20.1 INTRODUCTION

Coal is a complex and heterogeneous material comprised of a variety of organic and inorganic constituents in different forms. While silicates and carbonates constitute the major ash-forming minerals, the principal sulphur-bearing minerals in coal are pyrite and marcasite. Other sulphide minerals, e.g., elemental sulphur, calcium and iron sulphates, are found in minor quantities. A considerable portion of the sulphur content may be organic in the form of alkyl and aryl thiols, sulphides, and disulphides and as heterocyclic compounds of the thiophene type (Wheelock and Markuszewski, 1981; Stock, 1989). In bituminous coals, the thiophene type forms 40-70% of the organic sulphur, whereas the rest is composed of aromatic, cyclic and aliphatic sulphur compounds in different proportions depending upon the coal rank. Organic sulphur levels in coal commonly range from about 0.3% to over 2.0%, whereas the pyritic sulphur content may vary from 0.1% to 4.0%. However, in some unusual cases the organic sulphur levels may be as high as 10% with sulphate contents up to 1%. Pyrite may be present in a wide variety of forms ranging from large balls to micron and sub-micron size framboids.

Sulphur is one of the major undesirable constituents of coal; it contributes to air pollution and causes operational problems during combustion such as slugging, boiler fouling, corrosion and equipment wear. More importantly, the emission of sulphur dioxide into the atmosphere during coal combustion is of serious ecological concern. Therefore, severe environmental regulations have been issued to combat air pollution. Sulphur dioxide emissions can be reduced by one or more of a combination of the following:

- precombustion coal cleaning
- recovery of sulphur oxides during combustion
- postcombustion scrubbers and precipitators

The least expensive method of controlling sulphur emissions is cleaning the coal using various preparation methods such as gravity concentration and flotation methods. Since 1980, some novel technologies have been developed to enable the separation of pyrite from coal.

As precombustion coal cleaning technology seems the most economic way of coal desulphurization, the bulk of this chapter has been devoted to recent developments in this field. Only a summary of the basic aspects of desulphurization during and after combustion processes is presented.

20.2 PRECOMBUSTION COAL CLEANING

Desulphurization of coal prior to combustion can be accomplished by physical, chemical or biological methods. While the physical methods aim to separate the inorganic sulphur, the target of the chemical and biological
methods includes removal of the organic sulphur as well. A schematic illustration of the existing and novel precombustion techniques for coal desulphurization is given in Figure 20.1.

20.2.1 Physical Cleaning Methods

Physical cleaning methods are highly successful in removing the large fragments of associated minerals but fail in effectively removing the finer particles (~0.1 mm) in coal. However, novel technologies are being developed which show promise for removing the finer mineral fractions of coal as well. Constituents chemically bound to coal matrix such as organic sulphur cannot be separated by physical methods.

Reduction of the sulphur content of coal depends upon the coal rank, liberation size, the original sulphur content, and the pyritic/organic sulphur ratio. Coal can be cleaned to a desired level by adjusting the size distribution and the effective separation density in the cleaning process at the expense of coal recoveries.

Comminution machines developed for coal should ideally break along the grain boundaries separating the organic and the inorganic constituents. Chemical comminution using additives such as anhydrous ammonia, which adsorbs on coal but is not receptive to inorganic phases, is claimed to liberate coal along the interfacial boundaries (Howard and Datta, 1977).

20.2.1.1 Gravity Based Separations

The most widely used separation device to clean medium sized coal is the coal jig. About 35-40% of the total coal washed is processed by jigs. The Baum Type and its newer versions, Batac and Feldspar Jigs have increased the capacity and efficiency of the jigging processes for fine coal (~10 mm) and coarse coal (150-200 mm). Batac Jigs in the Homer City Coal Preparation Plant reportedly produce a low-ash low-sulphur product (Burger, 1986). Double Stroke Pulsation Jigs are reported to perform well in the desulphurization of minus 2 mm coal (Breuer and Jungmann, 1986).

About 25-30% of coarse coals are cleaned by heavy media separation circuits. Heavy medium processing is primarily effective on the coarser fractions of coal. However, dense medium cyclones can treat coals down to 0.1 mm at gravities as low as 1.3 (Matoney et al., 1988). The substitution of centrifugal force for gravitational force allows increasingly finer sizes to be processed. As the size of the particles approaches the size of the magnetite particles (~325 mesh) used to formulate the dense medium, an effective separation can no longer be made. Therefore, there is a growing interest in replacing the magnetite-water medium with heavy liquids such as Freon 113 and methylene chloride. Among dense medium cyclones, Vorsyl, Larcodems, Dynawhirlpool and Tri-Flò systems are suitable for relatively medium sized coals (Shah et al., 1982; Cammock, 1987; Brookes and Miles, 1987; Kolb and Steiner, 1986).

The performance of Humphrey Spiral and Reichert Cones appears to be optimum over a relatively wide size range from 3 to 0.1 mm. Spirals are gradually replacing hydrocyclones, fine coal jigs and coarse froth flotation due to higher yields, lower ash and pyritic sulphur in the cleaned product and ease of operation and maintenance. Spirals are particularly popular in the Republic of South Africa and Australia (Horsfall, 1988; Brookes and Miles, 1987; Gallagher et al., 1986; Ateşok et al., 1993).

Water-only-cyclones (hydrocyclones) which can treat 0.5x0.15 mm fractions are characterized by simple design, a low cost/high capacity ratio and the ability to clean without using an artificial heavy medium. The problems of these devices are the lack of efficiency and the need for large amounts of water. They are generally used as primary cleaning devices for cleaning raw coal (20 x 0.15 mm) at 1.4x1.9 specific gravities (Schlepp and Schmidt, 1988; Wills, 1985).
Figure 20.1 A schematic illustration of existing or emerging precombustion coal desulfurization processes.
Wet shaking tables can process particles in the size range of 8x0.15 mm and can be installed at up to four-stacked tables. The tables can treat coal only in certain specific gravity fractions. In China, centrifugal tables with cylindrical surfaces have enabled the processing of very fine particles (-0.04 mm) and the removal of 55-77% of the pyritic sulphur from coal (Fan et al., 1982). The use of pneumatic tables (air tables) appears to have declined in recent years. Mozley's Multi Gravity Separator (Figure 20.2), which is based on the action of a shaking table, has extended the size range of tables to sub-sieve size range and is reported to perform well in the separation of pyritic sulphur.

20.2.1.2 Separations Based on Surface Properties

Flotation is a promising method for separating pyrite from coal. There has been an upsurge of interest in developing both processing and reagent strategies to desulphurize coal by flotation. The problem arises partly from similarities in the surface properties of unweathered coal and fresh coal pyrite contaminated with hydrocarbons. Other problems include the incomplete liberation of pyrite from coal, recovery of pyrite by hydraulic entrainment, hydrophobization of pyrite by superficial oxidation, and hydrophobic interaction between pyrite and flotation reagents (Yoon et al., 1991).

Depressants are the major class of flotation reagents extensively studied for the desulphurization of coal because of their potential in depressing pyrite. These depressants include hydrolyzed metal ions (Baker and Miller, 1971), starches and polysaccharides (Im and Aplan, 1981; Perry and Aplan, 1985), polyxanthate (Attia et al., 1988), oxidizing and reducing agents (Celik and Somasundaran, 1980), anionic and cationic surfactants partially as collectors (Read et al., 1989; Stonestreet and Franzidis, 1988) and quinonoid compounds which show superior performance over the commercially available sulphur-based depressants (Celik et al., 1990). However, every effective depressant developed so far either depresses coal or requires prohibitively large reagent dosages (Aplan, 1993). It may still be possible, however, to tailor a suitable depressant for a particular coal.

Processing strategies include the two-stage reverse flotation process, the grab and run approach, and new cell designs such as microbubble column. The two-stage reverse flotation process, developed by USBM, uses combination of both reagent and process strategies (Miller and Deurbrouck, 1978). Coal is floated in the first stage and subsequently depressed in the second stage by polymeric depressants. This process has been shown to...

![Diagram of multigravity separator](https://example.com/diagram.png)

Figure 20.2 Laboratory or pilot plant version of multigravity separator.
be more effective than conventional flotation in reducing the pyritic content. While Appalachian coals exhibited 70 to 90% pyritic sulphur removal, Midwestern coals yielded 40 to 60% pyritic sulphur removal. The incorporation of a precleaning, fine grinding and classifying/desliming circuit improved the selectivity of this process (Hucko et al., 1988).

The Grab and Run approach developed by Aplan (1977) takes advantage of the difference in the flotation kinetics of coal and pyrite through successive removal of the products. Microbubble flotation technology developed by Yoon and his associates combines the advantage of fine bubbles with that of column flotation (Figure 20.3). A wide variety of coal samples processed in the Microbubble Flotation System shows the possibility of obtaining a superclean coal containing less than 2% ash and 1% sulphur (Hucko et al., 1988). Other novel flotation technologies in the process of development include the Deister Flotair Column, the WEMCO/Leeds Column, the Canadian Countercurrent Column, the Hydrochem Mechanically Agitated Column, the AFT Process, the Froth Separator and the MTU Static Tube (Miller, 1988).

Selective agglomeration has good potential for separating pyrite from micronized coals. This process using fuel oil has already been commercially utilized in the USA. Oil is added to raw coal slurry which is then subjected to intensive shearing which results in preferential coating of the oleophilic coal particles (Mehrotra et al., 1983). Fuel oil improves the dewatering characteristics of the finished agglomerates and enhances the heat value of the product. The addition of surfactants has considerably improved the emulsification of oil, and more importantly, it has reduced the quantity of oil required.

The CONVERTOL Process developed recently utilizes centrifugal forces, and the OLIFLOC Process employs a screen for separating hydrophilic particles (Brookes and Miles, 1987; Capes et al., 1986). The OTISCA Process using heptane, the LICADO Process using liquid CO₂ at 6000 kPa pressure, the Spherical Agglomeration Process developed by Bechtel and the AGLOFLOAT Process employing heavy crude oil are some of the novel technologies promoted under the auspices of the US Department of Energy (Hucko et al., 1988).

![Figure 20.3 Schematic illustration of VPI's microbubble flotation apparatus (Hucko et al., 1988).](image)

20.2.1.3 Other Physical Cleaning Methods

Differences in the magnetic susceptibilities of coal and coal pyrite enable their selective separation. While coal pyrite is generally considered weakly paramagnetic, coal is diamagnetic. Increase of the magnetic susceptibility of pyrite particles is possible through the conversion of pyrite to pyrrhotite-like material by various treatments involving
iron pentacarbonyl at 170°C and microwave energy. Lua and Boucher (1990) reported pyritic sulphur reductions of 99% on a pulverized bituminous coal in the size range of minus 0.1 mm. The use of alkaline extraction under pressure has been shown to increase the magnetic susceptibility of pyrite over coal and in turn, facilitate the separation of pyrite by high gradient magnetic separation (Hall and Finch, 1984). Desulphurization of lignites by high gradient magnetic separation has been attempted with success (Ozbayoglu, 1986).

The separation of materials in the electrostatic process is based on the differences in one or more of their electrical properties such as the dielectric constant, electrical conductivity, and work function. The Triboelectrostatic Separation process relies on selectively, placing positive charges on coal and negative charges on the associated matter, including pyrite (Hucko et al., 1988; Mills and Cheng, 1993).

20.2.2 Microbial Cleaning

Microbial beneficiation is capable of removing both organic and inorganic sulphur at relatively moderate temperature and pressure. Bacterial removal has been pursued in two ways: (i) bacterial leaching, and (ii) bacterial conditioning followed by flotation (Dogan and Celik, 1992; Dogan and Ozbayoglu, 1985).

The mechanism of oxidation of pyrite by Thiobacillus type bacteria has been ascribed to the formation of soluble species such as ferric sulphate and sulphuric acid as below:

\[ 4 \text{FeS}_2 + 15\text{O}_2 + 2\text{H}_2\text{O} = 2\text{Fe}_2(\text{SO}_4)_3 + 2\text{H}_2\text{SO}_4 \]  

The bulk of the research on sulphur removal by microbial methods has involved the oxidation of pyrite by bacteria such as Thiobacillus ferroxidans to form watersoluble iron sulphate. The removal of pyritic sulphur from coal has been reported in this case to be as high as 97% (Gullu et al., 1992; Dugan and Apel, 1978; Detz and Barvinchak, 1979; Bos et al., 1986; Torma and Gundiler, 1986). Studies on thermophilic pyrite oxidizing bacteria such as Sulpholobus have also been reported (Gokcay and Yurteri, 1983; Kargi and Robinson, 1982). Bioprocess variables involved in microbial pyrite removal are given in Figure 20.4 (Olson and Brinckman, 1986).

![Figure 20.4 Bioprocess variables in pyrite removal (Olson and Brinckman, 1986).](image)

A breakthrough has reportedly been achieved by the Atlantic Research Corporation which has developed a new strain, CB1 (Coal Bug 1, a mutant of pseudomonas); this microbe produces enzymes to oxidize the sulphur in thiophenic groups. The same research group also patented CB2, a member of the genus Acinetobacter, which is claimed to attack the diphenylsulphide form of the organic sulphur. Isbister et al. (1986) reports an average of 37% removal of organic sulphur from Illinois and Homer City coals by CB1.

The conditioning of coal by bacteria followed by flotation or oil agglomeration has markedly lowered the conditioning time required to minutes and improved the removal of ash and pyritic sulphur (Capes et al., 1973; Kempton et al., 1980; El-Zeky and Attia, 1987). For instance, Dogan (1990) reports that while bacterial leaching of a Turkish lignite required 10 days, bacterial conditioning followed by flotation required only four hours and produced a superior coal compared to that produced by the bacterial leaching alone.
Biological approaches still remain only as long term alternatives for development on a commercial scale due to long retention times, stability problems, lack of process control schemes and product consistency (Bos et al., 1986; Hucko et al., 1988).

20.2.3 Chemical Cleaning

The majority of the chemical beneficiation processes have demonstrated the ability to reduce the amount of ash, finely disseminated pyrite or organically bound sulphur from the coal matrix. While some remove only pyritic sulphur, others remove both forms of sulphur. The removal of sulphur from the inorganic constituents of coal is a serious challenge. Organic sulphur is not removed by physical cleaning or solvent extraction. A selective cleavage of carbon-sulphur bond is required to accomplish this task. However, despite considerable progress in modern analytical tools, the distribution of sulphur and the relative abundances of different substances in coal including thiols, sulphides and heterocyclic compounds have not been clearly understood (Chatterjee et al., 1990). Although Mass Spectroscopic (MS) and High Resolution MS studies have given evidence of the empirical formulas of coal extracts and coal pyrolysis products, their precise structures have not been established. Only X-Ray Absorption Near Edge Structure (XANES) appears to hold promise. Some of the organic sulphur compounds in various extracts have been compiled in recent review paper by Stock et al. (1989). These compounds are illustrated in Figure 20.5.

Chemical cleaning techniques can be classified according to the mode of action involving oxidizing, reducing and caustic treatments. Excellent reviews on the subject are available elsewhere (Wheelock and Markuszewski, 1981; Schobert, 1992; Stock et al., 1989).

Heat Treatment with Gases: Desulphurization studies in the presence of gases use nitrogen and carbon dioxide as inert; hydrogen, water vapor and ammonia as reducing; and oxygen or air as the oxidizing medium. The organic sulphur is converted to H2S in the presence of inert and reducing gases. While most organic

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Figure 20.5 Various sulphur compounds identified in coal (Stock et al., 1989).
sulphur compounds are decomposed at relatively lower temperatures, thiophenes decompose only above 800°C (Calkins, 1987). Coal pyrite, as opposed to mineral pyrite, is reduced by hydrogen to H₂S at temperatures as low as 250°C. Pyrite in the presence of an oxidizing agent undergoes reactions at 350-400°C and is converted to water soluble sulphates (Sinha and Walker, 1972).

Oxidation Treatments: Coal powder is leached with a solution containing dissolved oxygen or air at 120-200°C under 10-40 atm partial pressure for 1-2 h under either alkaline or mildly acidic conditions. This is the basis of the Ledgemont Oxygen Leaching Process (Sareen, 1977). An iron complexing agent is used in the Promoted Oxyde-sulphurization Process. While the PETC Oxyde-sulphurization Process is conducted at acidic conditions, the AMES Process employs an alkaline solution containing 0.2 M sodium carbonate. The Chlorinolysis Process (Hsu et al., 1977) utilizes chlorine as an oxidant at 50-100°C. This method is capable of removing up to 70% of the organic and 90% of the pyritic sulphur. Chlorine levels in the clean product are reduced to less than 1% by hydrolysis followed by dechlorination. The use of ferric salts under acidic conditions can remove up to 95% of the pyritic sulphur, and Hydrogen is the main reducing agent used in reduction processes such as the IGT Hydrodesulphurization process which employs high temperatures (800°C) and atmospheric pressure. Pretreatment by oxidation in air at 400°C prevents caking and also helps subsequent removal of the organic sulphur by hydrotreatment (Attar, 1978). Details of hydropyrolysis methods of coal desulphurization given by Sugawara et al. (1991) and Schobert (1992) are beyond the scope of this chapter.

Wet Chemical Methods: These methods involve the use of both gases and liquids in the presence of various chemicals such as metal salts, acids and bases, and can be classified according to the treatment mode.

Caustic Treatments: Heating of an aqueous slurry of powdered coal in the presence of 10% NaOH and 2-3% Ca(OH)₂ at 250-300°C for 10-30 minute is employed in the Batelle Hydrothermal Process. Over 90% of the pyritic and 50% of the organic sulphur can be removed by this process. The application of microwave irradiation on caustic treated and dewatered coal has been shown to remove 90% of the pyritic and 50-70% of the organic sulphur from coal (Zavitsano et al., 1978).

The Molten-Caustic-Leaching Process (MLC), commonly known as the TRW Geavimelt Process, consists of treating coal with molten caustic (a mixture of sodium and potassium hydroxides) at 350 to 400°C for up to four hours. A low-ash, low-sulphur coal is produced upon washing with water and dilute acid (Gala et al., 1989). Over 90% of ash and sulphur reduction is attained. One of the difficulties of the process is the recovery of the caustic solution to produce dry caustic flakes. Chriswell et al. (1991) reported that potassium hydroxide, which is an expensive chemical, may not be required for most coals, with the exception of high rank coals. Microwave irradiation was found to promote the rate of desulphurization by facilitating the contact between coal and the molten (Hayashi et al., 1990). Microwave irradiation followed by magnetic desulphurization is also reported to enhance sulphur removal (Rowson and Rice, 1990).

Radiation-Chemical methods: The desulphurization of coal under the influence of γ-rays and accelerated electrons appears to be a promising method because of the high selectivity induced by radiation-chemical
reactions (Roy, 1983; Mustafaev, 1992). The high electron density around the sulphur atom as opposed to the other elements in coal (C, O, H) makes the adsorption of radiation energy through sulphur more effective. The chemical bonds of sulphur, and in particular, aliphatic and bridge bonds decompose more easily. 60% desulphurization has been achieved on a lignite sample containing 4% sulphur under γ-radiation (D= 30 kJ/kg) at 400°C (Mustafaev, 1992).

Research has been conducted in Argonne National laboratory on Illinois No.6 coal using a combination of lithium aluminum hydride (LAH), single electron transfer (SET), and Lochmann’s base (BASE) reactions (Stock, 1992). The results of these investigations are presented in Figure 20.6. While the SET reagents should be particularly effective for the removal of heterocyclic sulphur compounds, BASE is expected to react with sulphidic sulphur compounds.

Chemical beneficiation processes such as the MLC generally produce better quality coal in terms of ash and sulphur than any physical beneficiation process. However, the processing costs for coal in the MLC Process ($2-3/GJ) are significantly higher than those of the physical cleaning processes ($0.3-0.6/GJ) (Hucko et al., 1988). In general, the cost of recovering chemical oxidizing agents, e.g. ferric salts, chlorine and ozone is rather high.

20.3 RECOVERY OF SULPHUR OXIDES IN THE BOILER DURING COMBUSTION

20.3.1 Fluidized-Bed Combustion (FBC)

The FBC of coal represents an in situ sulphur removal technique. It consists of adding limestone or other metal oxides to the burning bed of coal at a stoichiometric ratio of limestone (Shilling, 1983; Pawliger and Mudd, 1985). The FBC boilers have been developed into a commercially viable technique for coal combustion, especially for middle and small scale plants. Experience hitherto shows that a 80% desulphurization at a ratio of Ca/S = 1 can be achieved with this technology (Sadakata, 1991). The circulating fluidized-bed (CFB) can reach higher sulphur capture efficiency than FBC at the same Ca/S ratio.

20.3.2 Limestone Injection Multi Burners (LIMB)

This dry additive method is another potential technique that has attracted attention following the development of new low NOx burners. It has been studied mostly in the USA and tested on full scale plants in several countries. Using stoichiometric ratios of 2-5 of limestone, the SO2 emission can be controlled in the range of 50 to 60% with proper cleaning or blending (Werhane et al., 1991). The sorbent injection is expected to reduce SO3-concentration and in turn solve the problem of cold end corrosion and to improve the overall efficiency. This method seems to be applicable only to high rank coals, as low rank coals may have the risk of losing the flame. Since a plant adopting LIMB is equipped with electrostatic precipitators, limestone injection also causes serious waste disposal problems. Another limestone injection technology (LiFAC) exploiting limestone injection into the furnace followed by calcium oxide activation seems to be promising as well.
20.4 POST COMBUSTION SCRUBBERS AND PRECIPITATORS

Flue Gas Desulphurization (FGD) is the only commercially available desulphurization technique that has gained wide acceptance by the power industry (Karsten, 1983). Wet processes using calcium based sorbents are the most widely adopted FGD systems. However, only 15-20% of the operating boilers in the utility industry are equipped with scrubbers to desulphurize the flue gas (Hucko et al., 1988). A classification of FGD Processes is given in Figure 20.7 (Klingspor and Cope, 1987).

Nongenerable FGD processes that produce salable byproducts and include the throwaway systems producing residues for disposal are increasingly favored. Regenerable FGD systems with a regeneration step to release concentrated SO₂ are also in use, although there are few installed in coal-fired plants.

![Figure 20.7 Classification of FGD processes (Klingspor and Cope, 1987).](image)

20.4.1 Regenerative FGD Systems

Regenerative systems are more complex, more expensive and have more operating problems than the throw-away systems. These systems are therefore preferred in locations where permits are difficult to obtain like heavily populated industrial areas or where market exists to utilize the end product. The following regenerative FGD Systems have been developed.

*The Wellman-Lord Process*: The boiler flue gas is allowed in this process to react with a concentrated aqueous solution of sodium sulphite to produce sulphite/bisulphite liquor which is then steam treated to drive off SO₂. The sodium compounds are returned to the absorber, whereas the SO₂-rich off stream is further processed to obtain sulphuric acid or elemental sulphur.

*The Magnesium Oxide Process*: The process utilizes MgO as an absorbent for SO₂ removal in the wet scrubber. The magnesium sulphate produced is calcined to regenerate the MgO, which is then sent back to the utility.

*The Ammonium Sulphate Process*: Ammonia is injected into the flue gas in this process where it reacts with SO₂ to form ammonium sulphite, which is captured in a two-stage scrubber, oxidized to sulphate and dried in a spray drier. The contamination of ammonium sulphate with metal ions precludes its use as a fertilizer (Karsten, 1983).

*NOXSO Process*: The NOXSO process is a dry, regenerative flue gas treatment system that simultaneously removes 90% of the SO₂ and 70-90% of the NOₓ from flue gas generated from the combustion of coal (Belli et al., 1993). The process has been tested on small scale (0.017 MW) on a high sulphur coal (2.5%). The NOXSO sorbent consists of 1.23 mm diameter alumina beads impregnated with 5.2% Na, which removes the SO₂ and NOₓ from the flue gas as it passes through the fluid-bed absorber.

20.4.2 Throw-Away FGD System

*Wet Scrubbers*: Wet scrubbers with lime or limestone are the most widely used systems in FGD installations up to the largest coal-fired boilers. Lime or limestone ground to 325 mesh with a solid content of 2-10% is used as the absorbent. Processes producing gypsum are increasingly being favored. Sulphur removal efficiencies of 90% and over are successfully achieved (Sadakata, 1991). The reaction of SO₂ with the lime produces calcium sulphite and sulphate which are precipitated and separated from the mother
liquid for recycling to the scrubber. The scaling problem is overcome by adding an inhibitor such as thiosulphate to the scrubbing liquid. Wet scrubbers with lime or limestone slurry are the most widely used systems.

**Dry Scrubbers:** Dry scrubbing based on spray drying technology involves atomization of the liquid, contact between the drying gas and atomized droplets, transformation of the droplets (20-400 microns) into a dry free flowing product, and finally separation and recovery of the dry product from the drying gas. The dry powder is a free flowing and easily handled product with physical properties similar to those of fly ash. The powder can be utilized as construction material, synthetic gravel upon pelletization, or safely disposed in a landfill.

Gas Suspension absorption (GSA) employs an absorber based on gas suspension technology which involves the fluidization of a very high concentration of flyash, dust particles and lime inside the reactor (Goss, 1993). GSA with a 10 Mwe DOE demonstration plant is claimed to operate at low retention times, high circulation rates and to be capable of cleaning 80+% overall SO₂ removal for 3% sulphur coal application at a stoichiometric rate of 1.0. Unlike spray drying, GSA does not require an atomizer but a single low pressure dual fluid nozzle. It also results in less dust loading in the flue gas, which may enable the use of a fabric filter or an electrostatic precipitator rather than a specific dust collector.

Dry scrubbers are increasingly in use, particularly on small units, and consume 30-50% of the energy required for a comparable wet scrubber. The water need can be met from waste waters such as pond water or sludge from water treatment plants. Despite considerable progress in the development of conventional lime/limestone wet scrubbers, dry scrubbing is a more promising FGD technique due to its advantages in simplicity, cost, and product dryness. A schematic representation of a typical dry FGD system is shown in Figure 20.8 (Koch and Rosenberg, 1987). The capital and operating costs of FGD systems are greatly affected by the coal and coal ash characteristics, pollution control legislation, and power plant design and capacity. Capital and annual operating and maintenance costs for various plants employing FGD systems are found to vary between 140-400 $/kW, and 15-45 $/kW, respectively (Baki, 1992).

![Figure 20.8 A simplified flow diagram for DRY FGD system. (Koch and Rosenberg, 1987).](image)
Conventional dust collectors such as electrostatic precipitators or bag houses, as applied in the utility industry, can be conveniently used without much modification in their designs (Karsten, 1983).

20.5 CONCLUDING REMARKS

The various methods of precombustion techniques discussed in the foregoing sections indicate that separation of pyritic sulphur from coal is possible through a combination of conventional and advanced coal cleaning technologies. However, the removal of organic sulphur by chemical or biological processes presents a challenge, particularly in terms of cost. New and more efficient technologies are required to implement these methods on an industrial scale.

Laurila (1986) states that advanced coal cleaning technologies can remove sulphur at 40 to 50% less cost than flue gas desulphurization. However, an optimization is required to assess the level to which sulphur should be removed physically or chemically at the boiler. Most utilities will be required to install scrubbers or switch to low-sulphur coals to meet the more stringent standards implemented in many countries around the world. While scrubbers may be a viable option for large and relatively new power plants, they are a less realistic choice for smaller and older power plants. In fact, even the larger plants are cautious about installing scrubbers because of the high capital cost and operating and maintenance costs. Therefore, the option of cleaning coal prior to combustion is gaining momentum among many utilities (Coal and Synfuel Technology, 1991; Coal. 1992).

Studies carried out by the US Department of Energy reveal that for a moderate-sulphur coal, advanced coal preparation alone is sufficient to bring coal into the environmental compliance of 0.52 kg SO₂/GJ at a very competitive cost, but for a high sulphur coal, duct injection combined with advanced coal preparation provides an economically attractive alternative to the FGD system (Hucko et al., 1988). Other studies also indicate that physically cleaned coal substantially reduces the cost of the FGD Systems; this results from only 21% of the flue gas being processed by the FGD System as opposed to 85% when uncleaned coal is used (Holt and Deurbrouck, 1977).

Figure 20.9 presents a summary of the cost effectiveness in the USA of various coal cleaning options for SO₂ reduction from coal.

**Figure 20.9** Cost effectiveness in the USA of clean coal options versus existing technologies for SO₂ reduction (Yeager, 1990).
fired plants (Yeager, 1990). This data indicates that the combination of conventional physical coal cleaning and dry (in-furnace) sorbent injection competes effectively with the SO₂ emission reduction achieved by the application of advanced physical and chemical coal cleaning techniques (Thambimuthu, 1993). It should be noted that the data for AFBC (Atmospheric Fluidized Bed Combustor) and PFBC (Pressurized Fluidized Bed Combustor) systems seem to be most economic and efficient, but Couch (1991) suggests that these cost estimates fail to consider the disposal cost of large amounts of solid residues generated.

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