

**INDUSTRIAL METABOLISM:
WORK IN PROGRESS**

by

R. U. AYRES*

97/09/EPS

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

*** Sandoz Professor of Management and the Environment at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.**

A working paper in the INSEAD Working Paper Series is intended as a means whereby a faculty researcher's thoughts and findings may be communicated to interested readers. The paper should be considered preliminary in nature and may require revision.

Printed at INSEAD, Fontainebleau, France.

INDUSTRIAL METABOLISM: WORK IN PROGRESS¹

Robert U. Ayres

Center for the Management of Environmental Resources

INSEAD

Fontainebleau, France

February 1997

Abstract

This paper reviews the origins and current status of the concept of "industrial metabolism" or IM. The term is now ten years old. It is useful because it conveys a sense of the linkages between human-industrial and economic activity and the larger bio-geo-chemical system in which these activities are embedded. It particularly emphasizes the importance of materials (including fuels) processing and materials transformation in the "metabolism" of the economy. The paper touches on a number of related topics, including the impact of human activity on the bio-geo-chemical cycles of the earth, the actual and potential material cycles within the industrial economy, dissipative uses of materials, toxification of the earth, and measures of sustainability. The paper also reviews economic and policy implications of the IM perspective.

1. Introduction

The term "industrial metabolism" was coined and used for the first time a decade ago in the context of preliminary discussions leading to what is now known as the "Human Dimensions of Environmental Change Program" (1987). My purpose was to call attention to what I thought was a major gap in the program, as it was envisaged. I pursued this idea of a gap at a Tokyo conference sponsored by the UN University (1987), which led to an article published by the *International Social Science Journal* (UNESCO) [Ayres 1989], a UNU workshop at Maastricht (1988), a summer 1988 Workshop of the National Academy of Engineering at Woods Hole, the proceedings of which were published as a book by the National Academy Press [Ayres 1989a], and finally a book *Industrial Metabolism* co-edited with Udo Simonis and published by UNU Press [Ayres & Simonis, 1994].

The more recent term "industrial ecology" has a slightly different history and different connotation. It was chosen, in preference to "industrial metabolism", by the organizing committee for a 1992 summer study at Snowmass, Colorado. The product of that summer study was a large volume, entitled *Industrial Ecology & Global Change* edited by Socolow, Andrews, Berkhout & Thomas [Socolow *et al* 1994]. At first, I thought the two terms were interchangeable. However, industrial metabolism has increasingly been interpreted as the study of mass flows and transformations in the economy (analogous to the metabolic processes of an organism), while industrial ecology is often seen as the industrial analog of an ecosystem in which there is a hierarchical network of organisms (firms) each of which — in principle — consumes all of the products of the others, so there is no waste in the system taken as a whole. This paper concerns itself largely with the first interpretation.

It may seem odd to suggest that a mere viewpoint — in contradistinction to empirical analysis — may have policy implications. But it is perfectly possible. In fact, there are two implications that come to mind. First, the industrial metabolism (IM) perspective is essentially holistic in that the whole range of interactions between energy, materials and the environment are considered together — at least, in principle. The second major implication, which virtually follows from the first, is that from this holistic perspective it is much easier to see that narrowly conceived or short-run, myopic, quick fix policies may be very far from globally optimum. In fact, from the larger perspective, many such narrowly focussed policies can be positively harmful.

The best way to explain the virtues of a holistic view is by contrasting it with narrower perspectives. Consider the problem of waste disposal. Environmental protection policy has systematically ignored the fundamental reality that materials can change form, but that mass is conserved, by imposing regulations on emissions *by medium*. Typically, one legislative act mandates a bureaucracy that formulates and enforces a set of regulations dealing with emissions by point sources only to the air. Another legislative act creates a bureaucracy that deals only with waterborne emissions, again by point sources. And, so forth.

Not surprisingly, one of the things that happened as a result was that some residuals that were originally emitted to the air (e.g. fly ash and SO_x from fossil fuel combustion) were converted to another form of waste, such as flue gas desulfurization (FGD) sludge to be disposed of on land. Meanwhile many solid wastes were being incinerated, thus converting them into airborne wastes. Similarly, some waterborne pollutants, such as sewage, are captured and converted to sludges for land disposal or, even, for incineration. But landfills also *cause* water pollution (leachate), and air pollution, due to anaerobic decay processes. In short, narrowly conceived environmental policies over the past twenty years and more have largely shifted waste emissions from one form (and medium) to another, without significantly reducing the totals.

To be sure, these shifts may have been beneficial in the aggregate. But the costs have been quite large, and it is only too obvious that the state of the environment in the large is still deteriorating rapidly. One is tempted to think that a more holistic approach, from the beginning, might have achieved considerably more at considerably less cost.

2. What is Industrial Metabolism?

The word metabolism, as used in its original biological context, connotes the internal processes of a living organism. The organism ingests energy² rich, low entropy materials (food), to provide for its own maintenance and functions, as well as a surplus to permit growth and/or reproduction. The process also necessarily involves excretion or exhalation of waste outputs, consisting of degraded, high entropy materials. There is a compelling analogy between biological organisms and industrial activities — indeed, the whole economic system — not only because both are materials processing systems driven by a flow of exergy [Georgescu-Roegen 1971], but because both are examples of self-organizing dissipative systems (in Prigogine's sense) in a stable state, far from thermodynamic equilibrium [Nicolis & Prigogine 1977; Ayres 1988].

At the most abstract level of description, then, the metabolism of industry is the whole integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes in a, more or less, steady-state condition. The production (supply) side of the economy, by itself, is not self-limiting or self-regulating. The stabilizing controls of the economic system are provided by its human component. This human role has two aspects: (1) *direct*, as labor input, and (2) *indirect*, as consumer of output; i.e. determinant of final demand. The system is stabilized, at least in its decentralized competitive market form, by balancing supply of and demand for both products and labor through the price mechanism. Thus, the competitive free market plus its institutional adjuncts, is, in essence, the metabolic regulatory mechanism.

Industrial metabolism can be identified and described at a number of levels below the broadest and most encompassing global one. Thus, the concept is obviously applicable to nations or regions, especially 'natural' ones such as watersheds or islands. The key to regional analysis is the existence of a well-defined geographical border or boundary across which physical flows of materials and energy can be monitored.

The concept of industrial metabolism is equally applicable to another kind of self-organizing entity, a manufacturing enterprise or firm. A firm is one of the economic analogs of a living organism in biology.³ A household can also be regarded in this way. Some of the differences are interesting, however. In the first place, biological organisms reproduce themselves. Households, being essentially biological, can also reproduce. By contrast, firms produce products or services, not other firms (except occasionally by spinoff). In the second place, firms need not be specialized and can change from one product or business to another. By contrast, organisms are highly specialized and most cannot change their behavior except over a long evolutionary time period.

In fact, the firm and the household are generally regarded as the standard units of analysis in micro-economics. The economic system as a whole is essentially a collection of firms together with adjuncts and regulatory institutions and a collection of households or worker-consumers, using a common currency and governed by a common political structure. A manufacturing firm converts material inputs, including fuels or electric energy, into both marketable products and waste materials. It keeps financial accounts for all its external transactions; it is also relatively easy to track physical stocks and flows across the boundary

of the firm and even between its divisions. Households are also distinct units. At one time households were both consumers and producers of goods for the market. These roles are now largely distinct, inasmuch as most households now produce only labor.

3. The Bio-Geo-Chemical Materials Cycle

Another way in which the analogy between biological metabolism and industrial metabolism is useful is to focus attention on the life cycle of individual materials or nutrients. The hydrological cycle, the carbon cycle, and the nitrogen cycle are familiar concepts to earth scientists. The major way in which the industrial metabolic system differs from the natural metabolism of the earth is that many of the natural cycles (e.g. water, carbon/oxygen, nitrogen, sulfur) are *closed*, whereas most industrial cycles are *open*. In other words, the industrial system does *not* generally recycle its nutrients. Rather, the industrial system starts with high quality materials (fossil fuels, ores) extracted from the earth, and returns them to nature in degraded form.

This point particularly deserves clarification. The materials cycle, in general, can be visualized in terms of a system of compartments containing *stocks* of one or more nutrients, linked by certain *flows*. For instance, in the case of the hydrological cycle, the glaciers, the oceans, the fresh water lakes and the groundwater are stocks while rainfall and rivers are flows. A system is *closed* if there are no external sources or sinks. In this sense, the earth as a whole is essentially a closed system, except for the occasional meteorite.

A closed system becomes a closed *cycle* if the system as a whole is in a steady-state; i.e. the stocks in each compartment are constant and unchanging, at least on the average over a reasonable period of time. The materials balance condition implies that the material *inputs* to each compartment must be exactly balanced on the average by the *outputs*. If this condition is not met for a given compartment, then the stock in one or more compartments must be increasing, while the stocks in one or more other compartments must be decreasing.⁴

It is easy to see that a closed cycle of mass flows, in the above sense, can only be sustained indefinitely by a continuous flow of exergy.⁵ This follows immediately from the second law of thermodynamics, which states that global entropy increases in every irreversible process. Exergy is used up at the same time; it is not conserved. An open system of mass flows, on the contrary, is inherently unstable and unsustainable. It must either stabilize by closing, while continuing to be driven by an external source of exergy, or it must collapse to a thermal equilibrium state in which all mass and exergy flows, i.e. all physical and biological processes, cease.

It is sometimes convenient to define a generalized 4-box model to describe materials flows. The biological version is shown in *Figure 1*, while the analogous industrial version is shown in *Figure 2*. Reverting to the point made at the beginning of this section, the natural system is characterized by closed cycles, at least for the major nutrients (carbon, oxygen, nitrogen, sulfur) — in which biological processes play a major role in closing the cycle. By contrast, the industrial system is an open one in which nutrients are transformed into wastes, but not significantly recycled. The industrial system, as it exists today, is therefore *ipso facto* unsustainable.

At this stage, it should be noted that nothing can be said about open cycles (on the basis of such simple thermodynamic arguments, at least) with respect to any of the really critical questions. These are as follows: (1) Is there a significant risk that anthropogenic activity, projected into the future, could destabilize the climate? What about the ozone layer? (2) Is there a risk of accelerating global acidification? (3) Are the nutrient cycles (C, N, S)

inherently stable or not? If not, does there exist any stable state, i.e. a system of closed nutrient cycles, short of ultimate thermodynamic equilibrium? Could such a stable state be reached with the help of a feasible technological fix? (4) If so, what is the nature of the fix, and how costly will it be? (5) If not, how long do we have until the irreversible deterioration of the bio-geosphere system makes the earth uninhabitable? If the time scale is a billion years, we need not be too concerned. If it is a hundred years, civilization, and even the human race, could already be in deep trouble. It is fairly important to try to find answers to these questions.

It should be noted that the bio-geosphere was not always a stable system of closed cycles. Far from it. The earliest living cells on earth obtained their nutrients, by fermentation, from non-living organic molecules whose origin is still not completely understood. At that time the atmosphere contained no free oxygen; it probably consisted mostly of water vapor and carbon dioxide, and possibly nitrogen. The fermentation metabolism converted simple carbohydrates into ethanol and carbon-dioxide. The original system could only have continued until the fermenting organisms used up the original stock of food molecules or poisoned themselves on the ethanol buildup. The system stabilized temporarily when a new organism, blue-green algae (cyano-bacteria) appeared, about three billion years ago, that was capable of recycling carbon-dioxide into sugars and cellulose, thus closing the carbon cycle and producing free oxygen. This new process was anaerobic bacterial photosynthesis.

However, the photosynthesis process also had an open loop. For a long time (over a billion years) the oxygen generated by anaerobic photosynthesis was captured by dissolved ferrous iron or sulfide molecules, and sequestered as insoluble ferric oxide (magnetite), or sulfates. Iron oxide and calcium sulfate were precipitated on the ocean bottoms. The result is the large deposits of high grade iron ore and gypsum that we exploit industrially today. The system was still unstable at this point. It was only the evolutionary invention of two more biological processes, aerobic respiration⁶ and aerobic photosynthesis, that closed the oxygen cycle as well.

Still other biological processes — nitrification and denitrification, for instance — had to appear to close the nitrogen and sulfur cycles. The nitrification (nitrogen fixation) process was needed to supplement scarce natural sources of water soluble nitrogen compounds. Without it, the quantity of biomass supportable by the earth would have been very small. But denitrification — the bacterial process that takes oxygen from nitrate (NO_3) molecules and re-converts the nitrogen into the stable gaseous form — is also necessary. Without it the atmosphere would gradually be oxidized and the ocean would be converted to nitric acid.

Evidently biological evolution responded to inherently unstable situations (open cycles) by inventing new processes (organisms) to stabilize the system by closing the cycles. This self-organizing capability is the essence of what James Lovelock called 'Gaia'. However, the instabilities in question were slow to develop, and the evolutionary responses were also slow to evolve. It took several billion years before the biosphere reached its present degree of stability.

In the case of the industrial system, the time scales have been drastically shortened. Human activity already dominates natural processes in many respects. While cumulative anthropogenic changes to most natural nutrient stocks still remain fairly small, in most cases,⁷ the *rate* of nutrient mobilization by human industrial activity is already comparable to the natural rate in many cases. *Table I* shows the natural and anthropogenic mobilization (flow) rates for the four major biological nutrients, carbon, nitrogen, phosphorus and sulfur. In all cases, with the possible exception of nitrogen, the anthropogenic contributions exceed the natural flows by a considerable margin. This is the basic reason for concern about long-run stability. As indicated in *Table I*, anthropogenic activities like the use of synthetic fertilizers in agriculture and the combustion of fossil fuels add very significantly to the natural fluxes

of these nutrient elements. Based on relatively crude materials cycle analyses, at least, it would appear that industrialization has already drastically disturbed, and *ipso facto* destabilized, the natural system. This constitutes a natural introduction to the next stage, which is the industrial materials cycle *per se*.

4. Industrial Materials Cycles — Actual and Potential

As suggested already, the industrial metabolic (IM) system is not, at present, a closed cycle. It can be described schematically as a sequence of processing stages between extraction and ultimate disposal, with a number of actual or hypothetical intermediate loops that would permit the system to be closed with respect to mass flows (*Figure 3*). The IM system cannot, of course, be closed with respect to exergy flows. The extent to which mass-flow closure would be desirable from an environmental perspective depends on the nature of the materials being lost or discarded. Some kinds of mass flows, such as soil displaced by dredging, roadbuilding, mining or construction, and used for earthen dams, dikes and fill are quantitatively large but qualitatively unimportant except in special cases. Mining wastes other than overburden constitute a second category that is slightly less benign but quantitatively smaller. Industrial and municipal wastes are intermediate in quantity and harmfulness. At the other extreme are toxic chemicals such as pesticides, dangerous trace contaminants like dioxins, or ozone-destroying CFCs.⁸ Mass flow analysis of industrial subsystems is helpful, but not sufficient, for purposes of identifying linkages and tradeoffs between waste flows and for prioritizing opportunities for intervention [Ayres & Ayres 1996].

One of the most powerful arguments for closing the cycle is illustrated by the case of zinc *Figure 4*. When metal ores are extracted from the environment the extraction process itself generates enormous quantities of overburden and mine spoil with no conceivable economic use, but considerable potential for harm if not protected from erosion. The next stage of processing, concentration, also generates huge quantities of so-called "tailings" that contain significant quantities of toxic trace elements, such as arsenic, cadmium, lead and zinc, as well as chemicals used for the concentration process. The mine tailings are too low in grade to be utilized as sources of metal, although some tailings heaps from earlier mining operations are potentially recoverable in the future. Because of their contaminants they constitute a potential environmental hazard. For example, in the process of concentrating silver and gold ores mercury was commonly used — and discarded — in the past, and is still used by illegal gold miners in Brazil, Venezuela and elsewhere. The large-scale gold mining operations use cyanide instead.

The next stage of ore processing is reduction (smelting). This also produces another solid waste, slag, although slag from iron and steel mills can be used for road paving. Non-ferrous metals are usually found in nature as sulfides, so nonferrous ore processing (*Figure 5*) also generates significant quantities of sulfur dioxide. In principle this can be economically recovered for sulfuric acid production, as in the U.S. However, in many parts of the world SO₂ is simply emitted into the air without treatment because of the lack of a local market for the by-product acid. It is also of some interest to note that large quantities of chemicals are required. In the U.S. (1988), 1.87 million metric tons (MMT) of explosives and 4.5 MMT of other chemicals were consumed in the mining and concentration stages of non-ferrous metallurgy (*Figure 5*), as compared to roughly 6 MMT of finished product (metals) and 3.5 MMT of recovered sulfuric acid.

An interesting implication of the IM perspective is that the ferrous metals sector (*Figure 6*) is much bigger than the non-ferrous sector in terms of the quantity of finished product, but

far less so in terms of waste overburden, tailings and air pollution. Indeed, the process wastes from non-ferrous metallurgy are, in principle, more likely to be harmful. This would seem to be a powerful *a priori* argument for sharply increasing recycling in the non-ferrous sector especially (see Section 6 below).

The case of coal is even worse (*Figure 7*). Not only does coal mining disturb huge land areas and generate enormous quantities of overburden. It also causes methane emissions, subsidence (in the case of underground mines), water pollution by acid mine drainage and fire hazards. Moreover, the increasing requirement for coal washing, to reduce sulfur content, generates huge piles of sulfurous waste refuse near the mines. Finally, sulfur not removed by washing must later be removed from flue gases of electric power generating stations. This process, as currently implemented, also consumes large quantities of limestone and generates larger quantities of so-called flue-gas desulfurization (FGD) waste and CO₂.

An important observation at this point is that petroleum and natural gas are extremely special cases of natural resources that are available in large quantities, at low cost, in nearly pure (at least, usable) form. Even the sulfur contained in natural gas is easily recovered and constitutes a valuable by-product. Apart from emissions of small amounts of volatile organic compounds (VOCs) associated with petroleum refining and moderate quantities of saline water waste from drilling operations, the only pollutants associated with the extraction and processing of these resources are combustion products and downstream pollutants from the petrochemical sector (*Figure 8*). Thus, the end of the Age of Oil, which is likely to occur a few decades from now, implies much more than the substitution of other forms of energy.⁹ If the economic substitute for gas and oil is coal, as would seem likely based on current conditions and institutions, it also portends a vast increase in extraction and processing wastes.

The mass balance principle requires that, in steady state, the mass of inputs to a process or activity must be equal to the mass of outputs. This applies at all levels of aggregation: the sectoral level, the industry level and the plant level. Application of this principle in specific cases can lead to interesting questions with regard to waste flows.

A case in point is the petrochemical industry. Based on U.S. data published by the International Trade Commission [USITC 1989, 1990] it is possible to add up and compare process inputs and outputs, both for the petrochemical feedstock sector and for the organic chemicals sector (*Figure 9*).¹⁰ This enables one to obtain a rough estimate of process wastes — more precisely, materials unaccounted for. The latter can be further analyzed based on more detailed technical process information, where available, but it is mainly interesting as a way of raising interesting questions. For instance, total inputs to the feedstock processing sector (1988) appear to have been 55.4 million metric tons (MMT), not counting hydrocarbon wastes used for fuel internally. But only 45.7 MMT of products can be accounted for [ibid]. What happened to the remaining 9.7 MMT? It was presumably divided up between hydrogen recycled to other refinery operations, hydrocarbons burned as fuel within the refinery and VOC emissions. But the breakdown could be important in case it turns out that VOC emissions are really dangerous.

The organic chemical product sector is even more interesting, for several reasons. From various sources it is possible to identify feedstock inputs adding up to approximately 61 MMT, including chlorine, sulfuric acid, ammonia, caustic soda, sodium carbonate and other inorganics [Ayres & Ayres 1993, 1994, 1996]. In addition, application of mass-balance principles at the chemical process level implies that at least 2 MMT of process oxygen from the atmosphere must have been embodied in products, not counting oxygen consumed in combustion of hydrocarbons for process heat. The details of this estimate cannot be summarized here. But the total mass of inputs to the sector in 1988 amounted to about 63 MMT. On the other hand, the ITC accounted for synthetic organic chemical products adding

up to 39.1 MMT. The difference, 23.9 MMT must have been chemical process wastes. Again, this does *not* include combustion wastes from fuel used in the chemical industry.

Questions obviously arise: What is their composition? Are these process wastes solids, liquids or gases? In what environmental media are they disposed of? On superficial examination, it is clear that much of the total mass of wastes must be inorganic salts from the neutralization of acids and alkalis. But, even when all of the caustic soda (sodium hydroxide) reacts with sulfuric acid or hydrochloric acid and is converted into sodium sulfate or sodium chloride, a very significant residual remains unaccounted for. Again, it is fair to assume that most of this residual consists of carbon dioxide and water vapor. Many chemical reactions generate one or the other or both. But there would still be a residual of unknown organic compounds.

What might they be? This question would seem to be an interesting subject for future IM research. Proceeding both "top down" (as above) and "bottom up", from production and process data for individual chemicals one can begin to reduce the uncertainties significantly. In the case of chlorine, which is of particular interest to environmentalists, we have carried the analysis much further (next section).

It must be acknowledged that materials that cannot be accounted for, based on mass flow analysis do not necessarily become true waste effluents. But waste treatment does not eliminate mass. On the contrary, treatment is likely to increase mass; recall the example of FGD sludge, mentioned previously. There are only two possible long-run fates for waste materials: either recycling and re-use or loss to the environment¹¹.

5. Dissipative Uses of Materials

Another important implication of the IM perspective is that *all* extractive materials, even after refining and incorporation into products, are still potential wastes. Most materials return to the environment, generally in chemically or physically degraded form, within a few weeks or months. Fossil fuels are degraded by combustion. The combustion products have no economic value. But they are capable of causing significant environmental harm, ranging from climate warming to acid rain. Combustion wastes, especially micro-particulates, also cause or aggravate a number of respiratory and other health problems that arise in polluted areas. Agricultural products eventually become animal wastes, food wastes (garbage) and sewage. Organic wastes in water become pollutants and breeding grounds for infectious diseases.

Other materials return to the environment in different ways. Some materials embodied in durable goods, or structures, return to the environment slowly, in the form of solid wastes. Such wastes are normally accumulated in landfills and, under proper management, little damage may result. Other materials are returned to the environment as soluble salts, mainly from chemical processing. Sewage, garbage, ashes, slag, mine spoil, sludges and other categories are visible and well known. Less obvious are the invisible wastes resulting from dissipative uses of materials like lubricants, solvents, pigments, detergents, abrasives, fuel additives, water treatment chemicals, fertilizers, pesticides, explosives, fire retardants, cosmetics, pharmaceuticals and so on.

Yet these categories, which are easily overlooked, can be very important — and very harmful. Tetraethyl lead, a fuel additive, was accumulating hundreds of thousands of tons of lead *per year* in the environment — mainly in the soil near busy roads — until it was phased out.¹² This lead will remain in place for many decades, although most of it is (hopefully) immobilized by attachment to clay particles. The case of DDT, PCBs and CFCs are well known. To cite another example, chlorinated solvents, such as methylene chloride (a paint

remover), trichloroethylene (a vapor degreaser), perchloroethylene (dry cleaning fluid), and methyl chloroform (also a vapor degreaser) were being used in steadily increasing amounts until it was realized that they could be toxic or carcinogenic to humans with continued exposure, even at low levels. Now they are all being phased out gradually, at least in Europe.

Thus, another contribution of the IM perspective has been to call attention to the fact that many intermediate products of industry are inevitably dissipative. Some of these intermediates are certainly toxic. Chlorine is an interesting example in this context. Based on a recent detailed study of the chlorine industry in Europe [Ayres 1997; Ayres & Ayres 1997] it was determined that, based on total chlorine consumed in Europe (1992), two thirds was virgin, i.e. produced by electrolysis of salt, and one third was recycled within the industry, mainly by recovery from waste HCl. But looking at the outputs, only 46% of the total chlorine flux was embodied in chemical products crossing the boundary fence, i.e. sold to downstream users, while 33.7% was recycled back into the industry and 24.7% was lost as waste.

Most of this industrial chlorine waste was in the form of chlorine salts, mainly NaCl or CaCl₂, dumped into rivers. But as much as 1%-2% may have been lost in other chemical forms, some of which could be considerably more hazardous. Of the chlorine compounds crossing the fence 60% was embodied in the plastic PVC, Almost all of the rest is used for purposes like water treatment, pulp bleaching (largely phased out in Europe, but still practiced in the US and Canada), solvents, and other products that are dissipated in use. The special category of chlorinated pesticides and herbicides, while quantitatively small, probably accounts for a disproportionate share of environmental harm.

It hardly needs to be pointed out that so-called final products do not disappear from the environment after use. For instance, PVC is not a dissipative use, in the above sense. A large fraction of PVC is used for structural purposes, such as pipes, floors and window frames, that have a relatively long life — from 20 to 50 years. But at the end of its useful life, any such material must be disposed of, either in a landfill or an incinerator. Many environmentalists are strongly opposed to the incineration of chlorinated plastics, because of concerns about dioxin formation. The evidence available today suggests that this concern may be exaggerated. However, the long term consequences of landfill disposal are simply unknown at present, and there is a fairly strong case, based on the precautionary principle, to encourage more recycling and reuse of plastics like PVC, simply to retain them within the anthroposphere.

6.Toxification of the Earth

Industrial metabolism involves a wider selection of elements than natural metabolism. Natural bio-geo-chemical systems have evolved to recycle nutrient elements that are relatively scarce in nature, or at least in chemically available forms. By contrast, industrial systems have developed considerable expertise at extracting and utilizing elements and compounds that are not much found in nature. Such elements and compounds are more likely to be biologically hazardous than elements and compounds that are circulated within the natural world. Most heavy metals are in this category. They and their compounds are mostly eco-toxic to some degree. It is possible that this is because they are alien and disturbing influences in natural environments that evolved without them.

Of course there are many natural toxins, mainly developed by plants as defenses against pests or, in some cases, as weapons used by predators to paralyze or kill their prey. However organic toxins are almost always proteins. They are built from the standard building blocks of all living organisms, viz. the 20 amino acids, consisting of the five elements carbon,

hydrogen, oxygen, nitrogen and (in three cases) sulfur. Their antidotes can be formed from the same building blocks.

Toxic heavy metals or halocarbons are in a different category. There are no straightforward natural antidotes. Metals cannot be transformed into non-metals. At worst they are metabolized and hydrogenated or methylated by anaerobic bacteria, thus becoming volatile or soluble and metabolizable by higher organisms. This process is particularly important in the case of mercury and arsenic. The best that can happen in the case of metals is that a soluble or mobile form will eventually be immobilized by some by some natural process (such as adsorption by clay particles) and finally buried or otherwise physically removed from the scene. The major toxic heavy metals, and their sources, are shown in *Table II*.

In the case of another unnatural category of materials, halocarbons, there are also two natural processes of importance. One is called bio-accumulation. Many halocarbons are soluble in lipids and can be stored in body fat. When one organism is consumed by another — a grazer or a predator — the stored halocarbons are accumulated, becoming more and more concentrated. After moving up the food chain several steps in this manner, a very low original concentration in the water or soil can be converted in this manner into a lethally high concentration. This is a serious risk for so-called top predators, such as eagles and hawks or gamefish. Exactly this process has occurred in the case of DDT and PCBs, for instance.

A second important process is degradation of toxic organic chemicals (like halocarbons) through contact with oxygen, hydroxyl ions, or UV radiation. Degradation eventually reduces complex halocarbons to simple compounds like HCl. But intermediate products of degradation are not always harmless. Some breakdown products of DDT, for instance, are more toxic than the original.

Of course some halocarbons, especially CFCs, are extremely inert — resistant to breakdown by contact with oxygen — and therefore persistent. It is these compounds that eventually diffuse into the stratosphere where they are broken down by UV radiation. The breakdown products include atomic chlorine, which in turn, catalytically destroys stratospheric ozone. The chlorine itself is not destroyed. A single chlorine atom may destroy a hundred thousand molecules of ozone before it diffuses back into the lower atmosphere. This interaction between an industrial product and the natural environment is a good illustration of industrial metabolism "in action" so to speak.

A point worth emphasizing here is that, in the case of dissipative materials that are environmentally persistent, including PCBs, some pesticides, halocarbons and toxic metals, point source measurements are needed for monitoring purposes. But, point source measurements and local concentration measurements alone are totally insufficient for purposes of assessing environmental hazards or trends. The reason is that direct measurements cannot be made consistently at all the points where harm may occur. For instance, in the bodies of birds and fish. It is absolutely necessary to construct models that simulate and predict what happens to persistent toxic materials as they move from compartment to compartment in the environment itself. The associated processes of accumulation and degradation must also be reflected in such models.

The sort of model that is needed is illustrated schematically by *Figure 10*. This schematic emphasizes the importance of the so-called mobile environmental reservoir. The state of the reservoir itself cannot be measured directly with any confidence, although point measurements are clearly important. To quantify such a model, however, it is also necessary to keep track of production, use, industrial inventories, and transport mechanisms, over time. Unfortunately, industrial secrecy in the matter of production and consumptive use of most chemicals (and of virtually all of the chemicals of greatest concern) makes such models virtually impossible to build.

7. Measures of Sustainability

A strong implication of much of the foregoing discussion is that a long-term sustainable steady state industrial economy would necessarily be characterized by near-total recycling of intrinsically toxic or hazardous materials, as well as a significant degree of recycling of plastics, paper and other materials whose disposal constitutes an environmental problem. Heavy metals are among the materials that would have to be almost totally recycled to satisfy the sustainability criterion. The fraction of current metal supply needed to replace dissipative losses, i.e. production from virgin ores needed to maintain a stable level of consumption, is thus a useful surrogate measure of distance from a steady-state condition, i.e. a condition of long-run sustainability. Such a measure can, therefore, be regarded as an indicator of unsustainability.

Most economic analysis in regard to materials, in the past, has focussed on availability. Data on several categories of reserves (economically recoverable, potential, etc) are routinely gathered and published — by the U.S. Bureau of Mines, for example. However, as is well known, such figures are a very poor proxy for actual reserves. In most cases the true reserves are much greater than the amounts that are officially documented. The reason, simply, is that most such data are extrapolated from test borings by mining or drilling firms. Because of discounting, it is economically optimal for firms to stop searching for new ore bodies when their existing reserves exceed 20 to 25 years' supply. Only in the case of petroleum, which has been the subject of worldwide searches for many decades, is it possible to place much reliance on published data of this kind.¹³

However, a sustainable steady state, as discussed above, is less a question of resource availability than of recycling/re-use efficiency. As commented earlier, a good measure of unsustainability is dissipative usage. The more materials are recycled, the less will be dissipated into the environment, and vice versa. Dissipative losses must be made up by replacement from virgin sources. This raises the distinction between *inherently dissipative* uses and uses where the material could be recycled or re-used, in principle, but is not. The latter could be termed *potentially recyclable*.

Thus, there are really three important cases: (1) uses that are economically and technologically compatible with recycling under present prices and regulations; (2) uses that are not economically compatible with recycling but where recycling is technically feasible e.g. if the collection problem were solved; and (3) uses where recycling is inherently not feasible. Admittedly there is some fuzziness in these classifications. But it should be possible for a group of international experts to arrive at an acceptable reconciliation.

Generally speaking, it is arguable that most structural metals and industrial catalysts are in the first category of the above classification. Other structural and packaging materials, as well as most refrigerants and solvents, fall into the second category. This leaves coatings, pigments, pesticides, herbicides, germicides, preservatives, flocculants, anti-freezes, explosives, propellants, fire retardants, reagents, detergents, fertilizers, fuels and lubricants in the third category. In fact, it is easy to verify that most chemical products belong in the third category, except those physically embodied in plastics, synthetic rubber or synthetic fibers.

It is instructive to consider individual elements in this context. For instance, if one traces the uses of materials from source to final sink, it can be seen that virtually all sulfur in the economy, whether mined or recovered from oil, gas or metallurgical refineries, is in the third category. Sulfur is mostly (75%-80%) used, in the first place, to produce sulfuric acid, which in turn is used for many purposes. But in every chemical reaction the sulfur must go somewhere. The laws of chemistry guarantee that reactions will tend to continue either until the most stable possible compound is formed or until an insoluble solid is formed. Sulfur is

ultimately dissipated in use (e.g. as fertilizers or pigments) or discarded, as waste acid or as ferric or calcium sulfites or sulfates. Luckily, most of these sulfates are comparatively inert and harmless.

There is only one long-lived structural material embodying sulfur: plaster-of-Paris (hydrated calcium sulfate) which is normally made directly from the natural mineral gypsum.¹⁴ It follows from materials balance considerations that nearly all sulfur consumed by industry is ultimately dissipated into the environment. Globally, about 61.5 million metric tons of sulfur *qua* sulfur — not including gypsum — was produced in 1988. Of this, less than 2 million was recycled, mainly as waste sulfuric acid.

Following similar logic, it is easy to see that most chemicals derived from ammonia (fertilizers, explosives, acrylic fibers), and phosphorus (fertilizers, pesticides, detergents, fire retardants) also belong to class 3. In the case of chlorine, there is a division between class 2 (solvents, plastics, etc) and class 3 (hydrochloric acid, chlorine used in water treatment, etc.). It would be possible, with some research, to devise measures of the inherently dissipative uses of each chemical element, along the lines sketched above. Such measures could — and I believe, should — be compiled and published by national statistical agencies. Sustainability, in the long run, would imply that such measures should decline. Currently, insofar as we can determine, they are mostly increasing.

With regard to materials that are potentially recyclable (classes 1 and 2) the fraction actually recycled is a useful measure of the approach toward, or away from, sustainability. A reasonable proxy for this, in the case of metals, is the ratio of secondary supply to total supply of final materials: see, for example, *Table III*. This table shows, incidentally, that the recycling ratio in the United States has been rising consistently in recent years only for lead. It has also been rising for iron/steel, not shown. In the case of lead, the ban on using tetraethyl lead as a gasoline additive (an inherently dissipative use) is entirely responsible for the increase.

Another useful measure of industrial metabolic efficiency is the economic output, in monetary units, per unit of material/resource input. This measure can be called *materials or resource productivity*. It can be measured, in principle, not only for the economy as a whole (GDP) but for each sector. It can also be measured for each major nutrient element, e.g. carbon, oxygen, hydrogen, sulfur, chlorine, iron, phosphorus, etc.¹⁵ Materials productivity for the economy taken as a whole, however, would not be a reliable indicator of increasing technological efficiency, or progress toward long-term sustainability. The reason is that increasing efficiency — especially in rapidly developing countries — can be masked by structural changes, such as investment in heavy industry, which tend to increase the materials, and energy, intensiveness of economic activity. On the other hand, *within* a given sector, one would expect the efficiency of materials utilization — hence materials productivity — to increase, in general.¹⁶

This general framework has recently been extended by researchers at the World Resources Institute to include damage costs associated with emissions in the standard total factor productivity measure [Repetto *et al* 1996]. In brief, they add waste effluent outputs to standard outputs, using negative shadow prices reflecting economic damages caused by pollution, at the margin. Then when pollution is reduced, productivity is increased. The effect is similar to cost reduction. For three sectors studied in detail, this straightforward modification resulted in significant upward adjustments. Two cases were calculated, namely constant damages for the original year and damages proportional to GNP.

For instance, in the electric power sector, conventional measures show an average annual reduction in productivity of 0.35% per annum for the period 1970-1991, whereas when avoided damages are taken into account productivity increased by 0.38%-0.68% per annum. In the case of pulp and paper, the conventional method shows gains of 0.15% per annum on

average (1970-1990), whereas the more inclusive approach showed substantially larger productivity gains of 0.36% - 0.44% per annum. Finally, for agriculture (counting only soil erosion as a cause of damage) for the period 1977-1992, the conventional approach showed conventional productivity gains of 2.30% per annum, whereas the new approach gave 2.38%-2.41% per annum. These results, extrapolated roughly to the economy as a whole, imply that real productivity gains in private industry have been underestimated by about a third, as a result of ignoring damages avoided by pollution reductions. In other words, if the conventional method of calculation results in an estimated annual productivity gain of 2%, the real gain was probably more like 3% per annum. This method automatically takes into account the *costs* of pollution control.

One difficulty with conventional engineering/economic approaches to productivity analysis is that total mass is not a very satisfactory measure for heterogeneous inputs or outputs. It is quite acceptable to compare monetary outputs per unit of mass input, over time, or between countries, for a given industry; say steel, or petrochemicals. But comparing one sector with another in this manner introduces serious conceptual difficulties. While mass is definable for all materials, and hence mass inputs and outputs are definable for all sectors, the relationship between aggregate mass input and monetary outputs cannot meaningfully be compared, either between sectors or from period to period. A different measure is needed.

Recent work suggests that a useful aggregate quality measure (*exergy per unit mass*) can be constructed, from thermodynamic data. This measure is meaningful and comparable for heterogeneous mass flows [Ayres & Ayres & Martínás 1996]. It can be determined equally well for process inputs (resource flows, including fuels), process outputs (products and by-products), waste heat, and material waste effluents. The exergy measure applies both to organic materials and inorganic substances.

In brief, and oversimplifying for purposes of exposition, exergy can be regarded as the useful fraction of embodied chemical energy. (Referring to an earlier footnote, it is also a measure of the distance from ultimate thermodynamic equilibrium with the environment.) The exergy measure is applicable to, and computable for, all material substances from physical data that are already collected and compiled in reference books [e.g. Szargut *et al* 1988].

The value of such a measure, as noted above, is that it can be used for purposes of aggregation. Thus, the *stock* of all known mineral resources in a given country, at a given time, could be presented as a single number combining fossil fuels, metals and other minerals. The aggregate production and consumption of extractive materials could be given in the same unit. The annual production and consumption of renewable resources — agriculture and forestry — could be given in the same units, for a country. The consumption of all resource inputs to an industry can be expressed in exergy units. By the same token, the aggregate output of useful products, as well as the generation of material wastes, can also be expressed in exergy units. The same is true of waste heat.

It follows that meaningful and comparable ratios can be constructed. For instance, the aggregate output of useful products from a sector, measured in exergy terms, divided by the aggregate resource input, also in exergy terms, is a meaningful measure of the technical efficiency of the industry in converting inputs to outputs. Comparing the ratio from year to year would be a practical measure of technical progress. Where this ratio is already high, it can be safely concluded that opportunities for further efficiency improvement are limited. On the contrary, where the ratio is low, it can be concluded that major opportunities for efficiency improvement do exist.

Similarly, the ratio of exergy embodied in material wastes to exergy embodied in resource inputs is another potentially useful measure. It is perhaps the most general measure of pollution. If this measure is decreasing over time, the industry is improving its performance

as regards environmental protection, and conversely. In this connection, waste heat can be, and probably should be, excluded in almost all cases.

To derive these aggregates and publish them regularly would provide policy-makers with a valuable set of indicators at little cost. Thus, while exergy is not necessarily a good measure of environmental harm in any specific case, it is a very good basis for comparing inputs and outputs, both over time and between sectors, regions or firms in the same line of business.

As a simple illustration of the approach, if not the details, *Figure 11* shows mass flows in the timber, lumber, pulp and paper sector. These mass flows have different chemical compositions and correspondingly different environmental impacts. Aggregating these heterogeneous flows in terms of their exergy equivalents, however (see *Figure 12*), one can derive another equivalent picture in which all flows are comparable, being expressed in the same basic units. (Since exergy is essentially useful energy, it is measured in units of energy).

It is clear that other interesting and useful measures based on physical data are also possible. Moreover, if similar data were collected and published at the sectoral level, it would be possible to undertake more ambitious engineering-economic systems analyses and forecasts — of the kind currently possible only for energy — in the entire IM domain.

It is natural to conclude from the foregoing that the key to long-term sustainability is to close the open cycles. This is, however, a necessary but not sufficient condition. It is true that long-term bio-geo-chemical sustainability implies closed (or nearly closed) material cycles at the global level. It does not imply that these cycles need be closed at the local or regional level. Nor does it imply that closure need be achieved within a very short period. After all, the biosphere only managed to achieve quasi-closure for carbon, oxygen and nitrogen after a two or three billion years of evolutionary experiments. (It is not even approximately closed with respect to sulfur or phosphorus; these elements are only recycled geologically). I suggest, merely, that the only viable path to long-term eco-sustainability must also be characterized by moving toward, rather than away from, closure. To put it another way, and very simply, the present industrial trajectory is inconsistent with long-term sustainability because it is based upon the use of non-renewable resources.

Resource economists tend to assume perfect substitutability between produced capital (presumably including technological knowledge) and natural resources. The theoretical context of this argument is reviewed briefly in the next section. Insofar as capital as a factor of production is concerned, I think the substitutability argument is reasonable. However, the neo-classical perspective on this matter defines "welfare" only in terms of economic output or GNP, measured in monetary terms. But even economists realize that some elements of welfare are not monetizable. There is a tendency among the mainstream neo-classicists to assume (without evidence) that the only non-monetizable elements that are irreplaceable and non-substitutable are essentially amenities, such as the Grand Canyon or the Statue of Liberty [Solow 1992]. No serious effort is made by these economists to attach monetary values to essential features of human life on earth, such as the protective ozone shield in the stratosphere, or the moderate inter-glacial climate.

For this reason I cannot accept the common view among economists (see Pearce *et al* in this book) that increasing welfare — meaning GNP or even "green GNP" — is equivalent to long-term sustainability.

8. Economic Implications of the IM Perspective

Many of the economic implications of IM have been touched upon, at least glancingly, in the previous sections. But perhaps, it is worthwhile to reiterate some of them more

explicitly. The major implication of the IM perspective is that the economic system is embedded in a larger bio-geo-chemical system by material and energy (exergy) flows. Thus, the economic system is constrained by physical laws, such as the laws of thermodynamics. The first law, conservation of mass/energy, is the basis of the mass-balance principle, which has been cited repeatedly. The second law, often called the entropy law, states that all processes in isolated systems are irreversible.

The economic implications of the first law are fairly obvious. For instance, it is a consequence of the law of conservation of mass that the total quantity of materials extracted from the environment and processed through the economic system will ultimately return to the environment as some sort of waste residuals or "garbo-junk" [Ayres & Kneese 1969, 1989]. Of course, the mass balance principle is valid at every level of aggregation, from individual chemical processes to national accounts.

The relevance of the second law of thermodynamics to resource depletion and resource economics is equally obvious. From a thermodynamic perspective it is quite evident that the bio-geo-chemical environment is a dissipative system, in the sense of Prigogine, far from thermodynamic equilibrium. It is maintained in this state by a flux of exergy, i.e. available energy, from the sun, some of which drives the hydrological cycle and some of which drives the carbon and nitrogen cycles. Recall the discussion in Section 2. However, the deeper implications for resource scarcity are less clear.

The resource scarcity argument was thrashed out to some extent — and at a very abstract level — by neo-classical economists in the 1970's, largely in response to the worldwide publicity associated with the publication of the famous Report to the Club of Rome [Meadows *et al* 1972]. It is not necessary to recapitulate the discussion in detail. Suffice it to say that a number of leading theoreticians explored variations of economic growth models in which resources (meaning exergy) were given some explicit role. The general conclusion was that resource scarcity would not limit economic growth in the long run, given continued capital investment and technological progress. In most of these models, it was assumed that human capital and natural capital, i.e. resources, are inherently substitutable and interchangeable, *without limit* [e.g. Solow 1974; Stiglitz 1974, 1979]. Only a few theoreticians even acknowledged that natural resource inputs might actually be essential to production, although the quantities needed might still be virtually infinitesimal [e.g. Dasgupta & Heal 1974, 1979].

Evidently any conventional production function of the homogeneous type (Cobb-Douglas being only the simplest example) assumes unlimited substitutability between factors. This implies that resource inputs can be reduced to arbitrarily small levels, by correspondingly large capital and labor inputs. Georgescu-Roegen in his 1971 book and many subsequent papers, especially his 1979 critique of Solow and Stiglitz [Georgescu-Roegen 1979] argues that this is a "conjuring trick" based on failure to recognize that capital equipment necessarily embodies materials. He says: "A change in capital or labor can only diminish the amount of waste in the production of a commodity: no agent can create the material on which it works."¹⁷

Daly comments that the neo-classical production function (of labor and capital) is equivalent to an assertion that it is possible to make a cake with only a cook and a kitchen, but that no flour, sugar or eggs are needed. This clearly contradicts both the first and second laws of thermodynamics. It is evident that G-R, and Daly, envision the economic system as a materials-processing system in which final products — commodities — are necessarily material in nature. Indeed, this is a fairly accurate description of the real economic system as it functions today. This vision lies at the core of the emerging field of industrial ecology, for instance. If the above description were timeless, the G-R/Daly critique would be devastating.

But, a perfectly acceptable neo-classical answer to their critique would seem to be that in the distant future the economic system *need not* produce significant amounts of material

goods at all. In principle, it could produce final services from very long-lived capital goods, with very high information content, utilizing non-scarce renewable sources of energy, such as sunlight. At the end of its useful life, a capital good in this hypothetical economy would be repaired, upgraded and remanufactured, but rarely discarded entirely.

In short, it can be argued, as I have in the past, that there is no limit *in principle* to the economic output that can be obtained from a given resource input [e.g. Ayres 1978; Ayres & Kneese 1989]. Another way of saying the same thing is that there is no limit *in principle* to the degree of dematerialization that can be achieved in the very long run. This does not mean that no virgin materials need be processed at all. Nor does it imply that recovery, remanufacturing and recycling can be 100% efficient. No such claim need be made. It is sufficient to claim, simply, that nobody can define a finite absolute minimum material input requirement to produce a unit of economic welfare, with the obvious exception of food and drink. This conclusion is evidently in agreement with Solow, Stiglitz, et al.

It is clear that the formulation of the resource scarcity/resource recovery controversy, summarized above, is very straightforward within the IM-framework. The same can be said for a number of the emerging tools of environmental analysis and assessment, including the notion of materials-process-product chains, chain management, life cycle analysis (LCA), and substance flow analysis (SFA). Any of them could have developed without the framework, and some did, but they fit very naturally into it.

Actually, the introduction of exergy as a general quality measure for heterogeneous material flows, mentioned in the last section, has interesting potential economic implications. As noted in the previous section, by means of this measure it is possible to construct meaningful dimensionless measures of materials processing efficiency and waste effluent loss per unit input, at the sectoral level. The first of these measures, over time, can be interpreted as a direct measure of technological progress for the sectors that extract, refine, and process materials into finished forms (e.g. steel, paper, concrete, plastic, rubber etc.) and even material products.

This, in turn, suggests several new measures of productivity that could be constructed without great difficulty once the exergy calculations have been made and that might provide important new insights. One of them might be the ratio of value added (\$) per unit of (exergy) loss in processing (input less output), over time. Another might be the ratio of value to exergy content of the output, over time. A third might be the ratio of GDP to exergy input to the whole economy, over time. One might even speculate that an improved theory of technical progress, and ultimately of economic growth, could eventually be built around these concepts.

Having said all this, we are still left with an unresolved problem with regard to the problem of measuring eco-sustainability. Sustainability at the global bio-geo-chemical system level has some aspects that economics, the science of resource allocation among human activities *at the margin*, cannot begin to cope with. At this level, economics must take a subordinate role to natural science.

8. Policy Implications of the IM Perspective

I mentioned already in the introduction that the holistic IM perspective can be a helpful antidote to the reductionist tendencies of modern science, including economics, and government. I noted that the reductionist approach to legislation, which created a bureaucracy with responsibility for only one environmental medium, has a tendency to move wastes blindly from one medium to another without reducing their total quantity. In some cases,

policy has encouraged changes that merely dilute the waste stream without touching its volume at all. The use of high stacks for coal-burning power plants, and the building of longer sewage pipes to carry wastes further offshore exemplify this approach.

These narrowly focussed policies have real long-term consequences. In fact, there is a tendency for sub-optimal choices to get locked in by widespread adoption. Large investments in so-called "clean coal" technology would surely extend the use of coal as a fuel — an eventuality highly desired by the coal industry — but would also guarantee that larger cumulative quantities of sulfur, fly ash (with associated toxic heavy metals) and carbon dioxide would be produced. The adoption of catalytic converters for automotive engine exhaust is another case in point. This technology is surely not the final answer, since it is not effective in older vehicles. Moreover, the mining, concentration and processing of these very scarce and valuable metals (platinum, palladium, rhenium) consumes enormous resources, and cause significant environmental damage. Meanwhile the materials themselves are not used in large enough amounts per car to make efficient recovery economically feasible. Thus, they are being dispersed and lost after use. Worst of all, the adoption of catalytic converters on automobiles has indefinitely deferred the day when internal combustion engines will eventually be replaced by some inherently cleaner automotive propulsion technology. By the time that day comes, the world's automotive fleet will be two or three times bigger than it might have been otherwise, and the cost of substitution will be enormously greater.

To be sure, these short term, narrowly focussed policies may have been beneficial in the aggregate. But the costs have been quite large. Moreover, it is only too obvious that the state of the environment in the large is still deteriorating rapidly. One is tempted to think that a more holistic IM-based approach, from the beginning, might have achieved considerably more remediation at considerably less cost.

The implication of all these points for policy-makers, of course, is that the traditional governmental division of responsibility into a large number of independent bureaucratic fiefdoms is dangerously faulty.¹⁸ Yet the way out of this organizational impasse is far from clear. Top down central planning has failed miserably, and is unlikely to be tried again soon. On the other hand, pure free market solutions to environmental problems are limited in cases where there is no convenient mechanism for valuation of environmental resource assets (such as beautiful scenery) or functions (such as the UV protection afforded by the stratospheric ozone layer).

This is primarily a problem of *indivisibility*. Indivisibility means that there is no possibility of subdividing the attribute into parcels suitable for physical exchange. In some cases this problem can be finessed by creating exchangeable rights or permits, but the creation of a market for such instruments depends on other factors, including the existence of an effective mechanism for allocating such rights, limiting their number, and preventing poaching or illicit use of the resource.

Needless to say, the policy problems have economic and socio-political ramifications well beyond the scope of this paper. However, as the Chinese proverb has it, the longest journey begins with a single step.

Endnotes

1. This paper is largely based on materials previously published elsewhere, notably in the first chapter of a book entitled *Industrial Metabolism* edited by myself and Udo Simonis [Ayres 1994]. Also, the concluding section of this paper is largely based on a chapter from a more recent book *Industrial Ecology* [Ayres & Ayres 1996, Chapter 2]

2. Actually the word energy here is technically incorrect; it is exergy, the useful part of energy, that drives all metabolic — and industrial — processes.
3. This analogy between firms and organisms can be carried further, resulting in the notion of "industrial ecology". Just as an ecosystem is a balanced, interdependent quasi-stable community of organisms living together, so its industrial analog may be describe as a balanced, quasi-stable collection of interdependent firms belonging to the same economy. The interactions between organisms in an ecosystem range from predation and/or parasitism to various forms of cooperation and synergy. Much the same can be said of firms in an economy.
4. A moment's thought should convince the reader that if the stock in any compartment changes, the stock in at least one other compartment must also change.
5. Exergy is the term most widely used today. It has been called *available work*, *availability*, and *essergy* (essence of energy).
6. There are two kinds of respiration, viz. photorespiration and animal respiration. The former is an apparently useless process that reconverts about half of the photosynthetic product back into carbon dioxide. Not all plants do this; for example corn and sugar cane do not. Animal respiration is, of course, the biological process that converts sugar back into carbon dioxide, yielding energy to drive other metabolic processes, including muscles.
7. However, this statement is not true for greenhouse gases in the atmosphere. Already, the concentration of carbon dioxide has increased 20% since pre-industrial times, while the concentration of methane is up 50%. The most potent greenhouse gases of all, CFC's, do not exist in nature at all.
8. In general terms, the potential for environmental harm depends on the potential reactivity of the waste material with respect to its surroundings, including biological organisms. This can be expressed as the thermodynamic distance from local equilibrium conditions. See [Ayres & Schmidt-Bleek & Martínás 1993; Ayres & Martínás 1995; Ayres & Martínás 1996].
9. Obviously the end will not occur suddenly. It would be more accurate to think in terms of the end of stable reserve capacity/production ratios and price stability, probably occurring between 2020 and 2030, followed by an accelerating decline in reserves and rise in prices [WRI 1996]. What will end, rather more suddenly, is the long period of declining global energy prices. Thus the "end of the age of oil" really means the beginning of rising fossil energy prices. As regards pollution, admittedly, the immediate substitute for petroleum is likely to be natural gas, which is even cleaner than petroleum. However, this substitution would also hasten the end of the Age of Gas, which, on present estimates, could come as soon as two or three decades later (c. 2050).
10. This is feasible for only the US, using chemicals production data published annually by the International Trade Commission (ITC). It would be much more difficult for other countries, where such data is virtually never published.
11. The special case of indefinite storage in deep underground mines, wells or caverns, currently being considered for nuclear wastes, is not really applicable to industrial or consumer wastes except in very special and rare circumstances. Surface landfills, no matter how well designed, are hardly permanent repositories although little consideration has been given to the long run disposal of leachates.
12. TEL was gradually phased out in the US for passenger cars, starting in 1970. Europe did not really start to phase out leaded fuel until twenty years later, and much of the rest of the world still has not done so.
13. Even in this case, the reserve-to-production ratio has remained close to 20 years. For example, this figure was widely published in the 1920's [Graf 1924], cited by Rogner [Rogner 1987].
14. In recent years, sulfur recovered from some coal-burning power plants in Europe has been converted into synthetic gypsum and used for making wallboard used in construction. However this potential recycling loop is currently inhibited by the very low price of natural gypsum and the large "sunk" investment in the

industry.

15. Unfortunately, while collecting and compiling this data is possible, in principle, it is anything but straightforward in practice. Readers will note that we have presented data of this sort in several diagrams for the US in the year 1988. But for a researcher depending on published data to construct the same data sets for other years would require a major effort. Ironically, the task would be relatively straightforward for government statistical agencies with access to more complete data. Why don't they do it?
16. This need not be true for each individual element, however. A major materials substitution **within** a sector can result in the use of one material increasing, at the expense of others, of course. The substitution of plastics for many structural materials, or of synthetic rubber for natural rubber, would exemplify this sort of substitution. Currently, glass fibers are in the process of substituting for copper wire as the major carrier of telephonic communications.
17. I am indebted to Herman Daly for calling my attention to this quotation in his commentary "Georgescu-Roegen vs. Solow/Stiglitz" presented at the ISEE Conference, Boston, August 1996.
18. The analogous problem is beginning to be recognized in the private sector, as the legacy of Frederick Taylor is finally being challenged by new managerial/organizational forms. The large U.S. firms, which adopted Taylorism first and most enthusiastically at the beginning of the twentieth century, have been the slowest to adapt themselves to the new environment of intense international competition and faster technological change.

References

- [Ayres 1978] Ayres, Robert U., *Resources, Environment & Economics: Applications of the Materials/Energy Balance Principle*, John Wiley & Sons, New York, 1978.
- [Ayres 1988] Ayres, Robert U. "Self Organization in Biology & Economics", *International Journal on the Unity of the Sciences* 1(3), Fall 1988. [also IIASA Research Report #RR-88-1, 1988]
- [Ayres 1989] Ayres, Robert U., "Industrial Metabolism & Global Change", *International Social Science Journal* 121, 1989.
- [Ayres 1989a] Ayres, Robert U. "Industrial Metabolism", in: Ausubel, Jesse & Sladovich (eds), *Technology & Environment*, National Academy Press, Washington DC, 1989.
- [Ayres 1994] Ayres, Robert U. "Industrial Metabolism: Theory & Policy", in: Ayres, Robert U. & Udo E. Simonis (eds), *Industrial Metabolism; Restructuring for Sustainable Development*, Chapter 1 :3-20 (ISBN 92-808-0841-9), United Nations University Press, Tokyo, 1994.
- [Ayres 1997] Ayres, Robert U. "The Life-cycle of Chlorine: Part I; Chlorine Production and the Chlorine-Mercury Connection", *Journal of Industrial Ecology* I(2), 1997.
- [Ayres & Ayres 1993] Ayres, Robert U. & Leslie W. Ayres, *Use of Materials Balance to Estimate Aggregate Waste Generation & Waste Reduction Potential in the U.S.*, Working Paper (93/33/EPS), INSEAD, Fontainebleau, France, September 1993
- [Ayres & Ayres 1994] Ayres, Robert U. & Leslie W. Ayres, *Chemical Industry Wastes: A Materials Balance Analysis*, Working Paper (94/32/EPS), INSEAD, Fontainebleau, France, July 1994
- [Ayres & Ayres 1996] Ayres, Robert U. & Leslie W. Ayres, *Industrial Ecology: Closing the Materials Cycle*, Edward Elgar, Aldershot, UK, 1996.
- [Ayres & Ayres 1997] Ayres, Robert U. & Leslie W. Ayres, "The Life Cycle of Chlorine: Part II: Conversion Processes and Use in the European Chemical Industry 1992", *Journal of Industrial Ecology* I(1), 1997.
- [Ayres & Ayres & Martínás 1996] Ayres, Robert U., Leslie W. Ayres & Katalin Martínás, *Eco-Thermodynamics: Exergy & Life Cycle Analysis*, Working Paper (96/.EPS), INSEAD, Fontainebleau, France, January 1996.
- [Ayres & Kneese 1969] Ayres, Robert U. & Allan V. Kneese, "Production, Consumption & Externalities", *American Economic Review*, June 1969. [Reprinted in *Benchmark Papers in Electrical Engineering & Computer Science*, Daltz & Pentell (eds), Dowden, Hutchison & Ross, Stroudsburg 1974 & Bobbs-Merrill Reprint Series, NY 1984.
- [Ayres & Kneese 1989] Ayres, Robert U. & Allen V. Kneese. "Externalities: Economics & Thermodynamics", in: Archibugi & Nijkamp (eds), *Economy & Ecology: Towards Sustainable Development*, Kluwer Academic Publishers, Netherlands, 1989.
- [Ayres & Martínás 1995] Ayres, Robert U. & Katalin Martínás, "Waste Potential Entropy: The Ultimate Ecotoxic?", *Économie Appliquée XLVIII*, 1995 :95-120. [Type; Peer article]
- [Ayres & Schmidt-Bleek & Martínás 1993] Ayres, Robert U., Friedrich B. Schmidt-Bleek & Katalin Martínás, *Is There a Universal Measure of Environmental Disturbance*, Working Paper (93/36/EPS), INSEAD, Fontainebleau, France, September 1993.

- [Ayres & Simonis 1994] Ayres, Robert U. & Udo E. Simonis (eds), *Industrial Metabolism; Restructuring for Sustainable Development* (UNUP-841), United Nations University Press, Tokyo, 1994. (ISBN 92-808-0841-9)
- [Dasgupta & Heal 1974] Dasgupta, Partha & G. Heal. "The Optimal Depletion of Exhaustible Resources", in: *Symposium on the Economics of Exhaustible Resources*, Review of Economic Studies, 1974.
- [Dasgupta & Heal 1979] Dasgupta, Partha & G. Heal, *Economic Theory & Exhaustible Resources* [Series: Cambridge Economic Handbooks], Cambridge University Press, Cambridge, UK, 1979.
- [Georgescu-Roegen 1971] Georgescu-Roegen, Nicholas, *The Entropy Law & the Economic Process*, Harvard University Press, Cambridge MA, 1971.
- [Georgescu-Roegen 1979] Georgescu-Roegen, Nicholas, "Myths About Energy & Matter", *Growth & Change* 10(1), 1979.
- [Georgescu-Roegen-a 1979] Georgescu-Roegen, Nicholas, "Energy Analysis & Economic Valuation", *Southern Economic Journal*, April 4, 1979.
- [Graf 1924] Graf, G. E., *Erdöl, Erdölkapitalismus, und Erdölpolitik*, Urania-Verlags GmbH, Jena, Germany, 1924.
- [Meadows et al 1972] Meadows, Donella H, Dennis L. Meadows, Jorgen Randers & William W. Behrens III, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Universe Books, New York, 1972.
- [Nicolis & Prigogine 1977] Nicolis, Gregoire & Ilya Prigogine, *Self-Organization in Non-Equilibrium Systems*, Wiley-Interscience, New York, 1977.
- [Nriagu 1990] Nriagu, J. O., "Global Metal Pollution", *Environment* 32(7) :7-32, 1990.
- [Repetto et al 1996] Repetto, Robert, Dale Rothman, Paul Faeth & Duncan Austin, *Has Environmental Protection Really Reduced Productivity Growth? We Need Unbiased Measures* (ISBN 1-56973-101-2), World Resources Institute, Washington DC, October 1996.
- [Rogner 1987] Rogner, Hans-Holger. "Energy in the World: The Present Situation & Future Options", in: *Proceedings of the 17th International Congress of Refrigeration*, August 24-28, 1987.
- [Socolow et al 1994] Socolow, Robert H., C. J. Andrews, F. G. Berkhout & V. M. Thomas (eds), *Industrial Ecology & Global Change*, Cambridge University Press, Cambridge, UK, 1994.
- [Solow 1974] Solow, Robert M., "The Economics of Resources or the Resources of Economics", *American Economic Review* 64, 1974.
- [Solow 1992] Solow, Robert M., *An Almost Practical Step Towards Sustainability*, Resources for the Future, Washington DC, 1992.
- [Stiglitz 1974] Stiglitz, Joseph, "Growth with Exhaustible Natural Resources. Efficient & Optimal Growth Paths", *Review of Economic Studies*, 1974.
- [Stiglitz 1979] Stiglitz, Joseph. "A Neoclassical Analysis of the Economics of Natural Resources", in: Smith, V. Kerry(ed), *Scarcity & Growth Reconsidered*, Resources for the Future, Washington DC, 1979.
- [Szargut et al 1988] Szargut, Jan, David R. Morris & Frank R. Steward, *Exergy Analysis of Thermal, Chemical, & Metallurgical Processes* (ISBN 0-89116-574-6), Hemisphere Publishing Corporation, New York, 1988.
- [USBuMines 1993] United States Bureau of Mines, *Minerals Yearbook 1993*, Volume I: Metals & Minerals, (ISBN 0-16-048153-8) United States Government Printing Office, Washington DC, 1993.

[USITC 1989] United States International Trade Commission, *Synthetic Organic Chemicals 1989*, United States Government Printing Office, Washington DC, 1989.

[USITC 1990] United States International Trade Commission, *Synthetic Organic Chemicals 1990*, United States Government Printing Office, Washington DC, 1990.

[WRI 1996] World Resources Institute, *World Resources 1996-97*, Oxford University Press, New York, 1996.

Table I: Anthropogenic Nutrient Fluxes (Teragrams/year)

	<i>Carbon</i>		<i>Nitrogen</i>		<i>Sulfur</i>		<i>Phosphorus</i>	
	T/yr	% of natural flux	T/yr	% of natural flux	T/yr	% of natural flux	T/yr	% of natural flux
To Atmosphere, Total	7900	4%	55.0	12.5%	93.0	65.5%	1.5	12.5%
Fossil fuel combustion & smelting	6400		45.0		92.0			
Land clearing, deforestation	1500		2.6		1.0		1.5	
Fertilizer volatilization ^(a)			7.5					
To Soil, Total			112.5	21%	73.3	23.4%	15.0	7.4%
Fertilization			67.5		4.0		15.0	
Waste disposal ^(b)			5.0		21.0			
Anthropogenic acid deposition			30.0		48.3			
Anthropogenic (NH ₃ , NH ₄) deposition			10.0					
To Rivers & Oceans, Total			72.5	25%	52.5	21%	5.0	10.3%
Anthropogenic acid deposition			55.0		22.5			
Waste disposal			17.5		30.0		5.0	

(a) Assuming 10% loss of synthetic ammonia-based fertilizers applied to land surface (75 tg/yr).

(b) Total production (= use) less fertilizer use, allocated to landfill. The remainder is assumed to be disposed of via waterways.

Table II: Worldwide Atmospheric Emissions of Trace Metals (1000 tonnes per year)

<i>Element</i>	<i>Energy Production</i>	<i>Smelting, Refining & Manufacturing</i>	<i>Manufacturing Processes</i>	<i>Commercial Uses, Waste Incineration & Transportation</i>	<i>Total Anthropogenic Contributions</i>	<i>Total Contributions by Natural Activities</i>
Antimony	1.3	1.5	—	0.7	3.5	2.6
Arsenic	2.2	12.4	2.0	2.3	19.0	12.0
Cadmium	0.8	5.4	0.6	0.8	7.6	1.4
Chromium	12.7	—	17.0	0.8	31.0	43.0
Copper	8.0	23.6	2.0	1.6	35.0	6.1
Lead	12.7	49.1	15.7	254.9	332.0	28.0
Manganese	12.1	3.2	14.7	8.3	38.0	12.0
Mercury	2.3	0.1	—	1.2	3.6	317.0
Nickel	42.0	4.8	4.5	0.4	52.0	2.5
Selenium	3.9	2.3	—	0.1	6.3	3.0
Thallium	1.1	—	4.0	—	5.1	29.0
Tin	3.3	1.1	—	0.8	5.1	10.0
Vanadium	84.0	0.1	0.7	1.2	86.0	28.0
Zinc	16.8	72.5	33.4	9.2	132.0	45.0

Source: [Nriagu 1990]

Table III: U.S. recycling statistics & apparent consumption for selected metals, 1987-1993

Year	Quantity (kMT)			Apparent consumption ⁴	Recycle % of apparent consumption
	Recycled metal ¹		Total		
	New scrap ²	Old scrap ³			
ALUMINUM⁵					
1987	1134	852	1986	6603	30%
1988	1077	1045	2122	6450	33%
1989	1043	1011	2054	6000	34%
1990	1034	1359	2393	6298	38%
1991	979	1522	2501	6012	42%
1992	1144	1612	2756	6869	40%
1993	1312	1632	2944	7852	37%
COPPER					
1987	716	497	1213	2913	42%
1988	788	518	1306	3002	44%
1989	761	537	1298	2945	44%
1990	774	548	1322	2924	45%
1991	682	518	1200	2731	44%
1992	723	555	1278	3028	42%
1993	731	555	1286	3256	39%
LEAD					
1987	52.535	657.532	710.067	1259.029	56%
1988	45.274	691.127	736.401	1274.477	58%
1989	49.612	841.729	891.341	1384.725	64%
1990	48.104	874.093	922.197	1345.381	69%
1991	54.970	829.654	884.624	1283.474	69%
1992	55.424	860.917	916.341	1325.408	69%
1993	60.298	843.262	903.560	1390.464	65%
NICKEL⁶					
1987			32.331	155.781	21%
1988			41.039	159.019	26%
1989			52.131	157.103	33%
1990			57.367	170.042	34%
1991			53.521	156.663	34%
1992			55.871	159.373	35%
1993			54.702	159.313	34%
TIN					
1987	4.604	11.462	16.066	59.458	27%
1988	3.925	11.350	15.275	60.955	25%
1989	2.795	11.545	14.34	47.285	30%
1990	4.035	13.200	17.235	53.430	32%
1991	5.114	7.982	13.096	39.606	33%
1992	4.894	8.853	13.747	37.321	37%
1993	4.453	7.219	11.672	42.906	27%
ZINC					
1987	270	82	352	1324	27%
1988	240	97	337	1340	25%
1989	230	117	347	1311	26%
1990	232	109	341	1240	28%
1991	233	120	353	1165	30%
1992	234	132	366	1276	29%
1993	246	109	355	1367	26%

Source: [USBuMines 1993, "Recycling-Nonferrous Metals", Tables 1 & 2]

1. Recycled metal is metal recovered from reported purchased new plus old scrap supply.

2. New scrap is scrap resulting from the manufacturing process, including metal & alloy production.

3. Old scrap is scrap resulting from consumer products.

4. Apparent consumption is production plus net imports plus stock change. Apparent consumption is calculated on a contained weight basis.

5. Recycle quantity is the calculated metallic recovery from aluminum-base scrap, estimated for full industry coverage.

6. Nickel scrap is nickel contained in ferrous & non-ferrous scrap receipts.

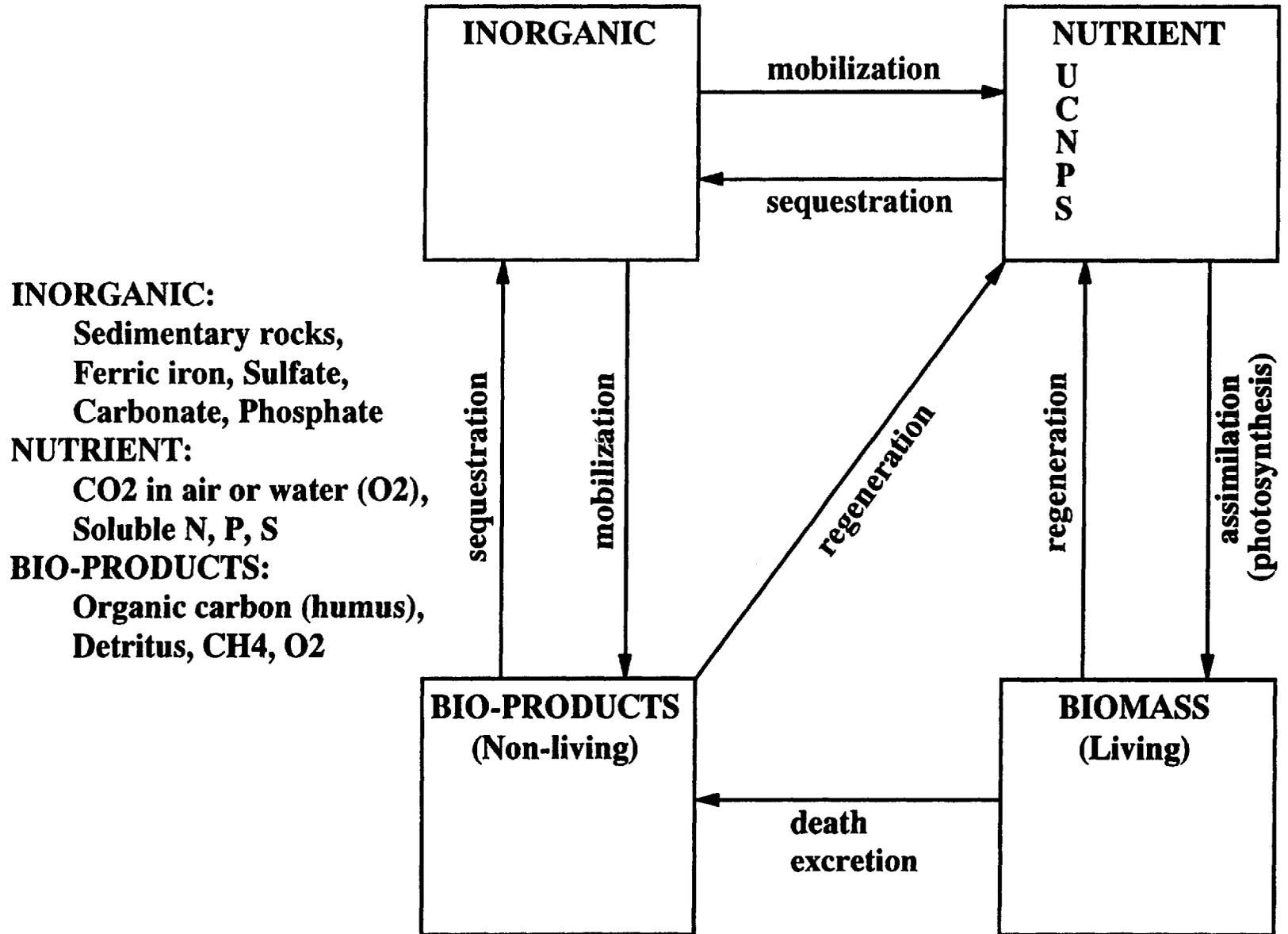


Figure 1: 4-Box Scheme for Bio-Geo-Chemical Cycles

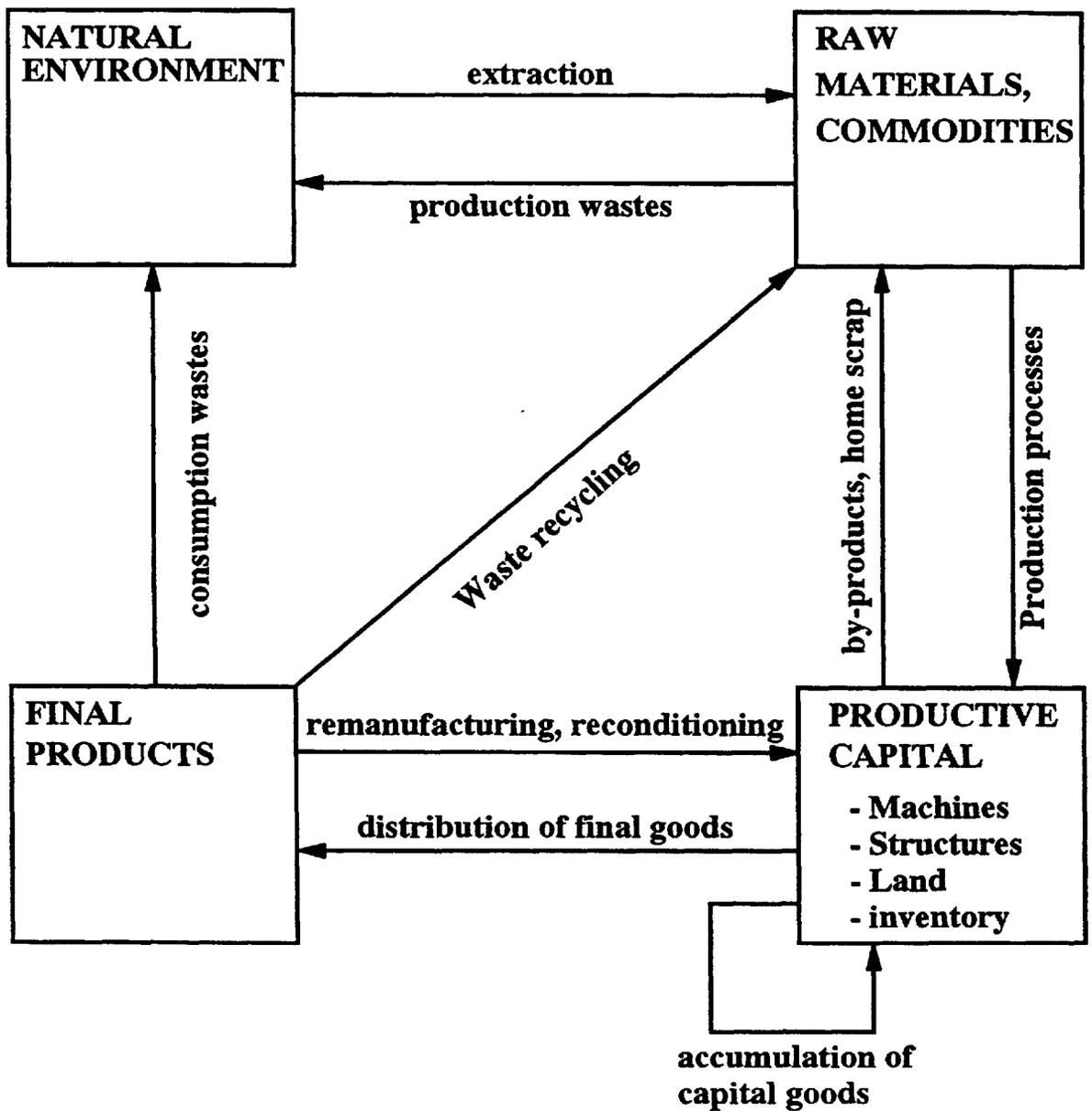


Figure 2: 4-Box Scheme for Industrial Material Cycles

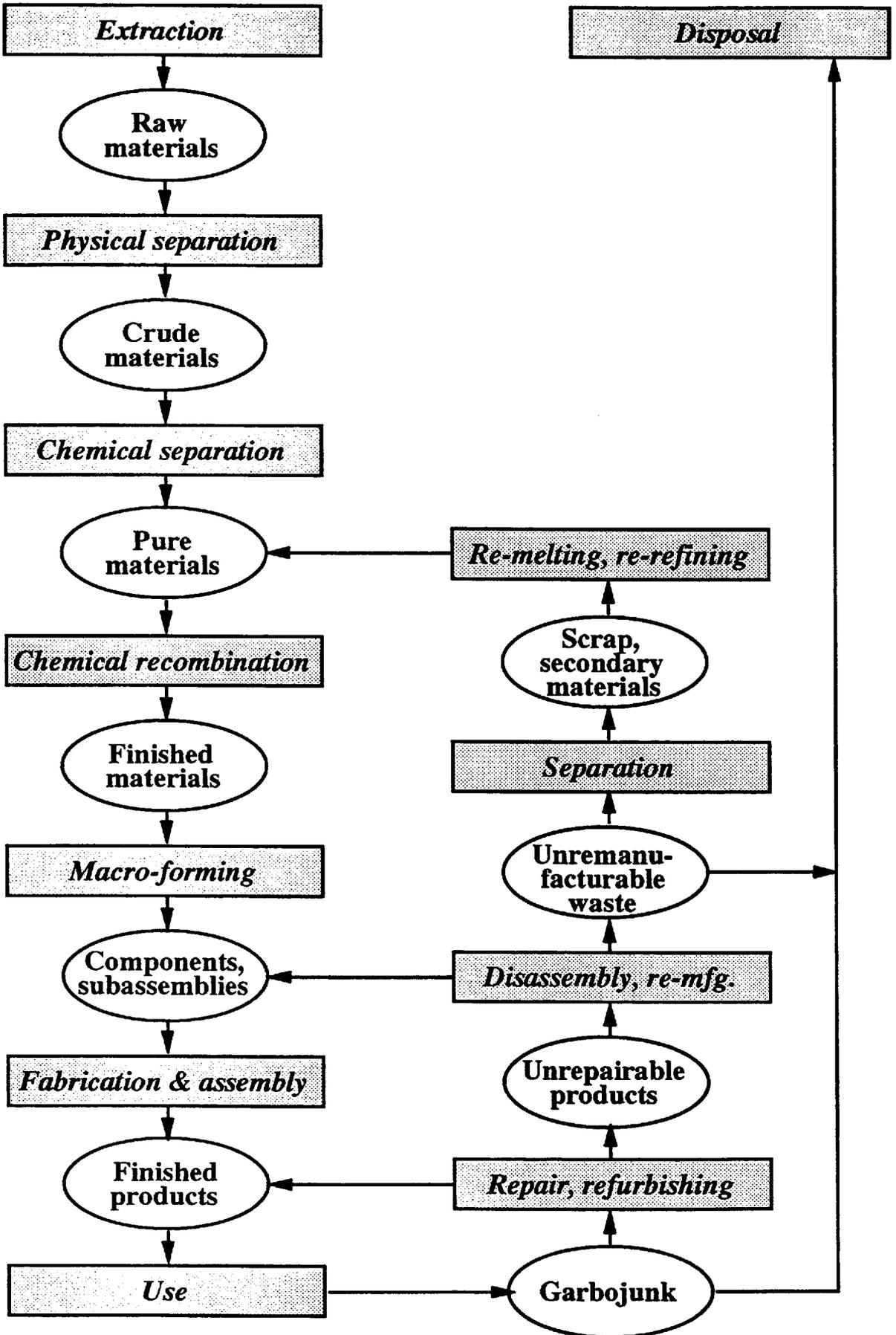
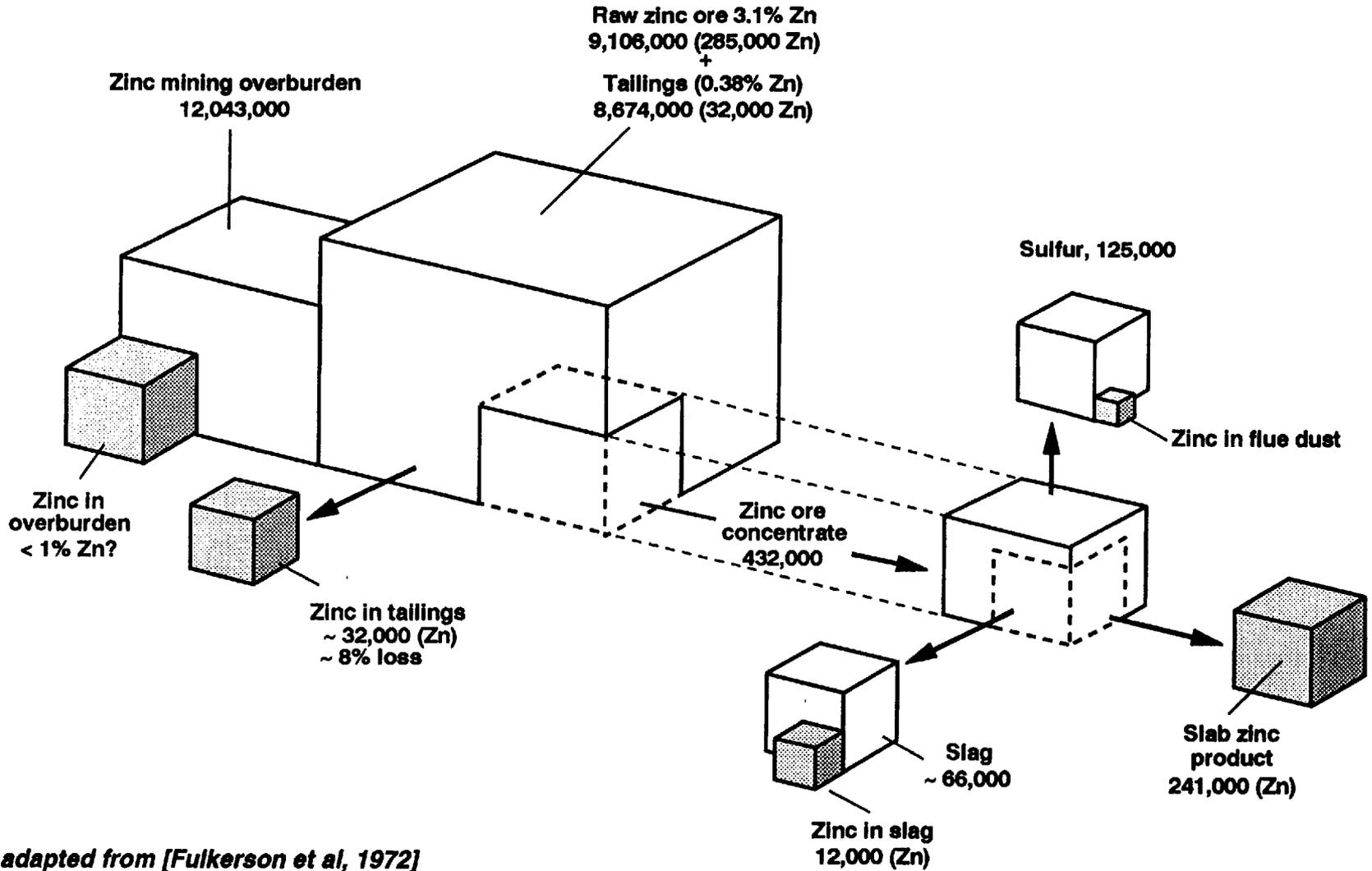


Figure 3: The materials cycle



adapted from [Fulkerson et al, 1972]

Figure 4: Zinc flow in mining & processing of zinc ores in the USA, 1988

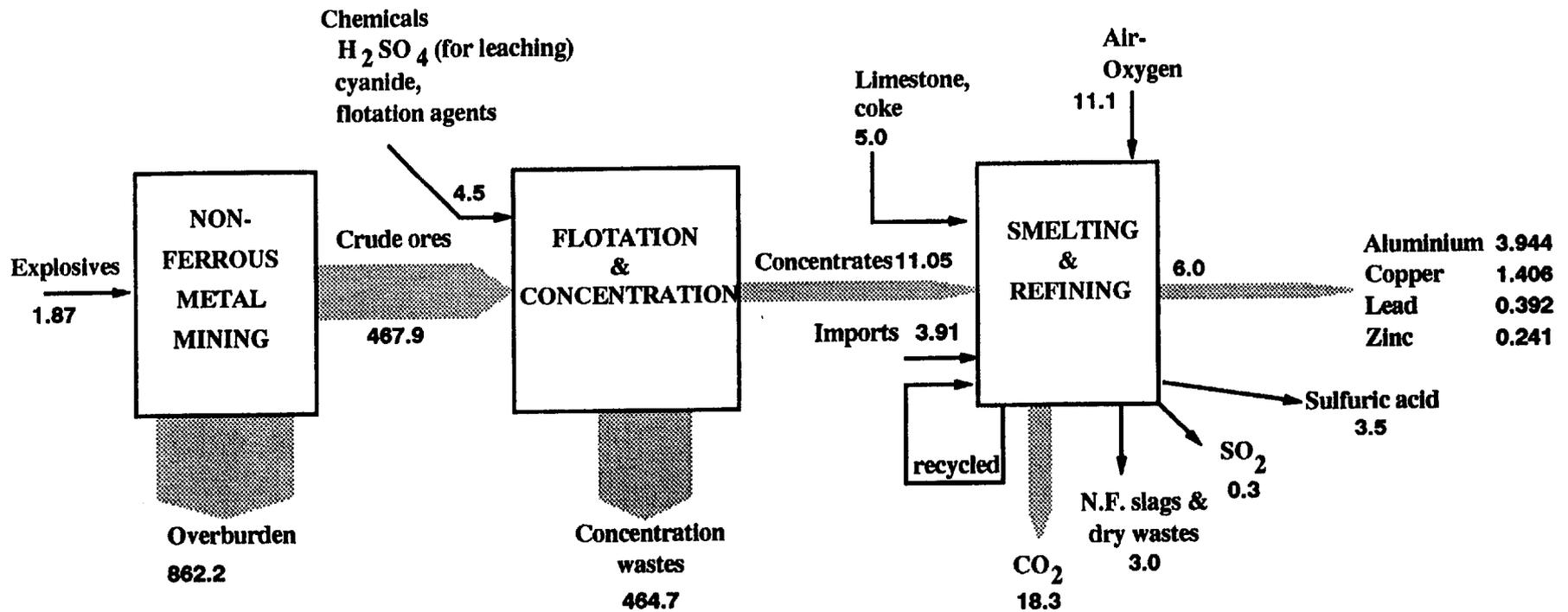
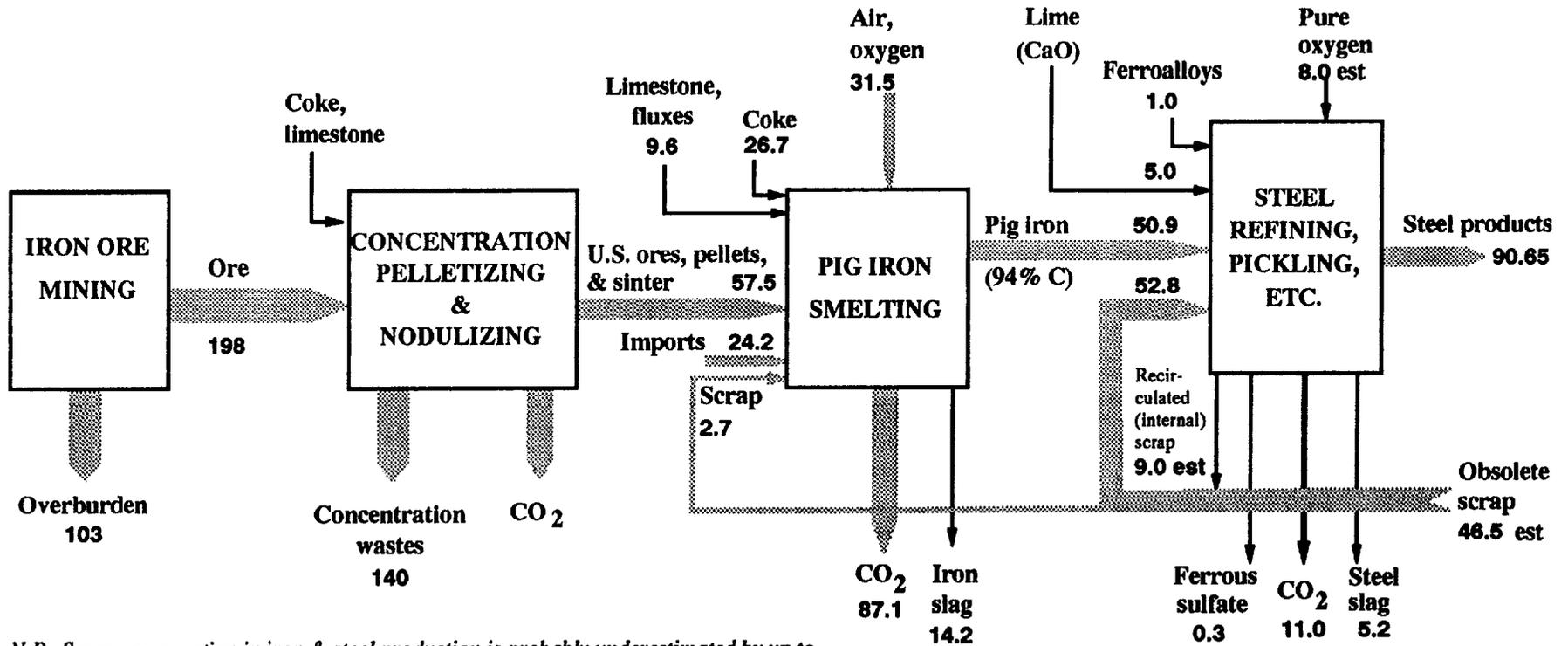


Figure 5: Mass flows in the U.S. non-ferrous metals sector, 1988 (MMT)



N.B. Scrap consumption in iron & steel production is probably underestimated by up to 4 million tonnes. Recirculated scrap may be underestimated by a similar amount.

Figure 6: Mass flows in the U.S. iron & steel sectors, 1988 (MMT)

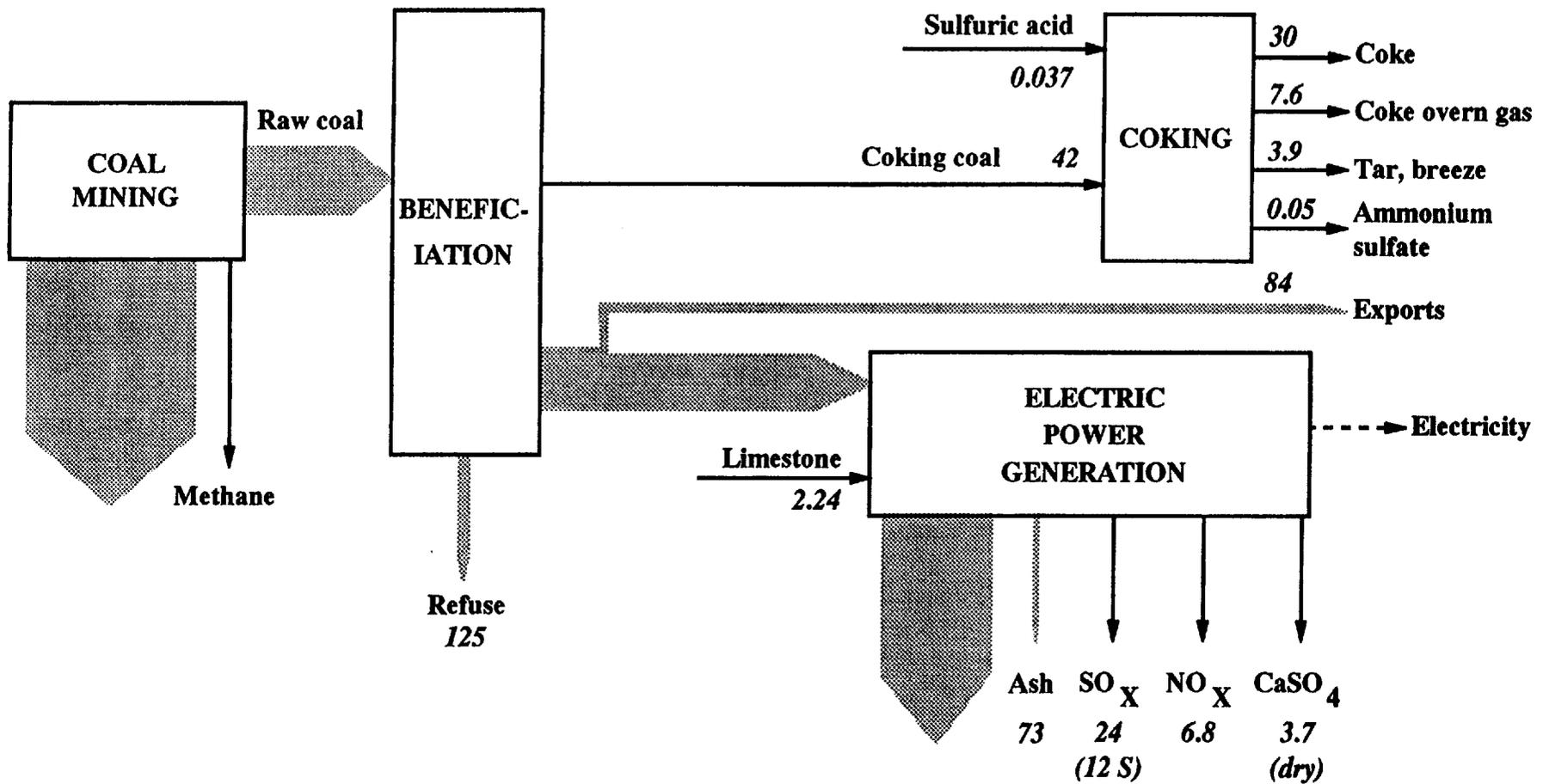


Figure 7: U.S. coal system 1988 (MMT)

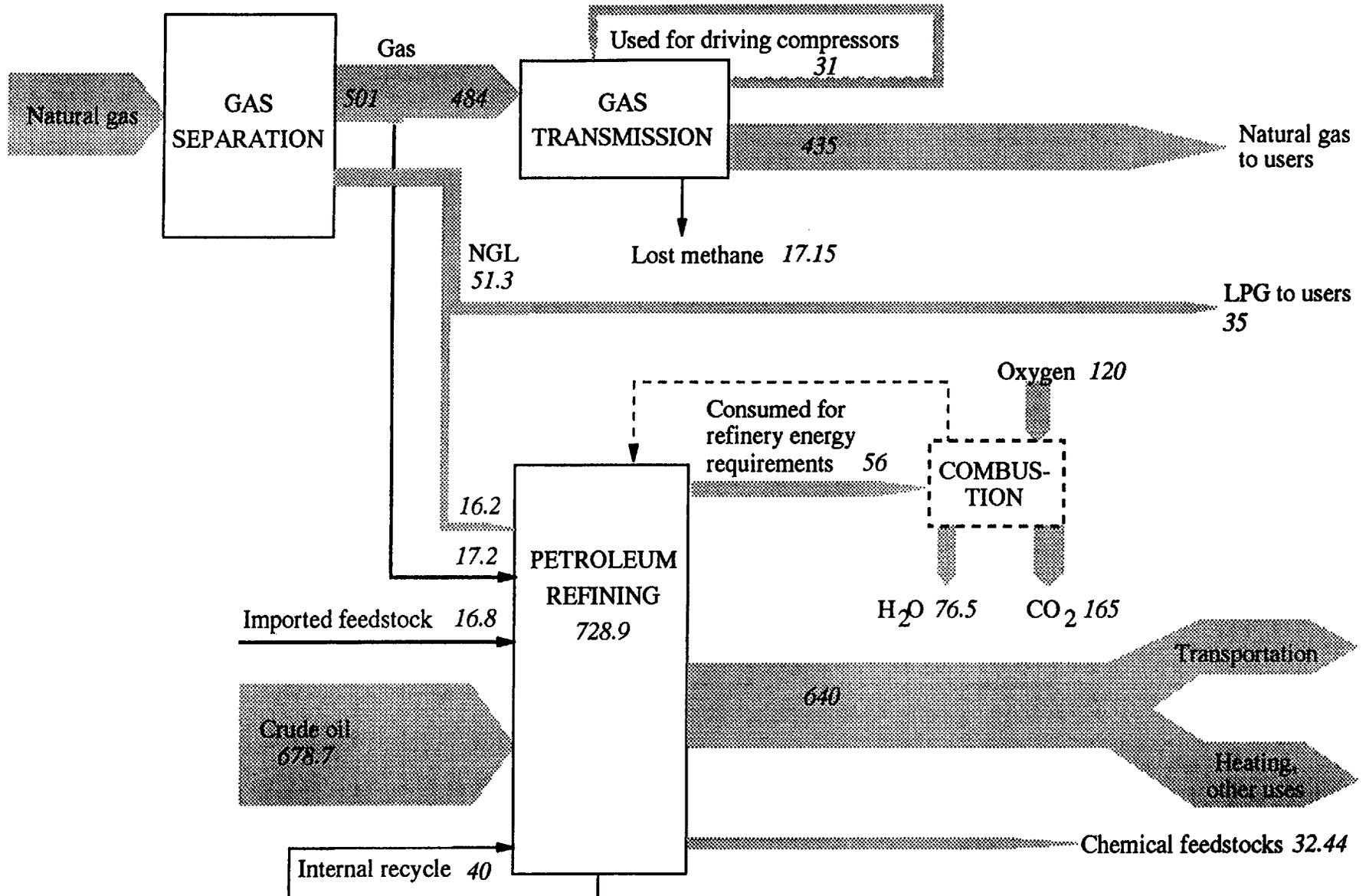


Figure 8: U.S. oil & gas system 1988 (MMT)

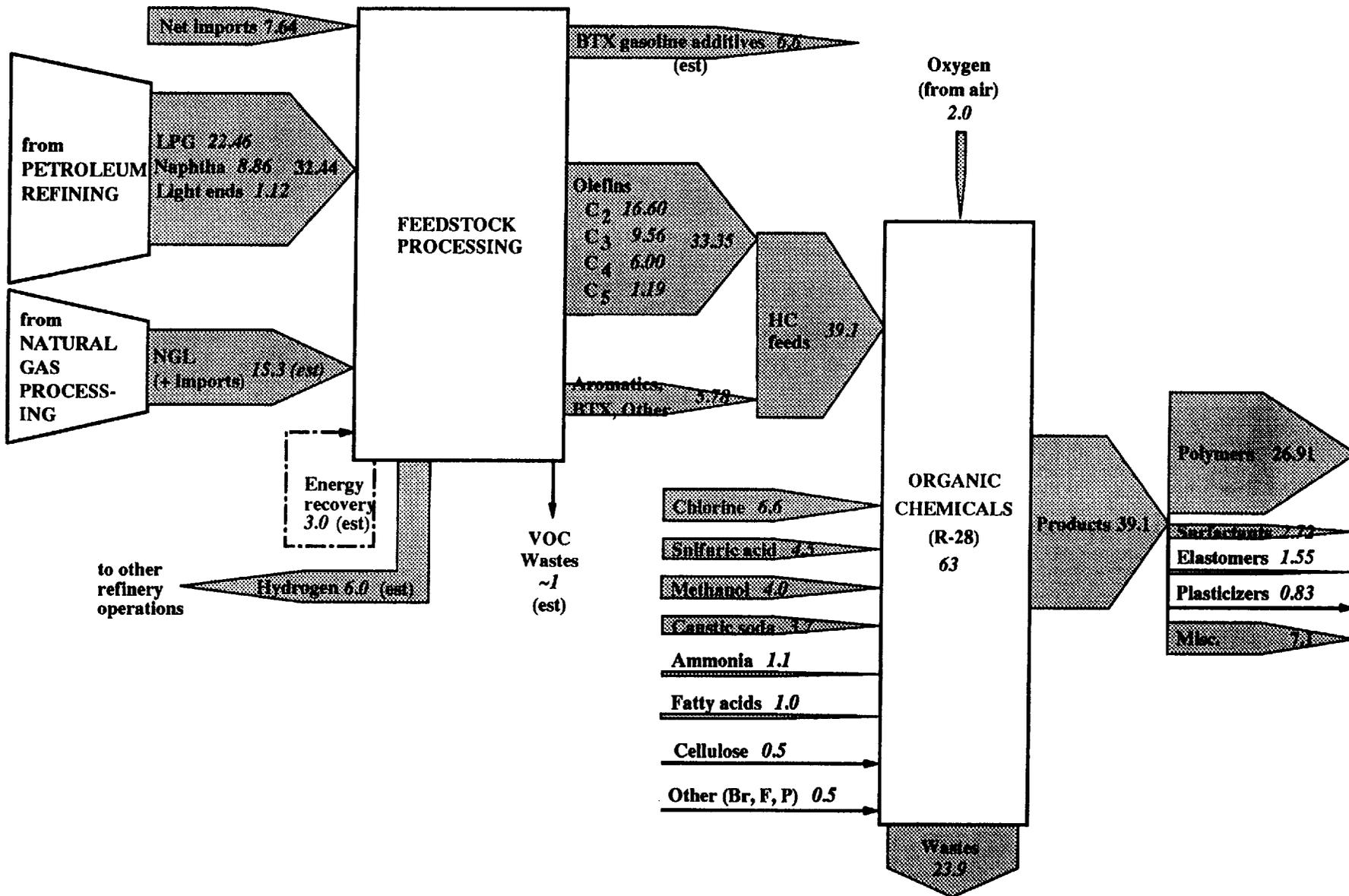


Figure 9: Organic chemicals sector, U.S. 1988 (MMT)

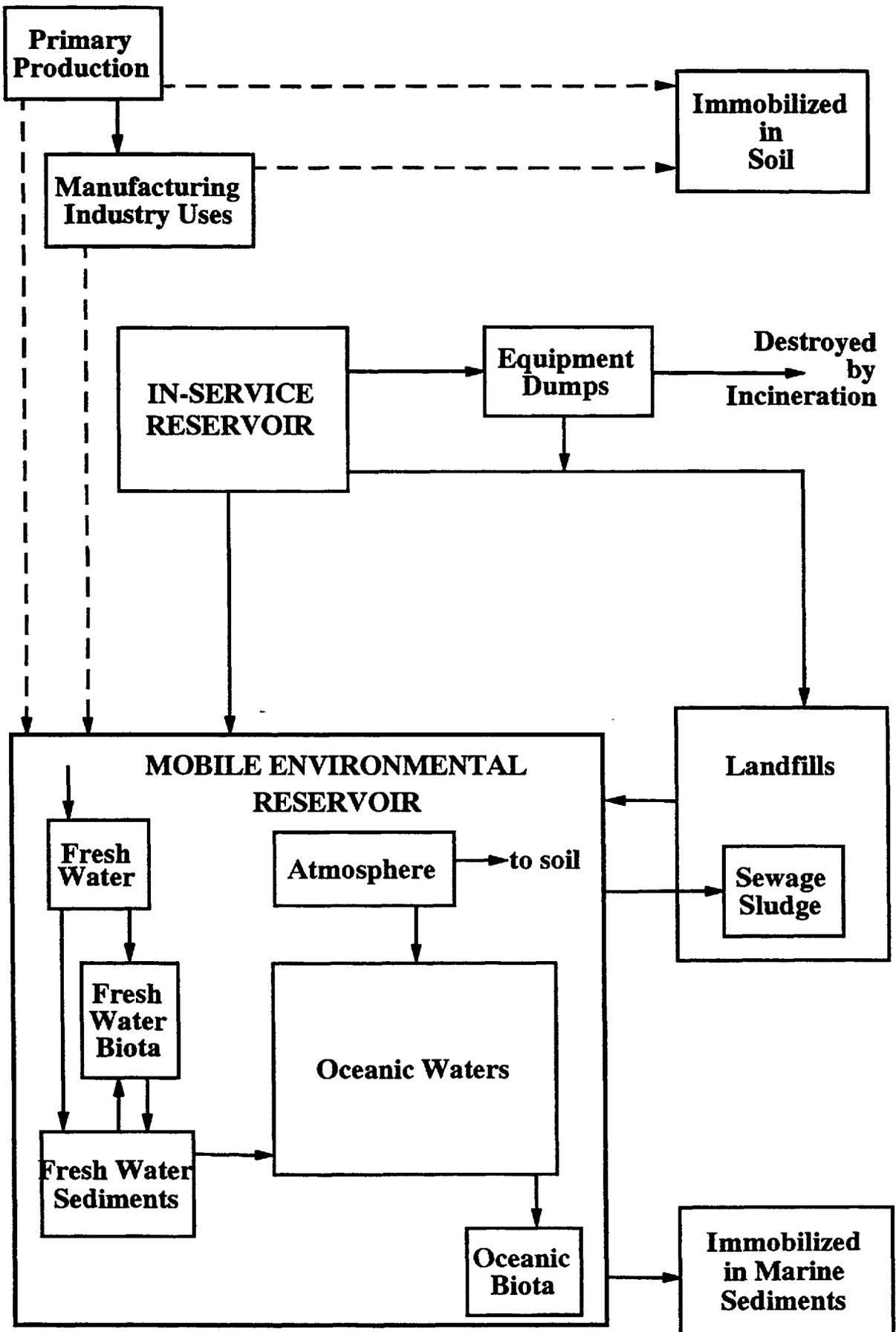


Figure 10: Relationships Between Sources & Reservoirs

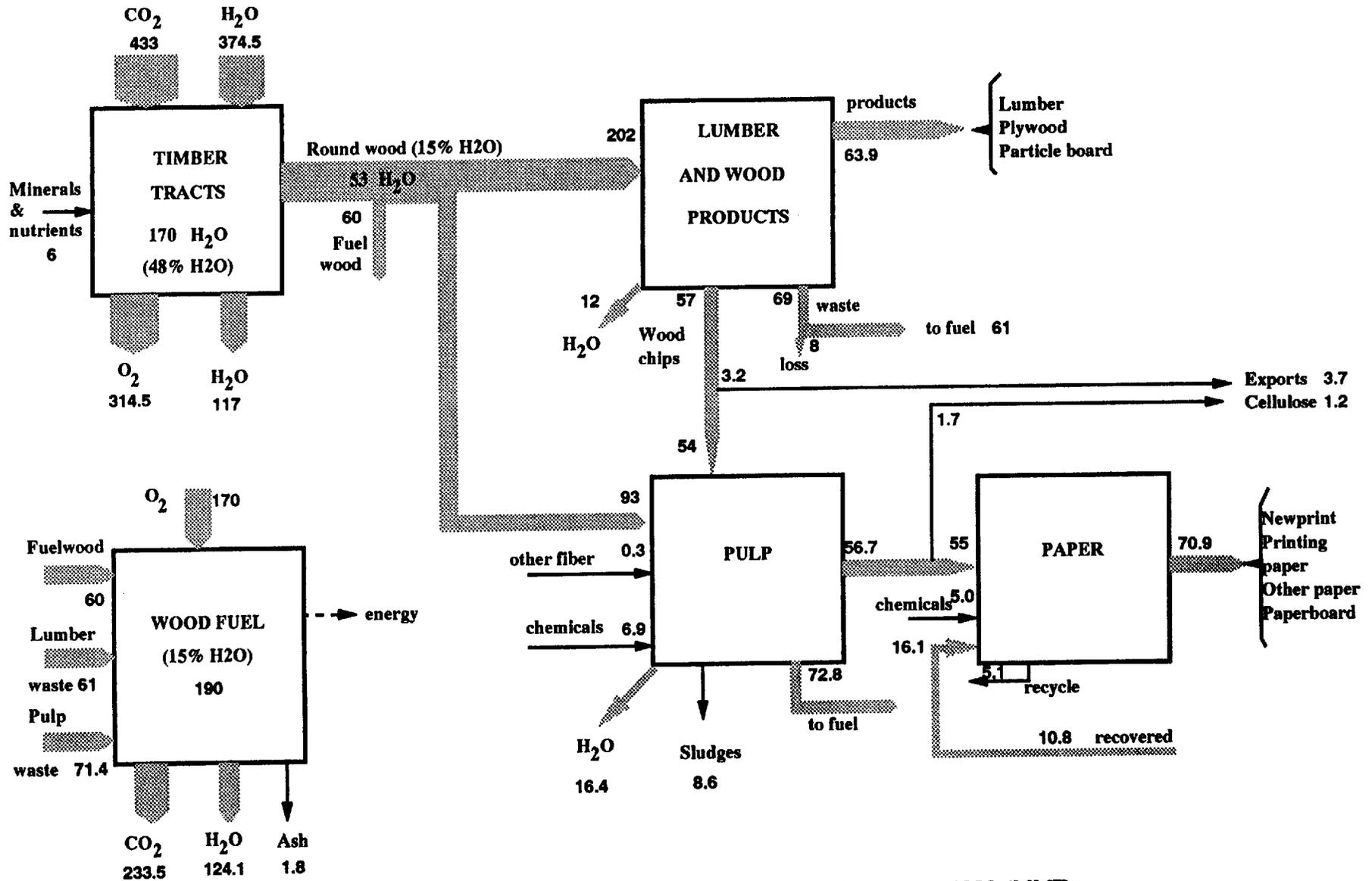


Figure 11: Materials flows, U.S. timber, pulp & paper industries, 1988 (MMT)

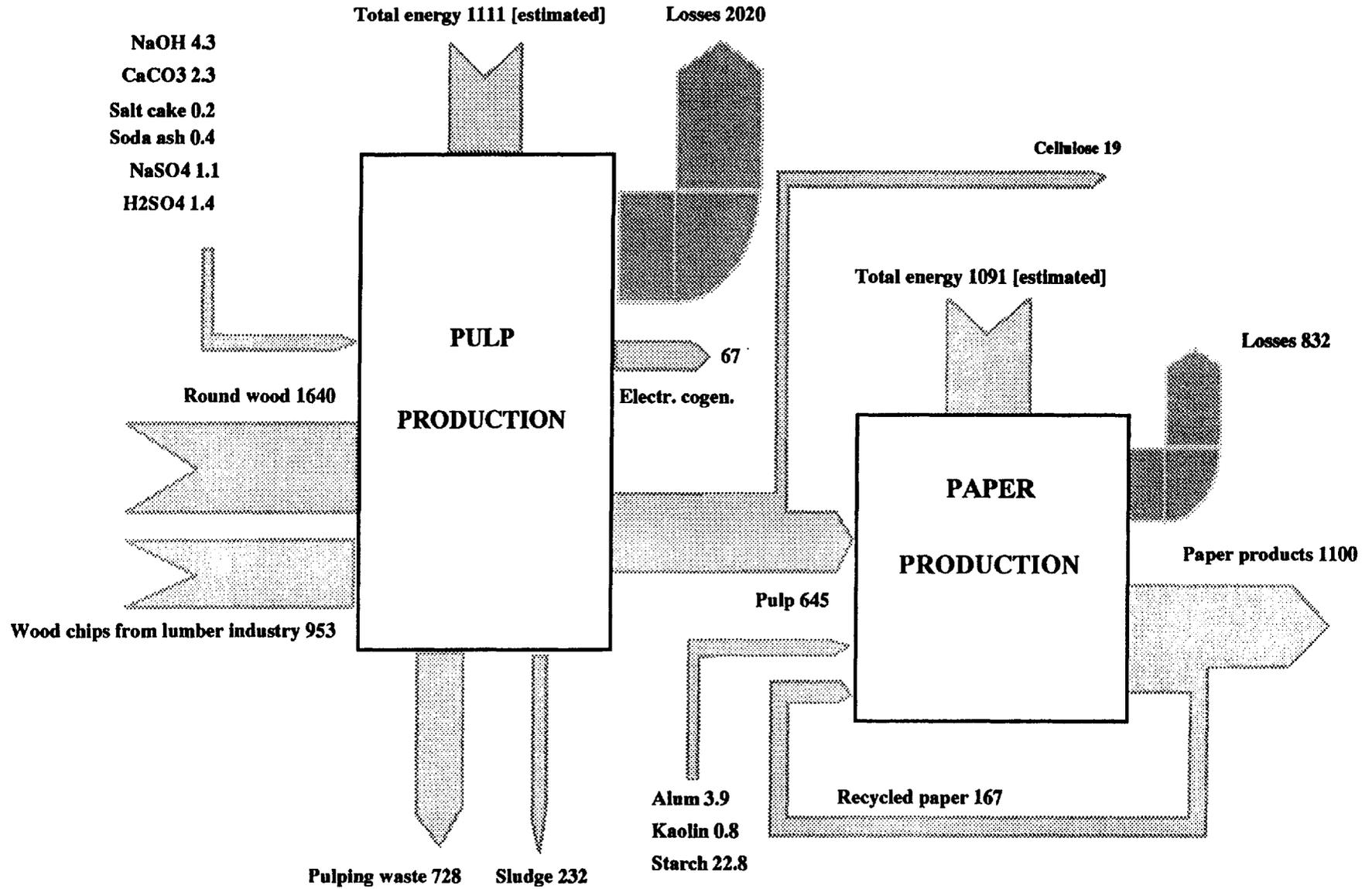


Figure 12: Exergy flows, U.S. timber, pulp & paper industries, 1988 (MMT)