As environmental considerations become more important factors in policy decisions and planning, the need becomes more compelling for reliable and precise indices of environmental use. This need becomes particularly apparent when one is confronted with alternative policies, among which some selection must be made. The problems arise at the most commonplace level, such as the housewife's choice between a paper sack or a polyethylene bag, and at the highest level of policy making, such as the choice among means and locations for power plants.

The problems call for the identification of variables that can be reasonably well and unambiguously quantified, that are general enough to compare quite different sorts of processes, that are key measures or indices rather than overly specific quantities, and that are truly measures of the amount of use to which the environment is put.

To a scientist seeking general quantifiable and unambiguous variables that serve as fundamental indices, the quantities derived from thermodynamics are the most obvious and natural. In particular, the change in thermodynamic potential associated with execution of a process fills all the criteria we have just laid down. Thermodynamic potential is the fundamental measure of the capability of a system to perform work, and every natural process involves the consumption of some thermodynamic potential. The science of thermodynamics tells us how to determine the minimum expenditure of thermodynamic potential, to achieve a given physical change. In other words, thermodynamics tells us how to determine the maximum efficiency of a process, and to compare the expenditures of thermodynamic potential required for different processes.

The change in thermodynamic potential contains within it all the energy exchanges associated with the process and also the effects of changes in organization and structure, as measured by entropy, the degree of dilution or disorder in a system.

Thermodynamic analysis may be applied as a global device for studying long-term development of a society, or as a micro-analytical tool for comparing specific processes, such as manufacturing practices.

For the scientist assessing the potential stored in a complex system, or the potential consumed when a complex system undergoes a process, the natural variables with which to describe the system are those of thermodynamics. This is true whether one is computing the work that can be done by a physical process or a biological system. The same laws, variables and concepts that apply to the burning of a million tons of coal to produce electricity to run the machines of a factory also apply to that metabolism of sugar to produce the energized molecules of adenosine triphosphate that generate movement and growth.

The two essential forms of stored potential are energy and order. We withdraw and use energy from many forms of storage: gravitational energy provides power for turning millstones and hydroelectric generators; chemical energy is readily available in the form of fossil fuels; solar energy powers electrical cells and the growth of green plants. We find and use the potential represented by order when we obtain minerals from concentrated ore bodies, rather than finding them distributed uniformly over the Earth's surface, or when we use ice as a refrigerant.

Our present task is to try to analyze the potential stored in the environment and how we make use of it. The world we inhabit contains a vast stored potential, in many different forms. In some of its forms, this stored potential is very accessible: the chemical potential stored in a tree, for example, can be converted to heat energy very easily, just by burning the tree. Other forms of stored potential are less available: it requires considerable work and energy to obtain a useful amount of energy from nuclear fission. We have not yet learned to unlock the potential, at least in a controlled way, that we know is available through the fusion of two nuclei of heavy hydrogen. Yet we can determine rather easily how much potential is locked up in each of the stored forms, and how much comes from our one important outside source, the Sun.

Determining the total amounts of stored potential of various forms depends on estimating reserves. Hence there is a degree of uncertainty in trying to evaluate total amounts of potential. We can, however, do much better, removing most of the uncertainties, if we examine the changes in stored potential associated with particular processes. The laboratory sciences have provided us with a rich source of accurate data on the changes in potential that accompany virtually any chemical or physical process, and even some biological processes. (Strictly speaking, while the thermodynamic data are always being improved, there are occasional examples for which the data are not yet very accurate. These exceptions are rare enough to leave our sweeping generalization quite valid.)

Knowing the changes in stored potential associated with processes is actually of far more use in choice-making situations than knowing the absolute amount of stored potential, up to the point that the supply of stored potential runs low. By comparing the amounts of potential consumed by alternative processes that achieve the same end, one can choose the more thrifty, the process that uses fewer resources to accomplish its task.

One can easily see how doing "energy economics" leads us to one of the root problems of environmental management — thrifty utilization of energy. It is remarkable how many of the environmental insults that we
Our world contains a vast, stored energy potential. By comparing the potential consumed by different processes, one can choose the process that uses fewer resources to accomplish a task. If we could identify areas in which there were economies to be found in energy utilization, then we could begin, perhaps, to reconcile the technological life style we have so thoroughly adopted with the increasing environmental insults that seem to accompany our technology. The author, professor of chemistry at the University of Chicago, carried out the calculations presented here, which are a rough first approximation, at the Aspen Center for Physics during the summer of 1971. A much more accurate and detailed study has now been carried out for the Illinois Institute for Environmental Quality. The real thermodynamic costs are considerably higher than reported here, but the inferences are, if anything, strengthened.

now recognize can be traced to the use of large amounts of energy. If we could identify areas in which there were large potential economies to be found in energy utilization, then we would begin, perhaps, to find a key to reconciling the technological life style we have so thoroughly adopted with the threat of increasing environmental insults that seem to accompany our technology.

If we look further into the future, past the immediate environmental problems of our decade or our century, we can see "energy economics" or "thermodynamic economics" taking a larger role. As the potential stored in one form of natural resource is depleted, we must make choices among alternative responses to the foreseeable shortage. Presumably, each choice carries long-term, large-scale implications; one cannot take seriously using a short-term market analysis to decide, say, in the year 2171, whether all the remaining fossil fuel should be reserved for the chemical industry. We must rely on the most long-range, most nearly ab-
solute measures available to make such choices; these measures are precisely the variables of thermodynamics, the potentials.

It is not accidental that the parallel between economic analysis and thermodynamic analysis continues to appear. Let us try to identify the essential difference between the two. Economic analysis is associated with a set of values based on shortage, as perceived by the participants in the marketplace. The perception of shortage is itself a recognition of supply and demand for the present instant and for some time in the future. Thermodynamic analysis is the way to measure the absolute supply of the only commodity of which there is a true shortage when one considers an arbitrarily long time scale into the future, the thermodynamic potential. So long as matter is conserved within the region we inhabit, there is no real shortage of any substance; there can only be a shortage of the thermodynamic potential to do the work required to recover the substance.

If the economists in the marketplace were to determine their estimates of shortage by looking further and further into the future, these estimates would come closer and closer to the estimates made by their colleagues, the thermodynamicists. In the jargon of the scientist, we may say that economic costing approaches thermodynamic costing asymptotically, as the time scale is extended. For the ultimate long-range planner, economic and thermodynamic analyses are equivalent.

Environmental analysis necessarily confronts many problems in which one wants to make long-termvaluations. Frequently the time scale one requires is far longer than one would use in market analysis. We are forced to treat the concept of shortage on the time scale, for example, in which some elements are available only through reuse or through recovery from their natural levels of abundance, rather than from ores. At this level, where the only true shortages are those of thermodynamic potential, thermodynamic analysis becomes imperative.

**System Defined**

In any thermodynamic analysis, the first step is the definition of the system. Our system consists of the materials that become the manufactured object, together with the other resources from our environment that enter directly in the processes. This means that we include the energy spent by the system to prepare the manufactured object, and the potential lost when the object is broken up and ultimately completely dispersed, when we evaluate the real thermodynamic expenditures for manufacture and disposal. To find the real thermodynamic cost of the new object, we evaluate the actual amount of thermodynamic potential that we withdraw from our environment when we make the object and subtract the amount of thermodynamic potential that is actually stored in the object. But we are more interested in the cost of the process of manufacture and discard: it is not really our concern to calculate the thermodynamic cost of a collection of mint automobiles. Therefore we calculate the total thermodynamic cost by adding to the net cost of pro-

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ducing the new machine to the thermodynamic potential lost when the machine is discarded.

The amount of thermodynamic potential stored in the new machine is exactly the unrealizable, ideal limit of its thermodynamic cost, the result of what scientists call a “reversible process.” In the ideal limit, either the system or the surroundings may pay the thermodynamic cost, but whichever pays the bill, the amount is the absolute minimum set by natural law. If the system pays, the net change in its thermodynamic potential is zero, and the process has merely changed one form of potential into another. If the surroundings pay — for example, if the required energy were taken from the Sun — then the stored potential of the system would increase by the amount stored in the new machine. In the real world, of course, we cannot expect to operate ideal systems. We always spend considerably more thermodynamic potential to make something than is stored in that thing. The difference between the potential we spend for the process of production and what is stored in the product is the net potential spent or lost in the process. This difference, this net cost, will provide the basis for our analysis in the last section. It is precisely because the thermodynamic potential is truly lost, that we describe the ultimate shortage of chemical potential as the only true shortage. The amount is limited to what we have stored in the Earth and what we receive from the Sun: one is limited in absolute amount and the other, for all intents and purposes in this context, comes only at a fixed, unchangeable rate.

There is a certain degree of arbitrariness in defining the boundaries that separate system from surroundings. We have made our choices largely on the basis of what kinds of data are available. For example, we have included the expenditure of electrical energy for mining and manufacturing as part of the process undergone by the system, but have omitted the processes of generating electricity from primary energy sources. (To include this conservatively, one need only multiply the first three entries in the last column of the table (p. 13) by a factor of about 2.6.) We have also omitted the thermodynamic costs of sustaining the people who do the work, on the basis of the assumption that the people would somehow be sustained whatever process one considers. We have also neglected the thermodynamic cost of operating the automobile because the operation of the vehicle belongs more properly to the thermodynamic system associated with transportation than to the process of manufacture and discard.

With this description of our system, we may now proceed to the analysis.

**Thermodynamic Estimates**

We have chosen as an example the thermodynamics associated with the manufacture of automobiles, both from new raw materials and from recycled automotive scrap. The quantities of principal interest to us are the amounts of thermodynamic potential consumed in mining and manufacture of automobiles from "new" raw materials, the amounts of thermodynamic potential consumed in recycling, and the minimum requirements of thermodynamic potential that would be required to manufacture an automobile by an ideally efficient process. The criterion for judgment is introduced at this point, the criterion of "thermodynamic thrift": that it is desirable to minimize the consumption of thermodynamic potential in achieving any chosen goal. (This is the thermodynamic analog of the statement "It is undesirable to throw away money needlessly.")

With the criterion of thermodynamic thrift and the results of our estimates of free energy consumption, we can compare and evaluate three policies, in terms of what they can achieve: The first is maximizing recycling; the second is extending the useful life of the machine; and the third is developing more (thermodynamically) efficient processes. By considering automobile manufacture as a prototype for manufacturing processes, we can immediately make certain generalizations and recommendations for long- and short-term policy regarding technology and manufacturing.

We take the first step in analyzing the process of automobile manufacture by defining the process and breaking it into manageable steps. Each step involves a transformation of matter from one state to another. We find it convenient to isolate six states: (1) Material as ores and other primary forms, (2) Pure raw materials, (3) The new, manufactured automobile, (4) The used automobile, no longer functioning, (5) The materials of the automobile, discarded and dispersed, (6) The chemically degraded dispersed materials, e.g., completely rusted iron. The six states are connected by the transformations indicated in the figure. These transformations are labeled, for convenience, as: (A) Mining and Smelting (but strictly, including manufacture of synthetics, production of fabrics and other basic industrial processes), (B) Manufacturing, (C) Normal use, (D) Recycling, (E) Junking, and, (F) Natural degradation. Often, steps E and F are not actually separate but occur simultaneously.

The two pathways of main concern for us are the manufacture of automobiles from basic raw materials, via steps A, B, C, E and F; or the recycling process, via steps B, C and D. We are interested in the real costs, in terms of energy and thermodynamic potential, for these two pathways. We are also interested in one other thermodynamic quantity — the minimum requirements of thermodynamic potential for production of an automobile either from the nonfunctioning wreck (state 4) or raw materials (state 1).

The next stage of the development is the determination of the thermodynamic quantities for the steps of interest. The actual energy expenditures are tabulated for a wide variety of processes which cover most of the important quantities of interest to us [1,2]. One real energy quantity must be estimated from rather nonspecific data, but, as we shall see, even with the uncertainty so introduced, we are still able to draw unambiguous conclusions. It would be desirable to know the actual entropy changes which, together with the energy, determine the real expenditure of thermodynamic potential. However, the analysis
shows that the changes of energy so clearly dominate the changes in thermodynamic potential that, at the present level of refinement and for the particular problem under discussion, these entropy changes can be neglected. Inclusion of real changes of entropy would only strengthen our final conclusions. The other quantities to be found are the ideal thermodynamic changes — the differences in energy and thermodynamic potential for each transformation in the figure. We must estimate the change in internal energy and in thermodynamic potential for the material that makes up an automobile, in each step of the process. These changes represent the ultimate natural limits on the energies and thermodynamic potentials that must be paid, in order to carry out the various steps.

Having used the term "thermodynamic potential" so freely, we must define it. For our purposes, we can consider the thermodynamic potential $F$ in terms of its relation to the energy $E$, the entropy $S$ and the absolute temperature $T$. (For systems involving gases, a slightly broader definition is required.) This relation is concisely stated by the equation

$$ F = E - TS. $$

Thus, the thermodynamic potential is equivalent to the energy, less a contribution $TS$, proportional to the degree of disorder as measured by the entropy. We concern ourselves here with finding the changes (represented by $\Delta$) in thermodynamic potential, $F_{\text{final}} - F_{\text{initial}} = \Delta F$. Since the world’s temperature is more or less constant, we can write the change in thermodynamic potential in terms of the changes in energy and entropy, $\Delta E$ and $\Delta S$, respectively:

$$ \Delta F = \Delta E - TS, $$

and, thereby, concentrate on the changes in energy and entropy, with each step. (There is some question regarding the appropriate quantity to be used for $T$ in certain parts of the treatment, but the ambient temperature gives a suitable upper limit for $\Delta F$, which is all we need.)

The energy changes are virtually all changes in the internal chemical energy of the materials, and are well-known, measured quantities, per unit of material [3]. Hence the theoretical values of $\Delta E$, per automobile, are readily determined from a knowledge of the composition of an automobile. Automobiles are almost all steel, iron, ferro alloys and aluminum, and the thermodynamics of automobiles are dominated by these materials. The contributions to $\Delta E$ and $\Delta F$ from fabrics, rubber, plastics and other materials become significant only if we require quite precise values for the thermodynamic quantities. At this stage, such precision would add nothing to our insight because of the uncertainties and variations in the parts of the cycle associated with mining and preparation of primary materials. For example, the energy differences between different iron ores (in the quantities required for an automobile), e.g., hematite vs. taconite, are comparable to the energy associated with the "minor materials" of the automobile. Hence we neglect the minor materials in the present treatment.

Most of the entropy changes are small, as it turns out, but have been considered explicitly for reasons that will become apparent. Entropy changes associated with chemical transformations are known from experiment and are available just as the corresponding energy changes are available [3]. Entropy changes associated with the creation of an ordered structure have been estimated from an extension of information theory [4]; (details of the method are presented in the appendix on p. 15).

Entropy changes associated with dispersal of used materials are sometimes quite significant. These quantities are readily evaluated from the well-known expression of the proportionality of $\Delta S$ and the logarithm of the dilution [5]:

$$ \Delta S = 3.68 \times 10^{19} n \log (C_{\text{Initial}}/C_{\text{final}}) $$

where $n$ is the number of atoms in the system, and the argument $(C_{\text{Initial}}/C_{\text{final}})$ of the logarithm is the ratio of the initial concentration (atoms per unit volume) to the final concentration. The initial concentration is essentially the density of the pure material. The final concentration is the mean concentration of the particular substance in the Earth’s crust, based on its natural abundance.

This method of calculating changes of entropy and thermodynamic potential is associated with a specific picture: discarding according to step E is equivalent to allowing the relatively pure materials of a junked automobile to become uniformly dispersed throughout the Earth’s crust, to the extent that, were the process to be pursued indefinitely, we would eventually be forced to recover the.
materials from their lowest state of thermodynamic potential. This is the state of uniform distribution. Iron, which, on the average, comprises about 0.6 per cent of the Earth’s crust, is now mined from ores that are about 50 per cent iron, so that we presently obtain iron from a relatively high-grade source. This is not true of all substances; iodine or gold obtained from seawater, for example, are taken from states approaching maximum dispersal and minimum thermodynamic potential. Examples such as iodine or gold only arise when high-grade sources are unavailable or when extremely efficient recovery methods have been developed.

**Numerical Values**

Having outlined how the thermodynamic quantities are obtained, we now attach numerical values to them. It is convenient to carry out the estimates on the basis of the energy and thermodynamic potential per automobile. Our figures are based on the projections for 1980, given by Landsberg, Fischman and Fisher [1], except where noted. The most uncertain figures in our estimates are those associated with mining and smelting. The total national energy expenditure for these processes is $33 \times 10^9$ kilowatt hours (kwh). On the basis of the weight of mined iron ore, relative to an estimate of the total weight of mined material, we assume that one-fourth to one-half of that energy is used for iron, and that one-fifth of the iron mined is used for automobiles [1]. We take seven million as the number of automobiles manufactured in 1960, and assume that about 14 million automobiles will be manufactured in 1980. We find that the iron in each new automobile is actually produced by the expenditure of about 115 to 230 kwh of energy for mining and smelting. (This figure probably has the indicated uncertainty of about a factor of 2, and could be uncertain by a factor of 3.) Producing the automobile’s 0.1 metric ton of aluminum requires about 1,640 kwh.

Now we consider the ideal limit associated with step A, mining and smelting. The absolute thermodynamic potential change associated with mining and smelting the metric ton of iron in an automobile is approximately 5 kwh, including both the chemical transformation of iron oxide to pure iron, and the mechanical work of lifting the ore to the Earth’s surface. The 0.1 metric ton of aluminum adds about another 0.5 kwh, so we can estimate the total change in thermodynamic potential of the materials in an automobile, the ideal thermodynamic limit that would be spent by producing pure starting materials from primary ores by a perfectly efficient machine, would be about 6 or possibly 7 kwh.

The actual costs in energy and, at the same time, a lower limit to the costs in thermodynamic potential for step B, manufacturing, were roughly 2,000 kwh per automobile in 1960, and are projected to be about 4,200 kwh in 1980 [1, Table A 10-28]. The theoretical limit to the change in thermodynamic potential for step B is essentially the change associated with introducing order and structure into the purified materials. This is of order $10^{-11}$ kwh, or conceivably $10^{-10}$ kwh at the very most. In other words, the actual expenditures of energy for manufacturing an automobile are reflections of the historically developed means of production and transport, rather than of the thermodynamic requirements for creating the ordered structure of an operable machine.

The thermodynamic potential for step C, normal use, is roughly that for the loss of the information content of the structure, and is therefore negligibly small for our present purposes. We do not take into consideration the consumption of thermodynamic potential associated with the use of an automobile, because that is fairly independent of its manufacture and dispersal. One aspect of the thermodynamics of use would play a role in a more refined treatment; this is the dependence of the fuel and servicing requirements on the age, condition and manufacturing tolerances of the automobile.

The actual requirements for recycling through step D are approximately 600 kwh for steel (because scrap steel is generally processed by electric furnace), about 60 kwh for cast iron, and between 600 kwh and 1,640 kwh, depending on the amount of refining and treatment required, for aluminum, giving a total between 1,260 and 2,300 kwh. The ultimate changes in thermodynamic potential are again negligibly small, associated simply with the segregation of a few relatively pure but functionally useless components into separate piles of relatively pure materials.

The next phase, step E, requires no energy input. It consists simply of the dispersal of the metric ton of iron (and a small contribution from aluminum) from its virtually pure state to its condition of uniform dispersal, comprising 0.68 per cent of the Earth’s crust. This gives a change in thermodynamic potential between 25 and 26 kwh per auto.

Finally, step F, the natural chemical degradation of the dispersed materials, is associated with a loss of chemical potential which is almost entirely due to rusting of the iron and steel. This gives a net loss of about 2 kwh per automobile, considerably less than the loss associated with dispersal.

The set of changes in thermodynamic potential associated with the various steps are collected in the table.

**Implications**

**Recycling.** The first comparison to be made is that of automobile manufacture, by existing processes, from ores and other primary materials, with recycling. The former process involves steps A, B, C, E and F, while the latter involves only steps B, C and D. The first process, according to the figures in the table, contributes a net loss of approximately 6,525 kwh of thermodynamic potential per automobile; with the uncertainty we estimate for step A, this could be as small as 5,000 kwh, but is very unlikely to be less than this. The recycling process, with present technology, uses between 3,260 and 4,300 kwh with the 1960 energy requirements for manufacturing, and will go up to between 5,480 and 6,500 kwh if the projections for 1980 prove correct. The savings associated with recycling at the present time are therefore between zero and about 1,040 kwh per automobile.

It is very probable that not all the needs for new automobiles can be met by recycling. The projections
### Real and Ideal Changes in Thermodynamic Potential for Processing an Automobile

<table>
<thead>
<tr>
<th>Step</th>
<th>Ideal</th>
<th>Real</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Mining and</td>
<td>(6 kWh for auto alone)</td>
<td>−2,300</td>
</tr>
<tr>
<td>smelting</td>
<td></td>
<td>(−2,000 in 1960)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(−4,200 in 1980)</td>
</tr>
<tr>
<td>B. Manufacturing</td>
<td>negl.</td>
<td>neg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(−1,260 to −2,300)</td>
</tr>
<tr>
<td>C. Normal use</td>
<td>negl.</td>
<td>−25</td>
</tr>
<tr>
<td>D. Recycling</td>
<td>negl.</td>
<td>−25</td>
</tr>
<tr>
<td>E. Junking</td>
<td>−25</td>
<td></td>
</tr>
<tr>
<td>F. Natural degradation</td>
<td>−2</td>
<td></td>
</tr>
</tbody>
</table>

Note: "Negl" means quantity is negligibly small. In all the steps of this example, with the exception of step E (and the negligibly small changes in the ideal limits for steps B, C, and D), the overwhelming contribution to the change in thermodynamic potential is given by $\Delta Q$, the energy change. Negative signs indicate losses or expenditures of potential. The figure of 6 kWh for ideal step A is actually the increase in thermodynamic potential associated with the automobile itself; in the ideal limit, this could all be taken from either the system (environment) or surroundings. If it were taken from the system, then the total net change in the thermodynamic potential of the system would, of course, be zero.

The data of Landsberg, Fischman and Fisher [1] indicate that up to about 50 percent of these needs can be met from "obsolete scrap." If this is reasonably accurate, then a program of maximum recycling would amount to an average saving up to about 520 kWh per new automobile, or about 10 percent of the present thermodynamic requirements for its manufacture. The maximum annual net saving in energy now would be of order 4 billion kWh. This represents a moderate saving in energy and thermodynamic potential, if it could be realized. However, it is not clear whether it is, in fact, realizable, so that recycling with present technology seems to be a questionable process. If the thermodynamics of step B, manufacturing (or D), could be improved, then recycling would provide larger benefits; by the same token, if the energy costs for step A, mining and smelting, increase, this also makes recycling more desirable.

At the level of ultimate costs of thermodynamic potential, recycling is also advantageous. Even if the component parts of automobiles are allowed to rust away, a decided saving is achieved by preventing the dispersal of nonfunctional automobiles. In effect, by collecting wrecked automobiles into stockpiles and letting them rust there, we save the 25 kWh per automobile of step E, even though we may lose the 2 kWh of step F. Consequently, there is a basis for retaining automobile scrap stockpiles, whether or not a policy of maximum recycling is adopted. Of course, the real saving achieved by recycling is far greater than the possible saving from a simple non-dispersion policy.

**Extended Life.** A second general means for achieving thermodynamic thrift comes to mind. This is a policy of extending the life of the machine. Presumably, the useful lifetime of a machine is a function of the precision with which it is manufactured and of the kind of maintenance it receives. It is difficult to assess the precise thermodynamic costs that would be required if the useful life of an automobile were doubled or tripled. However, one can say with full confidence that an upper limit for these costs is, at the very most, somewhat less than the real present expenditure for step B, that is, with the total expenditure required for manufacturing the vehicle.

A policy of extending lifetimes of automobiles would, in effect, increase the cost of manufacturing conceivably by as much as 1,000 kWh, more probably by no more than half this amount, but would require that mining and smelting be performed only one-half or one-third as often as it is presently. This would mean a net saving of order 2,750 to 4,500 kWh per lifetime of present vehicles and two to three times this much over the life of an extended-use vehicle, with one extended-use vehicle replacing two or three of the type now manufactured.

Presumably the economic cost of extended-life vehicles would be significantly higher than that of comparable vehicles now being made. The manufacturing manpower required, per mile traveled or per passenger mile, might well be comparable to present manpower requirements. However, these considerations are irrelevant to the kind of thermodynamic considerations on which we are focusing here. Balancing thermodynamic gains against the inconveniences or added financial costs is already at the level of policy decisions that may call for judgments outside the purely thermodynamic sphere. As the discussion in the second section indicates, we can expect that most economic judgments would coincide with decisions based on thermodynamic considerations, provided that the economic costing is done with a sufficiently long-term valuation and with the costs of "externalities" included.

The bases of economic and thermodynamic valuation tend to become more and more similar as one extends the time scale for consideration of economic value. We shall return to the question of the limitations on making decisions on strict thermodynamic grounds.

**Real and Ideal Costs.** The third general sort of approach to thermodynamic thrift is suggested by comparing the second and third columns in the table. The most striking aspect of the table is the enormous disparity between the magnitudes of the two sets of figures. Where the ideal expenditures of thermodynamic potential are tens of kWh per automobile, the actual expenditures are typically thousands of kWh per automobile.

The immediate implication of this disparity is the existence of possibilities for vast savings in thermodynamic potential. The discrepancy between real and ideal thermodynamic costs makes it clear that there can be technologies far more efficient than the ones we use now. Even "modest" improvements in efficiency could be expected to reduce the thermodynamic costs from thousands of kWh per vehicle. It is not at all unreasonable to suppose that improvements in

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basic technology could increase the efficiency (in terms of the ratio of ideal to real thermodynamic costs) from the present figure of 1980 projection of about 0.1 per cent up to 1 or even 5 per cent.

Clearly, the largest potential savings, in terms of energy and thermodynamic potential, can be achieved with improvements in the basic methods of metal recovery and fabrication. The savings that could, in principle, be so achieved would reduce the thermodynamic cost of an automobile by factors of 5, 10 or more. We saw, by comparison, that extending the life of a machine could achieve a saving of about 50 to 100 per cent, whereas recycling can apparently achieve a saving of about 10 per cent now and probably less than that in 1980.

The figures are reasonably compelling; the differences among the three courses we have considered are so large as to make the three choices almost qualitatively different. We need not worry about details of the computations, when the figures separate the possibilities so clearly. It is quite obvious that the savings to be achieved by recycling with present technology are at best small, compared with the savings that extended-life machines could provide, and that these savings are, in turn, small compared with the possible savings that could be accomplished by new technology. The decision to opt for thermodynamic thrift would immediately tell us which course is the most desirable. (The same concept has been termed "energy husbandry" by R. H. Socolow.)

At the same time that we consider which policy offers the greatest saving, we must also ask about the relative ease of adopting one policy or another. Recycling is a relatively minor perturbation on present policy; maximum recycling would only amount to reapportioning the relative amounts of effort among well-established courses that we now follow. In absolute terms, a moderate amount of energy and thermodynamic potential might be saved if a policy of maximum recycling were adopted. Making extended-life machines would require some changes in manufacturing technique and a moderate readjustment of the relationship between the owner and the vehicle. The adjustment, as well as the savings, would be significantly greater than in the case of maximum recycling, and the time required to put the policy into effect would be longer as well. Recycling might be adopted and put into practice rather soon, even as the changes necessary for extending the useful lifetime of machines are being developed.

The same sort of comparison holds for major technological change, but on a much grander scale. The basic ideas required to implement the changes probably do not yet exist. Only when these ideas have been conceived and developed into workable engineering methods could we begin to achieve some of the huge possible savings that can be made. Hence, we should plan to use, first, recycling and, then, extended-life machines, during the interval when the new technology is being developed.

Whether or not development of the new technology is slow or difficult is not important, unless, by some strange quirk of fate, its cost of development rivals the savings it provides. The potential savings are so great that we consider this possibility too unlikely to be worthy of consideration. We assume that the costs of development, even if they are large, will be infinitesimal compared with the eventual savings. A saving of only 1,000 kWh per vehicle would correspond to the total power output of eight or ten good-sized generating stations.

The assumption that the costs are small compared with the gains, together with the adoption of a policy of thermodynamic thrift, point to the desirability of establishing a new national goal. This goal would be the development of new technology for extractive and manufacturing industries, technologies that would operate with efficiencies closer to the ideal limits than do the present methods.

The desirability of such a national goal would carry with it some very surprising implications that differ sharply with current federal policy. The foremost implication is the need for numbers of scientists and engineers with the skills to do fundamental and innovative development in applied science and basic engineering. Rather than cutting back the supply of scientists now, we should be assessing how large a force may be needed to increase our scientific and engineering personnel enough to establish a major effort in technological development. The effort would entail far more detailed and careful analyses of real and ideal processes than the rough figures developed here. However, the analyses would only be the first step, and would only provide the measure against which the real innovations could be tested. Finally, a major engineering development would be required to convert the ideas into practical, full-scale methods.

A second implication of the adoption of developing new technologies as a national goal would be with regard to the National Laboratories, including the National Bureau of Standards. Just as national laboratories were the natural centers for our previous national goals — of nuclear weapons and space travel — the national laboratories become natural foci for development of new technologies. The requisite scale of development, in terms of both time and the scale of readjustment, is far too vast for the private sector to undertake it. Hence, instead of reducing the scale of national laboratories and focusing them on increasingly specific goals, this argument implies that we should be broadening and strengthening these laboratories.

The third implication is the desirability of training young scientists and engineers who are oriented toward technology and application, albeit at a very basic level within this context. The orientation of scientific and engineering training during the past one or two decades has been relatively heavy toward the most basic and fundamental levels of our understanding of nature. Now, it appears, there is a need for people who want to make use of this knowledge to develop basic changes in the way we do things.

A fourth implication concerns the problem of the energy needs of the nation and the world. Most of the attention to this problem has gone toward improving and extending energy production. The conclusions of our analysis are that we can go far in dealing with energy needs if we improve energy utilization. At pres-
The information content and entropy of an organized structure have been analyzed by Brillouin [4] in terms of the number of binary connections among elements of the structure. The reduction in entropy associated with N terminals or binary junctions, relative to an unorganized structure is

\[ I = k \log N, \]

where \( k \) is the Boltzmann constant and \( \log \) is taken to the base 2. The number of binary junctions or terminals \( N \) is given in terms of the number \( n \) of elements in the structure, the number \( m \) of internal terminals and the number \( q \) of external terminals:

\[ N = n m + q. \]

Our problem is one of defining the elements of structure of a machine.

We begin by recognizing that the machine functions as intended when it is made to conform to a set of manufacturing tolerances. If every part of every piece satisfies the tolerances, the machine will operate as it should. If the tolerances are not met, then the machine will not operate, or will have a shorter life than is intended, or in some other way will not perform. Hence, the tolerances define the characteristic dimensional unit for the organized structure of the machine.

We may next consider the terminals as the junctions between the machine and the outside world, the surface area of the machine, where the unit of surface area is the square of the tolerance dimension, \( \delta \). Thus, the number \( q \) of external terminals is the total area \( A \), measured in units of \( \delta^2 \):

\[ q = \frac{A}{\delta^2}. \]

The internal terminals may also be included, but do not change the magnitude of the result significantly. These, if they are included, are about 4 per unit of surface, or about \( 4A/\delta^2 \).

We estimate that the uncrical surfaces of a machine, such as the exterior of the engine block, the chassis and the body contribute about \( 10^9 \) to \( 10^{10} \) with a tolerance of about 1 millimeter. The internal, critical surfaces, with tolerances of order \( 10^{-3} \) mm, contribute a total of about \( 10^6 \) to \( 10^9 \), so that the uncrical components are relatively unimportant, in terms of the order in the operating structure. The information, in bits, is \( N \log n, 10^6 \log (10^6), \) or about \( 3.5 \times 10^{22} \) bits, so that \( N \log n \) is about \( 4 \times 10^{-18} \) ergs per degree, or entropy units. The appropriate "temperature" is not clearly defined for this system, but the ambient temperature of \( 300^\circ \) is probably a high upper limit, since all new automobiles are in, more or less, the same state. Hence, we estimate that \( T\mathbb{S} \) or \( TI \) is less than about 0.12 ergs. Even if I were as large as 1 entropy unit, the entropic contribution to the free energy of an automobile would surely be less than \( 10^8 \) ergs per vehicle, which would correspond to about \( 3 \times 10^{-18} \) kWh per vehicle. Hence, the figure of \( 10^{-15} \) to \( 10^{-18} \) was taken as an upper limit in the text; the correct figure is probably a thousandfold smaller.

REFERENCES