balance of the earth. The incoming solar radiation of $175 \cdot 10^3$ TW at 6000 K corresponds to an entropy flow of 39 TW/K (terawatt per kelvin). Essentially the same power is radiated back into space by the

Table 1: Example of information in locomotives based on a very rough estimate ($\approx$ dimensions in detail drawings)

$$I = N \,\mathrm{ld}\, q \quad , \qquad q = \frac{L}{\Delta L} = \text{reciprocal relative tolerance}$$

$$N = \text{number of specifications}$$

Steam locomotive $N = 8000 \quad q = \frac{100 \text{ mm}}{0.1 \text{ mm}} = 10^3; \quad I = 8000 \,\mathrm{ld}\, 1000 = 80 \cdot 10^3$ bit

Diesel locomotive $N = 30{,}000 \quad q = \frac{100 \text{ mm}}{0.05 \text{ mm}} = 2 \cdot 10^3; \quad I = 30{,}000 \,\mathrm{ld}\, 200 = 330 \cdot 10^3$ bit

Energy consumption over lifetime and Infocap:

$\dot{E}_{steam} = 25$ MW ($\approx$ 3.3 tons/hour) } relates to working load, but in-

$\dot{E}_{Diesel} = 5$ MW (360 kg oil/hour) } cludes an allowance for standby

Differences $\Delta\dot{E} = 2$ MW $\quad \Delta I_{cap} = 250 \cdot 10^3$ bit

Energy difference over 10 years = $320 \cdot 10^6$ sec lifetime

$\Delta E = 20 \text{ MW} \cdot 320 \cdot 10^6 \text{ S} = 6.4 \cdot 10^{15} \text{ J} = 6.4 \cdot 10^3 \text{ TJ}$

Relate ΔE and ΔI_{cap} through E_Q = macroscopical energy quantum

$$\Delta I_{cap} = \frac{\Delta E}{E_Q} \qquad\qquad E_Q = 26 \cdot 10^9 \text{J}$$

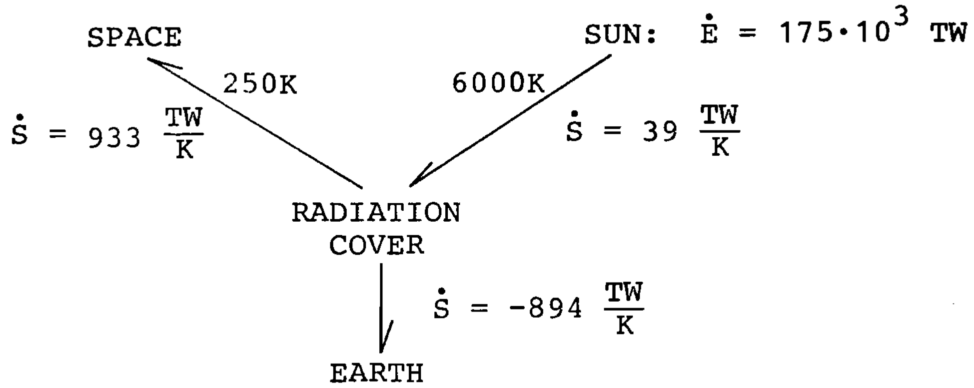

Fig. 4 Illustration of the earth receiving a negentropy flow but no net energy flux, since the solar power is radiated back into space at a much lower temperature.

radiation cover (upper atmosphere) at 250 K (different values are cited for this temperature) with an entropy flow of 933 TW/K. This gives a net outflow of 894 TW/K from the earth. In other words, the earth has no net power consumption but consumes negentropy at the above rate. Negentropy is available as long as the sun maintains its radiation and space its radiation absorption. Reference [14] contains interesting observations about the entropy balance of the earth.

It is seen that entropy flow and power flux in the preceding paragraph and in Fig. 4 are not connected by equation (1), but rather by

$$\dot{E} = \frac{3}{4} \dot{S} T \quad . \qquad (14)$$

In fact, thermal radiation is a kind of convection with the velocity of light, as demonstrated many years ago by Max Planck [16]. It follows from his calculations that the form factor mentioned after equation (1) has the value of 0.75. It is important in this context that the thermal (blackbody) radiation carries a definite entropy so that power flux and entropy flow are linked.

If the radiation cavity received its thermal power flux by conduction, additional entropy is generated by the emission of radiation. This friction process or irreversibility will be further influenced by the backradiation of the body receiving the primary thermal radiation. Due to their importance for solar energy (more precisely, exergy) collection, such processes should be further investigated.

As said in the beginning, the conventional efficiency is not a very good indicator of the performance of installations with thermal power fluxes. Further, such power fluxes frequently occur through convection, i.e. in association with mass flow. They are described by the enthalpy flux, $\dot{H}$:

$$\dot{H} = p\dot{V} + \dot{U} = \dot{m}(pv + u) = \dot{m}h \quad , \tag{15}$$

where

p = pressure;
$\dot{V}$ = volume flow;
$\dot{U}$ = flux of internal energy;
$\dot{m}$ = mass flow;
v = volume/mass ratio;
u = internal energy/mass ratio; and
h = enthalpy/mass ratio.

As a consequence, convection transports energy through both the hydrostatic part $p\dot{V}$ and the internal energy flux. The latter carries both entropy and volume, which change by heating/cooling and by compression/expansion, respectively. In matter, thermal and mechanical variables are generally coupled. Therefore, it is not possible to speak of separate thermal and hydraulic parts of internal energy; the exchange of both kinds of energy are the basis of heat engines.

The coupling and many other facts of interconnected effects and components are best described by a newer tool of systems and engineering, the bond graphs. They are a representation of interdisciplinary engineering systems on paper using specially defined symbols. These symbols are not simplified pictures of the components as in circuits, but use a letter code (e.g. C-elements for a generalized capacitor) which allows automatic computer programing [13].

An important bond graph symbol is the C-field or interdisciplinary capacitor network. It relates the efforts (generalized voltages) and charges (time integrals of flows), which include the relations between absolute temperature, pressure, volume, and entropy with their coupling in fluid matter. In fact, many theorems of classical thermodynamics are simply properties of C-fields and also apply to systems with other, non-thermal, C-fields.

It should be noted that a mass flow carries a definite entropy flow, but enthalpy flux and entropy flow are not connected exactly by equation (1). Rather one must introduce the form factor mentioned above. This correction for entropy flow with a given enthalpy flux and mass flow is usually masked by the entropy generation due to mechanical and thermal friction in machines and heat exchangers.

4.2 Various House Heating Schemes

Thermal energy for heating purposes, e.g. for a house, is really the provision of entropy flow at a certain low temperature of the order of 400 K. Although fuel combustion can be made at very high temperature levels, technology constraints limit the upper temperature to about 1000 K. The result is a corresponding entropy flow (10 W/K per 1 kW thermal energy flux), which corresponds to a temperature source.

There are the following possibilities for heating a house, starting from 1000 K:

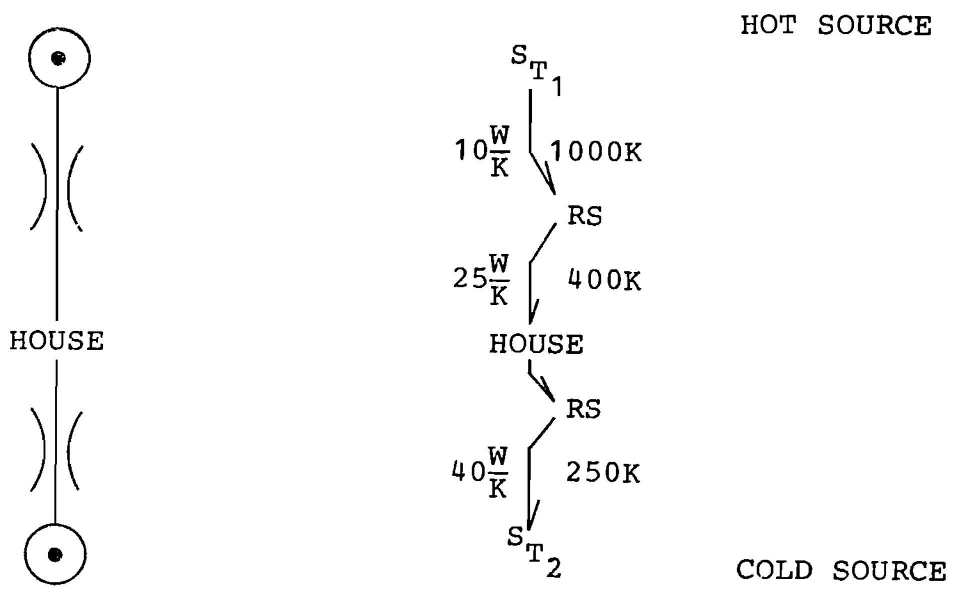

Fig. 5 Illustration of house heating represented as fluid power circuit (right), and as bond graph (left), from a hot source at 1000 K. The thermal resistors (RS) are power-conserving and produce new entropy flow, which is desired at approximately 400 K for comfort in the house. The lower thermal resistor shows the outflow of entropy and thermal power to the environment represented by the cold source T_2.

(1) In Fig . 5, the thermal heat flux is transformed from 1000 K through a thermal resistor into the same power at a lower temperature and a correspondingly greater entropy flow. This simple scheme produces entropy and wastes negentropy.

(2) In Fig . 6, the temperature drop between 1000 K and 400 K is used in an ideal engine to provide mechanical power. Such an engine conserves entropy but takes power from the thermal to the mechanical domain. Hence, less power is available for house heating.

(3) In Fig . 7, the engine drives an entropy pump that takes entropy from the environment represented by the cold source S_{T2} with 250 K, and pumps it to the 400 K level. The 6 kW mechanical power thus makes available additional pumped power of 10 kW, doubling, as compared to Fig. 5, the entropy flow available to heat the house.

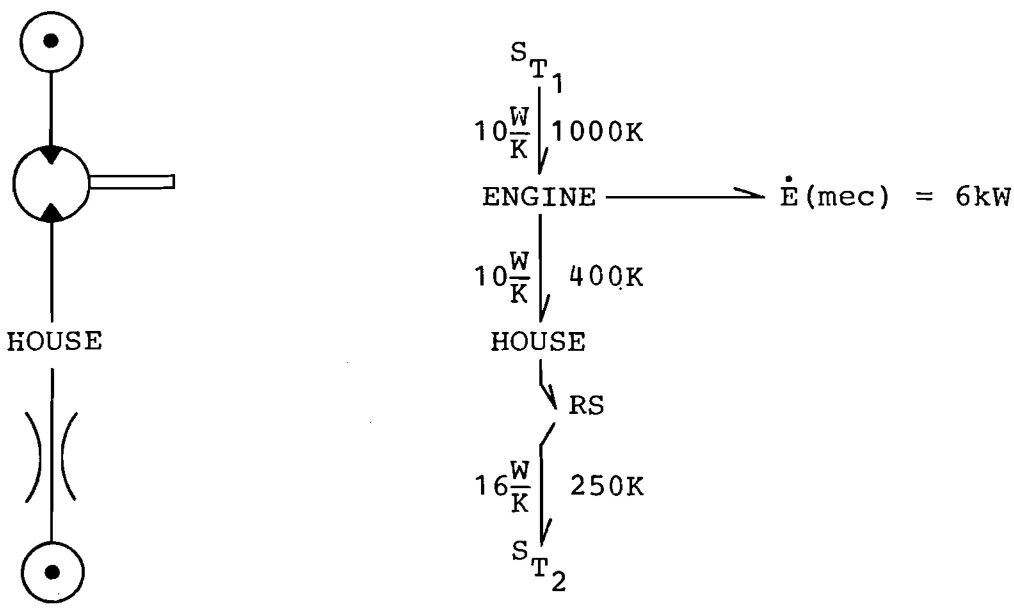

Fig. 6 House heating scheme, where the entropy fall between 1000 K and 400 K is used to make 6 kW power in an ideal engine. Consequently less thermal power, only 4 kW, is available for heating.

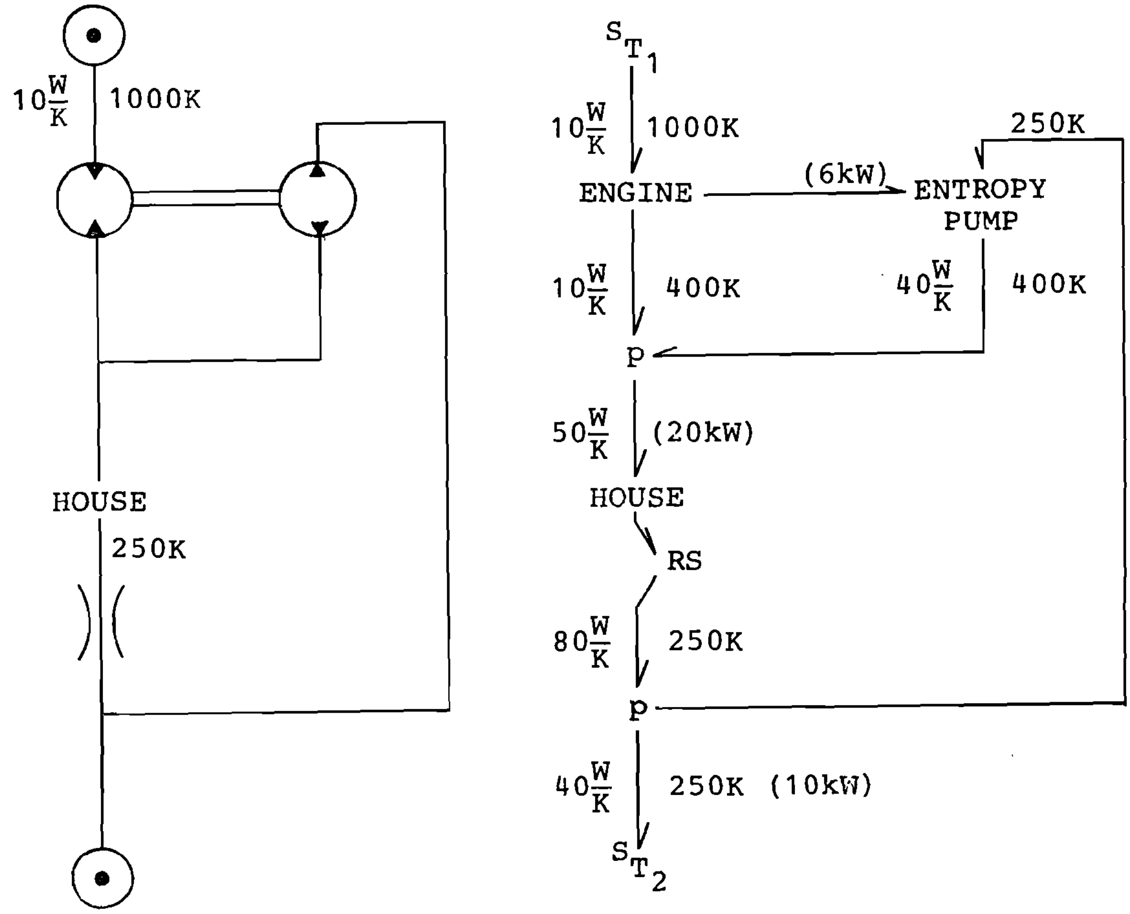

Fig. 7 Heating scheme (similar to Fig. 6), where mechanical power is used to pump entropy from the environment of 250 K to a heating input at 400 K. Consequently 20 kW heating power is available with 10 kW input, twice as much as in Fig. 5. (p = power)

It is useful to emphasize that thermal resistors conserve power but consume negentropy, and ideal engines conserve entropy and transform power from the thermal to the mechanical domain. In the absence of a high-temperature source, the scheme of Fig. 7 can be modified by driving the entropy pump with non-thermal power, for instance,by outside electricity. This allows to obtain 16 kW of thermal power for 6 kW of electricity--an improvement of a factor 3.3 compared to the heating by an electric resistor (RS-field). The improvement is greater if entropy is pumped through smaller temperature differences. The numerical values of Figures 5 to 7 refer to ideal engines and pumps, and the practical performance is considerably less favorable because of inefficiencies.

Another practical difficulty is to obtain entropy for pumping from the environment. The environment is really a very large entropy reservoir, an *entropy lake*, as is sketched in Fig..8 (left). However, there are always important thermal

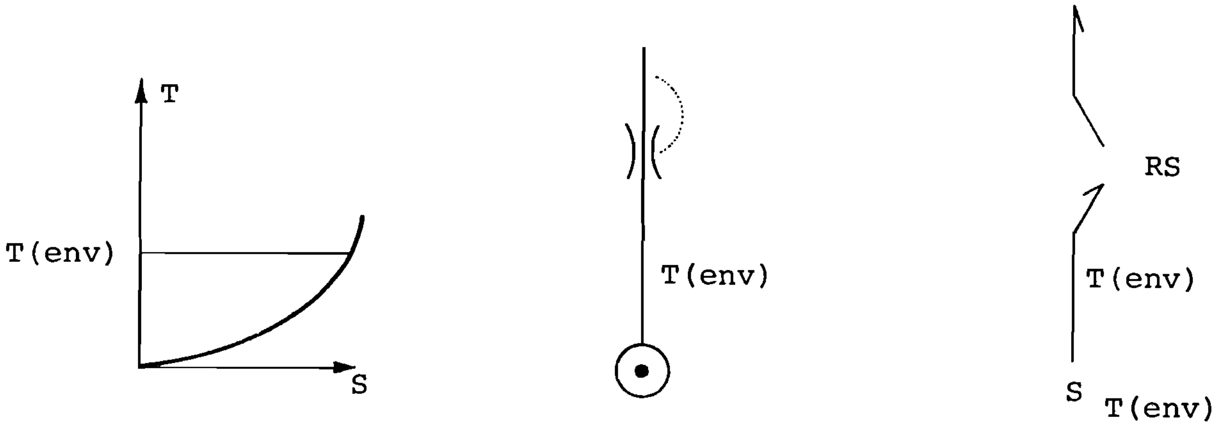

Fig. 8 The environment as a very large entropy reservoir or entropy lake with a basis T/S graph (left), or as cold source with a thermal resistor (fluid power circuit, center, and bond graph, right). (T = temperature; S = source).

resistors within it. Consequently, the effective temperature rises when entropy should be deposited and sinks when it is taken away. With air as an entropy lake, there is also the difficulty of moisture and ice formation on the entropy exchanger, as often happens when water vapor covers the heat exchanger.

An obvious method to improve the house heating scheme of Figures 5 to 7 is to increase the thermal resistance between the house and the environment. This reduces the entropy outflow at a given temperature difference, providing better insulation. No physical principle limits the amount of insulation that can be applied, only capital cost. It is also capital cost which has, so far, prevented the more widespread adoption of schemes such as in Figures 6 and 7.

From these examples it appears that the entropy pump has great potential for many applications. It is therefore desirable to further development to reduce its cost and to increase its efficiency towards the ideal values of Figures 6 and 7.

Also related to the subject of city heating and power supply is the proposed negentropy city of W. Häfele and C. Marchetti [1,17], from which Fig. 9 is reproduced. It allows to supply mechanical energy to the city by negentropy flow without any net energy flux.

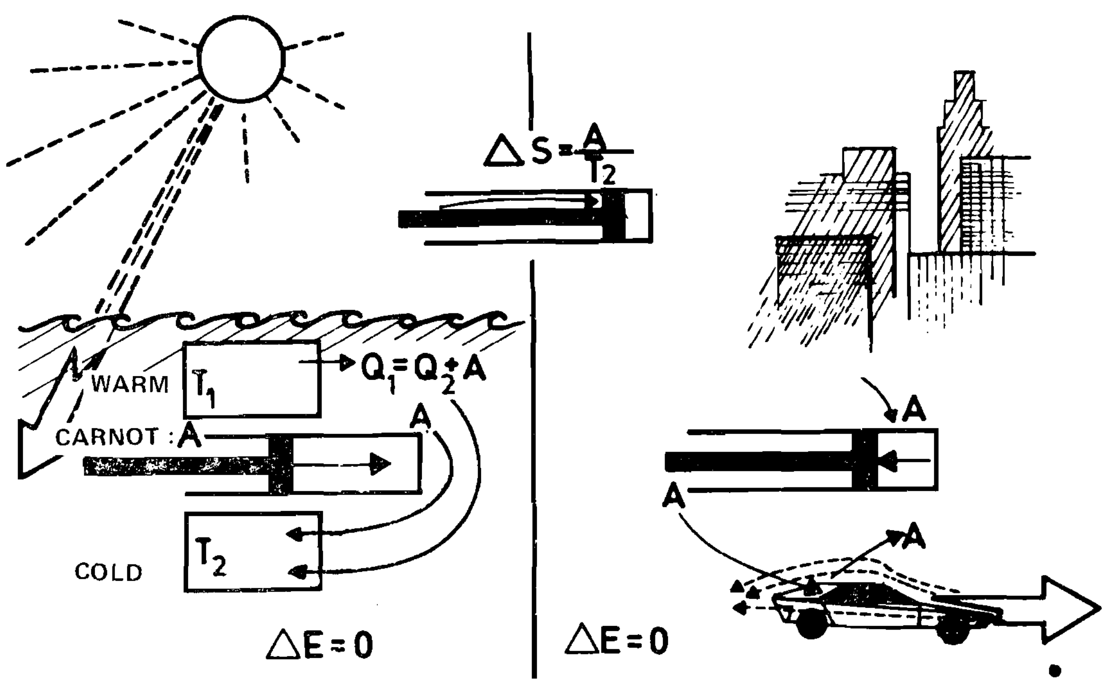

Fig. 9 Negentropy city after C. Marchetti [17] (A: work, E: energy, Q: heat, S: entropy, T: temperature)

Fig. 10 contains a bond graph for the negentropy city with numerical indication of temperatures and entropy flow. In this example, 1 MW mechanical power is produced in an ocean power plant by mixing surface water of 300 K with deep water of 290 K into 295 K outflow. This is used to compress air isothermically, whereby the entropy is squeezed out, and represents a thermal power flux of 1 MW. Hence, there is no power loss, only mixing of different water temperatures in the ocean. Given an arbitrary zero point on the entropy scale, as is the case with ambient pressure and temperature, the compressed air carries negentropy in bottles or in a pipe-line to a city. Since the internal energy of ideal gases depends on the temperature only, the internal energy content in the bottles equals the internal energy content of the returning air. In mechanical engineering tables, the zero points of entropy and internal energy are usually taken to be at 273 K and at atmospheric pressure (1 bar or 100 kP absolute).

In the city, the compressed air drives motors where, for isothermal operation, a thermal MW has to be taken from the environment, the entropy lake. The power is returned to it in mechanical form and is ultimately reconverted into thermal power by various frictions. Only a minute fraction will be stored as chemical or mechanical energy.

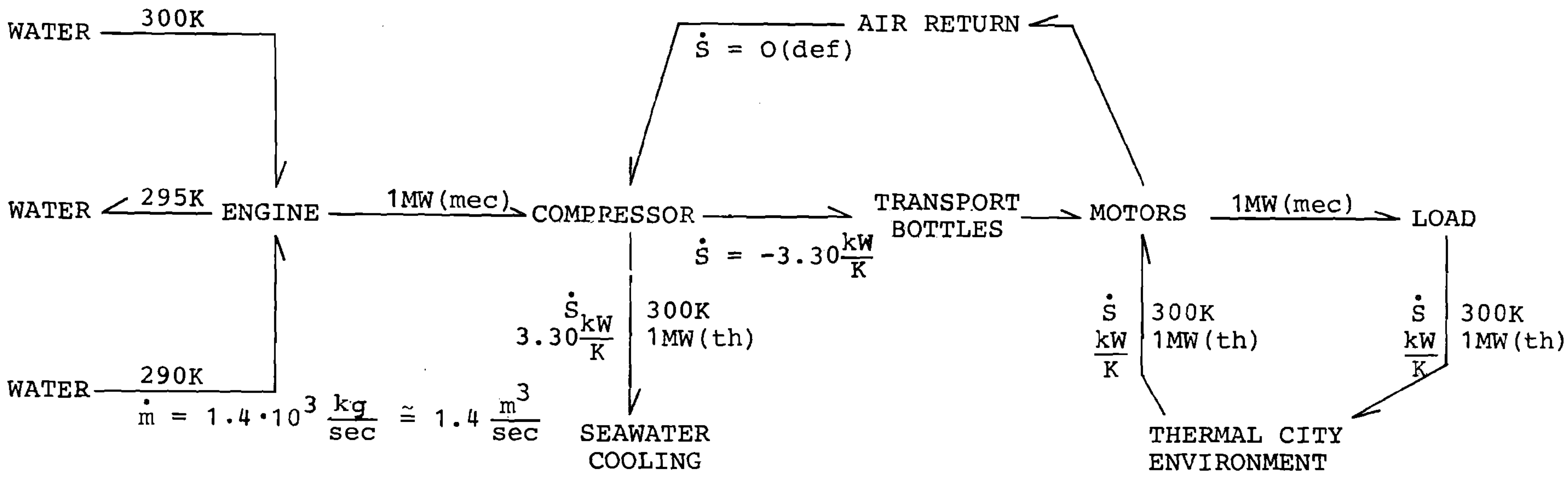

Fig. 10 Negentropy for city power, bond graph representation of the negentropy city after C. Marchetti [1]. For example, 1 MW is obtained by mixing ocean water of 300 K and 290 K, which is squeezed out again by isothermal compression of air. This air has the same internal energy when shipped to the city as on its return through the atmosphere. In the city, 1 MW (th) is taken from the environment for adiabatic air-motor operation, but returned to it as the mechanical power is ultimately dissipated by friction ($\dot{m}$ = mass flow).

Summarizing Fig. 10, negentropy is gained from the mixing of water at different temperatures, carried into the city and consumed there for human needs. No net power transfer is associated with it.

Providing mechanical energy where needed by negentropy flow in compressed air has been used since the 19th century, especially for mines and tunnel building. Here the cooling effect of the air outflow,in addition to its use for breathing, has been most welcome. The difficulty is to transmit to the environment the entropy squeezed out during compression and to put it back during expansion for truly isothermal operation. In practice, the losses have been great, and compressed air transmission has lost ground to electric transmission. However, this is a point where the development of better components, machines, and heat exchangers is called for.

A word of caution may be appropriate. Similarly as in most of the literature, our description assumes that entropy is available or must be disposed of at constant temperature, as given by a temperature source. In fact, it has to be taken out mostly from a mass flow which thus cools off, for instance, as shown in Fig. 10, from 300 to 295 K. To dispose of entropy, the mass flow increases its temperature from 290 to 295 K (Fig. 10). For a more detailed analysis, the temperature source will have to be replaced by an element representing this entropy take-out and the corresponding temperature decrease. It can be made entropy-conserving (frictionless) by appropriately setting the parameters such as mass flows.

4.3 Efficiencies with Thermal Power

In mixed thermal and mechanical power systems efficiency values should indicate how far performance deviates from the ideal values of Figures 6, 7, 8, and 10. The losses usually appear as additional entropy in the outflow.

A method to determine efficiency comes from the water power turbine practice and splits the real engine into an ideal engine and a friction element (RS-field), as shown in Fig. 11. The ideal engine produces a mechanical power of $\dot{H}_1 - \dot{H}_3$, but the real one has a friction power which is added to the outflow and increases $\dot{H}_2$ to $\dot{H}_3$. We thus have

$$\text{ideal case} \quad \dot{E}_{mec} = \dot{H}_1 - \dot{H}_3 \quad ,$$

$$\text{real case} \quad \dot{E}_{mec} = \dot{H}_1 - \dot{H}_2 \quad ,$$

and the efficiency as a ratio of both mechanical powers

$$\eta = \frac{\dot{H}_1 - \dot{H}_2}{\dot{H}_1 - \dot{H}_3} \quad . \tag{16}$$

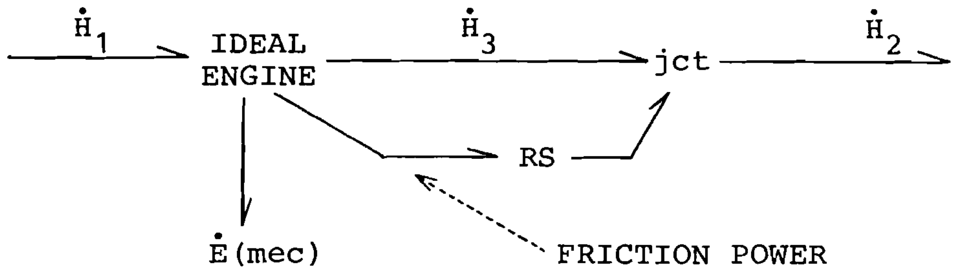

Fig. 11 Efficiency determination with mass flows ($\dot{H}$), by conceptually splitting the real engine into an ideal engine and a friction element. It absorbs the (generalized) friction power and produces new entropy flux, which is added via junction jct to the outflow.

Formula (16) presupposes that the direct exchange of entropy between the machine and the environment in one direction or the other is negligible. This is often the case, but should always be checked numerically. If it is not negligible, a thermal conduction bond can be added to Fig. 10 and its effect estimated.

For efficiency measurement of water turbines, the ideal outflow $\dot{H}_3$ is not accessible for measurement. This difficulty is avoided by noting that the ideal engine does not produce any entropy. Hence, $\dot{H}_3$ is the enthalpy at outlet pressure but with the same entropy as in the inlet. The inlet and outlet enthalpies $\dot{H}_1$ and $\dot{H}_2$ are determined by temperature and pressure measurements using the equation of state of the water or another working medium. More recently, this efficiency determination has been applied to oilhydraulic (fluid power) systems.

Heat exchangers lose negentropy and can presumably be characterized by a similar efficiency.

In the context of IIASA it would be interesting to develop a performance index based on the relative loss of negentropy. Here a difficulty appears to be a universal zero or reference point for entropy.

The performance of thermal machines can also be described by the loss of exergy defined as

$$E_x = \dot{H} - \dot{S}\, T_{env} \quad . \tag{17}$$

Exergy is then the real energy, expressed by the enthalpy in the flow case, minus the entropy multiplied by the environment temperature. This deduction is like an accounted reserve for the cost of disposing of undesirable goods, in this case entropy. Thermal energy at the temperature of the environment thus has no exergy, a fact that well describes the entropy lake.

L. Borel convincingly argues [15] that the economic value of energy should be represented by exergy. The advantage of this concept is that it works equally well for entropy pumps, which produce low temperature in refrigerators and airconditioners. Furthermore it shows that house heating by electric resistors wastes exergy, while heating with ideal entropy pumps from a cold source at environment temperature conserves exergy. The condition is that no thermal resistances act between the entropy lake and the pump intake.

Exergy flux is represented mainly by hot water or steam pipes, where it is linked with the entropy transported by the fluid. It applies also to non-thermal energy fluxes (electric, mechanical, hydraulic) through equation (17), only that they do not contain any entropy. Hence, in the non-thermal case, exergy flux and energy flux are the same.

With these properties, it is of advantage to use the efficiency of exergy, defined as output exergy flux by input exergy flux, to replace conventional efficiency. Frictionless machines would have 100 per cent exergy efficiency, but real machines and even heat exchangers have less exergy efficiency due to thermal and other friction. Further investigation along these lines will provide valuable insights into heat and power supply (or removal), in the context of network thermodynamics.[3]

One weak point of exergy is the precise determination of the temperature of the environment, which depends on the thermal resistor of Figure 8, location, and weather. This introduces a certain arbitrariness which could be reduced by referring to a standard environment. It comprises but minimizes the arbitrariness (contained in the word: useful) of conventional efficiency as useful energy outflux divided by energy influx.

4.4 Combustion or Heating Efficiency

For heating and continuous burning (external combustion) engines, one also uses combustion efficiency. Combustion efficiency is the heat supplied to the engine divided by the energy content (heat value) of the fuel. It essentially indicates the heat losses through the outflow of the combustion products and some thermal losses, and corresponds to the boiler efficiency in steam power plants. This efficiency can be made close to one by cooling the combustion gases to near inlet air temperature. In practice, especially in marine engineering, it is done by preheating combustion air or the feedwater of a steam boiler.

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[3]Network thermodynamics is a new approach, where the components of an installation are replaced by idealized elements, each having only one function, somewhat similar to electronic circuit theory. It is compatible with Subsection 2.1 above, and is much applied in biophysics.

REFERENCES

[1] Marchetti, C., *Transport and Storage of Energy*, RR-75-38, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975; and *Energy and Physics, Proceedings of the Third General Conference of the European Physical Society*, Bucharest, Romania, September 9-12, 1975, European Physical Society, Geneva, 1976.

[2] Lovins, A.B., Energy Strategy, The Road Not Taken? *Foreign Affairs*, 55, 1, 1976.

[3] Schurr, S.H., and J. Darmstadter, Some Observations on Energy and Economic Growth, *Symposium on Future Strategies of Energy Development*, Oak Ridge, Tenn., October 20-21, 1976.

[4] Häfele, W., Science, Technology and Society - A Prospective Look, *Bicentennial Symposium on Science: A Resource for Humankind?* National Academy of Sciences, Washington, D.C., October 11-13, 1976.

[5] Thoma, J.U., Bond Graphs for Thermal Energy Transport and Entropy Flow, *Journal of the Franklin Institute*, 292, 109-120, 1971.

[6] Oster, G., A. Perelson, and A. Katchalsky, Network Thermodynamics, *Quarterly Reviews of Biophysics*, G, 1-134, 1973.

[7] Thoma, J.U., Simulation, Entropy Flux and Chemical Potential, *Biosystems*, 8, 1-9, 1976.

[8] Ferdinand, L., Theory of System Complexity, *International Journal for General Systems*, 1, 19-33, 1974.

[9] Bagno, S., The Communication Theory Model and Economics, *IIIE Transactions*, __, 162-181, 19 .

[10] Peters, J., *Informationstheorie*, Springer Verlag, Berlin, 1967.

[11] Atlan, H., *L'organisation biologique et la theorie de l'information*, Herman, Paris, 1972.

[12] Thoma, J.U., Models, Bond Graphs and Entropy, in J. van Dixhorn, and F. Evans, eds., *Physical Structure in Systems Theory*, Academic Press, London, 1974.

[13] Thoma, J.U., *Introduction to Bond Graphs*, Pergamon Press, Oxford, 1975.

[14] Tribus, M., and E. McIrwine, Energy and Information, *Scientific American*, 184, 179-188, 1971.

[15] Borel, L., Energy, Economics and Exergy, in E. Camatini and T. Kester, eds. Heat Pumps and Their Contribution to Energy Conservation, *NATO Advanced Study Institutes Series E: Applied Science*, No. 15, Noordhoff, Leyden, 1976.

[16] Plank, M., *Theorie der Wärmestrahlung*, 5. edition, A. Barth, Leipzig, 1923.

[17] Häfele, W., Die Bedeutung der Energie für den Lebensstandard, die wirtschaftliche Entwicklung und die Umwelt, in Chr. König, ed., *ENVITEC '77 - Internationaler Kongreß "Energie und Umwelt"*, Vulkan Verlag, Essen, FRG, 1977.