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Materials Flow in the Production and Use of Coal Combustion Products

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ABSTRACT

One of the most versatile and therefore desirable forms of energy is electricity. Electricity accounts for more than one third of the total energy consumption in the United States, and more than half of the Nation's electricity is produced by burning coal. During 1997, over 800 million metric tons of coal were burned by electric utilities. As a result, more than 95 million metric tons of coal combustion products (CCPs) were generated. In 1997 more than 26 million metric tons of CCPs were used in many applications. The largest use area for a specific CCP was the use of 8.6 million metric tons of fly ash in concrete and cement applications. The leading uses of bottom ash include use as structural fill (1.3 million metric tons) and in roadbase and subbase materials (1.2 million metric tons). Nearly 100% of the boiler slag was used in the blasting grit and roofing granule markets, while more than 1.5 million tons of flue gas desulfurization (FGD) material was used in the manufacture of wallboard. In 1966, the first year for which data are available, only 12.2% of the CCPs generated where used. This figure has increased and currently close to 28% of all CCPs are used. Fly ash and bottom ash production are expected to increase in the future and match projected increases in coal burned by the electric utilities. The production of FGD material is also projected to increase. The magnitude of this increase will depend upon a number of factors, some of which are regulatory. Growth in CCP is also expected to occur. Applying the principles of materials flow to CCPs, from source to ultimate disposition, can help manage our natural resources and protect the environment.

KEYWORDS: fly ash, bottom ash, FGD Material

INTRODUCTION

The production and use of coal combustion products (CCPs) can be investigated effectively by applying materials flow analysis. Coal flows into a coal-fired electric generating stations and various CCPs are produced, are used many applications, or are disposed of. The amounts of CCP used in each application can be examined in terms of the factors that direct the flow of CCPs into its end uses, such as the physical and chemical properties of the CCPs, their availability, and transportation costs. Materials flow analysis may help to identify some factors which may allow for more CCPs to be used and less disposed in the coming years. The American Coal Ash Association (ACAA) has been documenting CCP production and use data since 1966 and these data will be examined using materials flow principles.

About 817 million metric tons (900 million short tons) of coal were burned by the electric utilities in 1997, to produce 1.8 million Gwh (Gigawatt hours) of electricity[2]. Approximately 56% of the electricity generated in 1997 came from coal. In the process of generating this electricity over 95 million tons of CCPs where also produced[2]. During the past decade, as evidenced by the enactment of 1990 Clean Air Act Amendments (CAAA'90, Public Law 101-549), environmental issues have become increasingly important for the United Sates as well as Europe. This has led to research efforts to develop methods leading to the beneficial uses of many industrial byproducts, which otherwise may be disposed of as wastes.

In the 21st century, environmental issues will play a leading role in the sustainable development of the electric utility and other industries associated with CCPs. The World Earth Summits in Rio de Janeiro, Brazil, in 1992 and Kyoto, Japan, in 1997, showed that unchecked emissions of greenhouse gases to the atmosphere are no longer politically and socially acceptable. Prior to these summits, many U.S. electric utilities began participating in Untied States Department of Energy's (USDOE) Climate Challenge Program, the intention of which was to reduce CO_2 emissions to 1990 levels by the year 2000. As part of this program, utilities signed participation accords pledging to increase the use of CCPs, particularly fly ash, to replace portland cement in concrete. The replacement of one ton of portland cement with one ton of fly ash eliminates one ton of CO_2 emitted from cement production.

The United State Environmental Protection Agency (USEPA) has become a proponent of CCP use, in selected applications, through its Recovered Material Advisory Notice (RMAN) and Comprehensive Procurement Guideline (CPG) programs. The RMAN and CPG provide guidance for procuring agencies in the purchase of certain items containing recovered materials. Concrete containing coal fly ash was one of the first materials listed in the CPG in 1983. Since 1997, fly ash concrete parking stops have been listed, and flowable fill containing fly ash and fly ash concrete railroad crossings have been proposed for listing. Fly ash for use in roadbase and structural fill applications is currently under consideration. The CPG and RMAN require government agencies to purchase products containing recovered materials if they meet the required specifications and are competitively priced. When CCPs are used, valuable landfill space is preserved and virgin raw materials and the energy needed to process them are saved. According to ACAA information, the productive use of more than 26 million metric tons of CCPs in 1997 avoided over $1 billion dollars in landfill costs.

CCP PRODUCTION

Coal combustion products are the resultant solid residues generated by coal-burning electric utilities in the production of electricity. Coal is crushed, pulverized, and blown into a combustion chamber, where it immediately ignites and burns to heat boiler tubes. The inorganic impurities, known as coal ash, either remain in the combustion chamber or are carried away by the flue gas stream. Coarse particles (bottom ash or boiler slag) settle at the bottom of the combustion chamber, and the fine portion (fly ash) remains suspended in the flue gas stream. Prior to leaving the stack, fly ash is removed from the flue gas by electrostatic precipitators, baghouses, or other collection systems, such as mechanical dust collectors, often referred to as "cyclones." In addition to the above products, electric generators equipped with flue gas desulfurization (FGD) units generate what is known as FGD material which, although a secondary product, is considered a CCP. The materials flows through a hypothetical 500-megawatt (MW) coal boiler of various designs are shown in Table 1.

The quantities and types of CCPs produced at a given electric utility plant depend, for example, on the type of coal burned, the type of boiler (Table 1), and the type of emission controls installed. In 1997, production of CCPs totaled more than 95 million tons, an increase of 3% from that of 1996. This closely matched a 2.8% increase in coal burned by electric utilities[1].

In 1997, fly ash production was 54.7 million metric tons; a 3-fold increase compared to 1966 (Figure 1). Through the years, fly ash production experienced a steady increase from 1966 to the late 1970's. From the late 1970's to the mid 1990's, fly ash production was relatively flat. Annual fly ash production began increasing in 1993 and has continued to the present. Bottom ash production was 15.3 in 1997 million metric tons, and this tonnage was a 3-fold increase from 1966 and represents a 5.3% increase over the previous year (1996). Bottom ash production followed a growth pattern similar to that of fly ash. Boiler slag production data was not included in ACAA's survey until 1968. From that time until the mid-1970's, boiler slag production increased steadily. Since that time, boiler slag production has remained relatively constant. Fly ash accounted for 57%, and FGD material and bottom ash accounted for 24% and 16%, respectively, of the CCPs produced.

Table 1. Typical CCP production for various coal-fired boiler types. Values given assume that 1.5 million metric tons of 10% ash coal are burned per year[3].

Boiler type	Fly ash (metric tons y^{-1})	Bottom ash (metric tons y^{-1})	Boiler slag (metric tons y^{-1})
Pulverized, Dry Bottom	130,000	20,000	
Pulverized, Wet Bottom	75,000		75,000
Cyclone	45,000		105,000
Stoker	130,000	20,000	

*Note: If the sulfur content of the coal warrants wet scrubbing for SOx control, the plant could generate an up to an additional 250,000 dry metric tons per year.

The Production of Flue Gas Desulfurization Material

The majority of electric power utilities, especially in the eastern and the mid-western areas of North America, use high-sulfur bituminous coal. Increased use of high-sulfur coal has contributed to acid rain in North America. To address this perceived problem, the U.S. Congress passed the CAAA'90 with stringent restrictions on sulfur oxide emissions. The sulfur oxide (SO_x) reduction provisions of CAAA'90, with a two-phase implementation plan, require the electric utilities to find ways of reducing SO_x emissions. Many utilities have switched to low-sulfur coal or fuel oil as partial and/or temporary solutions to the problem. A significant number of those powerplants still using high-sulfur coal installed flue gas desulfurization (FGD) equipment.

Numerous methods and processes and equipment to reduce SO_x and NO_x emissions have been developed, and some are available commercially. Close to 200 FGD systems with small to significant variations have been described in the literature[4]. Among the numerous systems mentioned, only a few have been developed to technically and economically feasible levels.

The majority of FGD systems being installed in the United States use limestone or lime as sorbent materials in the scrubbing liquid. In FGD systems using a lime (CaO) process, lime is slaked on-site to form a calcium hydroxide slurry. This slurry reacts with sulfur gases to form calcium sulfite and calcium sulfate, illustrated by the following reactions:

$$SO_2(l) + Ca(OH)_2(l) \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O(s) + \tfrac{1}{2}H_2O \qquad (1)$$

$$SO_2(l) + \tfrac{1}{2}O_2\,(l) + Ca(OH)_2(l) + H_2O \rightarrow CaSO_4 \cdot 2H_2O(s) \qquad (2)$$

In limestone ($CaCO_3$) systems, the chemistry is similar. However, carbon dioxide is also generated. The process is defined by the following reactions:

$$SO_2(l) + CaCO_3\,(l) + \tfrac{1}{2}H_2O(l) \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O(s) + CO_2(g) \qquad (3)$$

$$SO_2(l) + \tfrac{1}{2}O_2\,(g) + CaCO_3\,(l) + 2H_2O \rightarrow \underbrace{CaSO_4 \cdot 2H_2O(s)}_{\text{gypsum}} + CO_2(g) \qquad (4)$$

Where l means solution or slurry, s means solid, and g represents gas.

In addition to producing an additional product, these units also require the flow of an additional material into the power plant, in the form of lime or limestone. If the power plant in Table 1 were burning 3% sulfur coal, an additional 157,000 metric tons of lime (CaO) or 280,000 tons of limestone ($CaCO_3$) would be required each year.

The first year for which separate production data for FGD material were made available was 1987. The data show that the expected sharp rise in CCP production owing to the passage of CAAA ‘90 had not yet taken place, although CCP production is increasing at a steady rate. This is primarily because utilities, in order to avoid high initial capital expenditures for FGD installations, have opted for temporary solutions, such as fuel switching, power reduction, and purchase of emissions allowances. This trend is continuing, but increases in FGD production may accelerate owing to the implementation of Phase II of CAAA ‘90. Current proposed regulations on particulate matter may also result in the installation of more scrubbers.

In addition to over 10,000 megawatt (MW) (as of 1996) of operating systems, 6000 MW of limestone scrubbing systems and nearly 4000 MW of lime systems are being constructed. An additional 7000 MW of limestone and 6000 MW of lime systems are in the planning state. When operational, these systems are expected to triple the quantity of FGD products to about 70 million tons per year, from the current level of 23 million metric tons.

COAL COMBUSTION PRODUCT USE

The annual quantities of CCPs used from 1966 to 1997 have increased from 2.8 million metric tons to 26.5 million metric tons respectively (Figure 2). In comparison, over the same 32 year period, CCP production has steadily increased to 95.4 million metric tons from 22.9 million metric tons (Figure 1). If only fly ash and bottom ash are considered, the overall percentage of CCPs used has increased to more than 33% from 12.3% in 1966. The current overall use percentage of 27.8% is somewhat diluted due to the inclusion of FGD material which currently has a low use rate.

In 1997, most applications showed increases in CCP use in comparison to the previous year (1996)[2]. Some of the increases may be the result of changes in data analysis rather than actual increases. A good example of this is the use of fly ash in concrete, cement, and grouting. Use in these applications reportedly increased by 1.3 million metric tons (an 18% increase compared with 1996); the actual increase, however, is likely to be closer to 0.3 million metric tons (a 4% increase). Use of fly ash in waste stabilization and solidification applications and in road base and subbase applications increased by more than 20% compared with 1996. Overall increases are as follows: fly ash 19%; bottom ash 4.7%; boiler slag 7.6%; and FGD material 32%. The large increase in fly ash use in 1997 is likely the result of cement shortages in some regions of the United States. The large increase in FGD use represents greater gypsum use by wallboard plants. The 26.5 million tons of CCPs used in 1997 represents an increase of almost 16% from that of 1996 (Figure 2). On a percentage basis, total CCP use had changed little from 1994 to 1996, remaining at about 25%.

The method of handling CCPs also influences their use. Currently, about 68% of the fly ash, 60% of the bottom ash, and 54% of the FGD material produced are handled in a dry or moisture-conditioned state[2] and have higher use percentages than those handled by ponding. Boiler slag is produced in wet-bottom boilers and primarily is handled by ponding (62%). CCPs handled in a dry or moisture-conditioned state have a 32% usage rate compared with ponded CCPs, which have a 21% usage rate. This usage gap is the largest for fly ash. Dry and moisture conditioned fly ash has a usage rate of 37% compared with 20% for ponded fly ash.

Different types of CCPs possess distinct chemical and physical properties that make the group suitable for a wide range of applications. The flow of CCPs into these application is illustrated in Figure 3. Fly ash has a siltlike texture and is pozzolanic in character. The largest volume use of any one CCP is the use of fly ash in cement, concrete, and grout. To be used in concrete and grout, fly ash usually needs to meet American Society for Testing and Materials (ASTM) Standard C618[5]. The standard defines two classes of fly ash: Class F ash has a low calcium content and is usually produced by burning bituminous coals, and Class C ash has a higher calcium content and is usually produced by the burning of subbituminous coals. The standard also sets limits for carbon, sulfate, and alkali contents in the ash. When the appropriate specifications are met, the fly ash can be used as a partial replacement for portland cement in concrete. Fly ash can also be used as: kiln feed in the manufacture of cement, material for structural fill, bulking and dewatering agent in waste stabilization, a mine reclamation amendment, and road base or subbase material.

The use of fly ash in concrete applications has increased during the past 15 years. The use of fly ash as structural fill material has fluctuated between 1 and 2 million metric tons per year for the past decade. Use of ash in structural fill is expected to increase owing to the recently adopted ASTM Standard E1861[6]. The lack of standards for CCP use has been identified as a barrier to greater CCP use in the past. The use of fly ash in road base applications has remained steady at 1 million metric tons per year. Use of fly ash in waste stabilization and flowable fill are two of the more-recent applications and show promise for increased use of fly ash. Flowable fill usage should increase owing to recent proposed action by the USEPA to list flowable fills containing coal fly ash in RMAN in1998. The notice provides guidance for procuring agencies in the purchase of certain items containing recovered materials, including flowable fill containing coal fly ash.

Bottom ash is the coarser of the two ash compounds and has a sandlike texture. Leading uses for bottom ash include, as lightweight aggregate in concrete, or as cement kiln feed. Bottom ash is also used as a traction aid in snow and ice control, as structural fill, and for pipe-bedding material because of its lower density and good drainage characteristics.

More than 90% of the boiler slag produced is used as roofing granules and blasting grit. The material that is too fine to be used as roofing granules is primarily used as blasting grit. Roofing granules are the very coarse sand sized material used on the facing of asphaltic shingles. The ship maintenance industry uses large quantities of abrasives, such as boiler slag. Some boiler slag is also used for snow and ice control. Because the number of boilers that produce boiler slag is decreasing, the amount of boiler slag is expected to decline in the coming years.

Among the CCPs, the greatest use increase was recorded by the FGD material, which jumped to an all-time high of 2 million metric tons in 1997, a 32% increase over 1996. The use of the FGD gypsum in wallboard manufacture recorded the largest growth among the CCP's, increasing from 790,000 tons in 1996 to 1.46 million tons in 1997, an 85% increase. Among the other FGD application areas, agriculture (a 350% increase), mining (99%), road base/subbase (72%), structural fills (48%), and waste stabilization (49%) recorded significant gains although the tonnages used in these applications remains small.

Technically sound use of CCPs is an environmentally sound practice that saves landfill space and virgin materials for future use. Using the tools of life cycle assessment, fly ash use as structural fill was compared with the use of ordinary soil[7]. The study shows that, by comparison to ordinary soil, coal fly ash used as structural fill is always better with respect to materials consumed and land disturbance avoided. Similarly, fly ash was generally better than soil for structural fill with respect to energy consumed. In addition, fly ash allows a greater haul distance, for the same or lower loading and transportation air emissions, by comparison to soil. The study points out that the leachability of both CCPs and soil materials should be addressed on a case-by-case basis.

OUTLOOK

Increases in the production of fly ash and bottom ash will be proportional to the increase in coal used for electric power production and the level of environmental controls applied. The USDOE projects that U.S. coal production will increase 1% per year, to 1,268 million tons in the year 2015, from 1,033 million tons in 1996[1]. Most of this increase will be used for domestic consumption. The largest growth in CCP production is expected to be in the form of increasing amounts and types of FGD materials. Depending upon the a number of factors the amount of FGD material produced may undergo a 3-fold increase. The use of CCPs is also expected to increase. The use of fly ash in cement and concrete applications is expected to remain a large area of use. The use of fly ash, particularly class C fly ash, as roadbase material and in soil stabilization also is expected to increase. Most new gypsum wallboard plants are now associated with an FGD unit of a power generating station, and FGD use in wallboard will increase accordingly. Agricultural application of FGD material presents a large potential market that has yet to be well developed.

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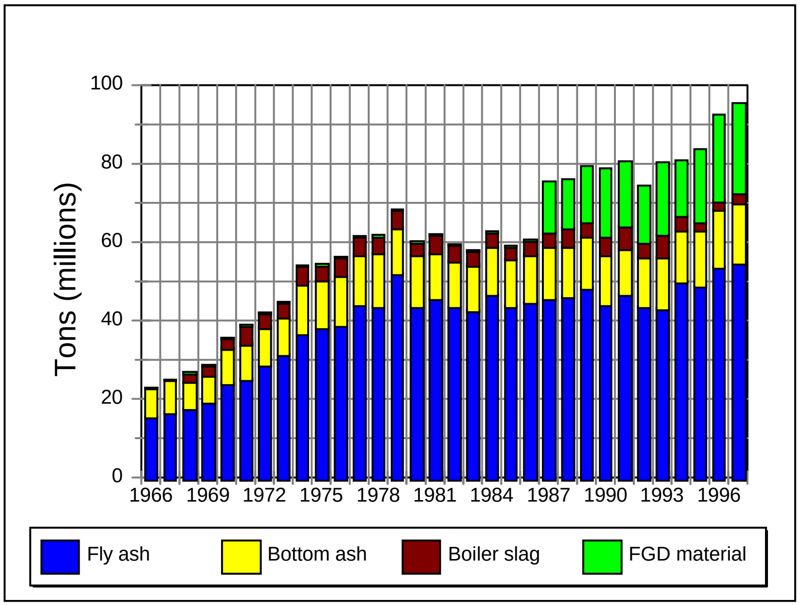

Figure 1. CCP production from 1966 - 1997 (metric tons).

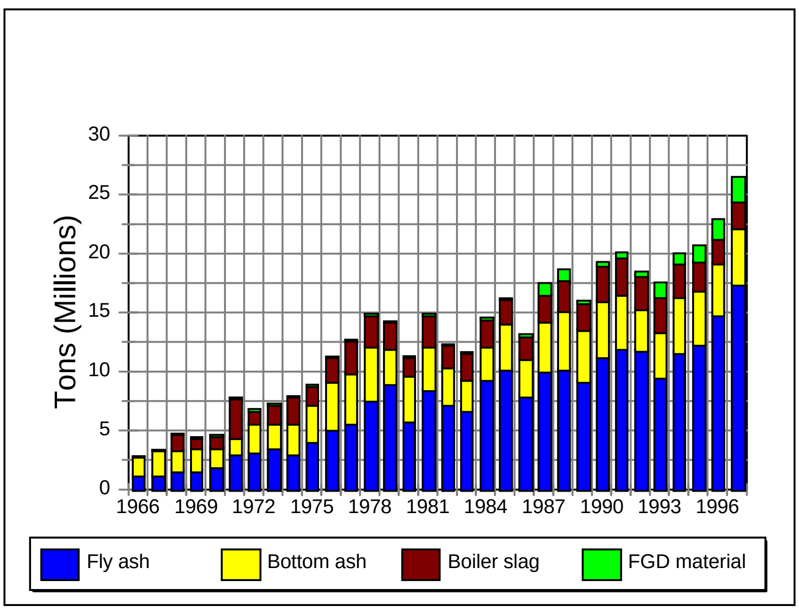

Figure 2. CCP use from 1966 - 1997 (metric tons).

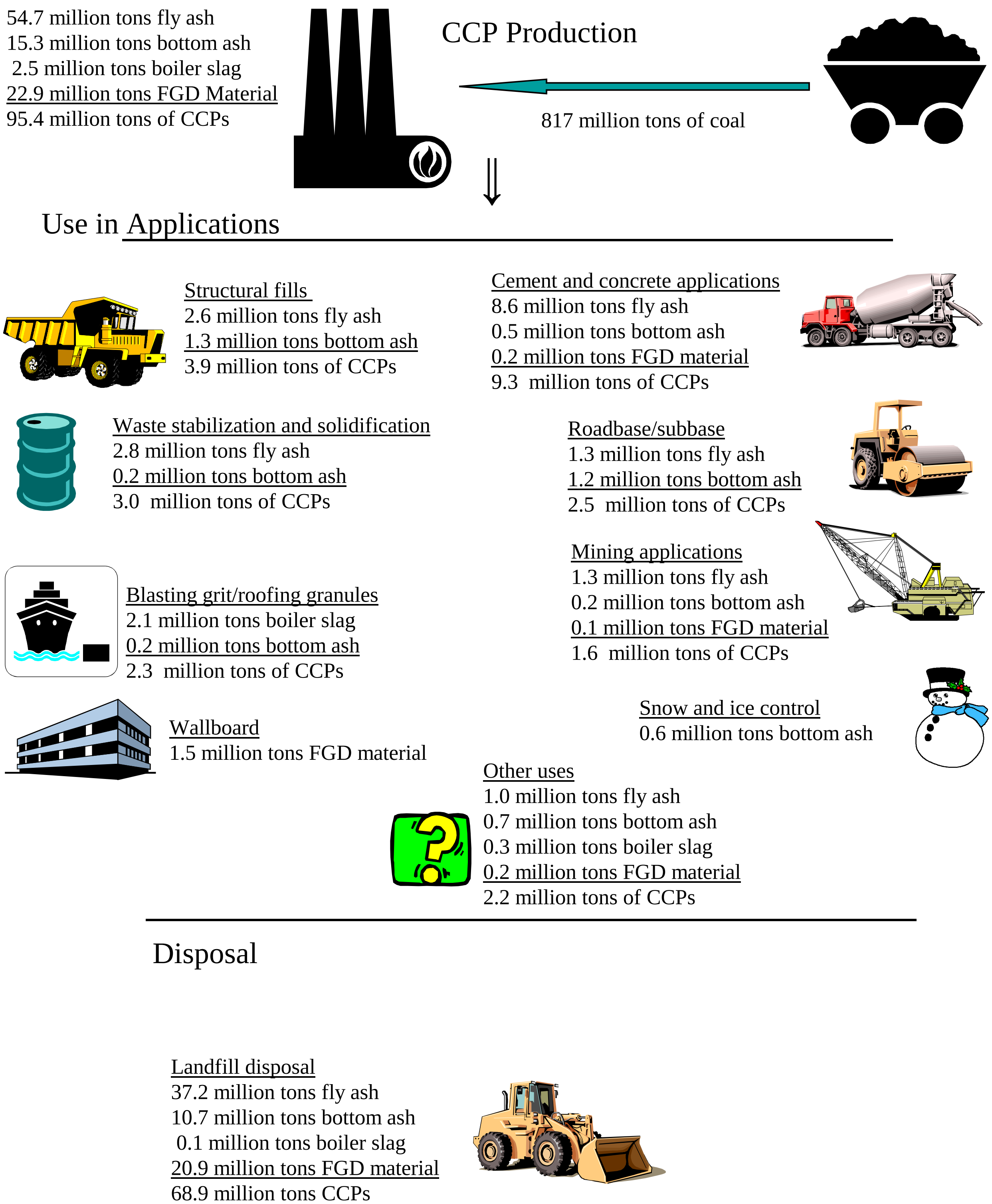

Figure 3. Production, uses and disposal CCPs in 1997, all tons are metric tons[3].