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It is generally conceded that we are, by our technology and burgeoning population, committing ourselves to a civilization which depends on a constantly increasing rate of energy comsumption. Furthermore, until recently it was widely believed that this state of affairs was to our advantage if only adequate supplies of energy could be tapped. However implicit in this concept of a high energy civilization is the belief that we will in some way be able to control the release, expenditure and disposal of energy with increasing efficiency. In the words of Cambel (1970):

"The solution to the conflict between energy and the environment must not be in curtailing energy supply, but in reducing the irreversible and dissipative effects when we convert and consume energy."

It is my contention that this hope of greatly increased efficiency in energy control is a vain one and that its futility stems directly from the second law of thermodynamics which is concerned with the spontaneous degradation of energy. Indeed, the problem here is simply a restatement of the older one regarding perpetual motion machines.

We may begin by generalizing the concept of a machine, which we define as any technological device or process which is intended to achieve some desired result through the expenditure of energy. This generalized machine, which is depicted in Figure 1, consists of a box in which a certain quantity of delivered "fuel" energy E_F is converted into "work," "W," and for which a quantity of wasted energy $E_1 + Q_1$ is emitted, where E_1 is energy stored in the environment, perhaps only temporarily, and Q_1 is dissipated heat. This energy is further dissipated as other forms is indicated by the underlying dashed line. The quantity of "work,""W," achieves a certain desired result (which we abbreviate as R) and is then also dissipated as $E_2 + Q_2$, etc.

It is a refinement to point out that sometimes a quantity of energy is stored in R as when work is expended in lifting a mass against the gravitational field. However frequently this is not the case and R does not represent a higher energy state than before it was achieved. In fact, R may actually represent a lower energy state that existed previously. In the cases of no energy gain, the energy has been expended on the environment. An example of the latter is work of transportation in which the energy is dissipated as friction or as other forms and does not reside in the transported mass.

The operation of a machine is most easily seen in the common cyclic engine in which E_F consists of fuel energy which is transformed into heat energy Q. In this case, the work is derived from Q and a quantity of heat, Q_1, is ejected into the environment. The thermal efficiency of such a machine is

$$\frac{W}{Q},$$

which is strictly limited by the difference in temperature between the heat source and sink and cannot exceed the efficiency of the ideal Carnot engine. An important point here is that in addition to Q_1 the quantity W must also be dissipated so that the machine can operate. This W is converted into $E_2 + Q_2$ and other subsequent forms of energy as it flows into the environment, as is indicated by the dashed line in Figure 1. This spontaneous conversion of mechanical work into other energy forms was noted at an early date by Rumford (Fairs, 1962).

It is interesting next to consider another quite different example, the expenditure of a chemical pesticide to kill some target organism. In this case also there is an initial input of chemical energy E_F which enters the habitat of the target organism. Some of this chemical energy impinges directly on the target organism and is analogous to mechanical work. However, probably the greatest amount of chemical energy misses the target and interacts with non-target organisms or with other substances of the habitat. In this process some energy storage occurs and some heat is released through the chemical reactions which occur. Thus, again, energy $E_1 + Q_1$ is dissipated. However, even that part of the pesticide energy which reaches the target organism continues to interact with the environment and with non-target organisms as partially degraded, but still reactive forms of the original chemical. This is the energy $E_2 + Q_2$.

We now make several observations: 1) A machine mimics a living organism in that it feeds on a flux of energy and thereby creates a local increase in the order of the environment or in a thermodynamic sense decreases the entropy. However, as a result of the energy flux there is a net increase in the overall entropy of the process, as there must be in any spontaneous process. 2) Although these second law effects form the basis of machine inefficiencies, these same effects are also vital to the very operation of the machine or technological process. Thus, the increase in entropy and energy loss associated with friction is not only necessary to the operation of the machine but is required to dissipate the energy after it is utilized. For example, friction between the wheels and the ground is required to move a vehicle. Similarly, in the case of the chemical pesticide, the increase of entropy associated with the spontaneous dissemination and dissolution of the pesticide is a necessary requirement to reaching the target organism, although it is also the source of inefficient use and undesireable impacts on non-target organisms.

While these points may seem obvious, they lead to a conclusion which is not so obvious, since it apparently has not been considered to date. This conclusion is that in the flow of energy depicted in Figure 1 the manifold spontaneous elements, which play such a vital role in the operation of any technological process, also effectively remove most of the energy flow path from the control of the operator. In other words, the very requirement of spontaneity eliminates the possibility of significant control over energy. If this effect has not been apparent until now, it is only because the energy flux has not been large enough.

It might at first be thought that the energy dissipative processes, which admittedly are the source of environmental difficulties, could be greatly mitigated by the application of ingeneously engineered processes or devices, that the generalized engine could be made more efficient or that through "pollution control devices" the dissipative processes could be modified in some way. In the past, indeed, many obstacles to high technology had been overcome in this way. However, in environmental problems the thermodynamic system is the entire earth and we cannot fall back on crude technologies to construct more sophisticated ones. Thus, it may happen that the construction of more efficient mechanical engines than we now possess will require some sophisticated metallic alloy. Then to judge the efficiency of the machine truly we should also have to include the efficiency of the alloy producing process. Similarly, in judging the effectiveness of pollution control devices we must determine the total effect they have on our technology.

More fundamental, however, than any argument of efficiency is our point that because of what may be called the "Rumford effect" the efficiency itself plays only a secondary role in the environmental impact of technology. This is the case because the entire energy input E_F or Q must be dissipated in the environment (Mueller, 1971), as shown diagrammatically in Figure 2. Thus increased efficiency of a process can benefit the environment only inasmuch as this efficiency enables the total energy input to be reduced for a given level of production. In any case, increasing efficiency cannot meet the problems of an increased rate of energy utilization.

Thus, although we may exert a certain amount of control over a part of the energy flow path this advantage will in general be purchased only through the expenditure of more energy elsewhere and this energy, too, must be spontaneously dissipated.

The foregoing conclusions should not be construed to mean that improvements are not possible in the production and utilization of energy. The point stressed here is that if such improvement is attempted through the expenditure of further energy, it probably will not occur. Thus, the reduction of the troublesome "irreversible and dissipative" effects seems to conflict with an increasing rate of energy expenditure. Rather, what is suggested for a solution to the energy problem is not a futile attempt to reduce irreversible effects resulting from the second law, but to plan to minimize the total energy flux and to formulate the goals of society in such a way as to make this possible.

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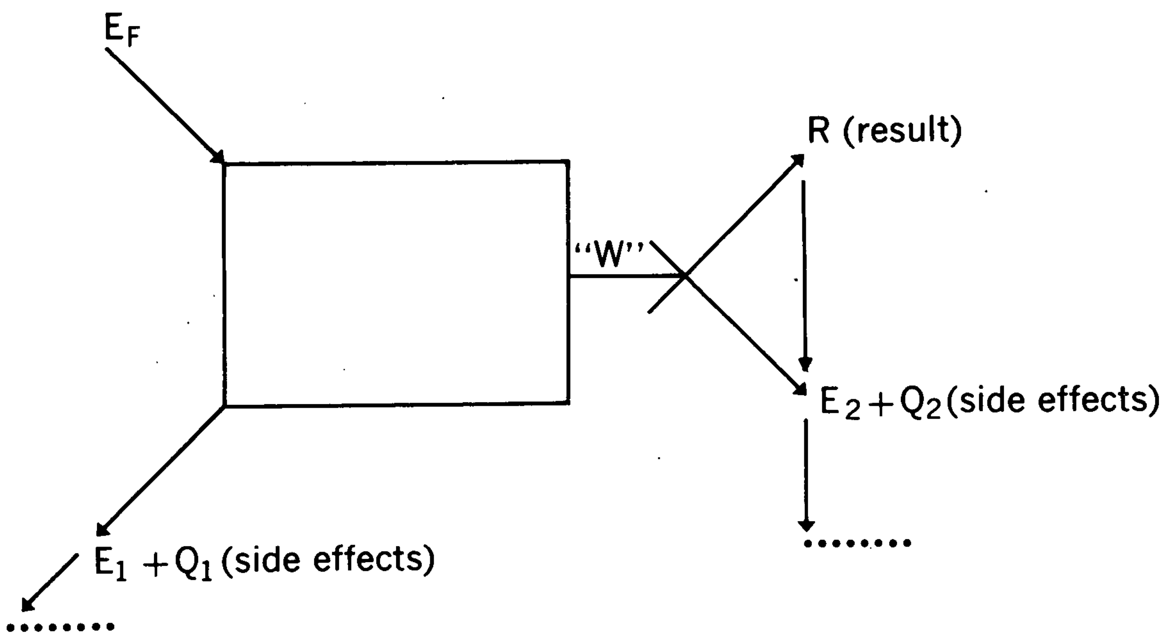

FIGURE 1

Flow of Energy through the Generalized Machine

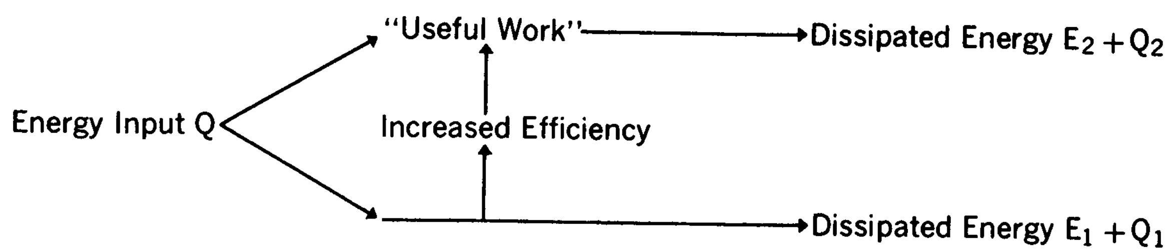

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FIGURE 2
Energy Dissipation as a Result of Technological Processes