"USE OF MATERIALS BALANCES TO ESTIMATE AGGREGATE WASTE GENERATION AND WASTE REDUCTION POTENTIAL IN THE U.S."

by

Robert U. AYRES*
and
Leslie W. AYRES**

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

** Research Associate at INSEAD, Boulevard de Constance, Fontainebleau 77305 Cedex, France.

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Robert U. Ayres and Leslie W. Ayres
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Abstract

The paper is a systematic derivation of aggregate production wastes for the U.S. economy (c. 1988). In principle, each industrial sector is thought of as a transformation process, converting material (and energy) inputs to outputs. Both inputs and outputs are published in well-established government statistics, with rare exceptions. This makes it possible to use the materials-balance methodology by comparing aggregate inputs and outputs. Some knowledge of the transformation processes themselves is occasionally needed, but except in the chemical industry (which we do not consider in this paper) process information is of secondary importance. We compare the results of this "bottom up" approach with other estimates of waste residuals. In several cases, significant discrepancies have been identified. However, the major value of this approach is to clearly distinguish between dry and wet wastes. Our approach is probably superior to the conventional one in this regard.

The data used is sufficiently standard so that it should be possible for a government agency to compile and present these data on a routine basis. Where there are major differences with other sources (including direct measures) the underlying data probably need revision.

Introduction

Estimates of total waste generated in the U.S. have been compiled by several different approaches. OTA estimated 20 billion tons of waste per year for the U.S., including agriculture, forestry, industry and consumers. Of this total, industry accounted for 12 billion tons. EPA has relied on a combination of reports from industry and municipalities, and surveys of various kinds. Recent EPA reports [USEPA 1986, 1988; Allen & Behmanesh 1992] have estimated total waste streams from various sources as follows:

Waste Type	Amount (million short tons)
Agricultural wastes (wet)	<1,500
Mine wastes (1983)	>1,400
Oil & gas wastes (1985)	
drilling waste	129 – 871
produced waters	1,960 –2,740
Industrial non-hazardous wastes (1985)[1]	7,600
Industrial hazardous waste[2]	300
Municipal solid waste (1986)	158
Utility waste (1984)	
ash	69
FGD waste	16
Construction & demolition waste (1970)	32
Other (sludge, incinerator ash, tires)	25

The industrial category, covering on-site disposal, has been further broken down by EPA's Office of Solid Wastes [USEPA 1988, 1991], and by an independent study explicitly identifying *dry* weights by Science Applications Inc [SAI 1985]. A partial list covering the largest contributors is as follows. The first column represents total (wet) waste figures, while the second (in parenthesis) supposedly represents "dry" wastes:

		million short tons	
Sector	**SIC**	**"Wet" Waste**	**"Dry" Waste**
Food & kindred products	20	374	7.0
Textile manufacturing	22	254	0.05
Pulp & paper	26	2252	9.5
Inorganic chemicals	2812-2819	920	28.9
Plastics & resins	2821	181	49.6
Fertilizers & agrichemicals	2873-2879	166	65.0
Petroleum refining	29	169	1.4
Stone, clay, glass & concrete	32	622	>20.5
Primary iron & steel	3312-3321	1301	66.8
Electric power generation	4911	1092	61.5

The subtotal of non-hazardous wastes for these industries adds up to about 7.35 billion tons (wet), or close to 97% of the total of 7.6 billion tons reported by EPA. However, it must be emphasized that off-site disposal is not included. In fact, 96.6% of industrial non-hazardous wastes are disposed of in surface impoundments, while 100% are supposedly disposed of on land. The total "dry" weight accounted for is around 310 million tons/year. Airborne wastes

[1] Excluding wastes managed off-site.

[2] Of this, 3 million tons is classed as toxic. The chemical industry is by far the biggest generator of hazardous wastes (70% of the total) and of toxic wastes (46% of the total).

from industry (not including carbon dioxide) total 12.9 million tons [USEPA 1991], allocated as follows:

Sector	Amount (million short tons)
Chemicals	3.9
Primary metals	3.2
Petroleum refining	2.3
Pulp & paper	1.3
Stone, clay & glass	1.15
Other manufacturing	1.0

The principal gaseous emission, other than CO_2, is carbon monoxide, followed by sulfur oxides, nitrogen oxides, VOC's, and particulates.

Methodology

One can view each industrial sector as a transformation process, converting raw material inputs into useful products and wastes. This conversion process is subject to the materials balance constraint, not only in the aggregate, but element by element. In other words, the sum of the weights of all inputs must exactly equal the sum of the weights of all outputs. When both inputs and outputs are known, one can estimate wastes, making due allowance for processes utilizing the "free goods", air and water. This means it is necessary to be quite careful in accounting for the consumption of oxygen (from air) in oxidation processes, and for the consumption or production of water in hydration, dehydration, dilution, dissolution and so on.

Due to the variety of different sources for the above estimates, gathered by different and not necessarily consistent methods, it would be desirable to cross check, using an independent methodology and different sources of data. In the following pages, estimates of national waste production are constructed *de novo* from published production statistics and, in a few cases, some straightforward process data. These estimates are made for the U.S. in the year 1988, for all major waste generating sectors except the chemical industry. The chemical industry is so complex that it seems best to treat it in a separate paper. It is felt that the methodology illustrated hereafter can be useful, not only to check on estimates by other methods, but also to provide some handle on estimating the potential for reduction in various categories. All figures given hereafter are in metric tons, rather than short tons.

Agriculture

Inputs to the agriculture sector consist of sunlight, water, carbon dioxide (from the air), soil and chemicals (fertilizers and pesticides). The greatest material waste of any sector is the loss of topsoil due to erosion, resulting from non-conservative modes of agricultural practice. A detailed study of topsoil loss due to agriculture was carried out by the U.S. Soil Conservation

Service in 1982 [Brown & Wolf 1984 p. 17]. It was found that 44% of U.S. cropland was losing topsoil at an unsustainable rate (i.e. faster than the natural rate of soli formation). The topsoil loss in 1982 was estimated at 1.53 billion metric tons. This rate of loss can be assumed to be roughly constant from year to year.

Raw products of U.S. agriculture include truck crops (fruits, vegetables) & tree crops, field crops (grain, oilseed, hay and alfalfa, sugar beets, sugar cane, potatoes, cotton, tobacco). Harvested output of field crops in 1988 was 416.3 MMT, of which 139.3 MMT was exported and the remainder consumed directly or indirectly within the U.S. There were no significant imports of raw products in this category. Indirect consumption (as animal feed) accounted for most of the difference. Final *direct* human consumption of foodstuffs derived from field crops (flour, sugar, vegetable oils, potatoes, beans) amounted to 31.81 MMT. See *Table I* (Appendix). Non-food field crops include cotton and tobacco.

In the food grain category (mainly wheat) production was 56.55 MMT and exports were reported to be 44.26 MMT, while calculated consumption was 15.78 MMT. These data appear inconsistent. They imply that domestic wheat consumption was about 2.1 MMT *greater* than production less exports. The probable explanation is that both consumption and export figures include "flour", which in turn includes contributions from some grains other than wheat. Wheat is also imported in finished products like pasta, which are included in the consumption figure, but not accounted for explicitly among the imports. A detailed breakdown is not available. However, the implication is clear that milling losses are negligible. (This is partly because wheat bran is no longer discarded as waste).

In the case of feed grains and oil seeds (which can be lumped together, because corn dominates in both categories) domestic production was 190.8 MMT, while exports were 66.6 MMT. Domestic production of vegetable oils was 6.4 MMT, and corn syrup accounted for another 7.64 MMT (dry weight), leaving 110.2 MMT of "unaccounted for" animal feed material. It might be assumed that the "extra" 2.1 MMT in the food grain consumption column, noted above, came from this pool. However, the statistics on animal feeding (below) do not exactly match the statistics on farm production and sales.

According to the US Department of Agriculture [USDA 1992, chapters I, VI], livestock in the U.S. in 1988 were fed 119.4 MMT of feed grains, plus 3.7 MMT of food grains (mostly wheat). Other harvested animal feeds included 123 MMT of hay and alfalfa, 4.76 MMT of sorghum as silage, and approximately 68 MMT of roughage (such as bran and cornstalk) mixed with other feeds, for a total of 319 MMT harvested inputs. By-product feeds such as mill products, oilseed meal, meat and fish meal, dried milk and molasses accounted for an additional 38.9 MMT. We have no direct estimates of animal intake of pasturage and forage (mainly by cattle). A very rough estimate might be 200 MMT pasturage and 25 MMT forage. This would imply total animal feed amounting to 583 MMT, of which 111.3 MMT can be accounted for as the weight of animal carcasses and dairy products produced for the market. Obviously animals produce large amounts of urine and fecal matter, although relatively most of this is presumably returned directly to the land. The major exception to this would be cattle feed lots and poultry feeding establishments, which are large concentrated sources and major polluters.

It should be noted that large tonnages of chemical inputs (fertilizers, pesticides) are used in the agricultural sector. Close to 76% of the synthetic ammonia consumed in the U.S., and an even larger percentage of the phosphates, are used for fertilizer purposes. Domestic agriculture consumed 33.5 MMT of phosphates (10.8 MMT P_2O_5 content). Urea, a fertilizer material, is also used in large tonnages (about 330 thousand MT) for animal feed supplements. Many of these substances find their way, either directly, or via animal excreta, into surface waters and ground waters.

The direct chemical inputs to agriculture (fertilizers, pesticides) are not counted explicitly as pollutants, though pollution results from their use. Animal wastes are a major pollution problem, especially in the vicinity of animal feed lots and large scale poultry producers. Thus, of 100 units of N in fertilizer, roughly 50 is taken up by harvested crops, of which 47 is subsequently consumed by animals and 42 is excreted as animal waste [Crutzen 1976]. About 24 units of N find their way to rivers, lakes and ground water, of which 10 units is direct runoff from the soil, 8 is from animal excreta, and 6 is from human sewage. Thus about 18% of agricultural nitrogen fertilizer use (N-content) reappears within a few weeks or months as waterborne pollution. In the U.S. about 12 MMT (N) were used for fertilizer in 1988, which implies a waterborne waste flow of 2.16 MMT (N-content).[3]

Of the 40 units of fertilizer nitrogen not accounted for above, some accumulates in the soil (but in unavailable form) and the rest is emitted to the air. It should be noted, too, that some of the ammonia in fertilizer is re-converted to nitrogen gas and returned to the atmosphere by denitrifying bacteria in the soil. For every 16 units of nitrogen emitted as N_2, it seems that roughly 1 unit is emitted as N_2O, a potent Greenhouse gas. Recently nitrogenous fertilizer use has come to be recognized as one of the major sources of N_2O buildup, with 0.7 MMT of N_2O being the current "best guess" of worldwide emissions from this source [Schlesinger 1991]. The U.S. was responsible for roughly 1/8 of worldwide nitrogenous fertilizer use in 1988, and probably a similar proportion of N_2O emissions -- or 0.055 MMT (N content).

Food Processing (SIC 20)[4]

Major waste streams occur in grain milling, oilseed milling and sugar production. In principle, about 108 MMT of grain and oilseed mash was used for animal feed in the U.S. (in addition to 114.3 MMT of hay). We have no direct way to estimate milling losses, but it is certain that some of this material was wasted. A 10% loss rate would not be surprising, considering the nature of the system. We reckon 5 MMT as a lower limit on milling and distributional wastes for animal feeds.

Sugar cane is reduced from 27.13 MMT to 2.88 MMT of cane sugar, the remainder being waste, mostly cellulosic "bagasse". Sugar beets weighing 22.51 MMT yield 2.97 MMT of beet

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[3] The details can be found in another paper [Ayres & Norberg-Bohm 1993]

[4] Production, export and import data in this section is from the *Statistical Abstract of the United States, 1991 edition*, Tables 1148, 1149, 1156, 1163, 1166, 1167, 1168, 1173, 1175, 1177. Data on per capita consumption of foods is given in Tables 207, 208. Beverages were not taken into account.

sugar, and large quantities of pulpy cellulosic material. This material has very little value, although it can be used as animal feeds. Organic wastes from these two subsectors, alone, amount to about 43.8 MMT. In the case of rice, production is 7.25 MMT, less exports of 2.30 MMT, leaving a gross domestic supply of 4.95 MMT. But final consumption of refined rice is only 1.59 MMT, implying a milling loss of 3.36 MMT, consisting of bran. If rice is exported in milled form, the implied loss is still 3.36 MT, although in this case the loss is a smaller percentage (roughly half) of the harvested rice.

In addition, truck crops (vegetables and berries) and tree crops (fruits and nuts) accounted for a harvest weight of 51.3 MMT. Exports took 4.06 MMT and imports added 8.21 MMT, for a total domestic supply of 55.45 MMT. Final consumption (on an "as purchased" basis) accounted for 37.17 MMT. The difference, 18.28 MMT was presumably waste, divided between food processing plants and retail stores. Some of this waste could have been used for animal feed, and some could have been burned for fuel, but probably not a great deal. Virtually all of this waste is probably released into waterways as organic materials (BOD).

There are potential opportunities for reducing waste from the above two categories, but they require some new technology. One possibility is to convert waste organic material to animal or fish feed, or to methanol, ethanol or some other chemical intermediate, by bacterial action or other bio-technology. Another is to compost the waste with methane recovery — a simple technology but probably not economic at present natural gas prices.

Animal products in the U.S. can be subdivided into red meats, poultry, eggs and dairy products. The live weight of animals slaughtered for red meat in 1988 was 28.05 MMT, with an additional 12.95 MMT of poultry. Salable weight for red meat, after processing, was 18.14 MMT, a reduction of roughly 10 MMT, or nearly 36%. By-products of meat processing include lard, hides (leather), glue, blood and bone meal. Most of this material is utilized in animal feed or in other industries, although actual waste flows are still non-trivial. We estimate wastes to be at least 10% or 1 MMT.

Exports of red meat products amount to 0.4 MMT and imports (mostly of beef) amounted to 1.63 MMT. Thus domestic supply of red meat was 19.41 MMT. However, final consumption of meat ("as purchased") was only 16.25 MMT. The difference of 3.16 MMT is waste fat and bone, largely generated by meatcutters in retail shops. This waste ends up in municipal refuse and, finally, in landfills.

In the case of poultry, a similar reduction from carcass weight to dressed weight is plausible, although we have no specific data. On this basis, live weight of 12.95 MMT would be reduced to around 9 MMT by large-scale processors. This implies a by-product flow of about 4 (3-5) MMT, most of which is probably recycled as animal feed. Final consumption ("a purchased") was 6.37 MMT. Thus, a further loss of 2.6 (1.6-3.6) MMT or so presumably occurred at the retail level, including restaurants. The latter ends up in municipal refuse.

Egg consumption in 1988 is reckoned to be 3.86 MMT. Production is presumably a little larger (due to breakage and spoilage) but the loss is probably negligible. We calculated the production to be 4.44 MMT, but the calculation depends on an estimate of average egg weight that could easily be off by 15% or so.

Dairy products are a special case. Raw milk production in 1988 was 65.86 MMT, whereas final consumption of milk products was only 33.42 MMT. However waste is very slight. The reduction in apparent mass is essentially entirely due to evaporative losses of water in cheese-making and drying.

Domestic production of raw fish was 3.26 MMT. Exports were 0.48 MMT and imports were 3.37 MMT. Thus the domestic supply was 6.15 MMT. Of this, 4.77 MT was designated for human consumption, but only 1.4 MMT was actually consumed. The remainder (4.75 MMT) was presumably used as animal feed or wasted. We have no exact way to determine the allocation. It would seem reasonable to suppose that all the parts of fish (e.g. tuna) that is canned or frozen are utilized for pet food or animal feed. However, a significant portion of fresh fish is lost as garbage. We estimate this portion to be at least 1 MMT.

In summary, wastes from the food processing sector as a whole (including losses in retail shops) amount to between 60 and 78 million MT, depending how much of the sugar-beet waste is consumed by animals. The material we have estimated to be wasted is "dry" in the sense that it does not include the weight of washing or cooking water. It is worth noting that our estimate is roughly ten times larger than the one cited above [SAI 1985].

Forest Products: Lumber (SIC 24) and Pulp and Paper (SIC 26)[5]

Harvested forest products consist of logs ("roundwood") in three sub-categories, softwood (from conifer trees), hardwood, and fuel wood. Data are given in terms of volume units (cubic feet and cords). Unfortunately actual weights are not given for raw wood. A cord is exactly 128 cubic feet; a cord of softwood is conventionally taken to weigh 2000 lbs, while a cord of hardwood is taken to weigh 3500 lb, on average. It would seem to follow from simple division that 1 cf of softwood weighs 15.6 lb, on average, and 1 cf of hardwood weighs 27.3 lb, on average. However, this is misleading, since stacked wood includes quite a lot of airspace. A cord of wood is not equal to 128 cf of *wood* because some of the volume is air. Correcting for this factor, therefore, we assume softwood weighs 34.2 lb/cf, while hardwood weighs 59.8 lb/cf.[6]

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[5] Data on wood and pulp production, exports, imports and consumption from [STATAB 1991] *Statistical Abstract of the U.S., 1991* edition, especially Tables 1184, 1185, 1192, 1193, 1194. Data on other chemical inputs from [USBM 1989] *Minerals Yearbook*, 1989 edition, Volume 1, especially chapters on clay, salt, soda ash, sodium sulfate and sulfur.

[6] As it happens, we can estimate an appropriate correction by comparing two tables in *Statistical Abstract of the United States, 1991*. Table 1184 gives quantities of lumber, plywood and pulpwood produced, exported, imported and consumed in millions of cubic feet (mcf). Table 1195 gives data for pulpwood consumed in millions of cords. In particular, Table 1184 gives pulpwood consumption for 1988 as 5585 mcf "roundwood equivalent" while Table 1195 gives U.S. pulpwood consumption for the same year as 95.6 million cords, or (multiplying by 128) 12,224 mcf. If the two figures actually represent the same amount (weight) of wood, then the ratio of total volume to wood volume in a cord of stacked wood must be 2.187. It follows that the weight of a cubic foot of hardwood would then be 27.3 * 2.187 = 59.8 lb. Similarly a cubic foot of softwood would weigh 15.6 * 15.6 = 34.2 lb.

On this basis, domestic softwood production in 1988 was 11,430 million cf or 177.17 MMT, while domestic consumption was 201.04 MMT. Domestic hardwood production was 3555 million cf or 96.43 MMT, while domestic consumption was 88.43 MMT. Taking both together, 52.09 MMT was exported, while 68.9 MMT was imported. Apparent domestic consumption of industrial roundwood (not including fuelwood) was 16,230 million cf or 289.47 MMT. Lumber accounted for somewhat over half the total or 8425 mcf. Pulpwood accounted for 5585 mcf or 45.45 MMT. The remainder of roundwood consumption was mainly for plywood. Fuelwood amounted to 52.08 MMT. See *Table II* (Appendix).

Lumber is measured in board feet, where 1 cf is equivalent to 6.46 board feet. Production of softwood lumber (from roundwood) in the U.S. in 1988 was 37,003 million board feet (5728 million cf), while production of hardwood lumber was 7727 million board feet, or 1191 million cf. The total domestic output of lumber, therefore, was equivalent to 6919 million cf, as compared to consumption of 8425 million cf. Volume reduction in milling was therefore 1506 million cf, or about 18%. However, much – perhaps most – of the sawdust is used for particle board or hardboard. The remainder is burned for process heat. Little is actually wasted.

U.S. domestic consumption of pulpwood in 1988 was 86.59 MMT, about 70% softwood. The woodpulp supply seems to have been 57.9 MMT, of which around 52 MMT was "virgin" and the rest was derived from recycled waste paper. Paper and pulp products produced from virgin pulp amounted to 70.85 MMT. Exports were 5.16 MMT and imports were 11.89 MMT. Wastepaper recovered for pulping was 6.71 MMT. Consumption of pulp and paper products was 77.56 MMT, of which 12.24 MMT was newsprint. The difference between pulpwood consumption and pulp production suggests a mass loss (waste) of roughly 34.6 MMT (40%) in mass terms from the original feedstock. *Table II* (Appendix) summarizes the basic data.

Wood pulping is one of the most inherently wasteful of all industrial processes. This is because a significant fraction of the raw weight of the pulpwood is not cellulose, but the organic "glue" that holds the cellulose fibers together, which is called lignin. In addition, the pulping process consumes enormous quantities of chemicals, many of which are dissipated in the pulping and paper-making processes. A partial list of inputs to the pulp and paper industry includes clay (kaolin), lime for acid neutralization, sulfur, soda ash, sodium hydroxide, sodium sulfate and sulfuric acid for pulping, chlorine and sodium hydroxide (as well as sodium chlorate) for bleaching. *Table II* (Appendix) summarizes these inputs.

In 1988 the paper and pulp industry was still the second largest user of chlorine, taking 3.6 MMT or 10% of the total worldwide output. In the U.S. the paper industry used 14% of total chlorine output (1989). The paper industry used 4.4 MMT of caustic soda in 1988, worldwide. U.S. consumption of chlorine for paper & pulp bleaching in 1988 would have been about 1.5 MMT, and consumption of caustic soda would have been about 1.2 MMT.

Kaolin in actually embodied in the paper products, as filling and coating material. It becomes a waste only in the recycling process. The other chemicals listed (which sum up to 5.34 MMT, excluding kaolin) are not embodied in the product, and must therefore be included in the production waste stream. It follows from materials balance considerations that the annual discharges of chemical wastes from the pulp and paper industry must be roughly equal to the annual inputs, element by element. Counting lignin and chemicals, we impute a total of more than 40 MMT waste for 1988, not including water. This figure is very much larger than the 9.5 million short tons of "dry" waste cited above [SAI 1985]. Most of these discharges are waterborne.

Admittedly, there is an increasing effort to incinerate lignin wastes for energy production and reduce the annual intake of other chemicals by recycling more efficiently. There is also a small but growing industry based on chemical by-products of lignin wastes. The most prominent of these is dimethyl sulfoxide (DMSO). However, by-products do not yet account for a significant fraction of the wastes from pulp & paper.

Mining and Quarrying[7]

There are two types of waste associated with mining *per se*. These are (i) earth displaced in the process of searching for and removing ore (overburden) and (ii) unwanted contaminants (gangue) removed on-site by physical methods, such as screening, washing, settling, flotation, centrifuging and so on. The material shipped to the next stage of processing is, typically, a "concentrate" that is fed into a smelting process. (Smelting wastes are discussed in connection with the metallurgical industry).

The Bureau of Mines estimates that mineral exploration and mine development activities in 1988 (not including energy fuels) generated 190 million metric tons or MMT of waste material, mostly from overburden stripping. Active mines also produced more than a billion MT of mineral waste, prior to the concentration stage of processing; again most of this is overburden and some tunnelling. Total overburden moved by U.S. mines was 1.19 billion MT; overburden moved to supply U.S. metals consumption, adjusted for both imports and exports, was 1.14 billion MT. Mining activities altogether consumed 1.87 MMT of industrial explosives, of which 85% was ammonium nitrate based. Some NO_X was doubtless produced in the process.

Total concentration wastes for metals mined and concentrated domestically were about 0.78 billion MT, including uranium (discussed later). Adjusting for imports and exports reduces the total slightly to 0.73 billion MT. The most common physical concentration process is froth flotation. It is used, especially, to separate sulfide minerals of copper, lead, zinc, molybdenum and silver from lighter minerals such as silicates, aluminates and carbonates. It is also used to concentrate phosphate rock and, to a minor extent, for coal cleaning. The most recent data available is for 1985 [USBM 1987]. In that year 380 million MT of mineral ores were concentrated by flotation, yielding 71.5 MMT of concentrates and 309 MMT of (dry equivalent) mineral wastes. Water used in the process was 947 billion gallons, or 3580 MMT. The water is not recovered. (Wastes are disposed of in ponds). Chemical reagents used amounted to 0.63 MMT. Grinding mills required 8 billion kwh of electricity and 134,000 MT of rods and balls.

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[7] Data on materials handled is from *Minerals Yearbook, 1989*, Volume 1, Tables 10, 11 on pp. 69, 70. The rest of the data on metals and minerals came from individual chapters.

Aluminum and iron ores are not concentrated by flotation. In the case of aluminum, the ore is bauxite, which is a relatively pure mineral that is already quite concentrated (about 30% Al). It is further concentrated to relatively pure Al_2O_3 by the so-called Bayer process, then reduced by electrolysis rather than carbothermic smelting. In 1988 8.2 MMT of bauxite ore was concentrated to 4.6 MMT of alumina (and some calcined bauxite) in the U.S. Almost all of the bauxite was imported. Primary aluminum production in the U.S. also consumed 3.2 MMT of imported alumina.

Iron ore mined in the U.S. is concentrated for blast furnaces by two processes, pelletizing (at the mine) and sintering. The latter process is carried out near the blast furnace, because it utilizes significant quantities of iron-rich "reverts", such as mill scale and dust, from later stages in the iron/steel production process. Blast furnace feed (concentrates) average 63% iron, whereas domestic iron ore is only about 20% iron. In 1988 197 MMT of crude ore was concentrated into 57 MMT of furnace feed, leaving 140 MMT of wastes.

Non-metallic minerals are mined or quarried in very large tonnages, mostly domestically. Stone (including limestone) is the largest item (1.15 billion MT), followed by sand & gravel (863 MMT). Imports and exports are comparatively small. Unlike the case of metals, overburden wastes are small in relation to production (except for clay, where the waste amounts to 35.7 MMT). The same is true of concentration wastes, except for phosphates — included with metals — and potassium salts (27.8 MMT).

Phosphate rock mining and processing is an extremely important activity, since phosphate fertilizers are absolutely essential for modern agriculture. Unfortunately the ore is not of very high grade, and is rather contaminated, especially with fluorine. In the U.S. 451.8 MMT of raw materials were handled to produce 224.1 MMT of crude phosphate rock in 1988. The crude ore was concentrated to 45.4 MMT of fertilizer grade product (13.2 MMT P_2O_5) by treatment with sulfuric acid. This refining operation is considered to be part of the chemical industry (SIC 28741) and will not be discussed further in this paper.

Uranium mining in the U.S. produced about 15 MMT of ore in 1980. This was reduced (mostly by flotation) to 19,500 MT of U_3O_8 concentrate ("yellow cake"), which yielded 4740 MT of refined uranium oxide (nuclear fuel). Thus 3600 metric tons of ore were needed to produce a metric ton of concentrated UO_2 pellets [LeBel 1982, Table 6.1]. Uranium production has been declining sharply; production in 1991 was 580,000 MT of ore and 1150 MT of yellow cake, down 96% from 1980. Uranium mining added 15 MMT to the 1980 figure for concentration waste, but nearer 1 MMT in 1988 (we don't have an exact figure for that year).

Mine wastes from metal and non-metallic mineral production within the U.S. in 1988 can be summarized as follows. For metal ores overburden wastes were 1192 MMT and concentration wastes were 600 MMT, not including phosphate rock processing. For non-metallic minerals (excluding coal) overburden wastes were 47 MMT and concentration wastes were 36.5 MMT. The overall total amounts to 2054.5 MMT, essentially dry weight. Water used in the flotation processes for ore concentration would add another 3580 MMT (1985), as noted above. Details are given in *Tables III and IV* (Appendix). It can be seen that the totals for mineral mining wastes in the U.S. are actually about 5.6 billion metric tons, far higher than the 1.4 billion estimate by EPA, cited earlier, even without including wastes from coal mining (see next section).

Opportunities for waste reduction in the mining and mineral processing area are essentially nil. In fact, as the best ores are used up and ore grades continue to decline, mineral wastes will increase even faster than consumption. Putting it another way, the only way to reduce wastes in this area is to reduce the consumption of virgin metals and minerals. This can be done, in principle, by increasing recycling (much easier said than done, however).

Mineral Fuels: Coal Mining & Oil & Gas Drilling

Coal mining is the largest single source of waste materials. Based on data supplied by the U.S. Department of Energy, 9 cubic yards or 81 cubic feet of waste (mostly overburden) are moved for each short ton of coal mined, at an average weight of 160 lb per cf [personal communication]. For 81 cf, this implies a waste overburden of 12,960 lb. (6.5 tons) per ton of coal. Since national soft coal production in 1988 was 862.1 MMT, total materials handled in coal mining, exclusive of the coal itself, was apparently of the order of 5600 MMT or 5.6 billion metric tons. (This is more than 3 times the loss of topsoil by erosion).

In addition, most utility coal is washed to remove pyrites and ash, resulting in a significant further production of waste refuse. In 1975 about 41% of soft coal produced was cleaned, resulting in 16 tons of coal refuse for every 100 tons of coal produced. By 1991 this figure had doubled. In 1988 we assume that 0.3 tons of refuse were produced per ton of coal, or 260 MMT of extremely sulfurous refuse (a significant cause of acid mine drainage). Combustion emissions are discussed later.

Petroleum and natural gas production involve relatively little mine waste, except water, although it might be mentioned that petroleum drilling accounts for virtually the whole national consumption of the mineral barite, or 1.6 MT. Barite is used as "drilling mud". During 1988 the oil and gas industry drilled 25,000 wells and drilled 124 million feet of holes. In 1988 63 lb of barite was used per foot of drilling. Assuming 6" pipe for the holes, the material removed would have been 5.5 liters per linear foot, or 682 million liters. Recalling that a liter of water weighs 1 kg, by definition, and assuming an average specific gravity of 3 for drilling wastes, this only amounts to about 2 MMT. Combustion emissions are discussed later.

Petroleum Refining (SIC 29)[8]

Total output of crude oil in the U.S. in 1988 was 402.6 MMT. Exports were 0.6 MMT and imports were 269.05 MMT, for a total domestic crude oil supply of 671.0 MMT. Reported inputs of crude oil to domestic oil refineries were 678.684 MMT; in addition, refineries

[8] All data in this section was extracted from a single source, [OECD/IEA 1991] *Energy Statistics of OECD Countries, 1980-1989* :664-665.

consumed 16.230 MMT of natural gas liquids, and 22.585 MMT of intermediate feedstocks (of which 16.864 MMT was imported and 6.319 MMT was internal transfers of "gasoil" to be upgraded), for a total input of 717.499 MMT. See *Table V* (Appendix).

Refinery products included non-condensible refinery gases amounting to 34.072 MMT and salable products adding up to 679.068 MMT. These refinery gases were either flared or used internally for energy purposes. Thus, apparent refining losses (input mass unaccounted for) amounted to approximately 4.3 MMT, presumably in the form of fugitive hydrocarbon emissions (VOC). The combustion of refinery gases is not 100% efficient, so additional VOC emissions and CO emissions can be presumed. However, if all of these hydrocarbons (85% C) were completely oxidized, CO_2 production would be 106 MMT (or 29 MMT C equivalent).

Fossil Fuel Consumption

It should be noted that when fossil fuels are burned there are combustion products that must be counted as wastes. This is particularly true for coal. On the average, U.S. coal has a sulfur content of 1.9%; coal burned by electric utilities averages 2.3% sulfur, while coking coal is 1% sulfur. In principle, coal burned in the U.S. emits about 16 MMT of sulfur (32.1 MMT of SO_2). Most of this sulfur dioxide is released to the atmosphere.

In 1988 1.24 MMT of lime (CaO) and 1.035 MMT of limestone ($CaCO_3$) were sold for purposes of sulfur removal from furnace stack gases. The limestone was equivalent to 0.495 MMT of lime. Since CaO has a molecular weight of 56 and SO_2 has a molecular weight of 64, the total amount of limestone and lime used in scrubbers accounted for only 1.96 MMT of sulfur dioxide, or about 6% of the total emitted. None of the sulfur from coal burning was recovered for use. (It is disposed of in landfills as a mixture of wet calcium sulfite $CaCO_3$ and calcium sulfate $CaCO_4$). Curiously, it is claimed that flue gas desulfurization (FGD) by utilities produced 16 million tons of wastes in 1984 [USEPA 1988, 1991]. The solid content of these wastes (even in 1988) was evidently no more than 3.7 MMT, the remainder being water.

If all the sulfur in U.S. coal were to be captured by wet scrubbers using lime, total U.S. lime production would have to be increased by 26 MMT (i.e. trebled), which would require an additional 55 MMT of limestone to be quarried. All of it would, of course, be converted almost directly into a waste stream.

Coal also contains several percent ash. The usual assumption is about 3.5% on the average in the U.S. Given 1988 national coal consumption of 801.6 MMT, the implied ash yield would be 21 MMT, including trace quantities of all the toxic heavy metals. Actually, utilities alone seem to have produced 69 million short tons — 62 MMT — of ash in 1983, which suggests an average ash content closer to 10%). We cannot account for the discrepancy, unless a significant fraction of the "ash" is actually water.

Coal ash contains significant quantities of heavy metals, as shown in *Table VI* (Appendix). For instance, 2750 MT of arsenic would be included (0.0093%) Admittedly, the figures in *Table VI* are only one estimate, and may be seriously in error, especially for the minor metals, it must be noted that the uncertainties could go either way. Most fly ash is captured, either in bottom ash (clinker) or by electrostatic precipitators. However, this yields a waste that must be disposed of somehow. Moreover, a fraction of the fly ash is still emitted as particulates, and the more volatile metals like arsenic and mercury escape as vapor and re-condense downwind of the stack. Coal contains a small but significant percentage of nitrogen (about 1 unit per 68 units of carbon). Most of this is emitted as nitric oxide (NO) but some may be emitted as nitrous oxide, N_2O, one of the "greenhouse" gases. However, figures on this are disputed.

More important, coal combustion in high temperature boilers, for electric power generation, produces a significant quantity of NO_X emissions, about 10 MMT/yr [USEPA 1986]. However, virtually all anthropogenic NO_X (about 20 MMT/yr in 1980, and probably a similar amount in 1988) is attributable to fossil fuel burning.

Finally, the carbon in coal (along with the carbon in other fuels) is converted by combustion into carbon dioxide. The sum total of all fossil fuels consumed in the U.S. in 1988 was 1884.4 MMT. The carbon content ranges from 75% for gas, 86% or so for petroleum and close to 90% for coal. It is reasonable to assume that the average fuel was 85% carbon, on average, by weight and that all of the carbon (740 MMT) was converted, within a few months at most, to CO_2 (2700 MMT).

Emissions reduction through "end of pipe" treatment (e.g. of SO_2 or NO_X) has not been very effective up to now, despite considerable costs. Universal use of limestone scrubbers would impose very significant environmental costs in terms of additional needs for limestone and disposal sites for the sulfite waste. A practical use for the waste material (e.g. to replace gypsum) would be extremely valuable, but as long as wet scrubbers are used, this is unlikely. Reduction of CO_2 emissions by end-of-pipe approaches will be even less cost-effective. The most plausible long-term approach for emissions reduction is to use energy more efficiently and/or substitute non-fossil energy sources for fossil fuels.

Primary Metals Smelting & Refining (SIC 33)[9]

The production of primary metals from concentrates is normally accomplished by carbothermic reduction (smelting with coke). By far the major product, in tonnage terms, is pig iron. U.S. blast furnace output in 1988 was 55.475 tons (49.8 MMT). This material has an iron content of 94%. It is entirely used for carbon steel production, mostly (>90 %) via the basic oxygen process. (Electric minimills use scrap exclusively).

It should be mentioned that blast furnace inputs in 1988 included about 3 MMT of scrap iron/steel, while sinter also utilized about 6 MMT of upstream reverts (dust, mill scale). Thus,

[9] Data mostly from Minerals Yearbook.

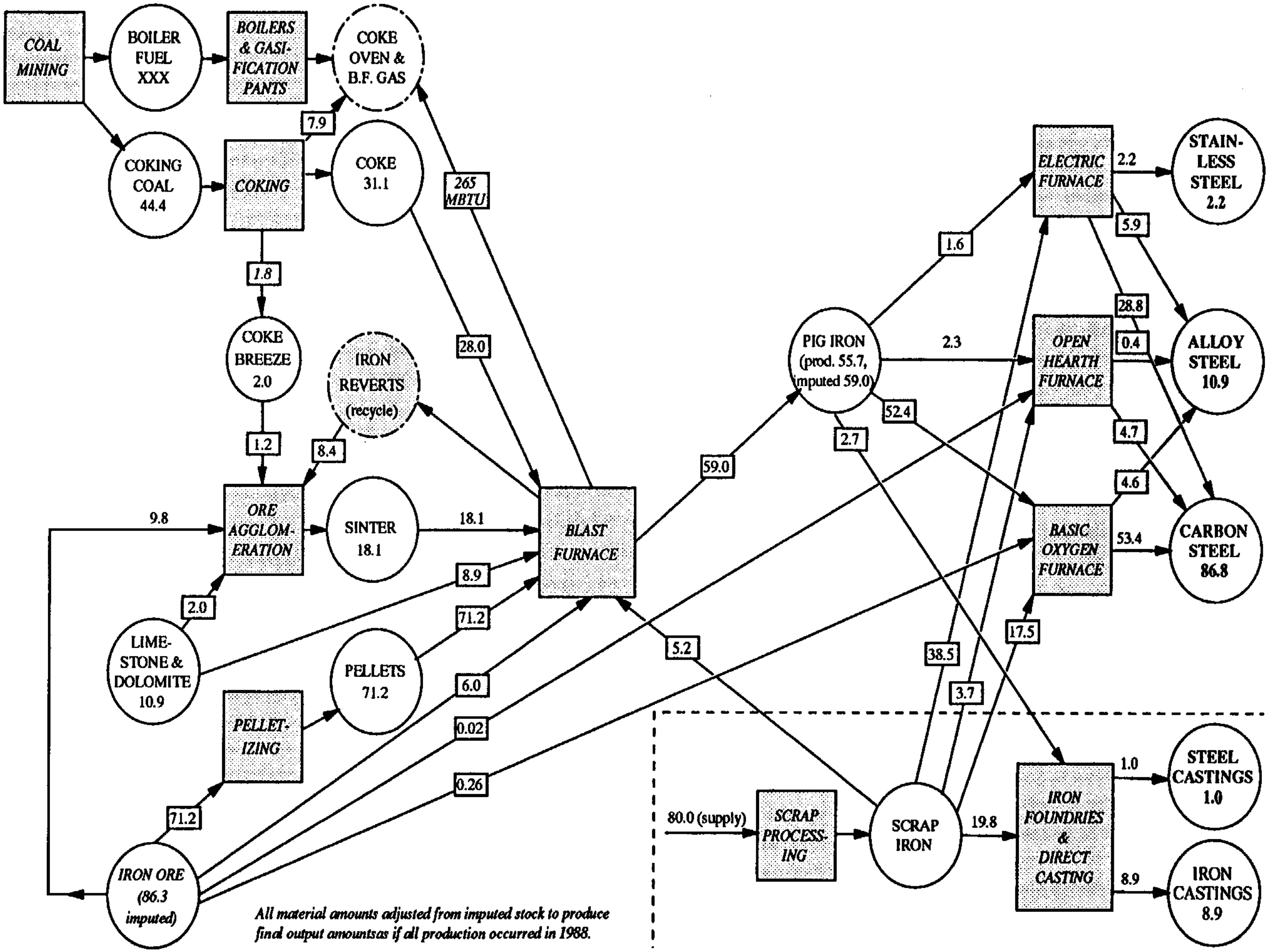

Figure 1: 1988 U.S. Composite Steel Production (million short tons)
Source: authors

to account for the virgin ore is somewhat complex (See *Figure 1*). However, without attempting a detailed reconciliation, we note that the iron content of U.S. ores in 1988 was reported as 57.515 MMT. More to the point, blast furnace inputs (pellets) averaged about 63% iron, 5% silica, 2% moisture and 0.35% other minerals (phosphorus, manganese, alumina). The remainder was oxygen. In the reduction process the oxygen combines with carbon (actually carbon monoxide) from the coke. About 1 metric ton of coke was used per metric ton of pig iron, along with 0.142 metric tons of miscellaneous materials, mostly fluxes (lime and limestone) for the sinter plants and to make the slag flow. Slag consists of the silica and other non-ferrous minerals in the sinter and pellets, plus the fluxes. Total iron blast furnace slag production in the U.S. was 14.2 MMT, or 0.35 metric tons of slag per metric ton of pig iron. However, slag is no longer considered a waste, since virtually all slag produced is marketed for a variety of uses.

As noted, the oxygen in the iron-bearing concentrates reacts in the blast furnace with carbon monoxide. The reduction process requires excess CO, so the emissions (blast furnace gas, consist mostly of unreacted CO. Currently most of this is utilized elsewhere in the integrated steel complex as fuel e.g. for preheating blast air. However, the capture of gaseous emissions from blast furnaces is not 100% efficient, so some CO escapes. However, considering the iron/steel process as a whole, all of the carbon (from coke) is eventually oxidized to CO_2. In 1988, the steel industry accounted for 182 MMT of CO_2, from coke, which is included in the 2700 MMT mentioned above. (In addition, some other hydrocarbon fuels were used).

Coke ovens and steel rolling mills are significant sources of hazardous wastes, even though the coke oven gas is efficiently captured for use as fuel, and about 55 thousand MT of ammonium sulfate (N-content) is produced as a by-product. This material is used as fertilizer. Coke is cooled by rapid quenching with water, and some tars, cyanides and other contaminants are unavoidably produced. Also, in the rolling process steel is cleaned by an acid bath ("pickling"), resulting in a flow of dilute wastewater containing ferrous sulfate or ferrous chloride (depending on the acid used). The excess acid is usually neutralized by the addition of lime. In 1988 about 215 thousand MT of 100% sulfuric acid (74 thousand MT sulfur equivalent) were used for this purpose, producing 250-300 thousand MT of ferrous sulfate mixed with calcium sulfate. Ferrous sulfate can, in principle, be recovered for sale. However the market is insufficient to absorb the quantity potentially available.

Light metals, mainly aluminum and phosphorus, are reduced electrolytically. The oxygen in the alumina reacts with a carbon anode, made from petroleum coke. The reaction emits 0.65 metric tons of CO_2 per metric ton of primary aluminum produced. In addition, primary aluminum plants emitted about 0.02 metric tons of fluorine, per metric ton of aluminum, partly as HF and partly as particulates. This is due to the breakdown of cryolite (the electrolyte used in the process, an aluminum-sodium fluoride) at the anode. Total airborne emissions from primary aluminum production in the U.S. (3944 MMT) were, therefore, 2564 MMT of CO_2 (already counted), 0.08 MMT of fluorides and about 0.17 MMT of particulates (Al_2O_3).

In the case of heavy metals from sulfide ores (copper, lead, zinc, nickel, molybdenum, etc.), the smelting process is preceded by, but integrated with, a roasting process whereby the sulfur is oxidized to SO_2. Roughly 1 metric ton of sulfur is associated with each metric ton of

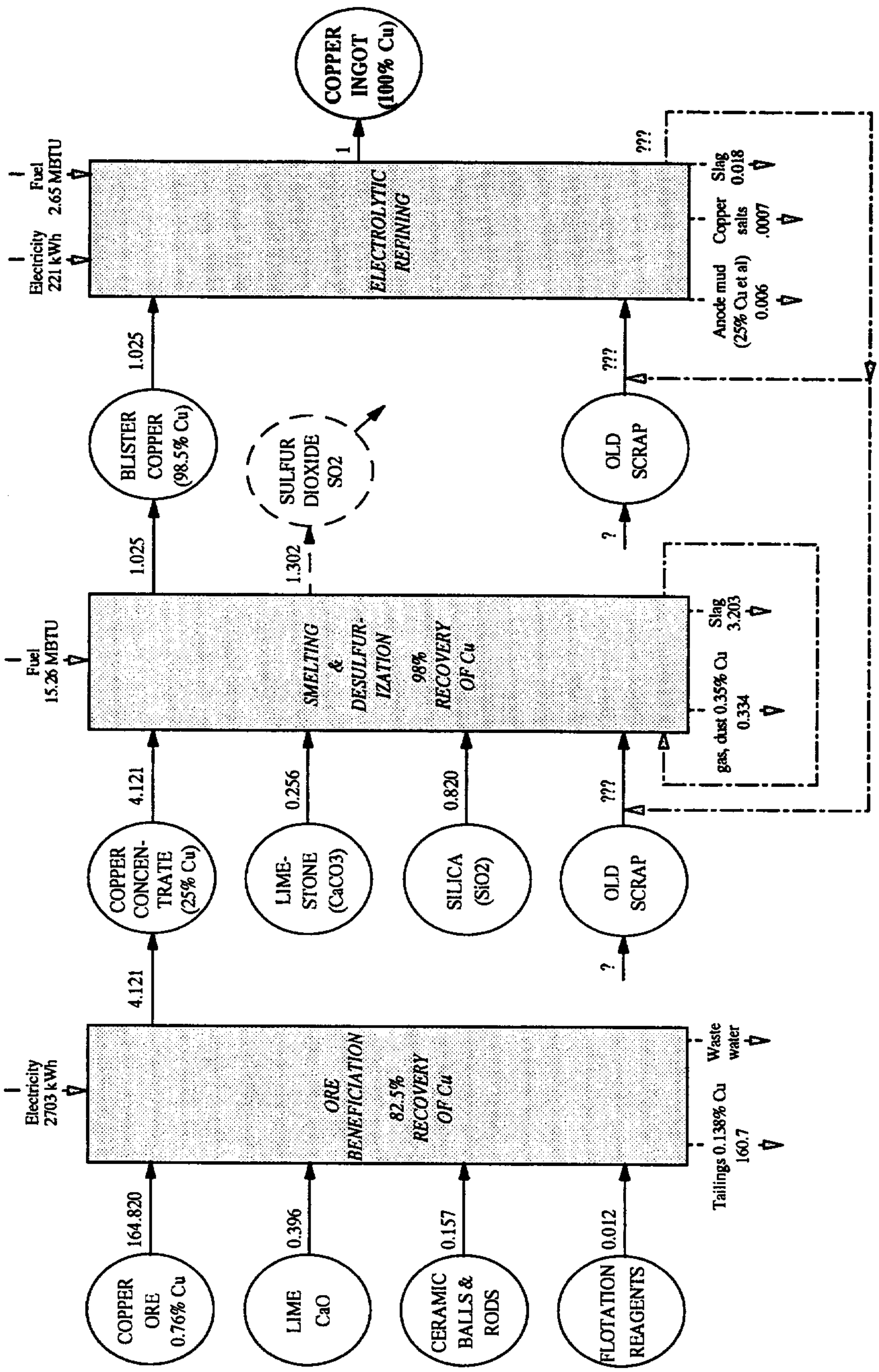

Figure 2: 1988 U.S. Composite Copper Production (million short tons)
Source: authors

copper smelted (see *Figure 2*), 0.43 metric tons of sulfur per metric ton of zinc, and 0.15 metric tons of sulfur per metric ton of lead. Most of this sulfur is captured and immediately converted to sulfuric acid. In 1988 1.125 MMT of by-product sulfuric acid, in terms of sulfur content was produced at U.S. refineries, as follows: copper (0.946 MMT), zinc (0.136 MMT), lead/ molybdenum (0.043 MMT). In terms of sulfuric acid (100% H_2SO_4) the quantity of by-product acid produced was 3.54 MMT. In the case of copper, most of this (1.2 MMT) was used by mines for leaching copper from old mine dumps. Leaching now accounts for a significant proportion of copper and uranium concentrates produced in the U.S.

In the case of copper smelting, typical concentrates fed to the roaster/smelter consist of about 35% Cu (23%-45%), 35% S and 30% other minerals. In addition, about 0.25 metric tons of limestone flux are added per ton of blister copper. Thus, slag production amounts to roughly 0.55 metric tons per metric ton of primary copper, or 0.77 MMT in 1988. In the case of zinc, a typical concentrate would be about 55% Zn (45%-64%), and 27% S, with other minerals accounting for 16%. For lead, the corresponding number appear to be (about) 60% Pb (50%-70%), 9% S, and 21% other. Thus, assuming flux per unit of slag to be the same as for copper (1.2:1), slag output should have been roughly 0.3 metric tons/metric ton for zinc and 0.38 metric tons/metric ton for lead. This implies total slag output of 0.06 MMT for zinc smelting and 0.14 MMT for lead smelting. Carbon monoxide and carbon dioxide emissions are not known exactly, but they are quite small in comparison with other sources. The waste numbers for other metals are insignificant.

Altogether we estimate "raw" smelting and refining wastes for metals, including CO_2, to have been 43.4 MMT in 1988. (This includes about 34.4 MMT of iron/steel slag, most of which is marketed commercially, mainly for road ballast). As noted above, much of the sulfur from sulfide ores was also recovered for use. The major airborne emission other than CO_2 is probably CO and particulates. In both cases, blast furnaces are the major sources.

Stone, Clay & Glass (SIC 32)

Mining of non-metallic minerals has been discussed above. It will be recalled that overburden and concentration losses for non-metallic minerals amounted to 47.1 MMT and 36.5 MMT respectively. The outputs of the stone, clay, glass sector include refractories, glass and portland cement. All three are basically durable products used in structures or long-lived products. We do not have detailed quantitative data on glass production. As regards clays, domestic production in 1988 was 43.9 MMT. Production of clay and refractory products (including clay used in Portland cement) was virtually identical. Some of these uses (e.g. fillers, binders, absorbents, drilling mud, filters) are essentially dissipative.

Portland cement manufacture is an important industry. Total tonnage produced in the U.S. in 1988 was 63 MMT. Most of the input materials were natural minerals already discussed (limestone being by far the most important, 71 MMT) but small quantities of fly ash and blast furnace slag were utilized. Total non-fuel inputs were 109.5 MMT. The major fuel consumed was coal (9.5 MMT), though some plants used oil or gas. Emissions are primarily carbon dioxide and particulates. Total weight of emissions from fuel are already counted above.

However, based on CO_2 emissions from limestone calcination amount to an additional 34 MMT (or 9.5 MMT carbon content). It is likely that particulate emissions from cement kilns exceed 1 MMT.

Lime (CaO) is made by calcining limestone. In 1988 U.S. production was 13.2 MMT (consuming 29.5 MMT of limestone and releasing 26.3 MMT of CO_2 to the atmosphere). Uses are extremely diverse, and not well documented. Use for stack gas treatment has been mentioned already. Many uses are substitutable by limestone (e.g. for glass manufacturing, soil stabilization, desulfurization, etc.) It must be emphasized that calcination of limestone releases CO_2 in a ratio of 1.1 metric tons per metric ton of CaO.

It appears that the major waste emissions from this sector (exclusive of losses in quarrying and concentration) are primarily related to combustion of fossil fuels and calcination of limestone and gypsum, which yields CO_2.

Again, opportunities for emissions reduction are very limited. The most promising long-term possibility is to reduce demand for products based on virgin materials. One possibility deserving serious attention is to substitute more fly ash for clay in Portland cement manufacturing. This would require some R&D, but the chemical compositions are close enough to justify a hard look, notwithstanding the problem of toxic trace metals.

Water Usage and Waterborne Wastes

Water withdrawal and use data are gathered by the U.S. Census of Manufactures. The last Census year was 1983. Results for mining and manufacturing are summarized in the National Water Summary 1987 [David 1987]. Data are all given in units of million gallons per day (mgd). For conversion purposes, note that (in the case of water) 1 mgd = 1.379 million metric tons/year.

For the mining sector, total 1983 water intake was 3280 mgd. Of the intake, 523 mgd was designated as cooling water, mainly for petroleum and natural gas fractionation; 1440 mgd was designated as process water (for coal washing and flotation); the remainder of the intake was unaccounted for. The ratio of gross water use to intake for the sector was 3.1. Discharges for the whole sector were 2840 mgd, of which 1930 mgd were treated and 907 mgd were untreated. Discharges from coal mining alone were 340 mgd. The difference between intake and discharge (440 mgd) was presumably lost as water vapor (e.g. from flotation ponds) or used for underground injection in the oil/gas sector.

The five biggest water users among the manufacturing industries are chemicals, paper & pulp, petroleum refining, steel, and food processing. The data given [David 1987] are inconsistent in some respects, so the following must be regarded as "soft". The chemical industry is the largest water user. Intake was 9310 mgd, of which 7700 was for cooling purposes. Gross use was 26,400 (a reuse ratio of 2.8) and 17,000 mgd of water was recirculated, of which 15,500 was for cooling purposes. Total discharges were 8160 mgd, and consumptive use (or loss) was 1150 mgd. If it is assumed that the losses were water vapor from cooling towers, then cooling water discharges would be 7700 - 1150 = 6550 mgd, leaving process water discharges of 1610 mgd. In reality, cooling water and process water cannot be easily segregated, however, since cooling water is typically recycled several times, then used as process water before final discharge. Within the chemical industry, organic chemicals account for nearly half the discharges (3780 mgd), followed by inorganics (2080 mgd), plastics and synthetics (1070 mgd) and agricultural chemicals (556 mgd).

The paper and pulp industry is the next largest user, with gross use reported as 21,000 mgd and a recycling ratio of 3.9. This implies an intake level of 5400 mgd. Cooling accounts for less than 30% of this (approx. 1570 mgd) leaving up to 3500 mgd as process water. Discharges are not reported, but would presumably be slightly less than withdrawals, allowing for some evaporative losses. For the petroleum industry gross use was 16,000 mgd, with intakes of 2100 mgd and a recycle ratio of 7.5. The ratio of cooling to process water is stated to be 10. Discharges are not reported directly, so losses cannot be estimated. For the steel industry gross use was 16,100 mgd, with a recycle ratio of 2.5 and intake of 6470 mgd. Of this, 3590 mgd was for cooling and 2460 mgd for process use (e.g. pickling). Discharges are not reported as such.

As regards the food industry, gross use of 4100 mgd was reported, with a recycle ratio of 2.2. This implies an intake of 1850 mgd, along with comparable discharged. (Discharges might actually exceed intakes, given the high water content of some foods, notably milk products). Cooling water use is especially high for the sugar sector, but otherwise not especially great.

Unfortunately, the above figures are inconsistent, as noted previously. Adding the gross use figures given by David, one obtains 83,600 mgd as against her total of 92,700 mgd. Similarly, reported and imputed intake figures add up to only 25,100 mgd as against her total of 27,500 mgd. The sums of for cooling water and discharges (imputed from other data given) are also significantly too low. It is possible that David's totals should have referred to the entire manufacturing sector, rather than the five largest sub-sectors, as stated. However this conjecture cannot be confirmed, at present.

Summary

It may be interesting to summarize our results by waste category, as well as by industry. Overburden moved by mining — mostly stripping — amounts to over 6.8 billion MT. By contrast, topsoil loss in agriculture was 1.5 billion MT. (In addition, the construction industry may move comparable amounts). Waste from mineral concentration activities, mostly by froth flotation, produce wastes of the order of 1.37 billion MT (dry weight). In addition, about 3.6 billion MT of water was used for flotation. Most of this was evaporated. Waste water discharged into rivers and streams by the mining industry amounted to 2840 mgd or 3.9 billion MT.

By contrast, the weight of solid wastes from metallurgical conversion and fossil fuel combustion processes, including metallurgical reduction (smelting), amounted to only about 122 MMT. We have included in this category 62 MMT of fly ash from thermal power generators and 14.4 MMT of FGD waste, but excluded 34.4 MMT of iron/steel slag that has commercial uses.

Organic wastes (mostly waterborne) appear to amount to 125-135 MMT, dry weight, mostly from food processing and wood pulping. However, this may be an overestimate to the extent that some of these wastes are burned, either for process heat or to reduce waste volume. In addition, the pulp & paper sector withdrew and discharged about 3500 mgd (4.8 billion MT) or process water, while the food industry added another 1850 mgd (2.55 billion MT).

Gaseous combustion products constituted another very large waste stream. We estimate a total of 2.866 billion MT of CO_2 (of which 2700 was from fossil fuel combustion), 32 MMT of SO_2 from coal, plus EPA's estimate of 20 MMT of NO_X from fossil fuel combustion. Our methodology is not well-suited to estimating fugitive emissions, or particulate emissions. However we note that petroleum refineries may be emitting around 4.3 MMT of hydrocarbons, which are not accounted for anywhere else.

Process water contaminated by acids or other wastes was also emitted in significant quantities by the petroleum refining and metallurgical sectors.

The quantitative values discussed above can be summarized as follows:

PRELIMINARY SUMMARY OF ESTIMATED U.S. 1988 DRY-WASTE STREAMS EXCLUDING WATER (million metric tons)

	Organic (waterborne or solid)	*Overburden moved*	*Concentration (flotation) waste "dry"*	*Conversion waste (including slag, ash)*	*Combustion, calcination (airborne)*
Grain	5-10	1500[a]			
Other food	74[b]				
Pulp/paper	40[b]				
Metal mining (inc. phosphorus)		1193	600		
Non-metallic minerals[c] (inc. stone, clay, glass, cement)		47	36	36.5	34 (CO_2)
Primary metals				9 [d]	[e]
Fossil fuels; mining, refining & consumption		5600	260	62 (ash) 14.4(FGD)	4.3(VOC) 32 (SO_2) 20 (NO_X) 2700 (CO_2)
Total accounted for	119-124	8340	896	121.9	2789.3

(a) Erosion losses of topsoil
(b) Not adjusted for possible combustion of organic waste (e.g. "black liquor" as fuel or to reduce volume
(c) The airborne CO_2 emissions shown are produced solely from calcination.
(d) Excluding iron/steel slag
(e) Included with fossil fuels

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Appendix: Detail Tables

TABLE I: AGRICULTURAL PRODUCTION IN THE U.S. 1988 (million metric tons)

Commodity	*Production*		*Exports*	*Imports*	*Consumption*		*Reference*
	Raw	*Finished*			*Raw*	*Finished*	
Beef & veal	17.82	10.88	0.31	1.09	11.62	11.20	1170,1168,A131
Lamb & mutton	0.32	0.15	0.00	0.02	0.18	0.18	1169,1168,A131
Pork	9.91	7.11	0.09	0.52	7.51	4.87	1171,1168,A131
Poultry	12.95					6.37	1175
Eggs	4.44					3.86	1177
Dairy products	65.86	64.41				33.42	1173,A131
Subtotal	111.30		2.77	1.26		59.90	1149
Food grains	56.55		44.26			17.37	A129,A133,1147,1149
Feeds & fodders			11.37				1149
Feed grains & products	147.06		55.21				A129,A133,1147,1149
Oilseeds & products	43.75		26.90				A129,A133,1147,1149
Hay	114.31						A129,A133,1147,1149
Sugar cane	27.13	2.88		1.21		3.40	A129,A133,1147,1149
Sugar beets	22.51	2.97				3.40	A129,A133,1147,1149
Other field products	5.03		1.57				A129,A133,1147,1149
Corn syrup						7.64	207
Subtotal	416.34		139.31			31.81	
Vegetables	25.14					22.27	1166,1167
Fruits	25.60					11.51	1166,1167
Nuts	0.55						1166,1167
Fruits, nuts & vegetables			4.06	6.74			1149
Coffee, cocoa				1.48		3.40	1149
Subtotal	51.30		4.06	8.21		37.17	1147,1149
Fish	3.26		0.48	3.37	4.77	1.40	1197,A131,1210
Vegetable oils		6.40	1.30	1.35		6.66	1147,1149
SUMMARY							
Animal products	111.30		2.77	1.26		59.90	
Field products	416.34		139.31			31.81	
Vegetable products	51.30		4.06	8.21		37.17	
Fishery products	3.26		0.48	3.37	4.77	1.40	
Vegetable oils		6.40	1.30	1.35		6.66	
TOTAL	582.20		147.92	14.19	4.77	136.94	

NOTES: (See detail tables for more explicit explanations)
Poultry conversion at $.33/lb
Egg conversion at .77 kg/dozen
Fruit & vegetable box weights averaged where not specified.
Food grains = wheat, rice, rye
Feed grains & products = corn & sorghum for grain, barley, oats
Oilseeds & products = soybeans, peanuts, cottonseed, flaxseed
Other field products = dry beans & peas, cotton lint, tobacco

Sources: Statistical Abstract of the United States 1991 - numbered references are to Table numbers.
World Almanac 1991 - references A(nnn) are to page numbers

TABLE II: FOREST PRODUCTS IN THE U.S. 1988 (million metric tons)

Commodity	*Production* Raw	*Production* Finished	*Exports*	*Imports*	*Consumption* Raw	*Consumption* Finished	*Reference*
TIMBER							
Hardwood	44.02		3.71		40.37		1184
Softwood	80.88		20.52	31.45	91.78		1184
Fuelwood	23.78				23.78		1184
Subtotal	148.68		24.24	31.45	155.92		
PAPER PRODUCTS							
Newsprint		5.43		8.59		12.24	1193
Other paper & board		65.41	5.16	3.30		77.12	1191,1192,1196
Net wastepaper recovered		6.71					1194
Subtotal		77.55	5.16	11.89		84.36	
TIMBER INPUT: PULP & PAPER							
Pulpwood-hard	26.54				26.54		1195
Pulpwood-soft	60.05				59.96		1195
Woodpulp		57.88				56.79	1195
OTHER INPUTS: PULP & PAPER							
Ammonia					0.15		est
Kaolin, coating						2.48	(a)
Kaolin, filling						1.48	(a)
Lime					1.14		(a)
Sulfur					0.29		(a)
Sulfuric acid					0.08		(a)
Sodium sulfate					0.48		(a)
Soda ash					0.11		(a)
Salt					0.34		(a)
Chlorine					1.80		(b)
Caustic soda					1.20		(b)
Aluminum sulfate					0.77		est
Titanium dioxide					0.22		est
Subtotal					6.43		

NOTES: 128 cubic feet/cord
Softwood converted at 2000 lb/cord = 15.6 lb/cubic foot
hardwood converted at 3500 lb/cord = 27.3 lb/cubic foot

Sources: Statistical Abstract of the United States 1991 - numbered references are to table numbers.

(a) U.S. Bureau of Mines, Minerals Yearbooks, 1988 & 1989

(b) Lowenheim & Moran, Faith, Keyes & Clark's Industrial Chemicals (1972 estimated data)

TABLE III: PRODUCTION & WASTE ALLOCATION FOR PRIMARY U.S. METAL PRODUCTION 1988 (thousand metric tons)

	Total material handled	*Ore treated or sold*	*Over burden*	*Concentrate (d)*			*Concen tration wastes*	*Primary metal production*			*Smelting /refining losses*
				production (metal content)	*production (gross weight)*	*consumption (gross weight)*		*domestic ores*	*foreign ores*	*total*	
	A	*B*	*A-B*		*C*	*D*	*B-C*			*E*	*D-E*
Aluminum	8246	1107	7140		4575	7730				3944	3786
Copper	523446	218631	304814	1341	5364	5794	213267			1406	4388
Gold	536146	117934	418212	0.201	0.201	392	117934			0.138	392
Iron	300278	197766	102512		57515	83694	140251			49242	34452
Lead	9707	6450	3257	385	481	490	5969	371	21	392	98
Molybdenum	127006	72212	54794	43	172	103	72040			26	77
Platinum Group	34189 (b)	11396 (c)	22793	0.005	0.005	.0003	11396			0.00030	
Silver	48444	15876	32568	1.661	1.661	2	15874			1.718	
Zinc	21149 (c)	9106 (c)	12043	244	432	429	8674	196	45	241	188
Uranium Oxide[a]	22000	15200	6800		20	20	15180			5	15
Phosphorus	451778	224075	227703		45389		178686				
TOTAL	2082389	889753	1192636		113950		779271			55258	43396

NOTES: (a) 1980 data

(b) Assumes 3:1 ratio material handled to ore - as with gold/silver

(c) Zinc data from page 1159 has been subtracted from "other" on page 59 of Minerals Yearbook 1989 to construct approximate platinum data.

(d) Reasonable concentration ratios were assumed to calculate gross weight where data was lacking

Source: U.S. Bureau of Mines, *Minerals Yearbooks, 1988 & 1989.*

TABLE IV: PRODUCTION & WASTE ALLOCATION FOR U.S. INDUSTRIAL MINERAL PRODUCTION FROM DOMESTIC AND FOREIGN ORES, 1988 (thousand metric tons)

	Total material handled P.70	*Ore treated or sold P.69*	*Domestic production from detail tables*	*Exports*	*Imports*	*Apparent Consumption*	*Over burden loss*	*Concen-tration losses*
	A.	*B.*	*C.*	*D.*	*E.*	*F=(C-D+E)*	*(F/C)*(A-B)*	*(F/C)*(B-F)*
Abrasives, natural	232	156	156			156	76	
Barite	404	404	404	0.205	1207	1611	0	0
Clays	83370	44633	44515	3535	33	41013	35689	109
Diatomite	3420	695	629	147	0	482	2088	51
Feldspar	649	649	649	12	287	924	0	0
Gypsum	18325	14869	14869	246	8782	23405	5441	0
Mica	130	130	130	6	12	136	0	0
Perlite	586	586	585	0	0	585	0	1
Potassium Salts	12247	11884	2999	579	6964	9384	1135	27801
Pumice	423	374	353	1	28	380	53	22
Salt	34470	34470	34470	802	4966	38634	0	0
Sand & gravel	863640	863640	863531	1837	357	862051	0	109
Soda ash	15728	15728	8738	2238	257	6757	0	5405
Stone (88 is est.)	1151000	1150000	1148533	3304	3300	1148529	1000	1467
Talc, soapstone, pyrophilite	1179	1234	1234	382	80	932	-41	0
Vermiculite	3393	1769	275	18	32	289	1704	1567
CALCULATED TOTAL	2189196	2141220	2122070	13108	26305	2135267	47146	36532

Source: U.S. Bureau of Mines, *Minerals Yearbooks, 1988 & 1989.*

TABLE V: U.S. ENERGY STATISTICS 1988 (million metric tons)

Commodity	*Production*		*Exports*		*Imports*		*Consumption*	
	Raw	*Finished*	*Raw*	*Finished*	*Raw*	*Finished*	*Raw*	*Finished*
REFINERY INPUTS								
crude oil	402.585		0.634		269.053		680.687	
Feedstocks						16.864	22.585	
NGL		51.325		1.617		7.108		
REFINERY PRODUCTS								
LPG		15.906						56.272
Motor Gas		297.439		1.069		19.351		315.690
Av gas		1.020				0.020		1.074
Jet fuel		63.935		1.362		3.802		66.893
Kerosene		4.347		0.054		0.173		4.689
Diesel		143.258		3.419		12.943		146.315
Residual fuel oil		56.789		11.044		32.818		61.429
Naphtha		6.170		0.479		3.216		8.864
Petroleum coke		36.131		15.344		0.110		20.709
Other		54.073		2.626		5.865		57.072
TOTAL PETROLEUM	402.585	679.068	0.634	35.397	269.053	95.162	703.272	739.007
Coal & coke	862.066	29.397	86.203	0.992	1.936	2.439	801.647	30.844
Natural gas (.714 kg/m3)		484.013				3.457		363.258
NGL to chemical industry							16.230	
TOTAL OTHER FUEL		513.410	86.203	0.992	1.936	5.896	817.877	394.102
TOTAL	1264.651	1243.803	86.837	38.006	270.989	108.166	1521.149	1133.109

Source: [Energy Statistics of OECD Countries 1980-1989 :pp 664-665]

TABLE VI: ESTIMATED U.S. DISCHARGE OF TRACE ELEMENTS FROM COAL COMBUSTION

Flows (1000 MT/year)

	1950 analysis	*Discharged slag & fly ash* *Estimated 1980 (1.6*1950)*	*% of total discharge*
Silicon	7276	11641	43.5%
Iron	3429	5487	20.5%
Aluminum	3302	5283	19.7%
Calcium	1370	2192	8.19%
Potassium	486	778	2.91%
Magnesium	381	610	2.28%
Sodium	220	353	1.32%
Titanium	160	255	0.95%
Zinc	24.3	38.9	0.145%
Barium	20.6	32.9	0.123%
Manganese	10.6	17.0	0.063%
Vanadium	9.0	14.4	0.054%
Strontium	7.3	11.6	0.043%
Chromium	5.6	9.0	0.034%
Nickel	5.1	8.1	0.030%
Rubidium	4.8	7.7	0.029%
Molybdenum	2.8	4.5	0.017%
Copper	2.6	4.2	0.016%
Arsenic	1.6	2.5	0.0093%
Lead	1.5	2.5	0.0092%
Cobalt	0.91	1.5	0.0054%
Scandium	0.70	1.1	0.0042%
Uranium	0.69	1.1	0.0041%
Thorium	0.66	1.1	0.0040%
Selenium	0.60	0.96	0.0036%
Cesium	0.34	0.55	0.0021%
Antimony	0.15	0.25	0.00092%
Cadmium	0.15	0.23	0.00087%
Bromine	0.09	0.15	0.00054%

CONVERSION FACTORS USED

	MULTIPLY THIS	BY THIS TO GET TONNES	(LONG MULTIPLIER)
Barley - 50 lb/bu	bushels	2.27e-02	0.02267962
Broilers - 4.2 lb/bird	birds	1.91e-03	0.00190508808
Chickens - 4.6 lb/bird	birds	2.09e-03	0.00208652504
Citrus fruit - 83 lb boxes	boxes	3.76e-02	0.0376481692
Corn (shelled) - 56 lb/bu	bushels	2.54e-02	0.0254011744
Cotton - 480 lb/bale	bales	2.18e-01	0.217724352
Cottonseed - 31 lb/bu	bushels	1.41e-02	0.0140613644
Cranberries - 100 lb bbl	barrels	4.54e-02	0.04535924
Crude oil - 42 gal/bbl	barrels	1.44e-01	0.1442423832
Eggs - 2.25 ounces/egg	dozen eggs	7.65e-04	0.00076543718
Flaxseed - 56 lb/bu	bushels	2.54e-02	0.0254011744
Fuelwood - 15.625 lb/cu.ft	cubic feet	7.09e-03	0.00708738125
Grapefruit - 80 lb boxes	boxes	3.63e-02	0.036287392
Hardwood - 59.801 lb/cu.ft	cubic feet	2.71e-02	0.0271251799
Hardwood - 3500 lb/cord	cords	1.59e+00	1.5875734
Lemons - 76 lb boxes	boxes	3.45e-02	0.0344730224
Limes - 80 lb boxes	boxes	3.63e-02	0.036287392
Mercury - 76 lb flasks	flasks	3.45e-02	0.0344730224
Natural gas	cubic meters	7.14e-04	0.000714
Oats - 31 lb/bu	bushels	1.41e-02	0.0140613644
Oil, crude - 42 gal/bbl	barrels	1.44e-01	0.1442423832
Oranges - 85 lb boxes	boxes	3.86e-02	0.038555354
Poultry - 5.1 lb/bird	birds	2.31e-03	0.00231332124
Pulpwood - 2000 lb/cord	cords	9.07e-01	0.9071848
Rye - 56 lb/bu	bushels	2.54e-02	0.0254011744
Softwood - 34.172 lb/cu.ft	cubic feet	1.55e-02	0.0155001028
Softwood - 2000 lb/cord	cords	9.07e-01	0.9071848
Sorghum - 50 lb/bu	bushels	2.27e-02	0.02267962
Soybeans - 60 lb/bu	bushels	2.72e-02	0.027215544
Tangelos - 90 lb boxes	boxes	4.08e-02	0.040823316
Temples - 90 lb boxes	boxes	4.08e-02	0.040823316
Turkeys - 22.3 lb/bird	birds	1.01e-02	0.01011511052
Water - 10 lbs/ Imp. gal	imperial gallons	4.54e-03	0.004535924
Water - 8.33 lbs/gal	U.S. gallons	3.78e-03	0.00377842469
Wheat - 60 lb/bu	bushels	2.72e-02	0.027215544
Wood, lumber	board feet	7.02e-05	0.00007019394
Wood, plywood	board feet	8.46e-05	0.00008458885