

**"USE OF MATERIALS BALANCES TO ESTIMATE
AGGREGATE WASTE GENERATION IN THE US
(EXCLUDING CHEMICALS)"**

by

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USE OF MATERIALS BALANCES TO ESTIMATE AGGREGATE WASTE GENERATION IN THE U.S. (EXCLUDING CHEMICALS)

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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.

1. 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 published 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, 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.

2. Agriculture (SIC 01-02)

Inputs to the agriculture sector consist of sunlight, water, carbon dioxide (from the air), soil and chemicals (fertilizers and pesticides). Outputs are harvested crops, dairy products and livestock for slaughtering. Losses include soil erosion, nitrogen (and phosphorus) carried away by water sources and gaseous emissions.

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 (exclusive of harvested roughage fed to animals), 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. According to one estimate, crop residues remaining on the land are about 59% of harvest weight, or 37% of total plant biomass. This material is not a waste, of course.

In the food grain category (mainly wheat, plus some rice) production was 56.55 MMT, exports were reported to be 44.26 MMT, and 3.7 MMT were fed to animals. Exports were mostly of unmilled grain, but some milled grain products (flour, bulgur) were included. Exports were very high in that year, resulting in a decrease in wheat stocks by about 15.2 MMT.

In the case of feed grains and oil seeds (which can be lumped together, because corn dominates in both categories) 1988 domestic production was 190.8 MMT, while exports were 66.6 MMT. Stock depletions during the year amounted to 59.16 MMT for corn and 3.27 MMT for soybeans, while 119.4 MMT of feedgrains were fed to animals on U.S. farms. However, the statistics on animal feeding (below) may not exactly match the statistics on farm production and sales, partly because animal feeds are conventionally expressed by the US Department of Agriculture as "animal feed units", which are equivalent in nutrient value (but not weight) to 1 lb or 0.453 kg of corn.

A feed unit in the U.S. is defined to be equivalent to 0.357 kg of Total Digestible Nutrients (TDN), which implies 79% digestibility. From this we can conclude that 21% of the mass of animal feed concentrates fed to dairy cattle, beef cattle in feedlots, hogs and poultry is lost

immediately as feces. This does not include the manure produced by cattle and sheep grazing on pastures, where the fecal material is remains on the soil.

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 harvested roughage (such as cornstalks) mixed with other feeds, for a total of 319 MMT harvested inputs. By-products of the food processing industry such as grain mill by-products, oilseed meal, meat and fish meal, dried milk and molasses accounted for an additional 38.9 MMT.

The USDA estimates animal intake of pasturage (mainly by cattle) to be about 200 MMT. This would imply total animal feed consumption amounting to 558 MMT, not including water. Of this, roughly 75 MMT (0.21×358) becomes undigested fecal matter produced in feedlots or dairy farms, while another 80 MMT of manure (assuming 60% digestibility) is probably left on pastures. (This figure could be too low; the digestibility of pasturage may be as low as 40%). A total of 111.3 MMT can be accounted for as the gross weight of animal carcasses and dairy products produced for the market (see below). Obviously raw milk is largely water, so not all of this weight originated as feed. Of course most of the carbon intake from feed ends up as carbon dioxide in respiration.

However one other pollutant is worth mentioning, namely methane. All animals have anaerobic organisms in their guts which convert a small amount of food intake into methane, typically 1-2% on an energy basis. However for cattle and sheep the percentage is larger, ranging from 5.5% to 7.5%, depending on quality and quantity of feed. Taking these factors into account, Crutzen and Seiler have estimated annual methane output of 60 kg per head of cattle and 8 kg per head of sheep [Crutzen & Seiler 1986]. Cattle population in 1988 was 99.6 million, while sheep population was 10.5 million. Methane emissions from these sources amounted to 680,000 MT.

It should be noted that large tonnages of chemical inputs (fertilizers, pesticides) are used in the agricultural sector. The nitrogen content of ammonia used for fertilizer consumed domestically was 11.2 MMT in 1988 (76% of all the synthetic ammonia consumed in the U.S.) 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. Much of the nitrogen content of animal feed ends up in urine, either on pastures or at feedlots, resulting in both air and water pollution. We do not have an accurate estimate of the quantities involved, but probably two thirds of the urine is generated at feeding stations.

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 eventually excreted as animal waste [Crutzen 1976]. Most of this waste is generated at feedlots, since fertilizer is seldom used on grazing

land, and the nitrogen uptake by grazing animals is largely left behind as manure or urine. 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 at feeding stations, and 6 is from human sewage reflecting downstream consumption of food. Thus about 18% of agricultural nitrogen fertilizer use (N-content) reappears within a few weeks or months as waterborne pollution, although only 10% is direct fertilizer loss. Since 11.5 MMT (N) was used for fertilizer and feed supplements in 1988, this implies an overall waterborne N-waste flow of 2.76 MMT (N-content).¹

Schlesinger and Hartley have estimated annual NH_3 emissions per head from animals as follows: 15.5 kg from cattle and horses, 2.4 kg from sheep, 2.35 kg from pigs and 0.21 kg from poultry [Schlesinger & Hartley 1992, Table 4]. Based on 1988 populations of 99.6 million cattle, 55.5 million pigs, 10.9 million sheep and lambs, and 5.7 billion chickens and turkeys, this comes to a total of 2.91 MMT. Fertilizer itself is also a source of ammonia emissions; the emission factors for urea and ammonium sulfate spread on the soil surface are estimated at 0.2 and 0.1 respectively; for other fertilizers — including anhydrous ammonia injected directly into the soil — the emission rate is lower (around 3%) [ibid Table 6]. In 1988 2.49 MMT of urea (N-content) was used as fertilizer in the U.S., along with 0.340 MMT (N-content) of ammonium sulfate and 6.84 MMT (N) of other types. Altogether, animal metabolism and fertilizer use apparently generated ammonia emissions of $2.91+0.88 = 3.79$ MMT (N), nearly 33% of the 11.6 MMT (N) of ammonia equivalent that was used as fertilizer. Of this, about 8% was a direct loss.

The rest of the unaccounted for nitrogen in the applied fertilizer (about 32%) is embodied in root and stem material that is unharvested or harvested directly by animals and remains with the soil (20%-25%), or is re-converted to nitrogen gas and returned to the atmosphere by denitrifying bacteria in the soil (5%-10%) [Meisinger 1993; Legg & Meisinger 1982; Meisinger & Randall 1991]. For every 16 units of nitrogen emitted as N_2 , it seems that roughly 1 unit (on average) is emitted as N_2O , a potent Greenhouse gas, but these emissions tend to be episodic and associated mostly with transitional periods. 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).

The greatest mass movement (albeit not necessarily waste) from agriculture is the loss of topsoil due to wind or water 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 soil 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. However, it must be pointed out that eroded material is not necessarily carried far; it may be redeposited on the same field, or in the bed of a nearby stream.

¹ The details can be found in another paper [Ayres & Norberg-Bohm 1993]

To summarize, we estimate overall annual losses from U.S. agriculture as follows: topsoil erosion 1500 MMT; undigested feedstuffs (feces) from animals at feeding stations — not including grazing animals on pastures — amounted to around 75 MMT (dry weight), including roughly 42% of total nitrogen added to the soil, or about 4.8 MMT. Around 2.76 MMT of this ends up in watercourses; the rest goes into groundwater or is recycled back to the land. Ammonia emissions to the atmosphere from fertilizer use seem to be about 3.79 MMT. Methane emissions to the atmosphere from grazing animals in the U.S. seems to be around 0.68 MMT.

3. Food Processing (SIC 20)²

Major waste streams occur in grain milling, oilseed milling and sugar production. Inputs to the domestic milling sector can be estimated as gross production, less exports of current year production (equivalent to total exports minus stock drawdowns) less grain fed directly to animals (see *Figure 1*). For food grains in 1988 domestic mill inputs amounted to $56.55 - [44.26 - 15.21] - 3.7 = 23.40$ MMT based on this calculation. Applying the above logic to feedgrains and oilseeds, we have $190.8 - [66.6 - 63.43] - 119.4 = 68.2$ MMT as inputs to domestic grain and oilseed milling operations during 1988.³ Thus, total grain and oilseed mill inputs were 92 MMT. Losses (chaff, hulls) have been estimated at about 15% of total mass, or about 14 MMT [various sources, including USDA, FAO and Deere & Co.]

Domestic food products consumed (flour, prepared cereals, packaged rice, etc) from all grain mills in 1988 amounted to 17.37 MMT. In addition, 6.4 MMT of vegetable oils and 7.74 MMT of corn syrup were produced. Grain-based beverage alcohol (excluding wine) consumed in the U.S. amounted to approximately 2.2 MMT in 1988 (100% basis), of which about 60% was beer and the rest distilled spirits. Some ethyl alcohol was also produced for use as a gasoline additive (we lack detailed data on this, but an inferential argument below suggest 9 MMT). Grain input per unit of alcohol is roughly 2.5:1 on a weight basis, so 4 MMT of grain was presumably used in beer production, and at least 2 MMT (depending on the amount of non-beverage alcohol produced) was used by distilleries.

Altogether, feed concentrates and mill by-products amounting to 38.9 MMT were fed to domestic livestock in 1988. The latter figure includes some fish and meat meal, dried milk, molasses and so on not from grain mills. As indicated below, we estimate that at least 9 MMT of this was derived from other sources (meat processing, fish processing, dried milk, molasses, distillery by-products) leaving a maximum of 30 MMT as the contribution from milling. On this basis, we can account for at least 66.4 MMT of mill products and by-products, not including gasohol. This implies $92 - 67 = 25$ MMT as an upper limit for wastes generated by grain and oil seed milling. However, based on the 15% figure given above,

² 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.

³ In this calculation we have assumed that 11.37 MMT of exports of "feeds and fodders" were not processed in U.S. grain mills. This assumption is not particularly critical, because if some of these exports are really grain mill products, the corresponding amount should be added both to grain mill inputs and outputs.

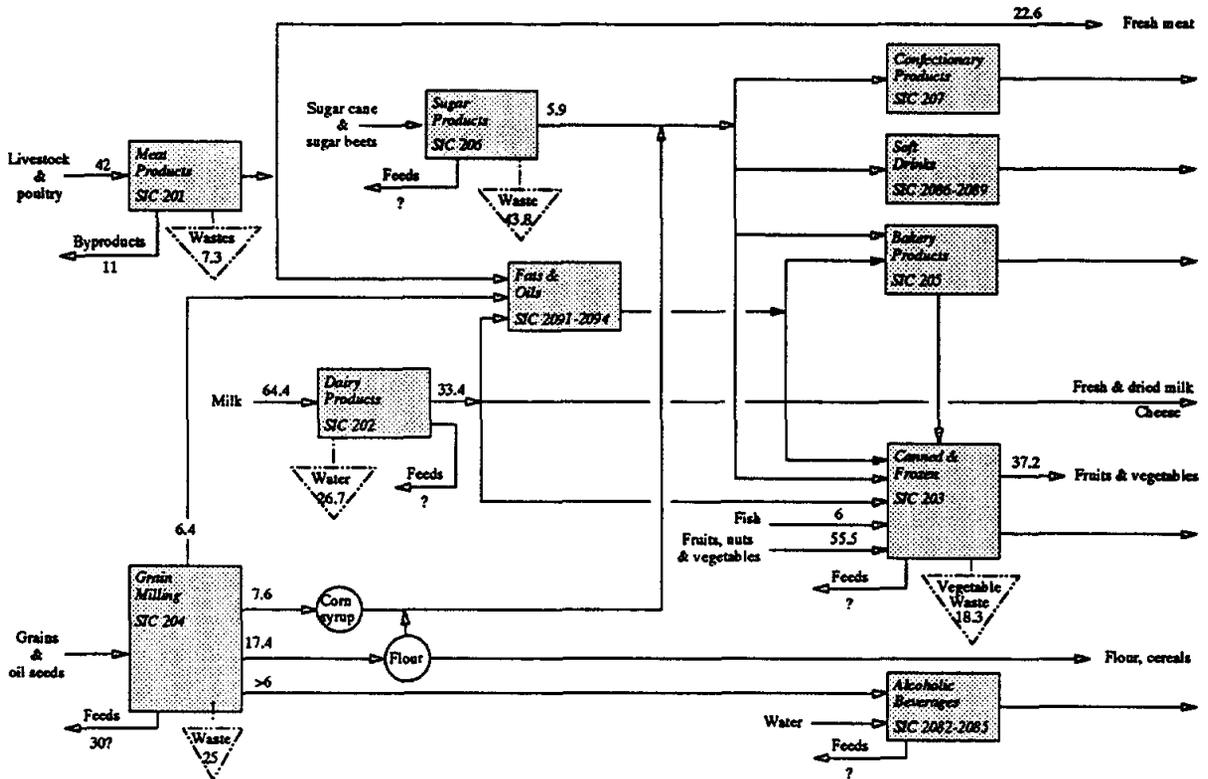


Figure 1: SIC 20: Food Processing in the U.S. 1988 (million metric tons)

Source: author

which suggests actual wastes of more like 14 MMT, the "missing" 9 MMT may be largely due to the use of grain for gasohol (ethanol) production. Another source of uncertainty is that more than 9 MMT of animal feed concentrates may be derived from sources other than grain or seed mills, as noted. As much as 2 MMT of the milling wastes may be lost in the form of dust. An unknown amount is burned in industrial boilers, incinerators or landfills. Relatively little goes into waterways.

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 sugar, and large quantities of pulpy cellulosic material. (About 0.69 MMT of lime were also used in this process). The residual from sugar milling has very little nutrient value, although some can be used as animal feeds. Organic wastes from these two subsectors, alone, amount to about 43.8 MMT, less whatever is consumed by animals. Virtually all of this waste will be waterborne.

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. The bulk of it goes into waterways or municipal wastes. A small amount may be burned for fuel.

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. 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 (roughly 1 MMT), dog and cat food, hides (leather), glue, blood and bone meal. The last two items are utilized in animal feed concentrates; we estimate 3 MMT may be recycled in this way. We estimate wastes from meat processing, at the plant, to be at least 10% of the weight reduction, or 1 MMT, mostly into waterways.

Exports of red meat products in 1988 amounted 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, live weight was 12.95 MMT in 1988. A similar 36% reduction from carcass weight to dressed weight would imply 8.3 MMT for the latter. However, whereas hides of cattle and hogs are removed and used for leather, and lard is also removed and rendered, this is not done for poultry. So, we estimate dressed weight of poultry to be about 9.5 MMT (?), which implies a by-product and waste flow at the processing plant of 3.5 MMT, part of which (2 MMT ?) is probably recycled as animal feed. The rest (mostly feathers) is dumped or burned. Final consumption of poultry ("as purchased") was 6.37 MMT in 1988. Thus, a further loss of $9.5 - 6.4 = 3.1$ MMT presumably occurred at the retail level, including restaurants. The latter ends up in waterways or 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, based on an estimate of average egg weight. This could easily be off by 15% or so, either way. However, it implies losses along the chain of 0.6 MMT (?), probably mainly in egg-using sectors like baking, prepared foods or restaurants.

Dairy products are a special case. Raw milk production in 1988 was 65.86 MMT, and 64.41 MMT was marketed. However final consumption of milk products was only 33.42 MMT. Some dried milk is used for animal feeding (2 MMT?) and some (about 2.3 MMT) is exported. However waste is very slight. Most of the reduction in apparent mass is essentially entirely due to evaporative losses of water in cheese-making and drying, about 26.7 MMT.

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 pet food, animal feed or wasted. We have no exact way to determine the allocation. Most imports arrive dressed and frozen (wastes being dumped directly into the ocean). 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 (fish meal). While a significant portion of fresh fish used by restaurants is lost as garbage. The latter is apparently a small portion of the total use. We estimate on-land processing losses (to waterways) as 10% of the "missing" weight, or 0.5 MMT (?) since many fish processing plants are small.

In summary, we estimate organic wastes from the domestic food processing sector as follows: grain milling 14 MMT, sugar milling 43.8 MMT, vegetable and fruit canning and freezing 18.3 MMT, meat and poultry packing and retailing 7.3 MMT, eggs 0.6 MMT and fish 0.5 MMT. For the sector as a whole (including losses in retail shops) this adds up to 86.5 MMT, (or slightly less, depending on how much grain is used for "gasohol"). We have not included a weight loss of 26.7 MMT evaporative water loss in manufacturing dairy products). This estimate takes into account the recycling of 39 MMT as by-product animal feed concentrates. We estimated that 30 MMT of these concentrates originated as grain and oilseed mill by-products, and 9 MMT as meat, fish and dairy by-products; the last number is unlikely to be too high, but it could be too low by as much as several (3-4) MMT. The exact allocation does not affect the sectoral total, however.

The material losses that we have identified as likely waste streams are "dry" in the sense that it does not include the weight of washing, cooking, or process water. In this connection, a survey by Science Applications Inc. (SAI) commissioned by EPA, attempted to identify dry wastes from the industrial sectors [SAI 1985]. The SAI estimate for SIC 20 was 6.3 MMT (based on 1976 data). We note that our estimate is roughly fifteen times larger.

On the other hand, the 1983 Census of Manufactures reported that the food processing industry withdrew 2550 MMT of water (1850 mgd) and presumably discharged a similar amount, less some evaporative loss. The sector reported an internal recycle ratio of 2.2. It is worth noting that EPA's Office of Solid Waste Management conducted a survey (1985) which estimated total waste generation by the food processing sector (SIC 20) to be 336 MMT for the year 1985 [USEPA 1988]. Evidently, this includes at least some washing and process waste water, but probably not all. EPA's estimate of waste discharges is only about 15% of the Census figure for 1983. The two estimates can only be reconciled if 85% of the intake was used for cooling purposes only, which is not likely. It seems more likely that EPA's figures are too low by a factor of 3 or 4.

4. Forest Products: Lumber (SIC 24) and Pulp and Paper (SIC 26)⁴

⁴ 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. 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. 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 $15.6 * 2.187 = 34.2$ lb.

Harvested forest products consist of logs ("roundwood") in three sub-categories, softwood (from conifer trees), hardwood, and fuel wood. The structure of this Sector is shown in *Figure 2*. 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.

Incidentally, the above does not account for the total mass of paper products. U.S. consumption of paper, paperboard and paperboard containers was 84.36 MMT, include imports of 11.89 MMT. Exports were 5.16 MMT. Pulp mills supplied only 56.8 MMT, leaving 16.9 MMT of domestic products unaccounted for. Meanwhile, the industry claimed that 30% of all paper products were recycled in 1988. If so, 25 MMT of cellulosic material must have re-entered the industry, of which only 6.71 went through pulping mills. This leaves 18.3 MMT of "missing" waste paper, which corresponds reasonably well with the 16.9 MMT of unaccountable paperboard products. The difference of 1.4 MMT presumably consists of process losses from recycling. We do not have exact data on these "phantom" processes.

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.

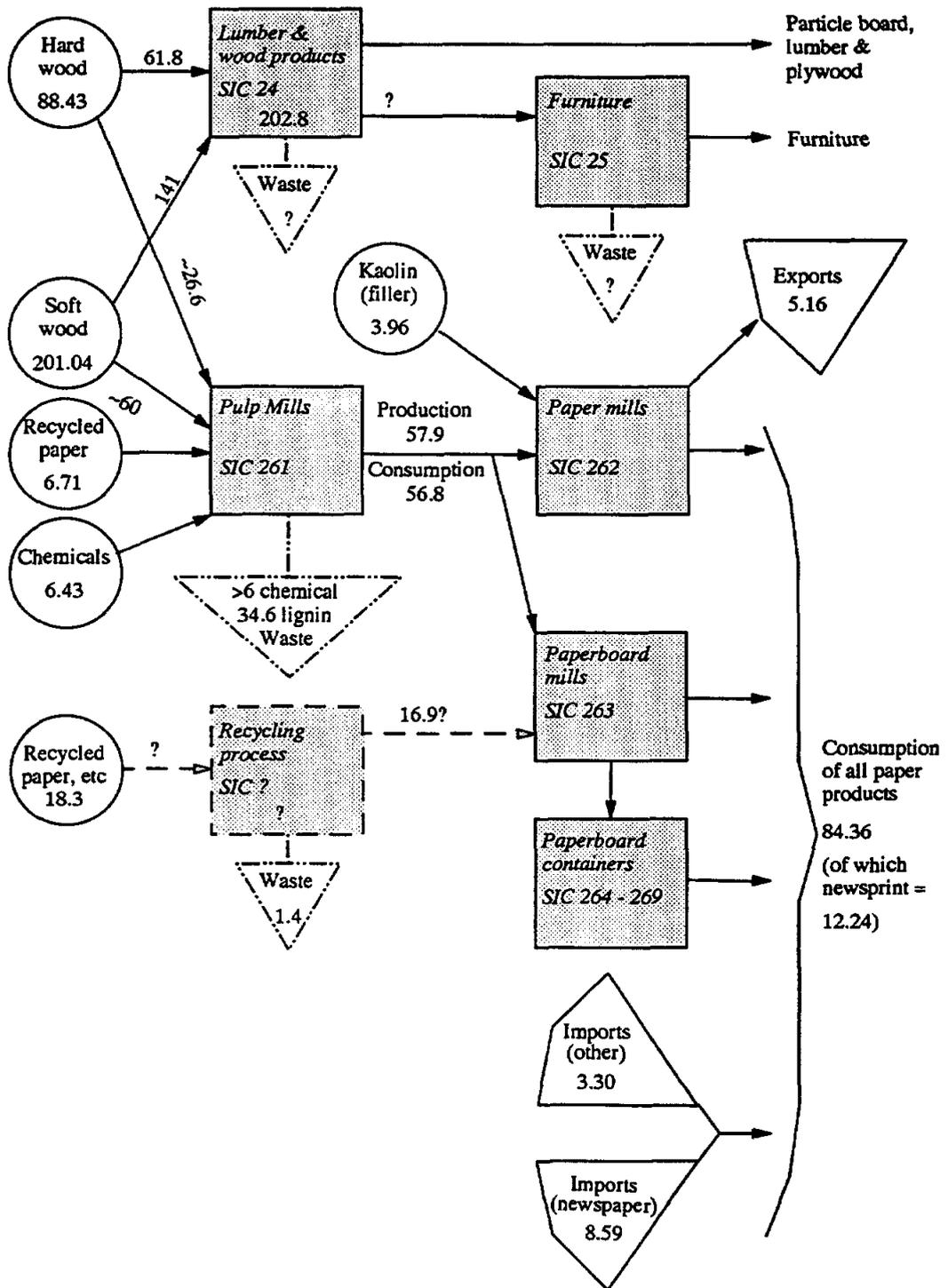


Figure 2: SIC 24-26: Wood, Pulp & Paper Sectors in the US 1988 (mmt)

Source: author

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 is 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.⁵ 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, plus recycling wastes, we impute a total of around 43 MMT waste for 1988, not including water. This figure is more than 5 times larger than the 8.5 million short tons of "dry" waste reported by an EPA contractor [SAI 1985]. EPA has estimated airborne effluents (excluding CO₂) from the sector to be about 1.15 MMT [USEPA 1991].

The 1983 Census of Manufactures reported water withdrawals by the pulp and paper sector (SIC 26) of 7452 MMT (5400mgd), of which 30% was used for cooling purposes and the rest for processing. Discharges of process water were therefore 4830 MMT, or slightly less to account for evaporative losses. The internal recycling ratio for the sector as a whole was reported to be 3.9. Since pulp and paper mills are mostly located in areas with ample fresh water supplies, there is little incentive to recycle cooling water. This implies that each unit of process water was recycled about 5 times before discharge into rivers and streams. By contrast, EPA estimated total (i.e. "wet") wastes amounting to 2200 MMT in 1985 [USEPA 1988].

It is difficult to reconcile these figures, unless EPA underestimated total wastes or water use was declining very rapidly in the 1980's.⁶ Actually, the latter is not unlikely. It has been relatively easy for the pulp and paper industry to reduce its water use, given that most of the weight of process wastes is water. Historically, most of the lignin waste discharges in the U.S. were (and still are) waterborne. Under pressure from environmental regulations, the pulp/paper industry is making an increasing effort to recover more of the chemicals, cut back sharply on water use, and incinerate the residual lignin wastes for energy production. This does not change the materials balance calculations exemplified above, but it does reduce the effluents into rivers and streams (by increasing the airborne emissions instead).

⁵ 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.

⁶ During this decade Finnish pulp and paper mills cut their water use by 90%.

5. Mining (Metal Ores) & Quarrying (SIC 10, 14)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 downstream process, either smelting (for metals) or combustion for fuels⁸. Smelting wastes are discussed in connection with the metallurgical industry (SIC 33); combustion wastes are discussed separately in connection with fossil fuel combustion.

The Bureau of Mines estimates that mineral exploration and mine development activities in 1988 (not including energy fuels) generated 190 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 1192 MMT; overburden moved to supply U.S. metals consumption, adjusted for both imports and exports, was 1140 MMT. Mining activities altogether consumed 1.87 MMT of industrial explosives, of which 85% was ammonium nitrate based. We have calculated that about 5% of the mass of explosive was probably converted to N₂O, 14 % to NO and 5% to N₂O. This implies N₂O emissions of 0.09 MMT and NO_x emissions of about 0.27 MMT from explosives alone.

Total concentration wastes for metals mined and concentrated domestically were about 780 MMT, including uranium (discussed later). Adjusting for imports and exports reduces the total slightly to 730 MMT. 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 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. Wastes from flotation are generally disposed of in ponds, mostly in dry areas. Chemical reagents used amounted to 0.63 MMT. Grinding mills required 8 billion kwh of electricity and 134,000 MT of rods and balls.

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%

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.

⁸ In the case of iron, concentrates for blast furnaces (pellets and sinter) are treated differently. Pellets are produced at the mine, while sinter is included in the smelting sector rather than in the mining sector. For consistency, we adopt this convention. In the case of aluminum, the "concentration" stage is taken to be the chemical conversion of bauxite ore into pure aluminum oxide (alumina). This process is conventionally included in the inorganic chemical industry (SIC 2819). Phosphate rock concentration (yielding fertilizer grade "superphosphate" is included in the fertilizer industry (SIC 2873). Phosphorus metal and phosphoric acid from phosphorus are both also included with inorganic chemicals in SIC 2819.

Al). It is further concentrated to relatively pure Al_2O_3 by the so-called Bayer process, included in the inorganic chemical industry (SIC 2819), 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 due to declining demand, it was 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 785 MMT, including alumina and crude phosphate rock processing, or about 600 MMT without them (both belong to the chemical industry, SIC 28). For non-metallic minerals (excluding coal) overburden wastes were 47 MMT and concentration wastes were 36.5 MMT. The overall total for metals and minerals amounts to 1239 MMT in overburden wastes, and 636 MMT concentration wastes, essentially dry weight, not counting alumina and superphosphate (included with chemicals). 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 2.05 billion metric tons (dry), excluding water used for flotation. It is interesting to contrast this

with other published estimates. The only one we could find was a figure for 1985, reported by an EPA contractor, namely 1.4 billion metric tons [SAI 1985]. But the latter figure supposedly included the coal mining sectors also (SIC 11-12), which we discuss below.

Water used in the flotation processes for metal ore concentration in 1985 was 3580 MMT, as noted above. The 1983 Census of Manufactures reported water intake by the entire mining sector (including coal, oil and gas) to be 4500 MMT (3280 mgd), while reported discharges were only 3900 MMT (2840 mgd), implying an evaporative loss of only 600 MMT. Since the flotation processes alone account for much more than this, it is hard to reconcile the figures. Either some of the flotation water is actually discharged (or seeps) into rivers, or unless the coal mining, oil and gas sectors produce much more water than they consume. Actually, EPA reported that the oil and gas sector alone produced somewhere in the neighborhood of 1800 to 2400 MMT of excess water, which would help to explain the apparent discrepancy. In any case, the Census data seem to be incomplete, since 12% of the water withdrawals was designated as for "cooling" (mainly in the gas fractionation sector) and 44% was designated as "process", while the remaining 44% was unallocated. Clearly, a much more detailed study of water use and waste production in the mining sector seems called for.

6. Mineral Fuels: Coal Mining & Oil & Gas Drilling (SIC 11-13)

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 rate of 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). The 1983 Census of Manufactures reported that coal mines discharged 470 MMT (340 mgd) of water, including washing water. Combustion emissions are discussed later.

Petroleum and natural gas production involve relatively little waste, except water. As an indicator, it might be mentioned that petroleum drilling accounts for virtually the whole national consumption of the mineral barite, or 1.4 MT. Barite, along with 0.88 MMT of clay, is used as "drilling mud". During 1988 the U.S. oil and gas industry drilled 25,000 wells and drilled 124 million feet of holes. 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 displaced by pipe, or about 2 MMT, plus (roughly) another 4-5 MMT or so of material that was removed and displaced by the drilling mud (allowing for water content). We therefore estimate a total of 6-7 MMT for drilling wastes (earth and rock).

EPA has published estimates of unspecified drilling wastes, namely 129-871 million (short) tons, plus 1,966-2738 million (short) tons of "produced waters" [USEPA 1987, cited by Allen & Behmanesh 1992]. It is difficult to interpret the EPA drilling waste estimate. (We wonder whether it is a misprint). However, the excess of "produced waters" would help to reconcile the water data for the mining sector as a whole, as noted in the previous section. The 1983 Census of Manufactures reported about 700 MMT (523 mgd) of water used for cooling in the gas fractionation process.

7. Petroleum Refining (SIC 29)⁹

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 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-condensable 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 most of this missing mass consists of hydrocarbons, including fugitive emissions (VOC). However, about 0.8 MMT of the missing mass is sulfur, discussed below. 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, CO₂ production would be 106 MMT (or 29 MMT C equivalent).

Crude oil contains small quantities of sulfur and mineral ash (of the order of 0.1%), depending on its origin. (For example, Venezuelan oil is particularly high in sulfur). The petroleum refining industry recovers sulfur from crude oil and produces some sulfuric acid as a by-product (2.4 MMT H₂SO₄, or 0.786 MMT S). Most of this acid is used, initially, within the refinery, for bleaching. However, over half of the spent acid recovered and sold as a by-product (1.3 MMT). Most of the ash in crude oil probably remains with the residual oil and asphalt. The remainder of the sulfuric acid (2.1 MMT) is presumably neutralized — probably by reaction with some of the alkaline minerals (NaO, KO, MgO, CaO) in the ash content of crude oil, and ends as liquid or solid waste in a landfill. We estimate 3-4 MMT. Refineries also utilize purchased materials from other sectors in the refining process, including salt (0.72 MMT) and clays (used as zeolite catalysts, 0.122 MMT) which subsequently reappear in (mostly solid or liquid) wastes. Since these materials do not appear in products, they must be part of the waste stream.

An EPA contractor estimated dry wastes by the petroleum refining sector to have been 1.25 MMT (1981 data). Given the fact that neutralized sulfuric acid wastes apparently account for

⁹ All data in this section was extracted from a single source, [OECD/IEA 1991] *Energy Statistics of OECD Countries, 1980-1989* :664-665.

considerably more than this, we suspect the correct number will be 3-4 times larger, although some of the sulfates and salt are soluble and may be disposed of in watercourses. (To estimate it more accurately we will need more complete data on materials inputs to the sector).

EPA estimated airborne effluents from the sector as 2 MMT [USEPA 1991]. This is consistent with materials balance arguments. EPA's estimate of total non-hazardous waste produced by the sector in 1985 was 150 MMT. Since the "missing mass" in the sector was only a bit over 5 MMT (including purchased inputs), and some of this must have been airborne, it is clear that most of the waste mass counted by EPA must have been water. The 1983 Census of Manufactures reported water withdrawals of 2900 MMT (2100 mgd), of which 91% was used for cooling purposes and 9% for processing. The sector reports a very high internal recycling ratio of 7.5. Wastewater discharges were therefore presumably less than 260 MMT (allowing for significant evaporative losses), which is not too far out of line with the EPA estimate.

8. 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. The latter is mostly recovered as ammonium sulfate. 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, EPA estimated that flue gas desulfurization (FGD) by utilities produced 16 million tons of solid 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 must have been 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 contains a small but significant percentage of "fuel bound" 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.

Coal also contains significant quantities of mineral ash (equivalent to the mineral shale). The average ash content of U.S. coal is approximately 10% [Torrey 1978]. Actually, utilities alone seem to have collected and disposed of 69 million short tons — 62 MMT — of ash in 1983. Assuming constant proportions of ash in coal used, and ash recovery, this would have risen to 76 MMT by 1988, which would account for almost all of the ash in the utility coal. However, while recovery of fly ash from electrostatic precipitators is in the neighborhood of 99.8% for the most modern units, some utilities are not so well equipped. Fly ash not captured in 1988 probably amounted to at least 1 MMT. Other industrial users of coal generate no ash, as waste. The ash content of coking coal (which is selected in part for its low ash content) ends up in metallurgical slag. The ash content of coal used as a fuel in the cement industry ends up as part of the cement itself. (In fact, the cement industry also uses some fly ash as a raw material, though we have no exact data on this for the U.S.)

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. While most fly ash is captured, the waste ash must be disposed of somehow. Moreover, the more volatile trace metals like arsenic and mercury, still escape as vapor and re-condense downwind of the stack.¹⁰

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 1521.149 MMT (Appendix Table V). The carbon content is 75% for methane (the major component of natural gas), and about 86% for petroleum products (assuming ash and sulfur are removed at the refinery). In the case of raw coal, we must first subtract 10% for ash and 8% for sulfur, nitrogen, water and oxygen. About half of the sulfur and some ash is removed by washing, as noted above, leaving about 2.3% sulfur in the coal as burned. The combustible remainder of the coal is close to 90% carbon, but overall the carbon content is closer to 75%. The Carbon Dioxide Information Analysis Center at Oak Ridge National Laboratory estimated that the carbon content of this fuel was 1288.6 MMT, or 84.7%. We can assume that all of the fuel carbon was converted to CO_2 (4726 MMT). This includes the CO_2 from carbothermic reduction processes using coke, but not from calcination processes (lime and cement manufacturing, which are counted separately).

9. Primary Metals Smelting & Refining (SIC 33)¹¹

¹⁰ U.S. coal is unusually low in ash, most of which is recovered. By contrast, most other countries burn coal that has a much higher ash content — 15% to 25% or more — very little of which is recovered. Thus the problem of heavy metal pollution from coal burning will be far more serious in eastern Europe, the former Soviet Union, China and India.

¹¹ Data mostly from Minerals Yearbook.

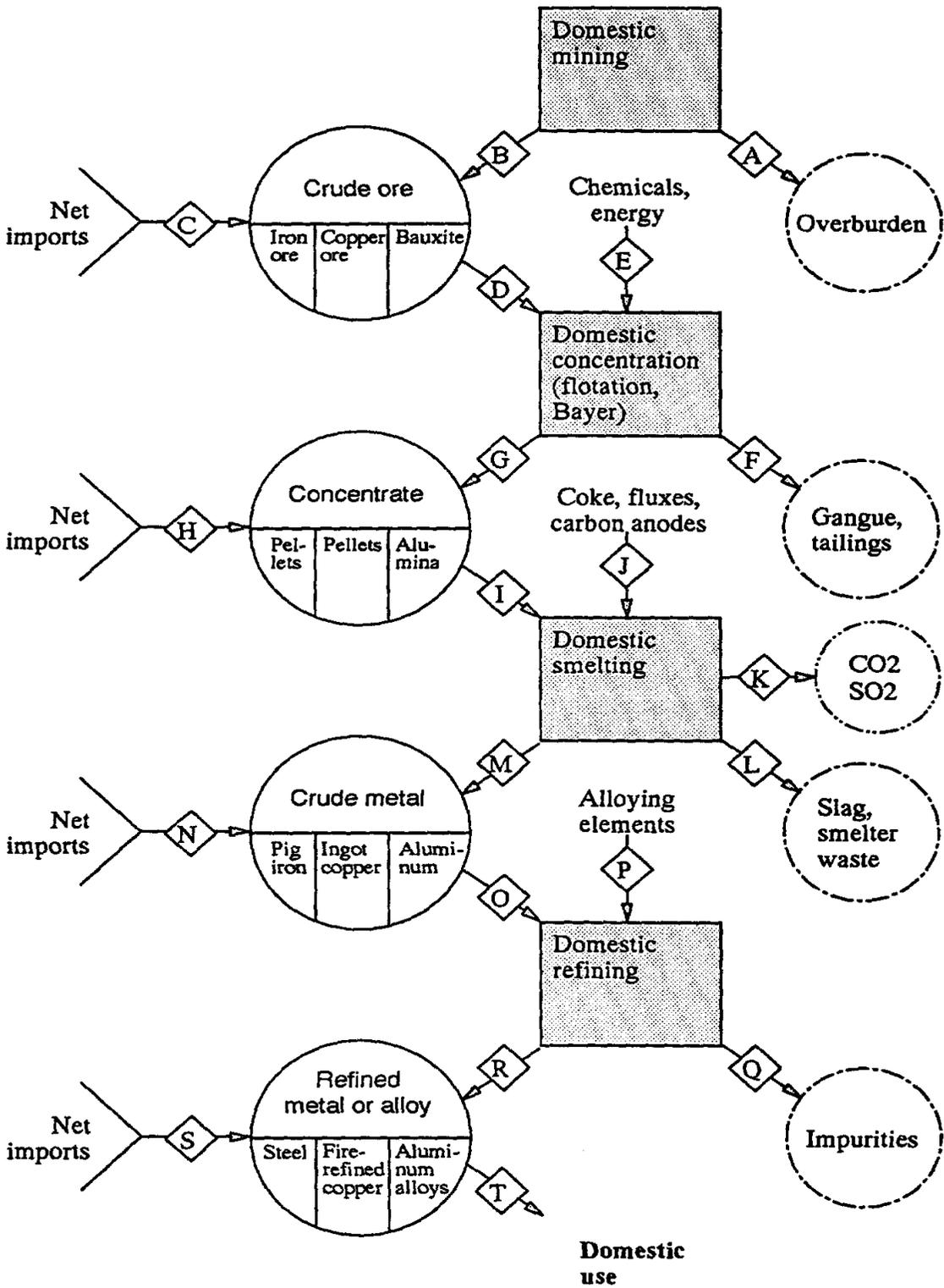


Figure 3: Metals Processing Relationships
Source: author

We have conceptually divided the processes of mining, concentration (or winning), reduction or smelting and refining as shown schematically in *Figure 3*. There are four stages of separation. The first two, being physical in nature, are assigned to the mining sector (SIC 11) or the quarrying sector (SIC 14). The last two, being chemical in nature, are assigned to the primary metals sector (SIC 33). At each separation stage, wastes are left behind and a purified product is sent along to the next stage. In principle, the wastes can be determined by subtracting outputs from inputs. Unfortunately, from the analytic point of view, published data is rarely available in appropriate forms. There are significant imports and exports of concentrates and crude metals (and even some crude ores) but trade data is often given in terms of metal content, rather than gross weight. Domestic data is also incomplete, due to the large number of data withheld for proprietary reasons. Thus, in a number of cases, we have been forced to work back from smelting or concentration process data to estimate the input quantities of concentrates. Our summary is given in Table III in the Appendix. It excludes ferroalloys, of which U.S. production was about 1 MMT, because of the extreme complexity of the subsector.

Inputs to the U.S. primary metals sector consist of concentrates (produced in the mining sector, or imported), fuels, fluxes, and processing chemicals. We have already discussed fossil fuel combustion above, whence fuel inputs and CO and CO₂ are equally excluded from our materials balance. CO is a major pollutant of smelting processes, but it results from partial oxidation which is later completed in the atmosphere. (Thus, the materials balance approach is not applicable for estimating CO emissions.) Major purchased inputs, other than concentrates, are fluxes. The most important is limestone (and dolomite). In 1988 approximately 9.6 MMT (10.9 million short tons) of limestone and dolomite were used, mostly in blast furnaces (*Figure 4*). It appears from data published by the U.S. Bureau of Mines that this was actually calcined on site and consumed as lime (4.8 MMT). Other inputs to SIC 33 reported by the Bureau of Mines include salt (0.33 MMT), manganese ore (0.123 MMT) and fluorspar (0.137 MMT).

The production of primary metals from concentrates is normally accomplished by carbothermic reduction (smelting with coke), or electrolysis. 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).

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, to account for the virgin ore is somewhat complex (See *Figure 4*). 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

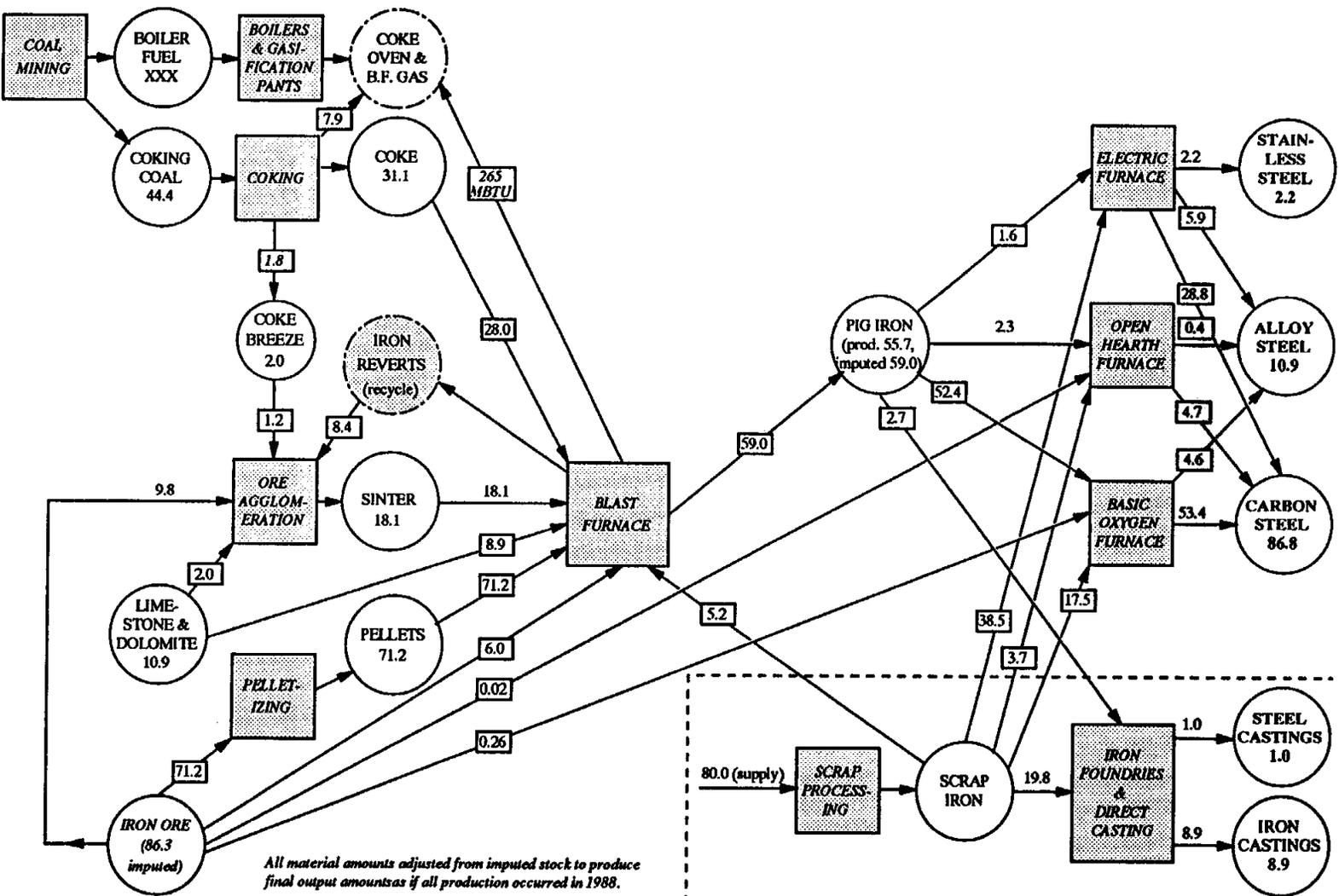


Figure 4: 1988 U.S. Composite Steel Production (million short tons)
 Source: authors

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 CO₂. In 1988, the steel industry accounted for 182 MMT of CO₂ from coke, which is included in the 2550 MMT from fossil fuel combustion, discussed above. (In addition, some other hydrocarbon fuels were used, also counted previously).

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. Unfortunately, materials balances cannot be used to estimate these wastes. However, they probably constitute a significant fraction of both water and airborne wastes from the primary iron and steel sector.

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 0.215 MMT of 100% sulfuric acid (0.074 MMT S content) were used for this purpose, producing 0.25-0.30 MMT 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, and most is waste.

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 CO₂ 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 CO₂ (already counted), 0.08 MMT of fluorides and about 0.17 MMT of particulates (Al₂O₃).

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 SO₂. Roughly 1 metric ton of sulfur is associated with each metric ton of copper smelted (see *Figure 5*), 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. non-ferrous metal refineries, as follows: copper (0.946 MMT),

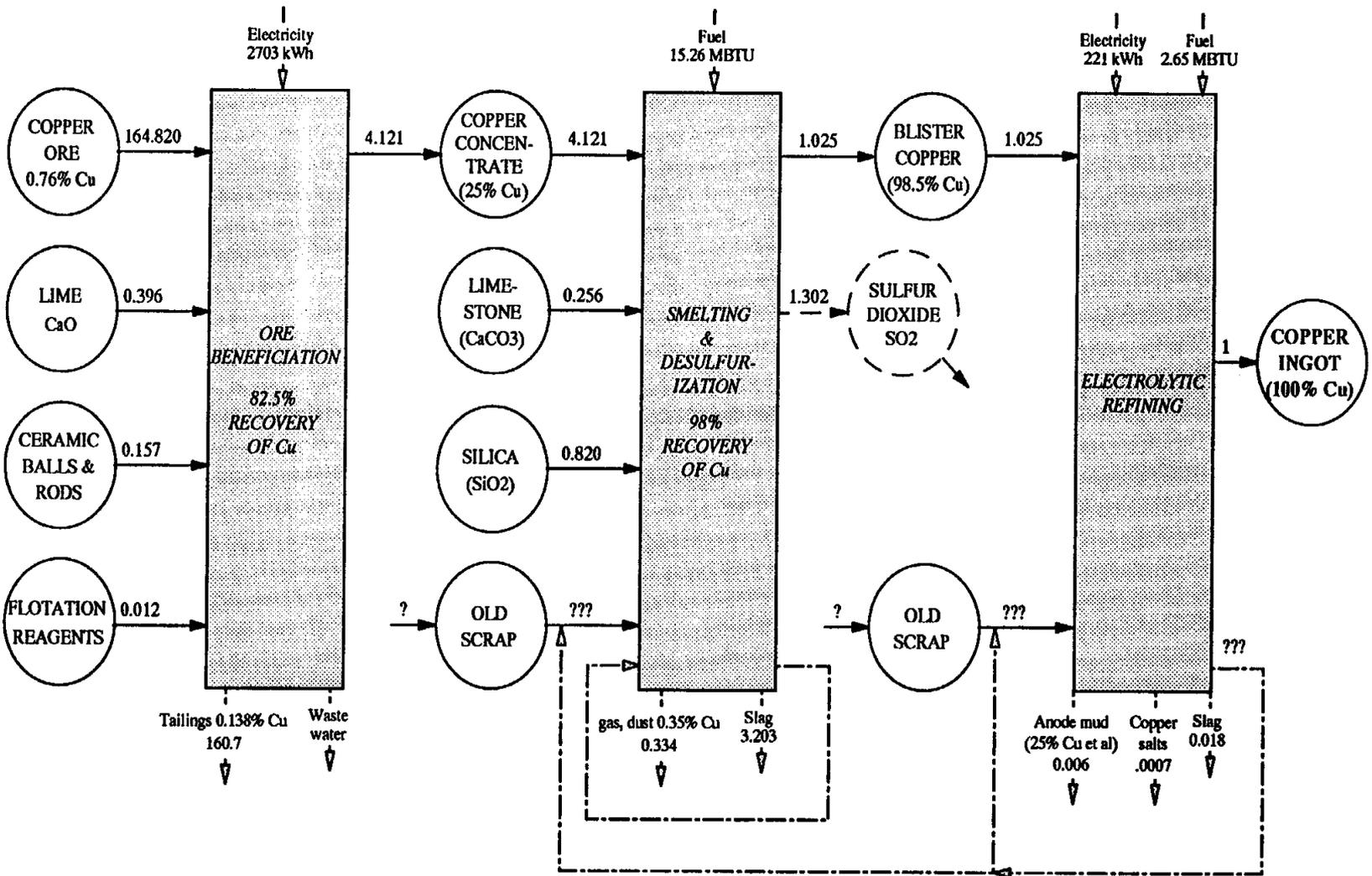


Figure 5: 1988 U.S. Composite Copper Production (million short tons)
 Source: authors

zinc (0.136 MMT), lead/ molybdenum (0.043 MMT). In terms of sulfuric acid (100% H₂SO₄) 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 is 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. Total slag production for the three main NF metals was therefore roughly 1 MMT *in toto*. 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, based on mass-balance considerations, we estimate smelting and refining wastes for primary metals, including CO₂, to have been 43.4 MMT in 1988, including the weight of limestone, manganese, fluorite, and other materials used in the blast furnaces and refineries. (This includes about 14.2 MMT of iron/steel slag, although most of this material is marketed commercially, mainly for road ballast). As noted above, much of the sulfur from sulfide copper, lead, zinc and molybdenum ores is also recovered for use, and sold as sulfuric acid (1.125 MMT S content in 1988). Subtracting the iron/steel slag, and the by-product sulfuric acid, we get 28.1 MMT as the residual waste. Of this, only about 1 MMT was solid (N.F. slag) and the rest would represent the oxygen content of the original ores — mostly iron — which is released as CO₂)¹². We have not included the wastes from coking, which we have not estimated. The major airborne emission other than CO₂ is probably CO and particulates. In both cases, blast furnaces are the major sources. The coking quench waters and some spent acids used for pickling constitute the major water-borne wastes.

For comparison, SAI estimated the 1983 wastes from iron and steel production (probably wet) at 6.0 MMT and from non-ferrous metals at 6.5 MMT [SAI 1985]. Their estimates were not specifically designated as "dry" so some water content can be presumed. EPA estimates airborne emissions from the primary metals sector as a whole to be 2.8 MMT, including particulates and CO, but not including CO₂ [USEPA 1991]. Both sets of estimates are roughly consistent with the above.

Water use by the iron and steel industry was reported in the 1983 Census of Manufactures to be 9000 MMT (6470 mgd), of which 3400 MMT (3590 mgd) was used for processing purposes and the remainder for cooling. The recycle ratio for the sector was reported to be 2.5. The iron and steel sector is mostly located on rivers or lakes with ample water

¹² Assuming the iron in ore is mostly in the form Fe₂O₃, the 57.5 MMT of iron content in ore (1988) would be combined with 25.55 MMT of oxygen. 100 kg of ore

availability, which probably explains this lavish use. By contrast, the non-ferrous smelters and refineries are mostly located in drier parts of the country where water is much less available, and much less is used. The EPA estimated total non-hazardous wastes from the primary metals sector as a whole as 1170 MMT. This was obviously mostly water, but it still differs significantly from the Census figures. We cannot explain the difference.

10. 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂. However SAI estimated dry wastes from the sector to be more than 18 MMT, for 1983 [SAI 1985]. EPA's latest estimate of airborne emissions (particulates and CO, primarily) is about 1.0 MMT [USEPA 1991].

We have no estimate of water use by the sector. However EPA estimated total (wet) wastes from the sector to be 560 MMT [USEPA 1985]. This seems quite high, given that most processes in the sector are dry.

11. Water Usage and Waterborne Wastes

To summarize, 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.

12. 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 waste (tailings) 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 76 MMT of fly ash and bottom ash from thermal power generators and 14.4 MMT of FGD waste, but excluded 14.4 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 CO₂ (of which 2700 was from fossil fuel combustion), 32 MMT of SO₂ 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)

<i>SIC</i>		<i>Organic (waterborne or solid)</i>	<i>Overburden moved, erosion</i>	<i>Inorganic concentration waste ("dry")</i>	<i>Inorganic conver- sion waste (includ- ing slag & ash)</i>	<i>Emissions to air</i>	
01-02	Agriculture	86.5	1500(a)	0	0	4.4 0.7	NH ₃ CH ₄
11	Metal mining & winning	0	1193	600(e)	NA	0.09 0.27	N ₂ O NO _x
12-13	Fossil fuels, mining & drilling	0	5600	260	NA	?	
14	Non-metallic minerals	0	47	36.5	NA	?	
20	Food processing	94(b)	NA	0	0	1.5	(part.)
24-26	Wood, pulp & paper	36(b)	NA	6	0	1.15	(part.)
29	Oil refining	0	NA	0	3	2	VOC
32	Stone, clay & glass	NA	NA	NA	?	34	CO ₂
33	Primary metals	NA	NA	NA	1.5 (c)	(d)	
	Fossil fuel consumption	0	NA	NA	76 ash 14.4 FGD	4.3 30 20 4725	VOC SO ₂ NO _x CO ₂
Total accounted for		196	8340	1087	95	4823	

(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) Excluding iron/steel slag

(d) Included with fossil fuels

(e) Aluminum & phosphate rock wastes excluded here - they are counted in the Chemical Sector (SIC 28)

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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: 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		Exports	Imports	Consumption		Reference
	Raw	Finished			Raw	Finished	
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)

Use of Materials Balance to Estimate Aggregate Waste Generation & Waste Reduction Potential in the U.S.

TABLE III: PRODUCTION & WASTE ALLOCATION FOR PRIMARY U.S. METAL PRODUCTION 1988 (1000 metric tons)

	US Mines			US concentrate production			US primary metal production		
	Total material handled	Ore treated or sold	Overburden	production (metal content)	production (gross weight) (d)	Concentration wastes	Concentrate consumption (gross weight)(d)	Primary production total	Smelting /refining losses
	A	B	A-B		C	B-C	D	E	D-E
Bauxite/Aluminum	8246 (e)	1107 (e)	7140		4575	4395	7730	3944	3786
Copper	523446	218631	304814	1341	5364	213267	5794	1406	4388
Gold	536146	117934	418212	0.201	0.201	117934	392	0.138	392
Iron	300278	197766	102512		57515	140251	83694	49242	34452
Lead	9707	6450	3257	385	481	5969	490	392	98
Molybdenum	127006 (b)	72212	54794	43	172	72040	103	26	77
Platinum Group	34189	11396 (c)	22793	0.005	0.005	11396	.0003	0.0003	
Silver	48444 (c)	15876	32568	1.661	1.661	15874	2	1.718	
Zinc	21149	9106 (c)	12043	244	432	8674	429	241	188
Uranium Oxide ^(f)	22000	15200	6800		20	15180	20	5	15
Phosphorus	451778	224075	227703		45389	17686			
TOTAL	2082389	889753	1192636		113950	783666		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) Where direct figures for gross weight of concentrate were unavailable, they were calculated by applying reasonable concentration ratios to the metal content.

(e) Bauxite at US Mines. Included in total of "ore treated".

(f) Crude bauxite ore, dry equivalent. Includes net imports. Not included in "ore treated" total.

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)

	<i>Total material handled</i> P.70	<i>Ore treated or sold</i> P.69	<i>Domestic production from detail tables</i>	<i>Exports</i>	<i>Imports</i>	<i>Apparent Consumption</i>	<i>Over burden loss</i>	<i>Concentration losses</i>
	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, pyrophyllite	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)

	<i>1950 analysis</i>	<i>Discharged slag & fly ash Estimated 1980 (1.6*1950)</i>	<i>% of total discharge</i>
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%
Mercury	0.005	0.01	0.00003%
Total	16724	26759	

CONVERSION FACTORS USED

	MULTIPLY THIS	BY THIS TO GET TONNES	
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