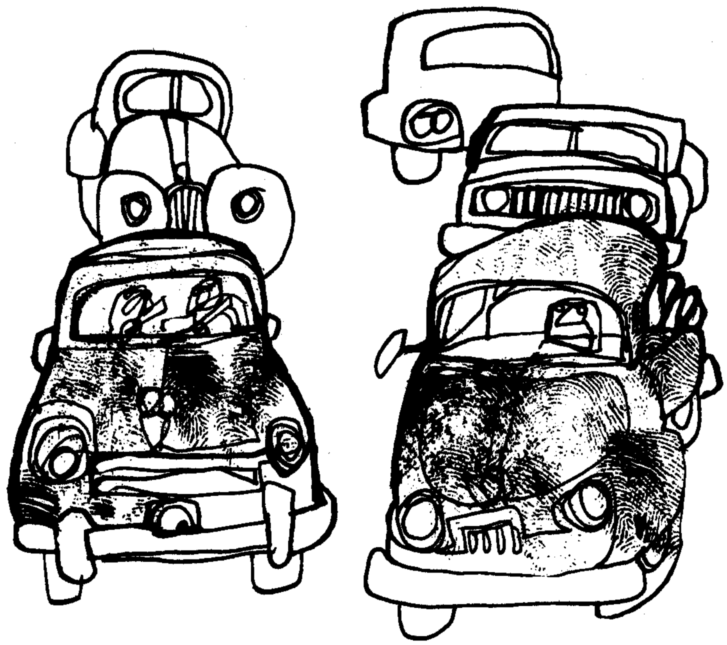
One of the consequences of the energy crisis has been a heightened interest in the amounts of energy we use for industrial processes. A conspicuous one is the manufacture of automobiles. How much free energy is harnessed in the manufacture of a motor vehicle? Are there ways of reducing the amount of energy used in auto production?

This report is based on a study by R. Stephen Berry and Margaret F. Fels of the department of chemistry, University of Chicago. The immediate purpose of the study was to provide the Institute of Environmental Quality of State of Illinois with assistance in making decisions on the disposal of automobile hulks and of solid waste in general. In a larger context, the analysis examines one aspect of how we use materials and energy from a thermodynamic point of view.

The study is a pioneering effort in a new field of energy analysis. Its significance is illustrated by only one of its conclusions—that recycling junked autos which scarify our landscape and reusing the scrap in the manufacture of new ones would achieve dramatic reductions in total power consumption.



The Energy Cost of Automobiles

R. STEPHEN BERRY and MARGARET F. FELS

How much energy is used to manufacture the materials in a typical 1967 automobile? From the data in the Census of Manufacturers on the materials comprising an auto or a truck, we conjecture that a prototype automobile contains 3,244 pounds of iron and steel, 74 lb of aluminum, 54 lb of copper, 50 lb of zinc castings, 24 sq ft of laminated glass and 29 lb of miscellaneous materials [1]. This equals a total weight of specified materials of 3,436 lb, approximately 100 lb short of the average weight of 3,545 lb based directly on total production figures. The discrepancy is taken up by upholstery and other minor materials.

By far the most costly step in the automobile's manufacture is the production of the 1.6 tons of iron and steel which are fabricated into automobile components. Therefore this step received the most attention in the analysis. The contributions to produce one ton of finished steel are these: mining of 1.63 tons of iron ore, 0.28 tons of limestone for flux and 0.89 tons of coal for coke; the conversion of the coal in the coke oven to 0.62 tons of high-carbon coke and by-products (particularly, 10,300 cu ft of coke-oven gas, a fuel with half the energy content of natural gas); the reduction, with coke, of the iron ore in the blast furnace into 0.99 tons of pig iron (where 58,000 cu ft of blast furnace gas is produced, a fuel with energy content one-tenth that of natural gas); the making of ferroalloys in the blast furnace and electric steel furnace; the production of 1.5 tons of raw steel (ingots) from pig iron, scrap and ferroalloys, in furnaces (open hearth, basic oxygen or electric); hot-rolling of the steel; and finally, the finishing done in cold-rolling, drawing, extruding or forging, to make one ton of finished steel (and 0.5 tons of home scrap). At each of these steps, other materials, such as oxygen, are consumed; the energy to produce them was included.

The energy consumed in the coke oven, blast furnace, steel furnace and hot-rolling mill processes represents over 80 per cent of the total energy. This energy includes "purchased" fuels and also the three fuels made and consumed in the steel

Table 1

Total Free Energy Change Per Ton of Finished Metal

Item	Free Energy Change (kwh per ton)
Iron and Steel	
Carbon Steel	
cold-rolled	15,455
wire	17,915
pipe	15,460
forging	22,275
Alloy[a]	770
Stainless[a]	7,645
Automotive Sheet[b]	14,870
Iron Casting	7,330
Steel Casting	13,680
Nonferrous Metals	
Aluminum	
rolled	73,440
forging	73,345
casting	62,770
Copper	
rolled	37,500
wire	31,130
casting	36,485
Zinc	
rolled	23,225
casting	25,705

[a] The alloy and stainless counterparts of the four types of finished carbon steel are obtained by adding the increment indicated to the corresponding figure for carbon steel.
[b] Sixty-five per cent of the automotive sheet is cold-rolled, according to the American Iron and Steel Institute.

industry: coke consumed in the blast furnace, and coke-oven and blast-furnace gases which are used in the coke oven, blast furnace and steel furnace.

Free Energy Changes

The four major components within the basic steel industry itself are coking, smelting, production of ferroalloys and manufacture of raw steel. If we include the materials consumed at each step, the resulting free energy changes, for the first two of these four steps are 865 kwh to produce one ton of coke, and 6,860 kwh to produce one ton of pig iron.* To produce the raw steel required for one ton of finished steel, the energy cost of melting and refining in each of the steel furnaces is 1,475 kwh in the open hearth, 2,500 kwh in the electric, and 395 kwh in the basic oxygen furnace where the only fuel is oxygen. The average of 1,375 kwh is based on the 1967 usage of the three types of furnace. In the steel furnace, ferroalloys are added to the charge of pig iron and scrap. The total free energies required to produce each ton of hot-rolled steel are 13,785 kwh for carbon, 14,555 for alloy, and 21,430 for stainless steel.

Adding to these basic quantities the energy of finishing—by cold-rolling, drawing, extruding or forging—we get the results for finished steel which are presented in Table 1.

The nonferrous metals make a small but significant contribution to the free energy content of an automobile; the most important of these are aluminum, copper and zinc. Table 1 includes free energy values for these materials in finished form.

Recovery of nonferrous metals from scrap is an efficient process. The data from the Census of Manufacturers for "Secondary Nonferrous Metals" show that even in the worst case, recovery costs less than one-fourth the energy required for producing primary metals from ore. The free-energy cost for secondary vs. primary production, in kwh per ton, is 3,105 vs. 65,785 for aluminum; 5,800 vs. 27,310 for copper; and 2,390 vs. 19,630 for zinc.

The nonmetallic content of an automobile contributes a small fraction of the total energy cost and, therefore, only the primary cost of manufacturing these materials, as found from the Census statistics for their parent industries, is considered.

We now have the data to calculate the total energy used to manufacture the materials in our prototype automobile. The quantities of materials and the change in free energy associated with their manufacture are shown in Figure 1; their totals are presented in Table 2, together with the requirements for fabrication. The production of metallics account for about 97 per cent of the total free energy cost of materials, which in turn, as we shall see, represents nearly three-fourths of the total free energy change involved in the entire automobile's manufacture. One-fourth of the total is consumed in fabrication.

The only remaining contribution to the total free-energy cost of a new automobile is the transportation of the materials (ores, primary metals, finished metals and nonmetallic constituents) and of the automobile itself. We find that this contribution represents only 2 per cent of the total free energy for the automobile [2].

Energy Cost

The contributions from the materials manufacture, the fabrication and transportation add to give us the total free energy consumed in the manufacture of a new automobile: total free energy = 37,275 kwh. The direct energy consumption alone (with no account taken for fuel costs of electricity production) is 30,460 kwh.

How valid are these results? Our effort to calculate and check each energy contribution was proportional to its significance in the total free energy consumed. Hence the energy figures for iron and steel are probably more accurate than those for the nonferrous metals, which in turn are certainly more accurate than those for the nonmetallic materials. With steel materials contributing 59 per cent of the total free energy and nonferrous metals contributing 11 per cent, the nonferrous calculation can tolerate an inaccuracy 5 times that for steel. (Within the nonferrous industry, the least

*One kilowatt-hour is equivalent to 3,400 Btus or 3.6 million joules.

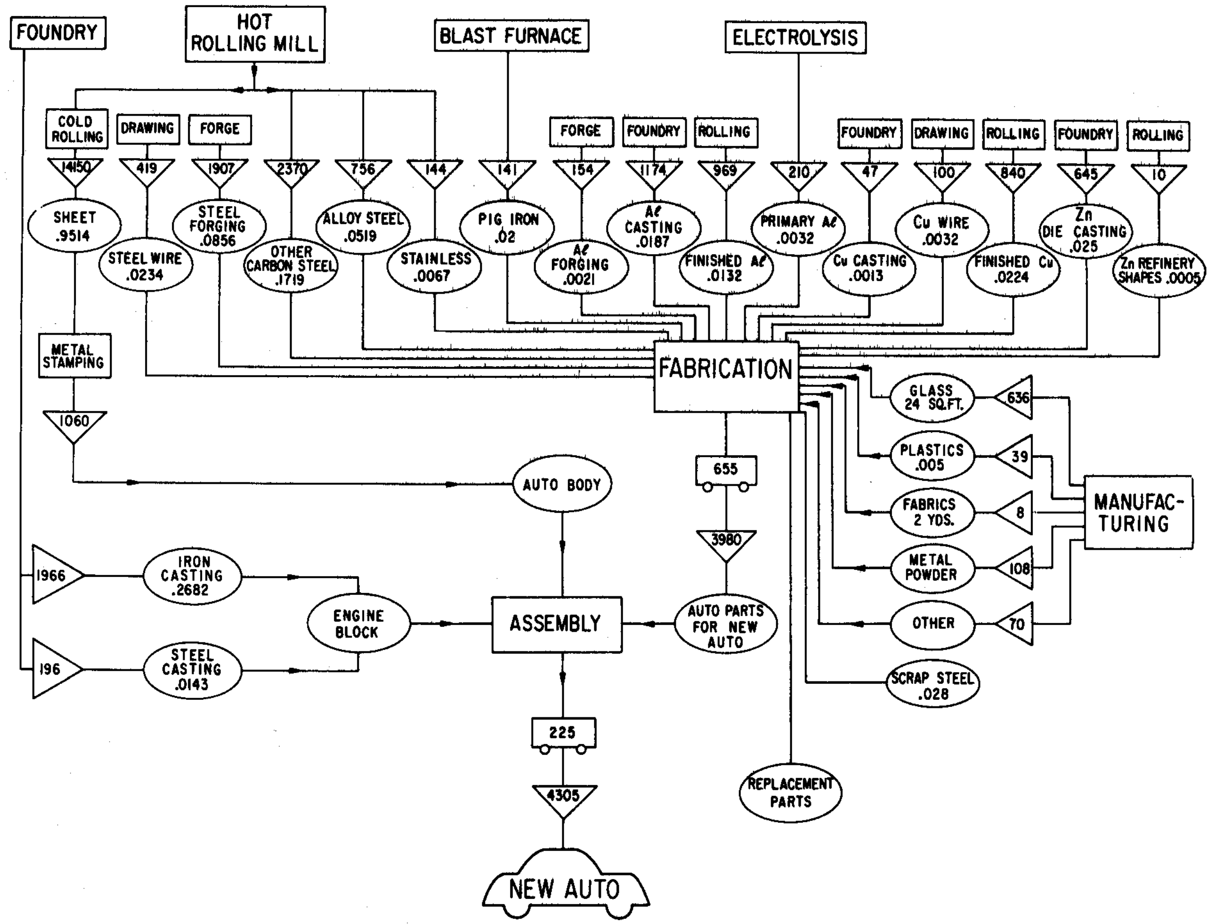


Fig. 1—A complete map of all of the materials, and processes, with corresponding free energies, which go into the manufacture of one new automobile from primary materials.

Table 2

Contributions to the Total Free Energy Change Due to the Manufacture of One Automobile

Item	Free Energy Change (kwh)
Manufacture of metallic materials	26,185
Manufacture of other materials	865
Fabrication of parts and assembling of automobile	9,345
Transportation of materials	655
Transportation of assembled automobile	225
Total Free Energy Change	37,275

certain energy cost was alumina production from raw bauxite, which represents only 0.4 per cent of the total.) The details of the checks to which this calculation was subjected are given by Berry and Fels [3]. We estimate that the final values for total free energy to manufacture a new automobile have an uncertainty of approximately 10 per cent.

We shall see that it is useful to calculate the ideal limits for the free energy cost to manufacture our prototype automobile. We evaluated these limits variously. For this discussion, let us focus on a calculation based on the limits of specific technology in use today, involving intermediate steps involved in current practice. (Berry and Fels [3] contains another approach also.)

In present technology, carbon is used to reduce iron ore and alumina; the ideal free-energy cost for these processes is less than that calculated from the total free energy of formation. We remark in advance that to represent "present technology" accurately by a few chemical reactions is only approximate, but is more than sufficient for present purposes. We do idealize the limits somewhat by supposing, for example, that all oxidation processes involving carbon *could* carry carbon all the way to carbon dioxide, even though real present technology often produces mixtures of carbon dioxide and carbon monoxide.

First, we consider the production of steel. If we assume that the net principal reducing reaction is the reduction of iron oxide, Fe_2O_3, with carbon, to form metallic iron and carbon dioxide, then the free energy change = 340 kwh per ton of iron produced. This technology requires the refining of coal into high-carbon coke. We assumed the carbon in the coal reacted in CH_2-groups with the water in the coal [4] to give carbon and the constituents of coke-oven gas, namely, CH_4, H_2, CO and CO_2 in known composition, with the release of

105 kwh when we obtain one ton of coke. The actual energy cost to be compared with this is an expenditure of 865 kwh per ton of coke. The carbon left in the pig iron from the blast furnace is simply oxidized later, in the steel furnace; this proceeds through an intermediate, represented frequently as the carbide Fe_3C. The oxidation of this intermediate releases 260 kwh of energy, per ton of pig iron, sufficient in practice to melt one-third ton and, in theory, to melt one ton of cold metal (e.g., scrap).

In addition, in the present steel-making process, for each ton of steel, 0.28 ton of limestone, calcium carbonate, undergoes the net reaction $CaCO_3 \rightarrow CaO$ (lime) $+ CO_2$ which contributes 90 kwh to the energy, and impurities such as silica are removed through reduction by carbon. If 5 per cent of the iron ore is silica, the resulting energy cost for its removal is 135 kwh per ton of iron produced. In practice, 1.5 tons of raw steel is produced for each ton of finished steel; most of the extra half-ton goes directly back to be remelted. We suppose that in the ideal system the states of raw and finished steel are equivalent, and that exactly one ton of iron is required for one ton of steel. Therefore we add up the contributions to find that the total ideal energy cost to produce one ton of steel becomes 545 kwh, approximately 5 per cent of the actual cost of mining, smelting and refining. Changing the assumptions, for example, taking into account the real amount of carbon monoxide made in a blast furnace, changes this percentage only slightly.

For aluminum, the reduction of alumina, Al_2O_3, by means of carbon, can be described by the net reaction (which does not describe the actual steps, but one of the beauties of thermodynamics is the way it lets us neglect the intermediate details) of aluminum oxide, Al_2O_3, plus carbon, to give aluminum metal and carbon dioxide. Smelting a ton of aluminum requires ideally 4,610 kwh. Adding to this the cost to extract alumina from bauxite, the total ideal free energy cost to produce one ton of aluminum becomes 4,610 kwh, which represents 6 per cent of the actual free energy change. For copper and zinc, the net reaction for the transformation of the respective metal sulfide ores are equivalent to roasting the ores with oxygen to form the metals and sulfur dioxide. Both of these reactions are accompanied by a release of free energy, so that the theoretical free energy change is negative: —425 to produce one ton of copper, and —390 to produce one ton of zinc. The roasting reactions assume that the sulfur dioxide produced is allowed to add freely to the atmosphere, a practice which is no longer considered tolerable.

Hence to free energy changes for these reactions, we should strictly add the energy cost of treating the sulfur dioxide, as by adding limestone to absorb it. However the resulting reaction for recovering sulfur dioxide this way itself involves a release of energy. We shall play the pessimists here and neglect this negative cost in the ideal free energy changes for copper and zinc.

Free Energy Cost

Based on the particular technology described, the resulting ideal free energy cost to manufacture one automobile becomes 1,035 kwh per automobile. The actual total of free energy consumed in its manufacture is approximately 35 times this value.

The comparison of the ideal results and the results from actual fuel consumption will form one of the bases for policy recommendations. These comparisons are presented in Table 3. Going beyond the costs themselves, to indicate how far we are from the ideal limit, we show values for two new indices: (1) "free energy *waste*," the result

Table 3

Comparison of Ideal Free Energy Cost and Real Free Energy Consumed (in kilowatt-hours) for Various Processes and for the Total Automobile

Process	Ideal Free Energy Cost[a] (kwh)	Real Free Energy Consumed (kwh)	Free Energy Waste (kwh)	Waste Factor[b]	To Produce
Coke oven	— 105	785	890	1.13	1 ton coke
Blast furnace	565	5,925	5,360	0.90	1 ton iron
Steel furnace	— 260	1,375	1,635	1.19	1 ton steel
Refining of bauxite	0	3,220	3,220	1.00	alumina for 1 ton aluminum
Smelting aluminum	4,610	60,970	56,360	0.92	1 ton aluminum
Smelting copper	— 425	11,730	12,155	1.04	1 ton copper
Smelting zinc	— 390	16,115	16,505	1.02	1 ton zinc
Total Process	1,035	37,275	36,240	0.97	1 automobile

[a] Based on the reactions of the dominant technology now in use.
[b] The ratio of waste to real total consumption.

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. . . . 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. (R. Stephen Berry, "Recycling, Thermodynamics and Environmental Thrift," *Bulletin,* May 1972.)

of total free energy consumed minus ideal free energy cost; and (2) the "waste factor," the ratio of waste to real total consumption. In both new indices, we use the technology-based ideal free energy cost so that free energy waste and the waste factor are, respectively, absolute and relative measures of how far present technology is from the ideal limit. They are our guides to identify where we can find leverage for useful changes. Clearly, a process for which the waste in free energy is high has a waste factor close to 1.0. This waste factor can actually be greater than 1 because some processes, such as coke oven and steel furnace operations, ideally release thermodynamic potential. The waste factor is a direct measure of the efficiency of the process, in terms of the fraction of total free energy consumed that is ideally required. From Table 3, it appears that the smallest waste factor is associated with the iron-smelting process, while the total process of automobile manufacture has a waste factor very close to 1.0.

The Recycled Automobile

Can thermodynamic potential be saved by the judicious use of automotive scrap? Potentially, the recoverable scrap from an automobile consists approximately of 1.3 tons of steel, 0.25 ton of cast iron, 0.04 ton of aluminum, 0.03 ton of copper and 0.02 ton of zinc. Until recently, after removal of the engine (and other parts, depending on the processor), all recovered hulks were compressed hydraulically into "No. 2 bundles." This scrap is low grade and, due to its impurities, can comprise no more than 10 per cent of the charge of a steel furnace: that is, the materials used to make a ton of finished steel can contain no more than 0.15 ton of No. 2 bundle scrap. This clearly limits the capacity for recycled automobiles, at least in the form of No. 2 bundles. By contrast, the most modern kind of processor—the shredder—produces a high-grade steel scrap, and in the process separates out the nonferrous metals for their reuse. With high-quality steel scrap and with electric furnaces which can accept charges composed entirely of scrap, the fraction of reused metal going into a new automobile is limited only by the number of hulks available for reuse.

We have, then, two extremes for recovering scrapped automobiles: at one extreme, 15 per cent of a new automobile may originate from No. 2 bundles, with the remainder made of new metal; at the other extreme, all the metal in an automobile could originate from automotive scrap. Figure 2 shows a comparison of the processes for these two situations. We want to examine the energy savings for these two extremes, and for various other policies between them. Before we proceed, we need some data.

Replacing a ton of new pig iron with a ton of scrap nets a savings in free energy of 7,040 kwh, including transportation; for aluminum, the savings is 63,505 per ton; for copper, 22,125 and for zinc, 17,840. On this basis, the scrap in an automobile is "worth" 14,475 kwh. To transport the scrapped auto 150 miles [5] and process it in a shredder costs 550 kwh, while the analogous figures for a compressor is 350 kwh. Compared with the average for all types of furnaces, use of the electric furnace alone (as is done for scrap recovery) is 1,125 kwh more costly per ton of finished steel. Combining these data, a scrapped automobile prepared by a shredder represents a potential savings of 12,640 kwh per auto, while preparation of the material by a compressor gives a potential savings of only 10,560 per auto because no nonferrous materials are recovered.

Open and Closed Systems

In our data year of 1967, the steel industry consumed 3.8 million tons of No. 2 bundle scrap, representing 2.9 million hulks [6]; approximately 720,000 tons of scrapped castings were also recovered from these hulks. To see what these figures mean, we could follow the flow of the scrap either into the production of steel for all purposes,

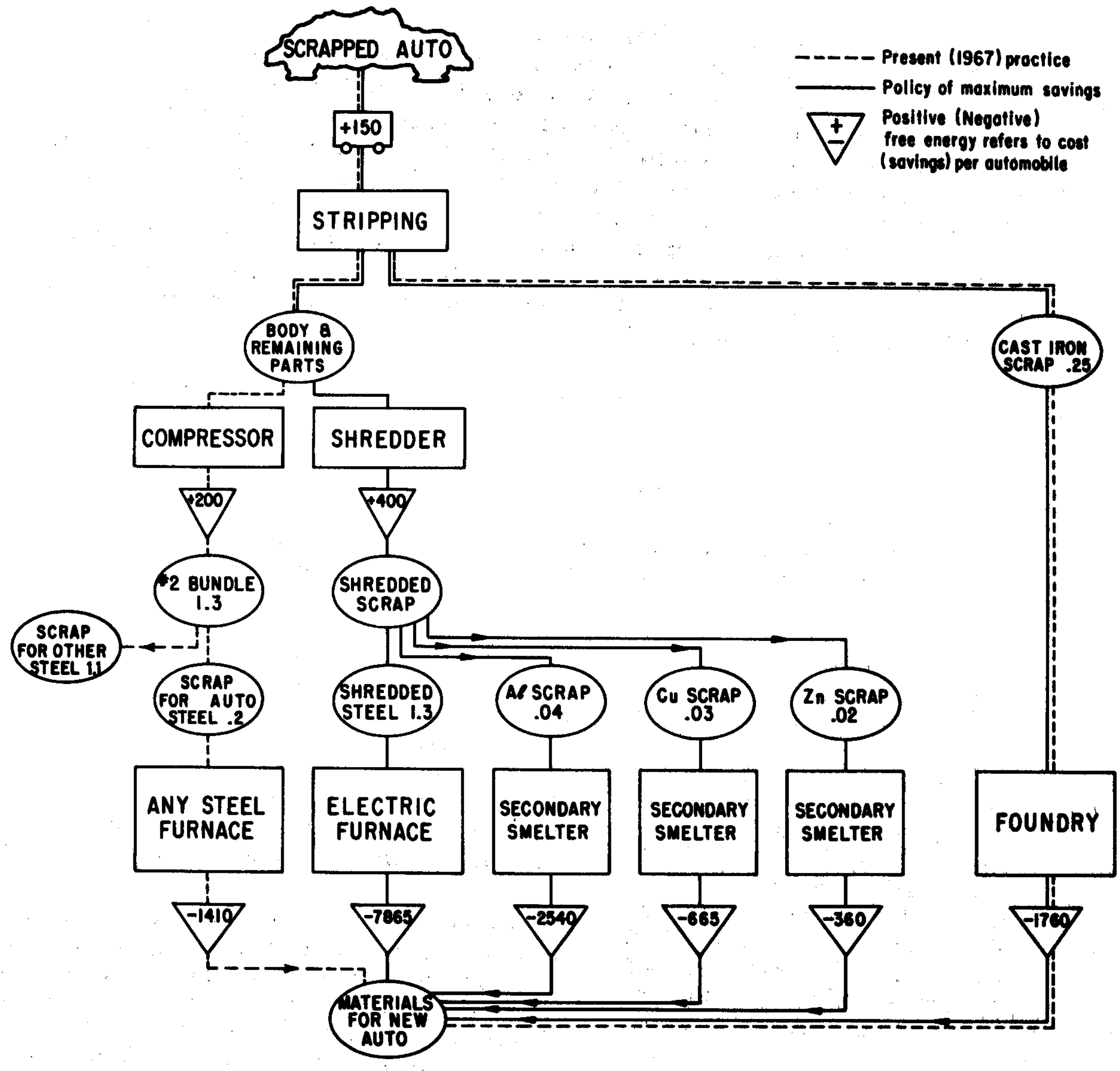


Fig. 2—A map showing alternate, extreme policies for use of automobile scrap: present (1967) policy of processing the automobile into low-grade scrap, for which usage is limited; and policy of maximum savings whereby all metallic material in new auto originates from automobile scrap.

or into a closed system involving only automobile production. In reality, automotive scrap goes, of course, into steel products of all sorts, but the closed model illustrates our analysis. To look at the open system, we would have to consider all the use of steel and the corresponding scrap recovery practices. In the first (open) system, actual use of automotive scrap in 1967 caused a savings of 300 kwh per ton of finished steel and 465 kwh per ton of iron casting. If, in this system, all 6.6 million junked autos had been recycled in No. 2 bundles, which was the customary method in 1967, the savings would have more than doubled.

In the closed system, in order to produce 7.4 million autos, only 1.1 million of the 6.6 million scrapped hulks can be consumed in the form of No. 2 bundles, because of the impurities in the steel. This corresponds to a savings of 1,585 kwh per auto and will be our reference point for "present practice." We shall assume that any additional scrapped autos which are processed will have to be shredded to produce upgraded scrap. We can now write a simple equation for the free energy savings, according to how many cars are shredded or compressed. Suppose S million scrapped autos are processed to be used in the production of P million new autos. Of these, a number B (limited to 15 per cent of P, or less) are compressed into No. 2 bundles and X (equal to $S - B$) are shredded, the savings in free energy per automobile produced is

$$\text{free energy saved per car} = 10{,}560\ (S/P) + 2{,}080\ (X/P)\ \text{kwh.}$$

Clearly the minimum savings is the "present practice" of 1,585 kwh per auto (i.e., $(S/P) = 0.15$ and $X = 0$). We would make the maximum saving by processing into high-grade scrap the same number of autos as are produced (i.e., $S = P = X$) for which the savings is an additional 11,055 kwh. Thus the maximum savings, 12,640 kwh, which can be expected from recycling an automobile represents 30 per cent of the total free energy cost of manufacturing an automobile. These extremes, of the minimum and maximum savings, correspond respectively to the minimum and maximum points on the graph in Figure 3.

dent of the number of autos produced or scrapped in a year; the savings calculated for the other policies depend on the year's statistics.

To evaluate these policies, we envision a pool of approximately 20 million hulks [5]; most of them lie in junkyards but one-fifth are dispersed throughout the countryside. A single reuse of the scrap contained in this pool represents a potential energy savings of over 200 billion kwh, energy enough to produce half of the steel made in the United States in a year. The energetic advantages of using this scrap are clear. At present, the reclaimable auto-

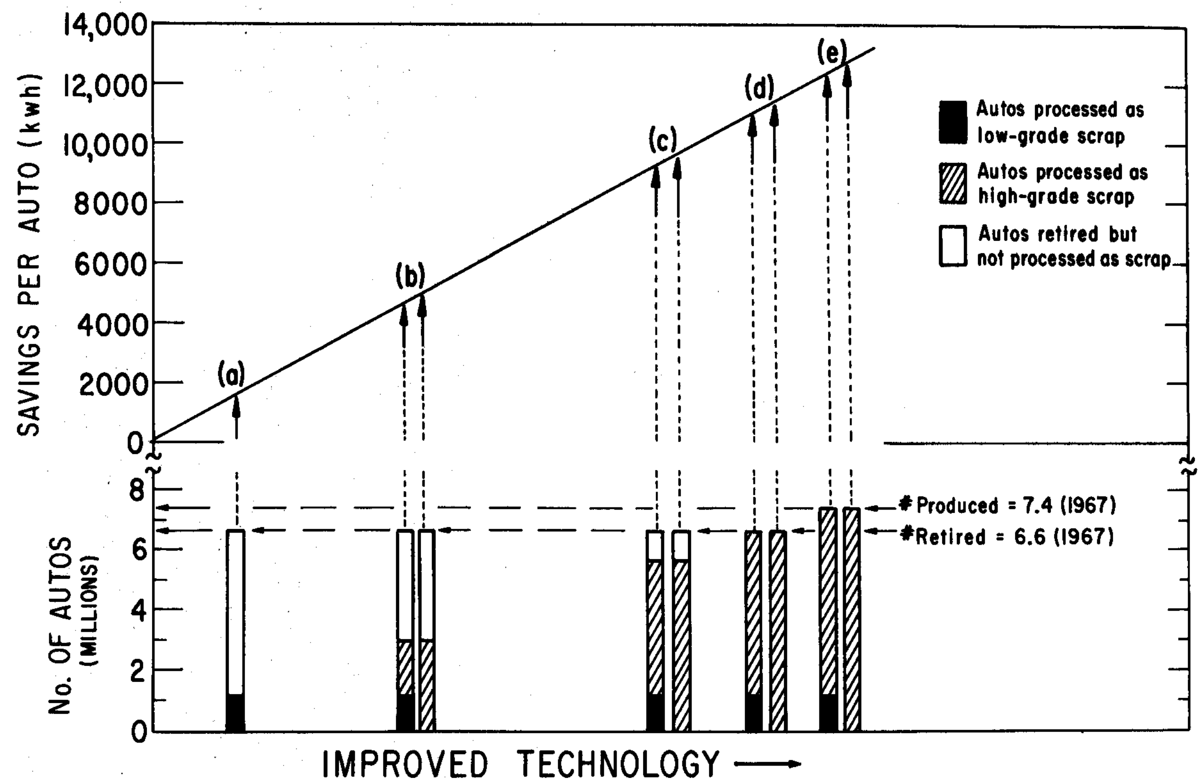


Fig. 3—Free energy savings per auto, plotted as a function of how many autos are processed into low-grade or high-grade scrap. Policies between and including the two mapped in Figure 2 are shown.

Between these two extremes lie several reasonable policies resulting from various combinations of bundled and shredded scrap. Some of these, shown schematically in Figure 3, are, in order of increasing savings: rechanneling all automotive scrap consumed (in 1967) into automobile production, thus necessitating some shredding (policy b in Figure 3); allowing the dispersal of one million hulks (as is done currently) but processing all remaining hulks scrapped during the year (policy c); and lastly, allowing no dispersal, and processing all scrapped autos (policy d). For each of these policies, the alternatives of using the maximum low-grade scrap are shown. The policies of minimum and maximum savings (policies a and e, respectively), the two end-points on the graph in Figure 3, are indepen-

motive parts have more value than the scrap contained in the hulks; thus the function of the junkyards is primarily to provide storage space for the parts, and the hulks are processed for scrap only when they are worthless otherwise (e.g., the space they occupy is needed for newer hulks).

The policy of maximum savings, wherein all the metal in a new automobile originates from scrap, becomes particularly reasonable when we examine it in the context of a stabilizing population. Presently, the annual number of new car registrations in the United States exceeds the number junked by two million. The policy of maximum savings advocates processing all autos which are junked each year and, in addition, drawing from the pool enough

(continued on page 58)

ENERGY COST

(continued from page 17)

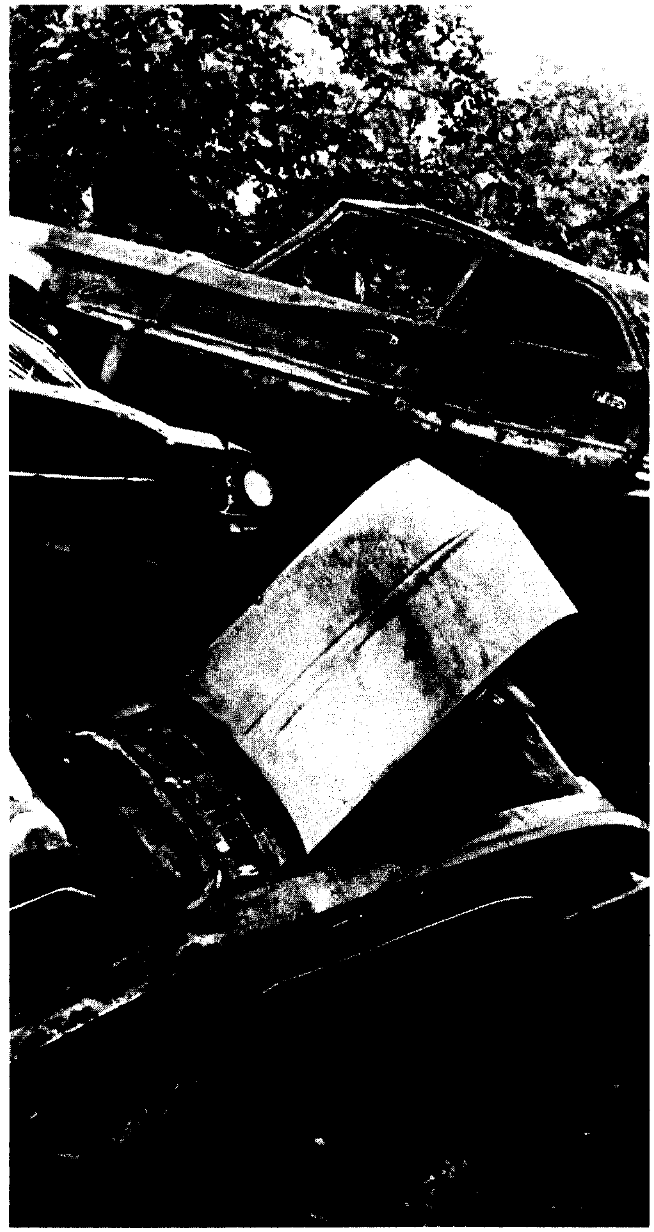
hulks to fill the "scrap gap," as measured by the annual increase in auto registrations. Suppose the U. S. population stabilizes in 10 years; then, at that time the "scrap gap" would decrease to zero. Current estimates say that enough scrap is available now—in junkyards and countrysides and in the cars to be junked in the next 20 years—to make this policy of "maximum savings," a feasible medium-term plan.

The return of automobile hulks to the materials pool is a matter for short-term and medium-term policy decisions. The requisite technology is already in use. In fact there are almost enough shredders now in operation and distributed widely enough to permit a policy of "maximum recycling" to be put into use without delay. The bottlenecks lie elsewhere in the system, with collection and transportation of hulks and with the supply-demand-price situation in the scrap steel market. In part, the demand has been held down by the limited number of electric furnaces, which are normally used to reprocess scrap iron and steel. There is apparently some elasticity in this component of the demand sector because it seems that there has been a recent increase in the number of small, independent electric furnace operations. Demand has also been held down by freight tariff schedules unfavorable to the transport of scrap [7].

Reducing Power Requirements

The free energy savings from recycling an automobile is significant—about 12,000 kwh per automobile—which is large in its absolute magnitude and its size, relative to the cost of an automobile. If such a savings could be achieved on all the (roughly) 8 million automobiles produced each year, the annual reduction in the energy demand would be almost 10^{11} kwh per year, or almost 100 billion kilowatt-hours. The national power requirement would be reduced by about 11,400 megawatts, roughly the rated capacity of 10 very large power plants. This figure is large; but for a comparison, a highly restrained projection for California recommends that only 23 plants of about this size be built in that state between now and the year 2000 [8]. The saving of 10^{11} kwh per year is about one-thirtieth of the total energy used annually by all road vehicles, or about half of one per cent of the total national energy budget.

The natural course regarding policy toward recycling would now be to weigh the savings in resources, as measured by the savings in thermodynamic potential, against the costs of a recycling strategy. Those costs (and benefits) that are quantifiable by thermodynamic measures are presumably already in our calculations. The costs and benefits associated with labor displacements in the mining and smelting industries, the costs of increasing the collection capacity, the possible benefits



from aesthetic factors, all should naturally enter into the policy selection process. We hazard the guess that the net benefits from increased auto hulk recycling make it attractive to move our recycling policy to the right, along the horizontal axis of Figure 3, by deliberate actions.

Policy Decisions

Do the thermodynamic data suggest broader courses of action for the longer term? Can we identify policies to make energy savings significantly larger than the 30 per cent, per automobile, achievable with total recycling by present technology? One possibility that comes quickly to mind is to extend the lifetimes of vehicles. The principal cost, in thermodynamic terms, for such a policy is the cost of replacement parts. Although the figures are less certain than those for the manufacture of a new auto, we have extracted an approximate cost for replacement parts of an automobile for its lifetime, according to current practice: the total free energy cost is 665 kwh, 1.8 per cent of the total free energy required for the automobile.

The most important replacement components are mufflers and tailpipes, which comprise 70 per cent of the total materials, by weight. On this basis, we can estimate the cost of replacement parts for extending vehicle life. The need for new mufflers and tailpipes presumably must go up slightly faster than linearly with time; we assume that the demand for the other components doubles with every current vehicle lifetime. Thus the replacement parts for the second lifetime of an automobile would require free energy of about 900 kwh; for the third lifetime, we expect no more than twice as large a requirement, so that the conservatively estimated total would be about 3,400 kwh. The increases in energy requirements in the original manufacturing process itself would be small because the principal difference between present practice and practices associated with extended-life vehicles would be achievement of higher tolerances and improved inspection procedures. Neither of these would require much manufacturing energy, although there would be some redistribution of labor associated with these changes. We estimate the energy increases to be no more than about 1,500 kwh, or 5 per cent of the present total manufacturing requirement, to triple the lifetime of an automobile.

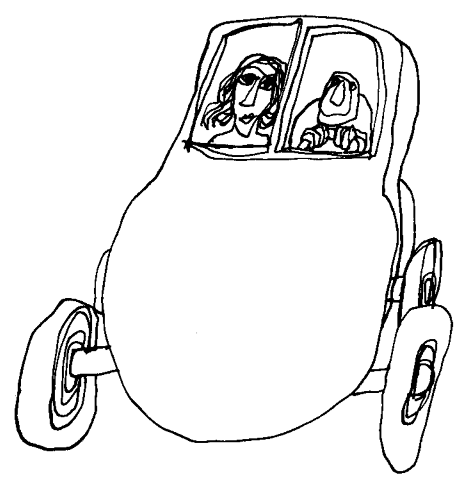
Thus the total free energy and energy requirements to triple the life of a vehicle are roughly 15 per cent of the total free energy required to make the car. This means that the manufacturing cost in energy units, per vehicle-mile or per vehicle-year, would be only about 38 per cent of the present cost; the *annual* cost of the equivalent of a currently-used vehicle, with its lifetime of about 10 years, would be only 1,400 kwh, and the savings would be about 23,000 kwh per present vehicle lifetime.

The change from present practice to using vehicles with two or three times the present vehicle life would clearly be a far greater change in industrial operations than would maximal scrap recovery. Such a change would effectively reduce the degree to which auto manufacture is metals-intensive and energy-intensive, and make the industry more labor-intensive. It is not at all clear whether the man-hours of labor, *per vehicle-mile*, would go up or down if we were to adopt a system of extended-life vehicles. We would clearly replace production with increases in inspection, both of new and used vehicles, and with increases in maintenance. Moreover, the extension of vehicle lives and the maximization of recycling are quite compatible. One can begin with recycling and work more slowly toward extending vehicle lives.

Can we look even further, toward still larger changes? The questions suggested by Table 3 are clear: We ought to find ways to do some of these steps better, in a thermodynamic sense. We might even expect identification and selection of processes for improvement to become an institutionalized social goal.

Every one of the processes is inefficient enough to deserve some improvement. Two criteria make certain processes of Table 3 more attractive for improvement than others. Some steps, even those with relatively low waste factors, involve such large total amounts of energy that the net return from even a relatively small fractional improvement would be large. Other steps such as coke manufacturing have such large waste factors that one suspects that it may be relatively easy to improve the technology and make fairly large savings for these processes. Any steps entering into the largest single contributor—the 14,150 kwh required to prepare cold-rolled steel from iron ore—are clearly good targets for technological development. Reducing the 4,737 kwh per ton associated with hot-rolling or reducing the amount of home scrap (now 0.52 tons per ton of finished steel) are among the ways that strike one immediately, as possible examples. There is no one major step for ferrous metal preparation that can be singled out for improvement. In the nonferrous metal area, aluminum recovery looks like a good target, despite its waste factor of 92 per cent, because the required amounts of energy are so large. (A more efficient process for aluminum smelting was announced in the winter of 1972-73 by Alcoa.) Naturally, if one were trying to select processes for improvement, it would be wiser to look at the material in the context of total annual U. S. production, rather than just the automobile, in assessing the importance of the potential improvement. Aluminum, for example, contributes very little to an automobile, but is clearly important for other goods.

To conclude, let us see how thermodynamic analyses can be used as a basis of costing at least part of the environmental impact of a process. Until that distant date when all the world's supplies of some substances are in demand for use at all times, the only resource that really is in shortage is thermodynamic potential, the capacity to do work, to make transformations [9]. Moreover, thermody-



namic potential is really the one quantity that is consumed when we conduct our activities. Admittedly, we do receive a steady supply from the Sun; but, because of the limitations of our technology, our processes are inflexible with regard to the forms of thermodynamic potential that they can now use. We get most of our supply of this potential by drawing on our capital reserves now in the ground. If we knew how to forecast the development of new energy or free energy sources, we would be far better than we are at discounting energy resources for the future.

The consumption of thermodynamic potential has several kinds of environmental and consequent economic impacts. First, there is the close correlation between the levels of pollution and the expenditure of thermodynamic potential and energy. We shall not consider here the costing procedures for the economic effects of pollution; this subject lies outside the present context. Second, there is a calculable difference between the real free energy consumption for a process and the necessary minimum, which is called ideal free energy in Table 3, whose value is set by the laws of nature. We *must* pay that minimum, as a sort of entry fee. We do not want to explore here the use of inherent minimum free energy costs for value judgements in an economic and social system. To do so would involve institutional manipulation of fundamental changes in the most basic technological processes and, very quickly, the valuation of basic social choices on the basis of "ideal" thermodynamic limits. The questions are challenging and ultimately important, but go far beyond the problem of policy determination for the short- and medium-term. The ideal limits are all very small, and it is enough just to see how far we are from these limits, from lists of data such as those in Table 3. Then we can explore replacing one technology with another, in terms of its technological impact and then on economic and social levels as well. Adapting institutional structures to cope with technological changes is itself a major problem and is the specific point at which a policy-oriented analysis goes beyond the range of this discussion.

One way to incorporate thermodynamic considerations into policy making now, within existing institutional structures, is to include the waste contribution to energy change into decisions to favor one or another existing technology. The waste contributions represent real losses of stored potential, with no physical benefits, from the production by present technology. These losses form one of the most important real costs, perhaps the largest real cost, that is not normally included in the costs that go into the present market value of goods. The wasted thermodynamic potential is probably the most readily identified of the presently uncosted quantities of our technological society. In principle, these costs could be reflected in the energy market, as increases in the price of energy. The increases would be a direct reflection of the estimated future benefits of saving, and of the costs of consuming energy now. The discount rate for energy would ideally reflect the full range of effects of energy use, including not only the consumption of fuel resources, the dependence of specific technologies on particular fuels, and the technological costs of changing these dependencies, but also the environmental impacts of pollution, weather change and climate modification. For the present, it is unrealistic to try to put very accurate cost values on all these impacts, but it is clear that the costs are real, that some of them can be estimated, and that the present market does not reflect a perception of these costs.

For these reasons, it is a reasonable policy course to start exploring the inclusion of wasted thermodynamic potential in the regulatory process. The first steps are the identification of these wastes, which is a primary purpose of this report for one specific system, and the creation of incentives to reduce this waste. Then we can begin to decide what form these incentives should take, and to select a set of criteria and priorities for the incentives, to implement a policy of thermodynamic thrift.

NOTES

1. *1967 Census of Manufactures* (Washington, D.C.: Bureau of Census, U.S. Department of Commerce, 1971); and "Fuels and Electric Energy Consumed," MC 67(S)-4, *1967 Census of Manufactures* (Washington, D.C.: Bureau of the Census, U.S. Department of Commerce, 1971).
2. *1967 Census of Transportation* (Washington, D.C.: Bureau of the Census, U.S. Department of Commerce, 1970); and "Carload Waybill Statistics, 1966, Mileage Block Distribution: Traffic and Revenue by Selected Commodity Classes, Territorial Movement, and Type of Rate" (Washington, D.C.: Interstate Commerce Commission, U.S. Bureau of Economics, 1968).
3. R. S. Berry and M. F. Fels, "The Production and Consumption of Automobiles: An Energy Analysis of the Manufacture, Discard and Reuse of the Automobile and Its Component Materials," Report to the Illinois Institute for Environmental Quality, July 1972. See also Berry, Fels and H. Makino in *Energy: Demand, Conservation and Institutional Problems,* edited by M. S. Macrakis (Cambridge, Mass.: The MIT Press, in press).
4. B. K. Mazumdar, *et al.,* "Aliphatic Structures in Coal," *Coal Science* (Washington, D.C.: American Chemical Society, 1966).
5. *Junk Car Disposal,* National Industrial Pollution Control Council (Washington, D.C.: Government Printing Office, 1970).
6. The remainder of the 6.6 million autos junked are exported as scrap (1.5 million tons in (1967) or abandoned. The estimate of 1.3 tons of steel per auto may be high, but this calculation depends on the total figure, 3.8 million tons, which is accurate.
7. H. Cutler and G. S. Goldman, *Environmental Science and Technology* 7 (1973), 408.
8. R. D. Doctor, *et al.,* "California's Electric Quandary: III. Slowing the Growth Rate" (The Rand Corp., R-1116-NSF/CSA, Sept. 1972).
9. Apparently the U.S. Geological Survey is releasing a study of resource supplies that suggests we will face real shortages of specific substances in the foreseeable future. This would mean, if true, that the demand for some element x exceeds the total amount available in the Earth's crust.