Human Materials Production as a Process in the Biosphere

Materials such as metals and concrete are not renewable. Man's problem is to devise cycles that will conserve resources of this kind and at the same time prevent their accumulation as solid waste

by Harrison Brown

The materials used by man for tools, shelter and clothing have traditionally been both organic (for example wood and natural fiber) and inorganic (stone, including glass and ceramics, and metals). To this classification we now add synthetic materials, which are mostly made from what are called in another connection fossil fuels. The organic materials are of course products of the biosphere, and assuming appropriate levels of use and sensible management they are self-renewing. The inorganic materials are the product of extremely slow processes in the lithosphere, and are hence not self-renewing in the human scheme of things. Yet the increasing need for such materials—mainly metals, stone and concrete—is one of the outstanding features of advancing societies. Moreover, the fact that inorganic materials are for the most part not recycled creates a pressing need for their disposal. These demands present men with numerous difficult choices, many of which inevitably involve the functioning of the biosphere.

For the greater part of the two million years or so of human existence man's need for materials was modest. With the adoption of each technological innovation that improved the chances of human survival, however, the need for materials increased in both absolute and per capita terms. For example, the controlled use of fire, which increased the variety of things that could be eaten and extended man's environment, created a substantial demand for firewood. Here, of course, a material was being used as fuel, but the development of tools that improved the efficiency of hunting and food gathering and protected men against predators created demands for materials in the strict sense: the right kinds of stone or of plant or animal substance.

With the invention of agriculture the need for materials increased considerably. The new technology made it possible for thousands of people to be supported by the produce of land that formerly could support only one person. Moreover, it was no longer necessary for everyone to be involved in food production. Farmers were able to grow a surplus of food to support nonfarmers. Until relatively recent times this surplus was never large, amounting to perhaps 5 percent, but it meant that some people could devote their energies to occupations other than farming. It was the surplus of food that made possible the emergence of cities and the evolution of the great civilizations of antiquity.

The oldest civilizations came into existence in regions that had ample areas of arable land and adequate supplies of water. Cities could become large only if they could draw on the agricultural surpluses of vast farmlands. Since water transport was by far the easiest way to ship foodstuffs in ancient times, the earliest civilizations and the first large cities came into being in the valleys of the great rivers such as the Tigris and the Euphrates, the Nile, the Indus and the Yellow River. With the emergence of major urban centers increasingly elaborate technologies were developed, and they in turn led to the need for larger per capita quantities of raw materials such as stone, wood, clay, fiber and skin. (The ancient urban centers also confronted a problem that continues today: the disposal of garbage and rubbish. Scavenger birds, such as the kites of modern Calcutta, were probably essential elements in the system of processing garbage, but even so life must have been unsanitary, unsightly and odoriferous, at least for the great masses of the poor. The evidence suggests the prevalence of high mortality rates. Many ancient cities appear to have been literally buried in their own rubbish.)

Until the development of metal technology men appear to have used renewable resources such as wood at rates that were small compared with the rates of renewal. The consumption of nonrenewable resources such as stone was also small, particularly in comparison with the nearly infinite availability of resources with respect to the demand.

Copper was the first metal to come into widespread use on a substantial scale. In actuality copper is not very abundant in the lithosphere, but the metal can be won easily from its ore. The reduction temperature is fairly low, so that smelting can be accomplished in a simple furnace. Once the technology of extracting copper was developed the use of the metal became widespread in the ancient civilizations and the demand for the ore grew rapidly.

COPPER IS MINED at the Twin Buttes mine of the Anaconda Company near Tucson. The conspicuous hole in the photograph on the opposite page was made by removing some 236 million tons of overburden and rock to get at the ore lying between 600 and 800 feet below the surface of the ground. The ore has a copper content of about .5 percent and is considered to be a low-grade ore. Since copper is not highly abundant in the lithosphere but is extensively used, the trend has been toward mining low-grade ores.

In this situation the high-grade deposits of ore close to the ancient urban centers were soon used up. Egypt, for example, quickly depleted her own copper reserves and had to develop an elaborate network of trade routes that enabled her to import copper from as far away as the British Isles and Scandinavia. Even so, high-grade ores of copper were uncommon enough to preclude widespread use of the metal. Copper did make possible a number of new technologies, but farmers, who were by far the greater proportion of society, were almost unaffected. Their implements continued to be made of stone, clay, wood and leather.

Gold is considerably easier to extract from its ore than copper; often the "ore" is metallic gold itself. As one might expect, therefore, the use of gold appears to predate the use of copper by a considerable span of time. Gold, however, is one of the rarest metals in nature, so that its ores are extremely scarce. Its rarity precluded its widespread use, except in small quantities for ornament.

Iron is considerably more abundant in the lithosphere than copper, but it is a much more difficult metal to win from the ore. The reduction temperature is high, and furnaces capable of attaining it were not developed until about 1100 B.C. The new high-temperature technology appeared first in the Middle East and quickly spread westward. The widespread availability of the ore made it possible for metal to be used on an unprecedented scale. New tools of iron helped to transform Europe from a land of dense forests to a fertile cropland.

One of the primary limitations to economic development in the ancient empires was the lack of ability to concentrate large quantities of energy. Insofar as it could be done at all it was usually accomplished by mobilizing gangs of men and to a lesser extent by the use of work animals. Use of the water mill and the windmill spread slowly. Only in sea transport was the wind used even with moderate effectiveness on a large scale as a prime mover. Remarkable as the Roman engineers were, they were limited by the concentration of energy they could mobilize. They went about as far as engineers could in the absence of a steam engine.

The development of a practical steam engine had to await the convergence of a series of developments in England in the late 17th century and the early 18th century. The island entered the Iron Age richly endowed with iron ore. Forests were also abundant, and the trees were used to produce charcoal, which in turn was used to reduce the iron oxide to the metal. These resources enabled England to become a major supplier of metallic iron for the world.

As iron production expanded English trees were consumed faster than they grew. Eventually the depletion of wood for charcoal threatened the entire iron industry. Clearly a substitute for charcoal was needed. The most likely one was coal, which existed abundantly on the island. Unfortunately, although coal can be used to reduce iron ore to the metal, the impurities in it render the metallurgical properties of the iron quite unsatisfactory.

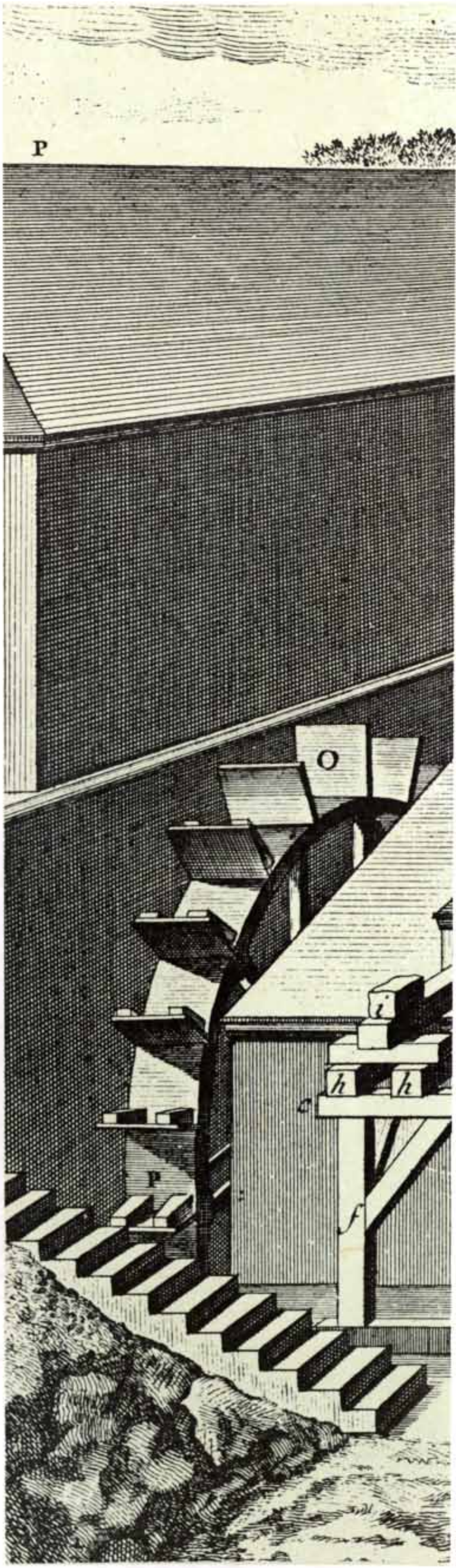
The Darby family, which owned a substantial iron industry, spent many years attempting to transform coal into a substance suitable for the reduction of iron. Eventually a successful process was developed. It was based on the discovery that volatile impurities could be driven off by heating coal under suitable conditions. The resulting product, called coke, yielded metallic iron of satisfactory quality.

Here was a development—the linking of coal to iron—second only to agriculture in its importance to man. The new development led to a rapid expansion of the iron industry. Even more significant, it led directly to the development of the steam engine, which gave man for the first time a means of concentrating enormous quantities of inanimate energy.

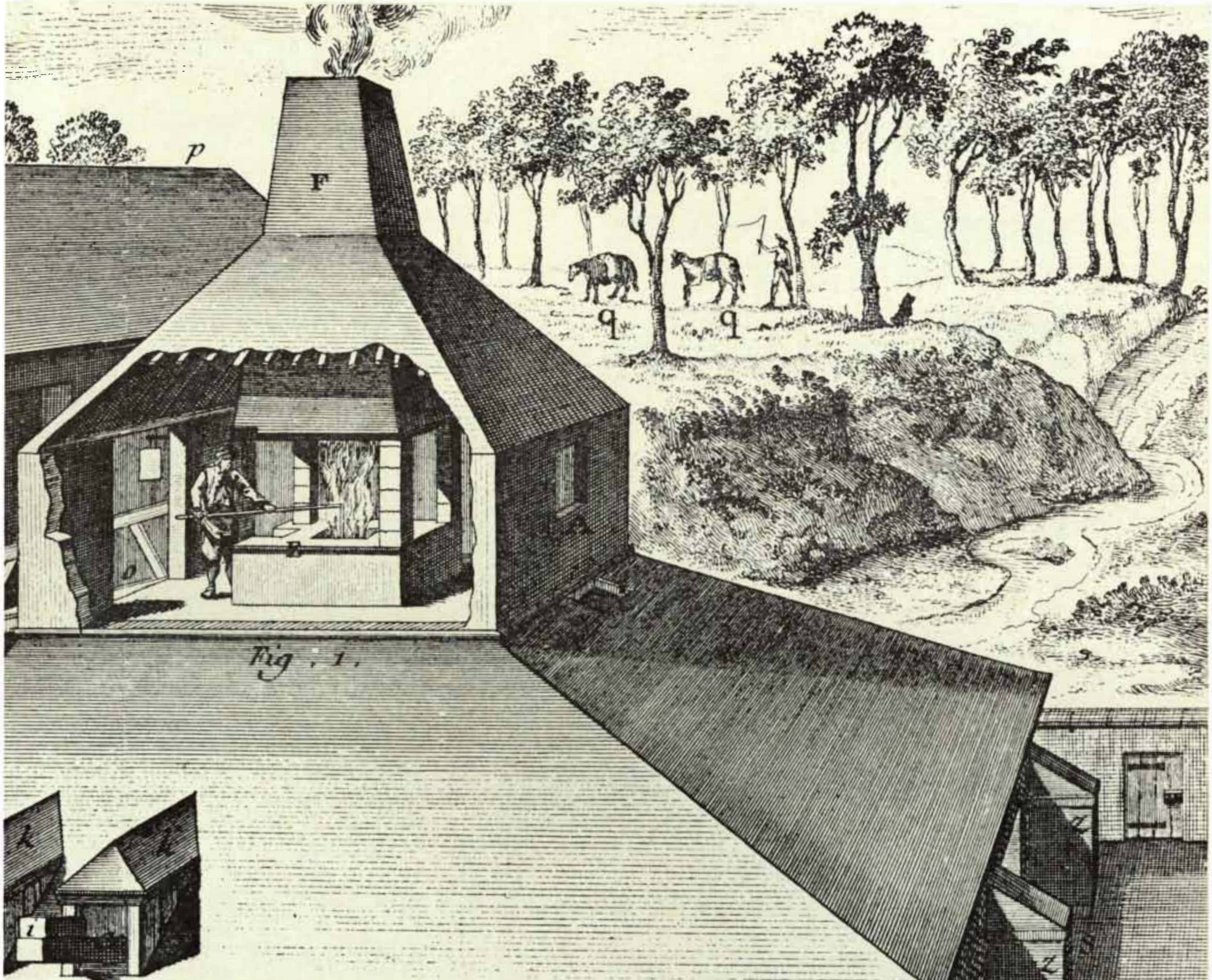
Coal, iron and the steam engine gave rise to the Industrial Revolution, which spread from England to Europe and then to the U.S., the U.S.S.R. and most recently to Japan. Why did it start in the 18th century in England and not several centuries earlier in Rome? The Romans in many ways were the better engineers, and yet the harnessing of steam eluded them.

It is interesting to speculate on the role that random natural processes have played in cultural evolution. What would the course of history have been if copper had been as abundant as iron or if iron could be reduced from its ore as easily as copper? Perhaps the Iron Age would have started in the third millennium B.C. Suppose the Roman iron industry had run out of wood in the second century. Would there have been a linking of coal to iron and would the steam engine have emerged some 1,500 years earlier than it did? Such questions are diverting, but they cannot be answered with anything better than guesses.

The most important characteristics of



BLAST FURNACE for smelting iron in the 18th century was depicted in Diderot's *Encyclopédie*. The reason for the furnace's lo-



cation near a wooded area was the need for charcoal, which is what the horses in the background are carrying. In England the consumption of charcoal virtually exhausted the supply of trees before the technique of making coke from coal was developed. A furnace of this type might produce some two tons of iron a day. In the foreground a freshly produced pig, No. 289, is being weighed.

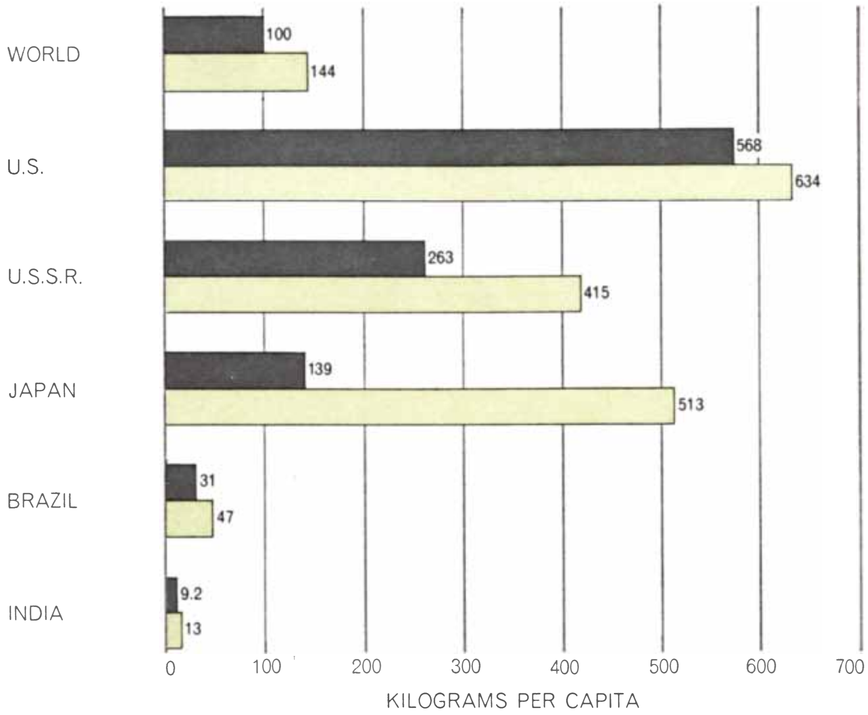
the Industrial Revolution have been rapid change and rapid increases in rates of change. Since the beginnings of the epoch mankind has seen the emergence of almost innumerable technological innovations that have competed with existing ways of doing things and have further released men from physical labor. It is now generally recognized that technological innovation has been a prime contributing factor to economic growth, perhaps equaling the combined effect of the classical factors of land, labor and capital.

Successful innovations have driven many older technologies to extinction and have resulted in higher productivity, greater consumption of energy, increased demand for raw materials, accelerated flow of materials through the economy and increased quantities of metals and other substances in use per capita. The history of industrial development abounds with examples.

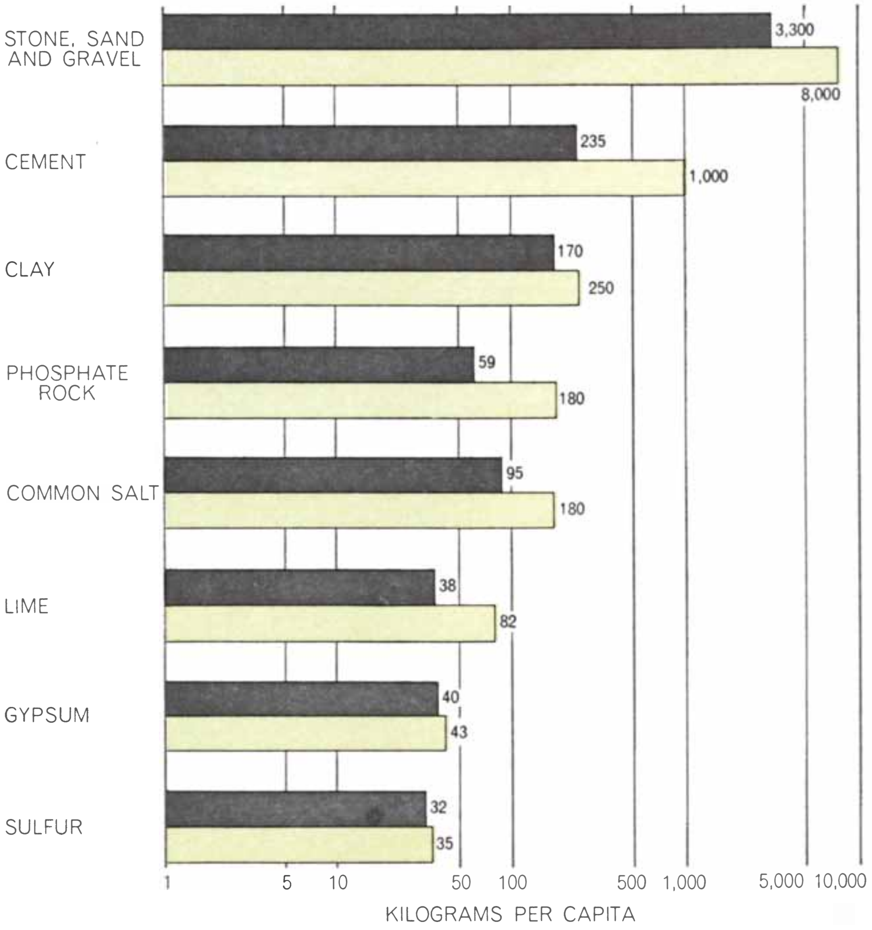
In 1870 horses and mules were the prime source of power on U.S. farms. One horse or mule was required to support four human beings—a ratio that remained almost constant for many decades. Had a national commission been asked at that time to forecast the horse and mule population in 1970, its answer probably would have depended on whether its consultants were of an economic or a technological turn of mind. Had they been "economists," they would in all likelihood have estimated the 1970 horse and mule population at more than 50 million. Had they been "technologists," they would have recognized that steam had already been harnessed to industry and to ground and ocean transport. They would have recognized further that it would be only a matter of time before steam would be the prime source of power on the farm. It would have been difficult for them to avoid the conclusion that the horse and mule population would decline rapidly.

In fact, steam power appeared on the farm in about 1875 and spread rapidly. Had it not been for the introduction of the internal-combustion engine shortly after the turn of the century, steam power alone would have driven the horse off the farm. The internal-combustion engine, which was unforeseen in 1875, succeeded in driving off both the horse and the steam combine. Today the horse population is little more than 1.5 million, and most of the horses cannot in any real sense be regarded as work animals.

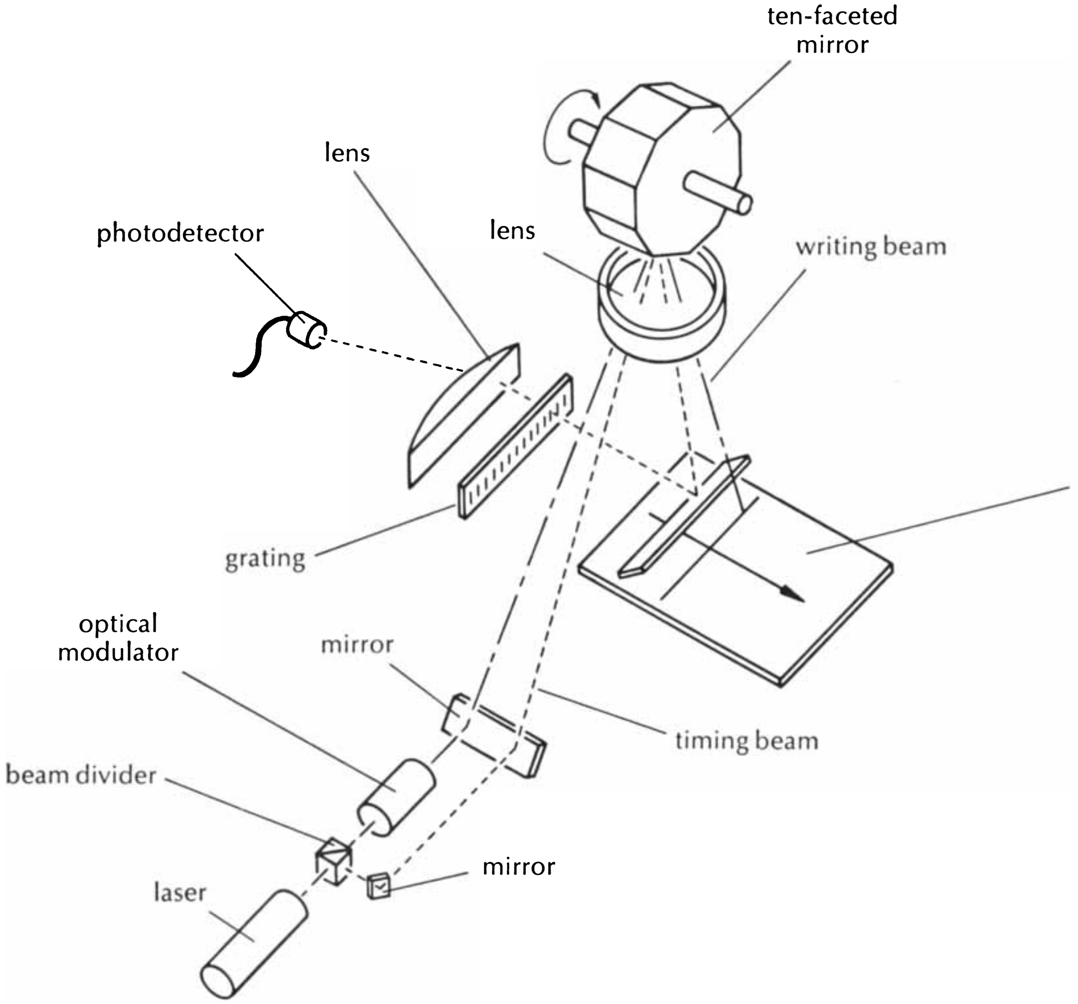
A second example of technological competition was the introduction of the steam-powered iron ship. In a period of



STEEL CONSUMPTION rose substantially but unevenly in the world and five major countries between 1957 (*gray*) and 1967 (*color*). The units are kilograms per person per year.



BASIC MATERIALS other than metal were produced in greatly increased amounts in the U.S. in 1967 (*color*) as compared with 1949 (*gray*). Units are kilograms per capita.



Better circuit masks exposed

Making integrated semiconductor and thin-film circuits requires a set of photographic masks to outline the application or removal of materials during processing. The demand for these masks has increased as integrated electronics has come of age and it will continue to grow with the technology.

Mask-making has long been automated. The engineer feeds a geometric description into a standard program and a computer generates a tape. The tape controls a machine which moves a light beam or a knife along coordinate axes to draw the mask. This takes many hours.

Now, Bell Labs has developed a machine which can produce complex masks in under 10 minutes. The machine contains an argon-ion laser. The laser beam is scanned across an 8 by 10 inch photographic plate and switched on and off to expose the emulsion on the plate according to the mask pattern. As each scan is completed, the plate is shifted one linewidth. Scanning time—20 milliseconds per line—is independent of the number of times the beam is switched on and off.

Each facet of a ten-faceted rotating mirror (above) sweeps the beam once across the plate. At the same time, each facet sweeps an auxiliary laser beam across a grating, generating 26,000 timing pulses for each scan. A digital computer processes the pulses to determine the position of the scanning beam and to generate control signals for an acousto-optic modulator which switches the beam on and off.

The laser beam can be directed with an accuracy better than 2 arc-seconds, the equivalent of a mile-long straight line with less than 5/8 inch deviation. For such precision, the machine is operated in a special controlled-environment chamber where temperature is maintained within 1/7°C and a cubic meter of air contains fewer than 3500 dust particles larger than one micron.

These high-speed, precise machines will supply the Bell System's mask needs for several years. As integrated circuits gain wider telephone use, this will keep costs down.

From the Research
and Development Unit
of the Bell System:

Bell Labs

only 30 years (1870 to 1900) the composition of the United Kingdom's merchant marine was transformed from 90 percent wooden sailing ships to 90 percent iron ships powered by steam. This technological transformation resulted in a greatly enhanced ability to transport goods rapidly and inexpensively over long distances. It also resulted in a greatly increased demand for iron and coal.

In the modes of intercity transportation in the U.S. one can see a dramatic sequence of competitions. In the first years of this century nearly all passenger traffic between cities was carried by the railroads. By 1910 the private car was competing seriously, and by 1920 the automobile was accounting for more passenger-miles between cities than the railroads were. Since World War II the airplane has competed with both the railroad and the automobile for intercity traffic. The combined impact of the automobile and the airplane has come close to putting railroads out of the passenger business. In the decade of the 1970's the airplane will probably make serious inroads on intercity automobile traffic as well. The net result of these changes, as with others, has been increased expenditure of energy and increased demand for materials in both absolute and per capita terms.

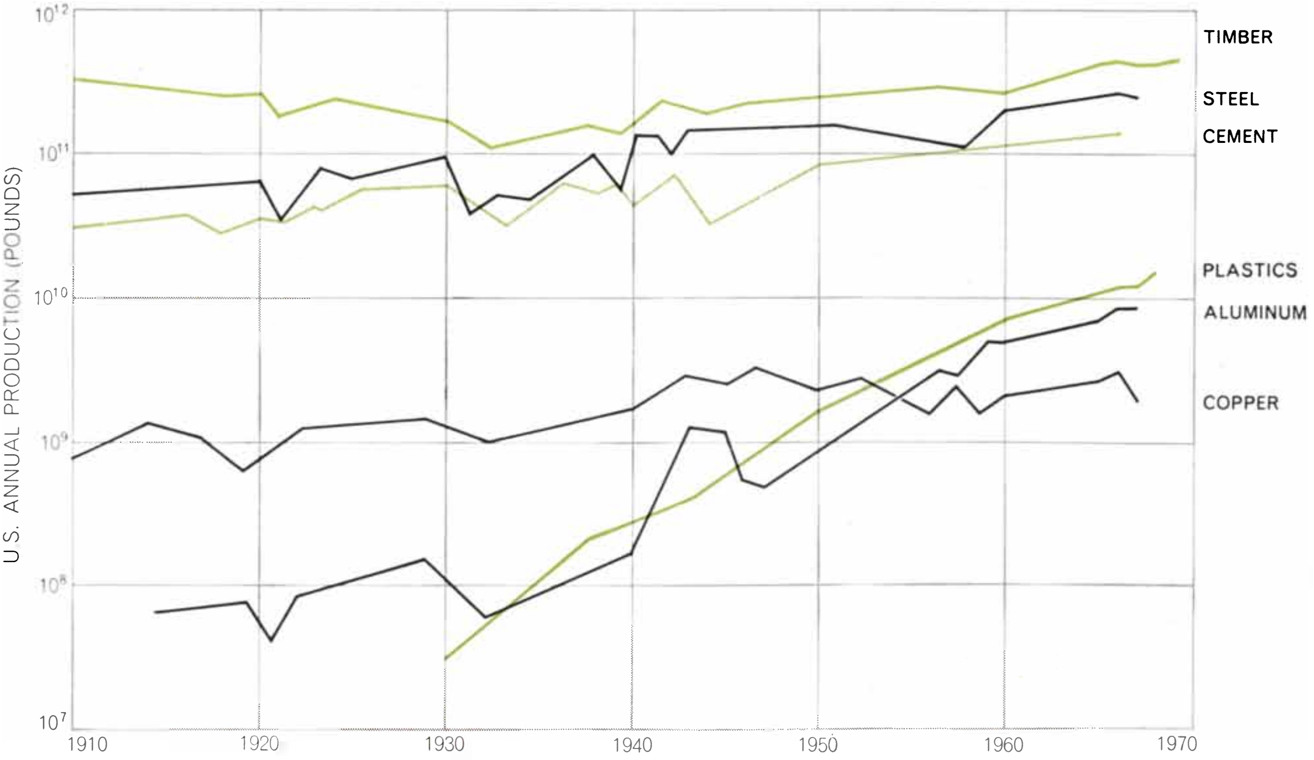
Levels of steel production and consumption are among the most useful indicators of worldwide technological and economic change. In the 19th century England became the dominant producer and consumer of steel, later being replaced by Germany. After World War I the U.S. became the largest industrial power, and steel production rose rapidly. In 1900 per capita steel production in the U.S. reached 140 kilograms, and by 1910 it was up to 300 kilograms. The level exceeded 400 kilograms during World War I, and during World War II it rose to 600 kilograms. Since World War II the picture has changed: although total steel production has continued to rise, the annual per capita level has changed little, averaging about 550 kilograms.

Per capita steel consumption has risen since World War II, but the rise has been slow. The difference between production and consumption has been made up by an increase in imports. In 1967 U.S. steel consumption was 634 kilograms per capita.

Although this is at present the highest per capita level of steel consumption in the world, the U.S. is being overtaken rapidly by other countries. Levels of consumption in much of western Europe and in Japan, Czechoslovakia, East Germany, the U.S.S.R. and Australia are now close to the U.S. level, and the rates of growth are such that Japan will overtake the U.S. quite soon. The per capita level of steel consumption in the U.S.S.R. will probably equal that of the U.S. within another decade. The worldwide rate of increase in per capita steel consumption from 1957 to 1967 was 44 percent, compared with the U.S. rate of 12 percent and the Japanese rate of 270 percent [*see top illustration on page 198*]. In view of the fact that virtually all elements of economic growth correlate reasonably well with per capita steel consumption, it is useful to inquire into the future levels of consumption in the U.S. and the rest of the world.

Consumption of metals other than iron can conveniently be stated in terms of steel consumption. When this is done, it becomes apparent that the consumption levels of certain metals, such as copper, zinc and lead, have remained remarkably constant over the past 50 years in spite of rapidly changing technologies. Consumption of certain other metals, such as tin, has been decreasing with respect to steel as a result of decreasing availability of ore and the development of substitutes. Consumption levels of the light metals, such as aluminum, are rising. Although these metals are still much less used than steel is, they will increasingly supplant steel for certain purposes.

If all the metallic iron that has been produced in the U.S. were still in ex-



TREND IN CONSUMPTION of key materials is traced. The production of timber is usually reckoned in terms of board feet or cubic feet. For purposes of comparability it has been stated here in pounds, assuming an average density of 35 pounds per cubic foot.

istence, there would now be in use some 15 tons of steel per capita. In actuality a great deal of the steel produced has disappeared as a result of junking, production losses, corrosion and other causes. Analysis of production figures and losses suggests that the amount of steel now in use is some 9.4 metric tons of steel per capita. The greater part of it is in the form of structural materials such as heavy structural shapes and pilings, nails and staples, galvanized sheet metal and wire fence. About 8 percent of the steel, or 750 kilograms per person, is in the form of private automobiles, trucks and buses.

Of the roughly 600 kilograms of new steel consumed annually per capita in the U.S. about a third is returned to the furnaces as plant scrap, which is created as a result of the production of standard shapes and forms such as beams, sheet, pipe and wire. Therefore about 410 kilograms of the new steel enters the inventory of steel in use. At the same time about 350 kilograms of steel becomes obsolete or is lost as a result of corrosion and other processes. Of this some 140 kilograms (about 40 percent) is recovered and returned to the steel furnaces in the form of junked automobiles and other worn-out iron and steel products. The balance, corresponding to some 210 kilograms, is lost, probably never to be recovered. Some of it is dissipated widely; much of it is buried in dumps. During the course of the year the steel inventory increases by about 80 kilograms per capita, or somewhat less than 1 percent.

The mean lifetime of steel products varies enormously. Whereas an item such as a can may be in use for only a few weeks or months, steel in motor vehicles is in use on the average for about 10 years. Steel in ships may be in use for about 25 years. Steel structural shapes such as girders and concrete reinforcement may be in use for 50 years or more. The mean lifetime of all steel in use appears to be some 25 to 30 years.

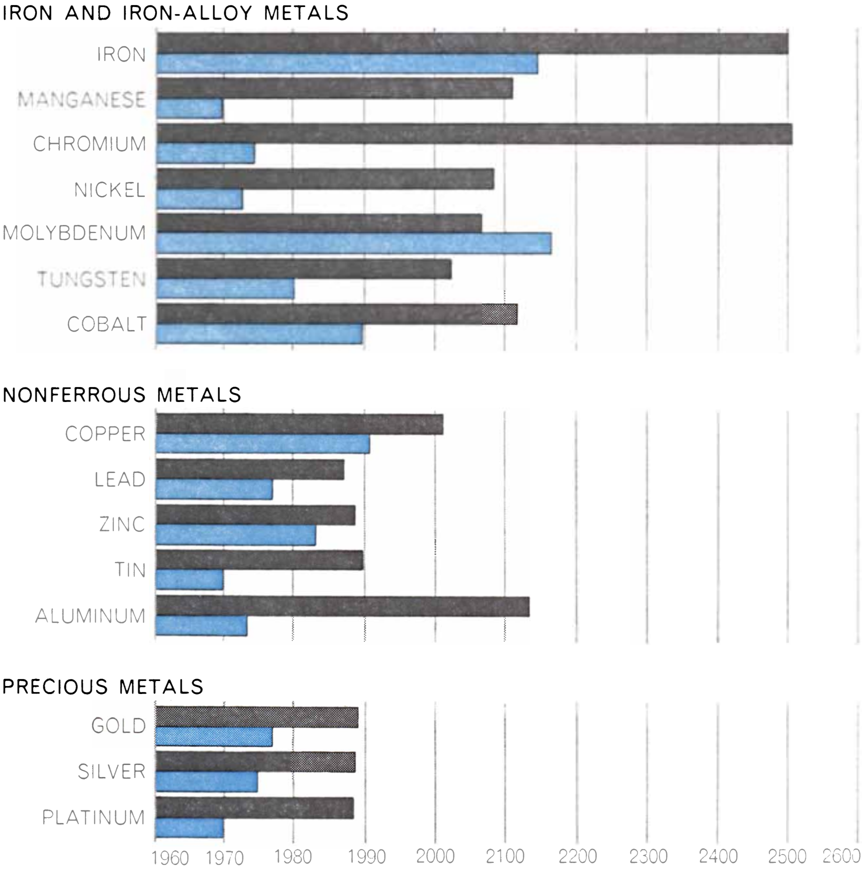
Similar considerations apply to other metals. They are extracted, introduced into the national inventory and eventually lost or recycled as scrap. The mean lifetime of most of them appears to be shorter than that of steel.

Although the quantities of metal in use and the volumes of metalliferous ore that must be dug up and processed to support a human being in our society are large, the quantities of nonmetals consumed each year loom even larger and are increasing extremely rapidly [*see bottom illustration on page 198*]. Between 1949 and 1967 the per capita consumption of stone, sand and gravel in the U.S. rose some 2.5 times to about eight tons per capita. For cement the rise was by a factor of four to one ton per capita. In the same period the per capita consumption of phosphate rock rose by a factor of three and that of ordinary salt by a factor of two. All together, in order to support one individual in our society, something like 25 tons of materials of all kinds must be extracted from the earth and processed each year. This quantity seems certain to increase considerably in the years ahead.

The use of synthetic plastics is now increasing with impressive speed. Total world production of these materials now exceeds in both volume and weight the production of copper and aluminum combined. The production of synthetic fibers is now about half the combined production of cotton and wool. The relative rates of growth suggest that the output of such fibers will exceed that of cotton and wool within a short time.

Between 1945 and 1965 the price of polyethylene dropped by about 75 percent while the price of steel tripled. Already polyethylene is less expensive than steel on a volume basis, although per unit of strength it remains some 15 times more expensive than steel. It is quite possible, however, that before long fiber-glass laminates will compete seriously with steel for structural purposes.

The overall figures suggest that the U.S. now has in use for every person about 150 kilograms each of copper and lead, well over 100 kilograms of aluminum, some 100 kilograms of zinc and perhaps 20 kilograms of tin. To meet the need for raw materials and the products derived from them the nation transports almost 15,000 ton-kilometers of freight per capita per year. Each person travels on the average each year some 8,500 kilometers between cities, makes more than 700 telephone calls and receives nearly 400 pieces of mail. There is now a ratio of almost one private automobile for every two people. In order to accomplish all the mining, production and distribution the American people spend energy at a rate equivalent to the burning



LIFETIMES OF METAL RESERVES are indicated for the world (*gray*) and the U.S. (*color*). These rough estimates are based on the assumption that the utilization of metals will continue to increase with population growth and rising per capita demand. They take into account, however, that new reserves will be discovered by exploration or created by innovation. It is estimated U.S. demands will increase four and a half times by the year 2000.

of about 10 tons of coal annually per person or about 16 tons of coal per ton of steel consumed or about one ton of coal per ton of steel in use. A convenient rule of thumb is that we must burn about one ton of coal each year, or its equivalent in some other source of energy, to keep one ton of steel in use.

Clearly man has become a major geologic force. The amount of rock and earth he moves each year in the present industrialized regions of the world is already prodigious and will continue to grow because of rising population levels, increasing demand from the industrialized nations and the gradual decline in grades of raw materials. If one adds to these requirements the fantastically high demand that would arise if the development process were to be accelerated in the poor countries, the total potential demand staggers the imagination. If the entire human population were to possess the average per capita level of metal characteristic of the 10 richest nations, all the present mines and factories in the world would have to be operated for more than 60 years just to produce the capital, assuming no losses.

Given an eventual world population of 10 billion, which is probably a conservative estimate, and a per capita steel inventory of 20 tons, some 200 billion tons of iron would have to be extracted from the earth. The task would require 400 years at current rates of extraction. Anything approaching such a demand would clearly place enormous strains on the earth's resources and would greatly accentuate rivalries between nations for the earth's remaining deposits of relatively high-grade ores. Most of the industrialized nations already import a substantial fraction of their raw materials. Japan is almost completely dependent on imports. Whereas the U.S. imported in 1950 only 8 percent of the iron ore that it consumed, the figure today is more than 35 percent.

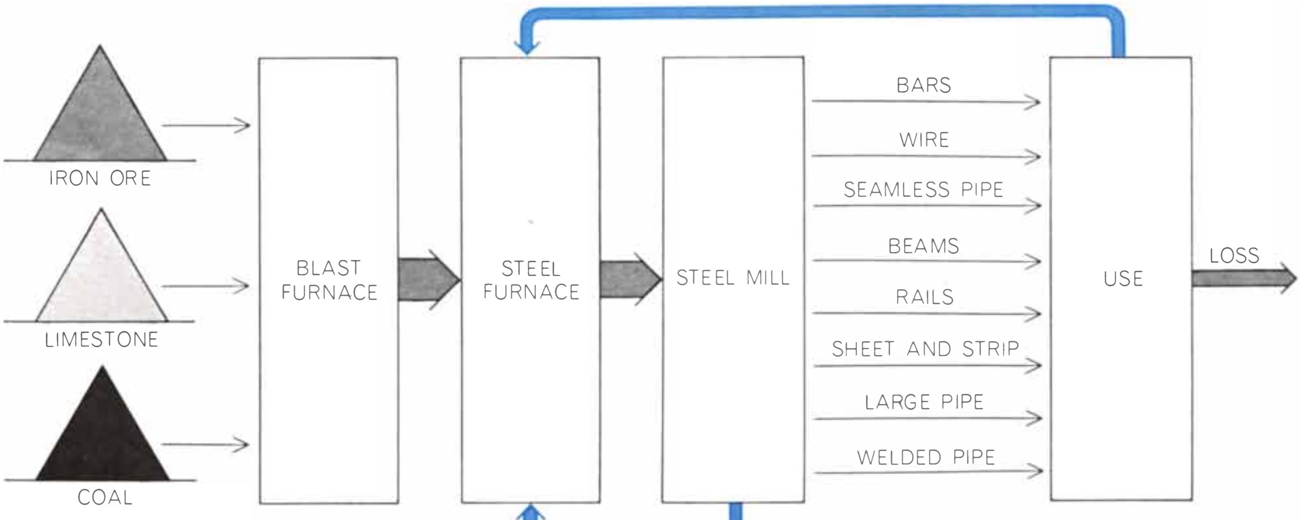
At present the world can be divided into two major groups of steel consumers. The first group consists of about 680 million people, living in 18 nations, who consume steel at rates varying between 300 and 700 kilograms annually per capita. The total consumption of this group comes to about 420 million tons of steel per year. The second group consists of 1,400 million people, living in 13 nations, who consume steel at rates varying between 10 and 25 kilograms annually per capita. The total consumption of this group comes to 27 million tons of steel per year. An additional 400 million people live under circumstances that are still poorer, and 440 million more live under circumstances intermediate between those of the rich and the poor. The distribution of per capita energy consumption follows a similar pattern, as does the distribution of per capita income.

The slowness of the development process and the magnitude of the task the poor countries face can be gauged by the fact that with existing production facilities the poorer group (not the poorest one) would need about 500 years to produce the per capita quantity of steel in use now characteristic of the U.S. Although production levels in the poorer group are increasing fairly rapidly (close to 50 percent per decade on a per capita basis), many decades will be required, even in the absence of any major upheaval, before the amounts of steel in use can enable those nations to feed, clothe and house their populations adequately.

What goes into a system must eventually come out. As I have noted, somewhat less than 4 percent of the steel inventory in the U.S. is exuded annually into the environment, and only about 40 percent of this amount is recovered. As the grades of resources dwindle and locations for dumping solid wastes become more difficult to find, the economic and social pressure for more substitution, more attention to priorities of use of scarce materials and more efficient cycling will increase.

It is clear that various metals can substitute for one another, and that plastics can substitute for a number of metals. Aluminum already substitutes for copper in many roles, as copper and nickel now replace silver in coinage. Synthetic crystals come increasingly into use. All these techniques can be pushed a good deal farther than they have been up to now.

Improved efficiency of cycling is desirable for all solid wastes not only to lower the rate of depletion of high-grade resources but also to reduce the injurious effects of such wastes on the biosphere. The quantities of wastes are becoming substantial. They now amount to nearly one ton per year per person, of which



FLOW OF MATERIALS through the biosphere is depicted using steel as an example. Of the steel produced from iron ore, about a third is recycled immediately in the form of scrap left over from the production of beams, wire and other shapes. Two-thirds enters the national inventory. During each year, however, a somewhat smaller amount of steel becomes obsolete. About 40 percent of it is recycled in the form of scrap. The remainder is lost as a result of such factors as wear, corrosion and disposal through junking.

about a third consists of packaging materials. In 1968, for example, the average American threw away almost 300 cans, 150 bottles and about 140 kilograms of paper. The quantities are increasing rapidly on both an absolute and a per capita basis. Properly cycled, they could provide raw materials for the glass, steel, aluminum and plastics industries.

From a purely technological point of view man could in principle live comfortably on a combination of his own trash and the leanest of earth substances. Already, for example, copper ore containing only .4 percent copper is being processed. If the need arose, copper could be extracted from ore that is considerably leaner than .4 percent. Eventually man could, if need be, extract his metals from ordinary rock. A ton of granite contains easily extractable uranium and thorium equivalent to about 15 tons of coal, plus all the elements necessary to perpetuate a highly technological civilization. Such a way of life would create new problems, because under those circumstances man would become a geologic force transcending by orders of magnitude his present effect on the earth. Per capita energy consumption would come to the equivalent of perhaps 100 tons of coal per year, and there might be some 100 tons of steel in use per person. The world would be quite different from the present one, but there is no reason a priori why it would necessarily be unpleasant.

Man has it in his power technologically to maintain a high level of industrial civilization, to eliminate deprivation and hunger and to control his environment for many millenniums. His main danger is that he will not learn enough quickly enough and that he will not take adequate measures in time to forestall situations that will be very unpleasant indeed.

SHREDDING TECHNIQUE was recently developed for turning worn-out or wrecked automobiles into scrap that can be recycled to steel furnaces. At top stripped automobile bodies are being fed into the shredder; the product that emerges is shown at bottom.