have tapered cross sections; the gaps between the bars are smaller on the top side than on the bottom. This design reduces plugging.

A *revolving screen* consists of a slowly rotating cylinder with a slight downward slope parallel to the axis of coal flow. The cylinder is comprised of a perforated plate or a wire cloth, and the size of the openings determines the separating size. Because of the repeated tumbling as the coal travels along the cylinder, considerable breakage can occur. For this reason, revolving screens are not used for sizes larger than about 3 in. (76.2 mm). Because only a small portion of the screen surface is covered with coal, the capacity per area of screen surface is low.

A *shaker screen* consists of a woven wire mesh mounted in a rectangular frame which is oscillated back and forth. This screen may be horizontal or sloped slightly downward from the feed end to the discharge end. If the screen is horizontal, it is given a differential motion to help move the coal along its surface.

Bituminous coal generally fractures into roughly cubicle shapes, while commonly associated slate and shale impurities fracture to form relatively thin slabs. This shape difference enables the impurities to be separated with a *slotted shaker*.

Vibrating screens are similar to shaker screens except that an electric vibrator is used to apply a high frequency, low magnitude vibration to the screen. The screen surface is sloped downward from the feed to the discharge end. The vibration helps to keep the mesh openings clear of wedged particles and helps to stratify the coal so that fine particles come in contact with the screen surface. For screening fine, wet coal, water sprays are used to wash fine particles through the coal bed and the screen surface. Vibrating screens are the most widely used types for sizing and preliminary dewatering.

It is common practice to separate the fines from the coarse coal to improve the efficiency of subsequent cleaning and dewatering processes. The fines may be discarded, cleaned separately, or bypassed around the cleaning process and then blended back into the coarse clean coal product.

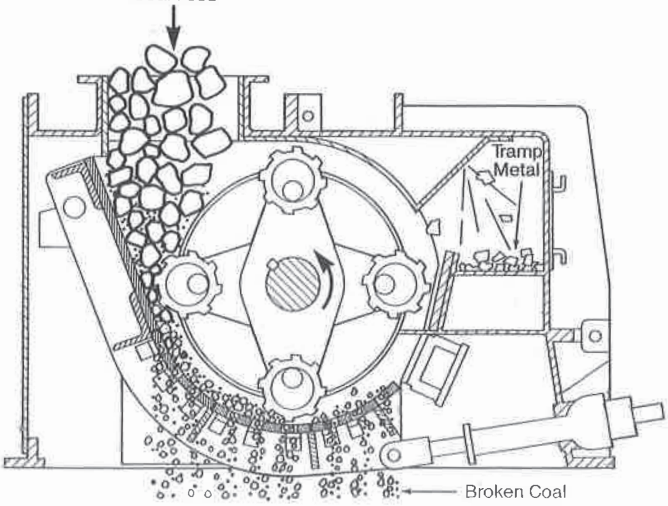


Fig. 7 Ring hammer mill crusher — diagrammatic section (*courtesy of Pennsylvania Crusher Corporation*).

Coal cleaning and preparation

The demand for coal cleaning has increased in response to environmental regulations restricting sulfur dioxide (SO_2) emissions from coal-fired boilers. The demand is also due to a gradual reduction in run-of-mine coal quality as higher quality seams are depleted and continuous mining machines are used to increase production. Approximately 70% of coal mined for electric utility use is cleaned in some way.

Coal cleaning and preparation cover a broad range of intensity, from a combination of initial size reduction, screening to remove foreign material, and sizing discussed previously, to more extensive processing to remove additional ash, sulfur and moisture more intimately associated with the coal.

The potential benefits of coal cleaning must be balanced against the associated costs. The major costs to consider, in addition to the cleaning plant capital and operating costs, include the value of the coal lost to the refuse product through process related inefficiencies and the cost of disposing of the refuse product. Generally, the quantity of coal lost increases with the degree of desired ash and sulfur reduction. An economic optimum level of ash and sulfur reduction can be established by balancing shipping and postcombustion cleanup costs against precombustion coal cleaning costs.

Coal characterization

Coal is a heterogeneous mixture of organic and inorganic materials as described in detail in Chapter 8. Coal properties vary widely between seams and within a given seam at different elevations and locations. The impurities associated with coal can generally be classified as inherent or extraneous. *Inherent impurities* such as organic sulfur can not be separated from the coal by physical processes. *Extraneous impurities* can be partly segregated from the coal and removed by physical coal cleaning processes. The extent to which these impurities can be economically removed is determined by the degree of material dissemination throughout the coal matrix, the degree of liberation possible at the selected processing particle size distribution, and physical limitations of the processing equipment.

Mineral matter associated with the raw coal forms ash when the coal is burned. Ash forming mineral matter may also be classified as inherent or extraneous. Inherent mineral matter consists of chemical elements from plant material organically combined with coal during its formation. This mineral matter generally accounts for less than 2% of the total ash. Extraneous mineral matter consists of material which was introduced into the deposit during or after the coalification process, or is extracted with the coal in the mining process.

Sulfur is always present in coal and forms SO_2 when the coal is burned. If the sulfur is not removed before combustion, the SO_2 that forms is exhausted through the stack or removed by postcombustion flue gas treatment, discussed in Chapters 32 and 35. Sulfur is generally present in coal in three forms: pyritic, organic or sulfate.

Pyritic sulfur refers to sulfur combined with iron in the minerals pyrite (FeS_2) or marcasite. Pyrite may be present as lenses, bands, balls or as finely disseminated particles. *Organic sulfur* is chemically combined with molecules in the coal structure. *Sulfate sulfur* is present as calcium or iron sulfates. The sulfate sulfur content of coal is generally less than 0.1%.

The total sulfur in U.S. coals can vary from a few tenths of a percent to more than 8% by weight. The pyritic portion may vary from 10 to 80% of the total sulfur and is usually less than 2% of the coal by weight (Table 1).

The larger pyritic sulfur particles can generally be removed by physical cleaning, but finely disseminated pyritic sulfur and organic sulfur can not. Advanced physical and chemical cleaning technologies under development to remove these sulfur forms have not yet proven economical.

Moisture can also be considered an impurity because it reduces the heating value of raw coal. Inherent moisture varies with coal rank, increasing from 1 to 2% in anthracite to 45% or more in lignite. Surface moisture can generally be removed by mechanical or thermal dewatering. This drying requires an energy expense at the cleaning plant or the steam generating plant (in pre-drying or during combustion). Drying before shipment reduces transportation costs on a per-Btu basis. When predrying is used, atmospheric oxidation will tend to be increased for low rank coals because of the exposure of additional oxidation sites in the particles.

The distribution of ash and sulfur in a coal sample can be characterized by performing a *washability analysis*. This analysis consists of separating the raw coal into relatively narrow size fractions and then dividing each fraction into several specific gravity fractions. The coal in each size/specific gravity fraction is then analyzed for ash, sulfur and heating value content. The hardness and distribution of the impurities relative to the coal determines if the impurities are concentrated in the larger or smaller size fractions. Relatively soft impurities are generally found in the finer size fractions. In general, the lowest specific gravity fractions have the lowest ash content, as indicated in Table 2.

The information generated by these *float/sink* characterization tests can be used to predict the degree of ash and sulfur reduction possible using various specific gravity based cleaning technologies discussed below. In general, the more material that is present near the desired specific gravity of separation, the more difficult it is to make an efficient separation.

Table 1
Distribution of Sulfur Forms in Various Coals (%)

Mine Location County, State	Coal Seam	Total Sulfur	Pyritic Sulfur	Organic Sulfur
Henry, MO	Bevier	8.20	6.39	1.22
Henry, MO	Tebo	5.40	3.61	1.80
Muhlenburg, KY	Kentucky #11	5.20	3.20	2.00
Coshocton, OH	Ohio #6	4.69	2.63	2.06
Clay, IN	Indiana #3	3.92	2.13	1.79
Clearfield, PA	Upper Freeport	3.56	2.82	0.74
Franklin, IL	Illinois #6	2.52	1.50	1.02
Meigs, OH	Ohio #8A	2.51	1.61	0.86
Boone, WV	Eagle	2.48	1.47	1.01
Walker, AL	Pratt	1.62	0.81	0.81
Washington, PA	Pittsburgh	1.13	0.35	0.78
Mercer, ND	Lignite	1.00	0.38	0.62
McDowell, WV	Pocahontas #3	0.55	0.08	0.46
Pike, KY	Freeburn	0.46	0.13	0.33
Kittitas, WA	Big Dirty	0.40	0.09	0.31

Table 2
Typical Ash Contents of Various Bituminous Coal Specific Gravity Fractions

Specific Gravity Fraction	Ash Content % by wt
1.3 to 1.4	1 to 5
1.4 to 1.5	5 to 10
1.5 to 1.6	10 to 35
1.6 to 1.8	35 to 60
1.8 to 1.9	60 to 75
Above 1.9	75 to 90

Coal cleaning and preparation operations

The initial steps in the coal cleaning process include removal of trash, crushing the run-of-mine coal and screening for size segregation. These preliminary operations and associated hardware were discussed previously. The following operations are then used to produce and dewater a reduced ash and sulfur product. Fig. 8 provides a general layout of coal cleaning unit operations.

Gravity concentration Concentration by specific gravity and the subsequent separation into multiple products is the most common means of mechanical coal cleaning. Concentration is achieved because heavier particles settle farther and faster than lighter particles of the same size in a fluid medium. Coal and impurities may be segregated by their inherent differences in specific gravity, as indicated in Table 3.

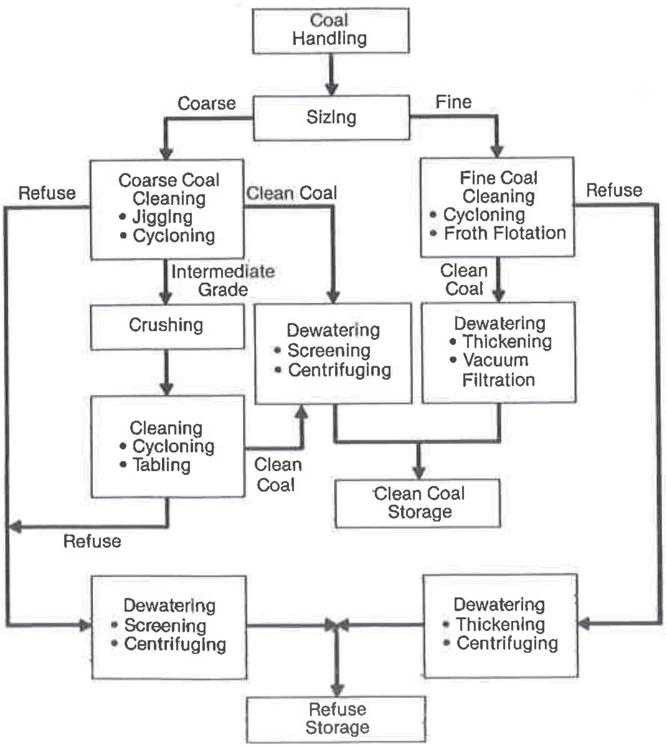


Fig. 8 General layout of coal cleaning operations.

Table 3
Typical Specific Gravities of Coal and Related Impurities

Material	Specific Gravity
Bituminous coal	1.10 to 1.35
Bone coal	1.35 to 1.70
Carbonaceous shale	1.60 to 2.20
Shale	2.00 to 2.60
Clay	1.80 to 2.20
Pyrite	4.80 to 5.20

The fluid separating medium may consist of a suspension of the raw coal in water or air, a mixture of sand and water, a slurry of finely ground magnetite or an organic liquid with an intermediate specific gravity. Aqueous slurries of raw coal and magnetite are currently the most common separating media.

If the effective separating specific gravity of the media is 1.5, particles with a lower specific gravity are concentrated in the clean coal product and heavier particles are in the reject or refuse product. Several factors prevent ideal separation in practice.

Gravity separation processes concentrate particles by mass. The mass of a particle is determined by its specific gravity and particle size. Raw coal consists of particles representing a continuous distribution of specific gravities and sizes. It is quite possible for a larger, less dense particle to behave similarly to a smaller particle with a higher specific gravity. For example, a relatively smaller pyrite particle may settle at a similar rate as a larger coal particle. The existence of *equal settling* particles can lead to separating process inefficiency. Fine pyrite in the clean coal product and coarse coal in the refuse are commonly referred to as *misplaced material*. The amount of misplaced material is determined by the quantity and distribution of the raw coal impurities, the specific gravity of separation, and the physical separation efficiency of the segregated material.

A significant amount of material with a specific gravity close to the desired specific gravity of separation results in a more inefficient separation. If the amount of *near gravity material* exceeds approximately 15 to 20% of the total raw coal, efficient gravity separation is difficult.

The most common wet gravity concentration techniques include jigging, tabling and dense media processes. Each technique offers technical and economic advantages.

Jigging In a coal jig, a pulsating current of water is pushed upward in a regular, periodic cycle through a bed of raw coal supported on a screen plate. This upward or pulsion stroke of the cycle causes the bed to expand into a suspension of individual coal and refuse particles. The particles are free to move and generally separate by specific gravity and size, with the lighter and smaller pieces of coal moving to the upper region of the expanded bed. In the downward or suction stroke of the cycle, the bed collapses, and the separation is enhanced as the larger and heavier pieces of rock settle faster than the coal. The pulsion/suction cycle is repeated continuously. The separated layers are split at the discharge end of the jig to form a clean coal and a refuse product. The bed depth at which the cut is made determines the effective specific gravity of separation.

The upward water pulsation can be induced by using a diaphragm or by the controlled release of compressed air in an adjacent compartment. Operation of a Baum jig is illustrated in Fig. 9. This type of jig may be used to process a wide feed size range. Typically, the specific gravity of separation ranges from 1.4 to 1.8. The separation efficiency may be enhanced by pre-screening the feed to remove the fines for separate processing.

Tabling A concentrating, pitched table is mounted so that it may be oscillated at a variable frequency and amplitude. A slurry of coal and water is continuously fed to the top of the table and is washed across it by the oncoming feed. Diagonal bars, or *riffles*, are spaced perpendicular to the flow of particles. The coal-water mixture and oscillating motion of the table create a *hindered settling* environment in which the lower gravity particles rise to the surface. Higher specific gravity particles are caught behind the riffles and transported to the edge of the table, away from the clean coal discharge.

Tables are generally used to treat 0.375 in. x 0 (9.53 mm x 0) coal. Three or four tables may be stacked vertically to increase throughput while minimizing plant floor space requirements.

Dense media separation In dense or heavy media separation processes, the raw coal is immersed in a fluid with a specific gravity between that of the coal and the refuse. The specific gravity differences cause the coal and refuse to migrate to opposite regions in the separation vessel. In coal preparation, the heavy media fluid is usually an aqueous suspension of fine magnetite in water.

Flotation Coal and refuse separation by *froth flotation* is accomplished by exploiting differences in coal and mineral matter surface properties rather than specific gravities. Air bubbles are passed through a suspension of coal and mineral matter in water, which is agitated to prevent particles from settling out. Air bubbles preferentially attach to the coal surfaces which are generally more hydrophobic, or difficult to wet. The coal then rises to the surface where it is concentrated in a froth on top of the water. The mineral matter remains dispersed (Fig. 10). Chemical reagents, referred to as collectors and frothers, are added to enhance the selective attachment of the air bubbles to the coal and to permit a stable froth to form.

Flotation is generally used for cleaning coal finer than 48 mesh (300 microns). The efficiency of the process can be enhanced by carefully selecting the type and quantity of reagents, fine grinding to generate discrete coal and refuse particles, and generating fine air bubbles.

Dry processing Dry coal preparation processes account for a small percentage of the total coal cleaned in the U.S. In general, pneumatic processing is only applied to coal less than 0.5 in. (12.7 mm) in size with low surface moisture.

Dewatering Dewatering is a key step in the preparation of coal. Reducing the fuel's moisture content increases its heating value per unit weight. Because coal shipping charges are based on tonnage shipped, a reduction in moisture content results in lower shipping costs per unit heating value.

Coarse coal, greater than 0.375 in. (9.53 mm) particle size, can be sufficiently dewatered using vibrating screens. Intermediate size coal, 0.375 in. (9.53 mm) by approximately 28 mesh (600 microns), is normally dewatered on vibrating screens followed by centrifuges.

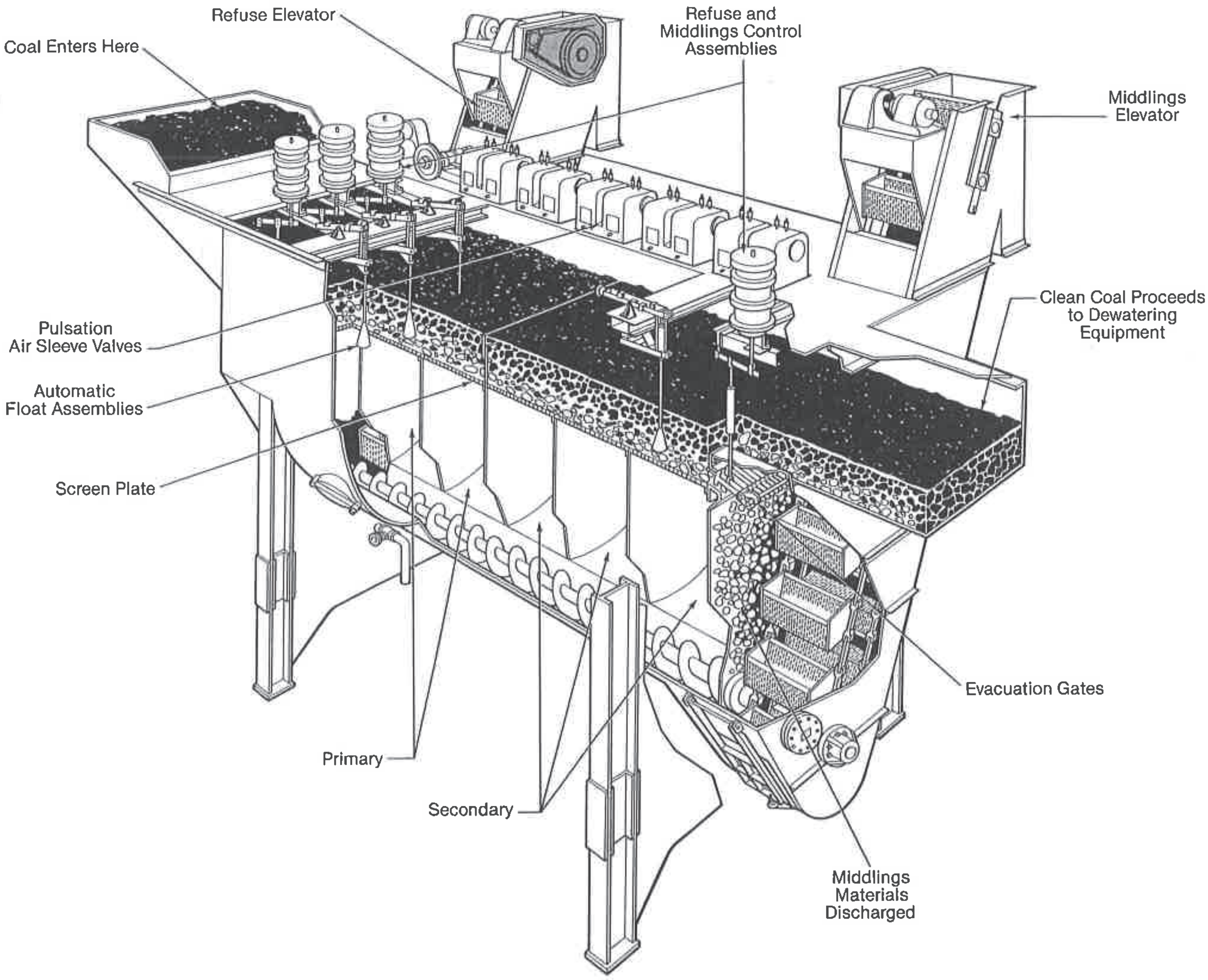


Fig. 9 Baum jig for coal preparation *(courtesy of McNally Pittsburg Mfg. Corp.).*

Fine coal dewatering often involves the use of a thickener to increase the solids content of the feed to a vacuum drum, vacuum disc filter or high gravity centrifuge. The filter cake may be mixed with the coarser size fractions to produce a composite product satisfying the specifications. Fine coal dewatering also serves to clarify the water for reuse in the coal preparation plant. Fines must be separated from the recycled water to maximize the efficiency of the separation processes.

Thermal dewatering may be necessary to meet product moisture specifications when the raw coal is cleaned at a fine size to maximize ash and sulfur rejection. The various types of thermal dryers include rotary, cascade, reciprocating screen, suspension and fluidized-bed dryers. Cyclones or bag filters are used to prevent fine dust emissions from the dryer. The collected fine coal may be recycled to support dryer operation. Thermal drying represents an economic tradeoff of reduced product moisture content versus heat required to fire the dryer.

Impact on steam generator system operations

The principal benefit of coal cleaning is the reduction in ash and sulfur content. Reduced ash content results in lower shipping costs and reduced storage handling requirements at the plant on a cost per unit heating value basis. Boiler heat transfer effectiveness may increase as a result of reduced ash deposition on tube surfaces. A reduction in sulfur content leads directly to reduced SO_2 emissions. Lower sulfur feed coal may preclude the need for or reduce the performance requirements of postcombustion SO_2 emission control systems. A reduction in sulfur content may also reduce spontaneous combustion during storage and

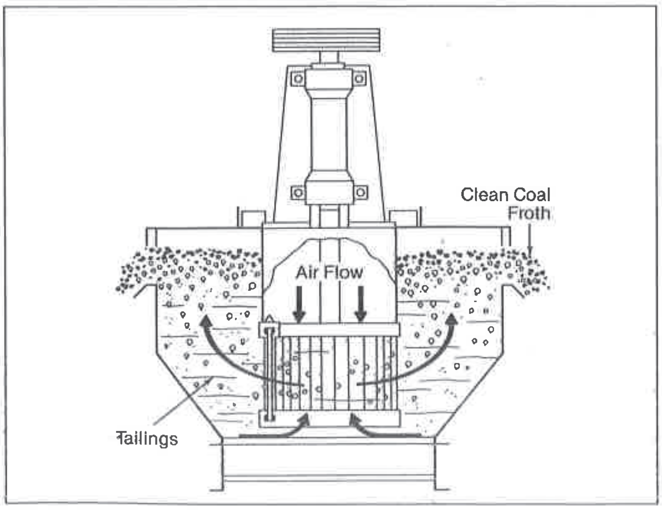


Fig. 10 Flotation cell.

corrosion in coal handling and storage equipment. Reduced ash content can result in reduced maintenance through removal of abrasive pyrite and quartz from the coal. Reduction of clay in the coal can improve handling but this may be offset by the effects of higher fines content and higher surface moisture on cleaned coal.

Coal transportation

The means of transportation and the shipping distance significantly influence the total fuel cost, reliability of supply, and fuel uniformity at the power plant. In some cases where Western U.S. coal is shipped over an extended distance, freight costs may represent 75 to 80% of the total delivered fuel cost. At the other extreme, transportation costs may be negligible for mine mouth generating stations. In transit, the coal's handling characteristics may be changed by freezing, increased moisture content or size degradation. When open rail car or barge transport is used, the moisture content of the delivered coal depends on the weather conditions in transit, the initial moisture level and the particle size distribution. Size degradation during shipping is dependent on the coal friability (ease of crumbling) and the techniques and number of transfers. As previously stated, for pulverized coal applications, size degradation is generally not a concern.

Coal is primarily shipped by rail, barge, truck and conveyor. The volume and distribution of coal transported by various means is summarized in Table 4. Combinations of these methods are often used to obtain the lowest delivery cost. Available transportation infrastructure, haulage distance, required flexibility, capital cost and operating cost are important factors in selection of a system for delivering coal to the power plant.

In general, barge transport represents the lowest unit cost per ton per mile followed by rail, truck and conveyor in terms of increasing cost. Combinations of these four transportation systems may be used to move coal to loading docks for overseas shipment. The major coal export ports in the U.S. are Hampton Roads, Virginia; Baltimore, Maryland and Philadelphia, Pennsylvania.

Transportation systems are generally designed to minimize intermediate storage of coal to control inventory costs, reduce insurance costs and minimize the effects of changes which can reduce the commercial value of coal. Potentially harmful changes include a reduction of heating value, particle size degradation, and loss due to self-ignition or wind and water erosion.

Rail

Approximately 57% of the coal delivered to power plants in the U.S. is shipped by rail. About half of this total is shipped in unit trains. Unit trains are dedicated rail shipments of coal normally consisting of 100 or more cars with a total of 10,000 t of coal or more. Bottom dump rail cars (100 t capacity) are typically used. The high capacity rail cars are generally not uncoupled from the time they are loaded at the mine until they arrive at the plant. In 1989 coal accounted for 40% of the rail industry's total freight tonnage and 22% of the revenues.

Table 4
Distribution of Coal Transportation Methods (1988)[2]

	10^6 t/yr	10^6 t_m/yr	% of Total
Rail	550	499	57.4
Barge	155	141	16.2
Truck	128	116	13.3
Conveyor/pipeline	126	114	13.1

Rail transport provides for the movement of large quantities of coal over distances ranging from 10 to 1500 mi (16 to 2414 km).[1] Dedicated service between one mine and the steam generating plant simplifies management of coal deliveries.

The advantages of rail transport are somewhat offset by the restricted rail access. Generally only one rail line is available to transport coal from a mine or to a specific steam generating plant. The installation of dedicated rail lines must be factored in to the cost of the coal handling and storage system. Rail spurs to a specific mine location are useful only for the life of the mining activity. Transit time is typically on the order of 4 to 20 days.[1] The rail car unloading system and intermediate storage facilities must be designed to quickly process the cars to avoid demurrage (delay) charges at the plant.

Barge

Barge transport of coal is the most cost effective alternative to rail. Approximately 16% of all coal shipped to steam generating plants in the U.S. is delivered by barge as illustrated in Fig. 11. Coal is the second largest single barge commodity and coal traffic accounts for a large fraction (23% in 1985) of annual barge tonnage.

Two standard sizes of open top coal barges are commonly applied to coal transport. The 1000 t (907 t_m) capacity Pittsburgh standard barge measures 175 ft (53 m) long x 26 ft (8 m) wide with a draft of 9 ft (2.7 m). The jumbo barge has a nominal capacity of 1500 t (1361 t_m) and is 195 ft x 35 ft (59 x 11 m) with a 12 ft (3.6 m) draft.[2] A single tow, or group of 20 barges, can carry 20,000 to 30,000 t (18,144 to 27,216 t_m).

The major waterways for coal traffic in the U.S. are the Ohio, Mississippi and Black Warrior-Tombigbee Rivers.[3] The quantity of coal shipped in a single tow or string of barges is determined by the lock requirements of the river system being navigated. For example, on the Ohio River system, a tow of three barges wide by five barges long is commonly used because of the River's lock requirements.[4]

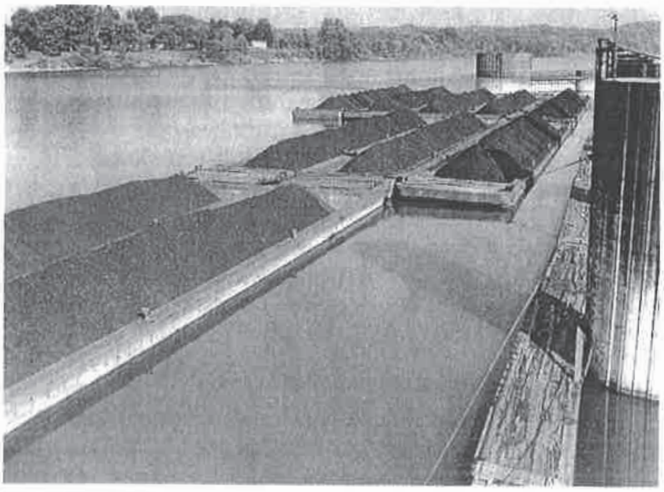


Fig. 11 Typical barge transport for large quantities of coal.

However, on the relatively unobstructed lower Mississippi, tows of 30 barges are not uncommon.

There is a significant degree of competition and transport prices are generally stable. Some cost differences between upstream and downstream travel are common.

Barge transportation of coal to steam generating plants is constrained by the location and characteristics of the available river systems. Close proximity to waterways for direct loading and unloading is needed for efficient barge transportation. Barge delivery must be supported by truck, rail or belt conveyor trans-loading at the mine location or the steam generating plant. The natural river network is not always the most direct route and may result in increased delivery time. The channel width and seasonal variability in water level are natural limitations for barge traffic. River lock sizes and condition of repair may restrict the maximum permitted tow size. Delays due to deteriorating locks and congestion may be significant on some river systems. In some areas lock repair costs are recovered through a surcharge on tonnage shipped through the lock. Barges are not self-unloading. The capital investment required for the unloading facilities may restrict barge deliveries to plants using more than 50,000 t/yr.[1]

Truck

For power plants located near mines, trucks loaded at the mine deliver coal directly to the power plant storage site. Trucking accounts for about 13% of the total tonnage of coal delivered to steam generating plants. Usually, a small receiving stockpile for truck deliveries is set up separate from the main storage pile to permit isolation until it is determined that the coal satisfies the required quality specifications.

Trucking also pays a key role in both rail and barge transport. Approximately 70% of the coal transported by rail or barge is first trucked to the loading dock or involves truck transfer at some point.[5] Highway trucks typically carry 15 to 30 t (14 to 27 t_m) of coal over distances ranging up to 70 mi (113 km). Off-road vehicles can handle 100 to 200 t (91 to 181 t_m) over a range of 5 to 20 mi (8 to 32 km) at mine mouth generating stations.

Trucking is the most flexible mode of coal transportation. It is relatively easy to adjust to changes in demand to meet the generating plants' variable supply requirements. The short haulage distances, and therefore short delivery times, can be used to minimize storage requirements at the generating plant. Trucks are simple to unload and a minimum of on-site handling and distribution is needed. Use of the existing highway infrastructure provides for flexible delivery routes and reduces travel restrictions associated with rail and river transport. Trucks are very efficient for short haulage distances and for smaller generating plants. Trucking is the least capital intensive mode of transporting coal and a high degree of competition exists.

Truck transportation is characterized by a high operating cost per ton mile relative to barge or rail transport. Practical haulage distances are usually limited to 50 mi (80 km). State and local transportation regulations often limit loads to 25 t (23 t_m) or less. A large generating plant would require a significant amount of truck traffic and congestion at the delivery site may be severe. Truck deliveries require the highest degree of monitoring at the plant. Frequently, every truck must be weighed.

Continuous transport

Coal may be transported from the mine to the generating plant by continuous belt conveyors or slurry pipelines. In 1988 continuous transport systems accounted for approximately 13% of the total coal deliveries. Belt conveyors are normally limited to lengths of 5 to 15 mi (8 to 24 km). The coal delivery rate is a function of the belt width, operating speed and the number of transfer points. Only one major coal slurry pipeline is in operation. The 273 mi (439 km) long Black Mesa pipeline runs from a mine in Arizona to a generating plant in Nevada. The coal transport rate is determined by the pipe diameter, slurry velocity and solids loading.[6]

Continuous systems can move large amounts of coal cost-effectively over short distances. Often, continuous systems can be used where the terrain limits the use of other modes of transport. Social and environmental impacts are minimal.

The application of continuous transportation systems is limited by the proximity to the generating plant, a low degree of operating flexibility due to the fixed carrying capacity, the inflexibility of the loading and discharge locations, high capital cost and a relatively high energy consumption per ton mile of coal delivered. Pipeline builders must overcome significant opposition in obtaining rights of way and water resource allocation. The added costs associated with dewatering the coal at the generating plant must also be considered.

Coal handling and storage at the power plant

Bulk storage of coal at the power plant is necessary to provide an assured continuous supply of fuel. The tonnage of coal stored at the site is generally proportional to the size of the boiler. A 100 MW plant burns approximately 950 t/d (862 t_m/d), while a 1300 MW plant requires approximately 12,000 t/d (10,887 t_m/d). For some public utilities, a minimum of 60 to 90 day supply must be stored at the plant by law. However, stored coal represents substantial working capital and requires land which may be otherwise productive. Economic considerations are a key factor in determining when to purchase coal and how much coal to store at the plant. Additional considerations, such as the changes to coal characteristics due to weathering, restrict the maximum amount of coal stored on site.

For smaller, industrial boiler applications, bin or silo storage may be preferred over stockpile storage. The advantages of bin storage include shelter from weather and ease of reclamation. Prefabricated bins with capacities up to 94,500 ft^3 (2674 m^3) holding approximately 2400 t (2177 t_m) are commercially available.[7]

The complexity of the coal storage and handling operations increases in proportion to the size of the steam generating plant. Efficient techniques have been developed for large and small plants. The components of a sophisticated coal storage and handling system for a large, 1000 MW electric generating plant are illustrated in Fig. 12. Coal is delivered in self-unloading, bottom dump railcars and is transferred to a large stockpile. An automatic reclaim system recovers coal from the stockpile for crushing and distribution to in-plant storage silos. The system is automated and a two man crew can handle 7000 t/d (6350 t_m/d) of coal. All the equipment from the reclaim feeders to the in-plant silos and boiler is unmanned and controlled by the central control room operator.

The storage and handling operations of a utility boiler are depicted in the chapter frontispiece.

Raw coal handling

An extensive array of equipment is available for unloading coal at the plant site and distributing it to stockpile and bin storage locations. Equipment selection is generally based on the method of coal delivery to the plant, the boiler type, and the required coal capacity. For small plants, portable conveyors may be used to unload rail cars, to reclaim coal from yard storage piles and to fill bunkers. Larger plants require dedicated, installed handling facilities to meet the demand for a continuous fuel supply. However, even relatively small plants may benefit from the improved plant appearance, cleanliness and reduced coal handling labor requirements associated with mechanical handling systems.

The coal handling system components are determined by the design and requirements of the boiler. A crusher is normally integrated into the system to generate a uniform top size coal feed to the pulverizer or boiler. The system normally includes a magnetic separator to remove misplaced mining tools and roof support bolts which could damage the pulverizer. Crushing and tramp metal removal needs are generally less critical for stoker-fired boilers than for pulverized coal units.

The coal handling system capacity is determined by the boiler's rate of coal use, the frequency of coal deliver-

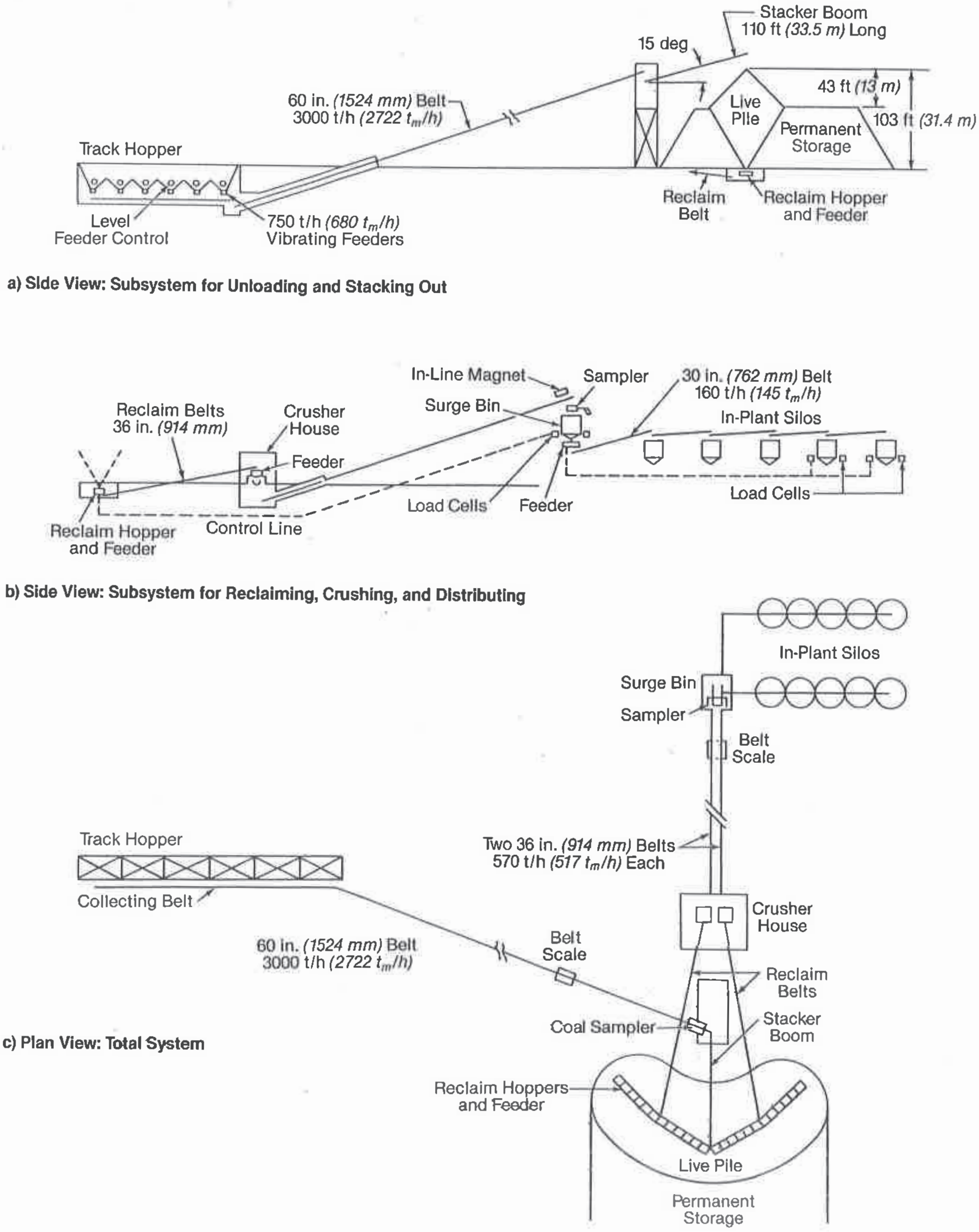


Fig. 12 Typical coal handling system and subsystems for a 1000 MW coal-fired power generation plant.

ies to the plant, and the time allowed for unloading. In most large plants, only four to six hours per day are dedicated to unloading coal deliveries.

Rail car unloading

In automatic rotary car dumping systems, the rail cars are hydraulically or mechanically clamped in a cradle, and the cradle is rotated so the coal falls into a hopper below the tracks. The dumping is completed without uncoupling the cars. The rotary dump system advantages of short cycle time and high capacity are offset by a relatively high capital cost.

With bottom dump cars, unloading is relatively simple when the coal is dry and free flowing. However, high surface moisture can cause the coal to hang up in the car and, in cold weather, freeze into a solid mass. In hot, dry weather, high winds can create severe dust clouds at the unloading station unless special precautions are taken. The coal supplier frequently sprays the coal with oil or an anti-freezing chemical such as ethylene glycol as the car is loaded to settle the fines and to ease handling in freezing weather. The treatment does not appreciably affect combustion or cause problems in the pulverizers. There is also some evidence that the treatment may reduce hangups in bunkers and chutes.

A rail car unloading system which includes a crusher and magnetic separator is illustrated in Fig. 13. A screw conveyor is used to distribute coal along the length of the bunker. The capacity of the bucket elevator generally limits this system to relatively small plants.

A rail car unloading and handling system for a large plant using at least 3000 t/d (2722 t_m/d) of coal is shown in Fig. 14. Coal from the car dump hopper is fed to a rotary breaker, in which the coal breaks into smaller pieces as it is tumbled and passes through a screen shell. The broken coal is then conveyed to the storage bunker, where a tripper belt conveyor distributes it over the length of the bunker.

Barge unloading

The simplest barge unloader consists of a clamshell bucket mounted on a fixed tower. The barge is positioned under the bucket and is moved as necessary to allow emptying. With this type of unloader, the effective grab capacity of the buckets is only 40 to 50% of the nominal bucket capacity. A shore mounted bucket wheel or elevator unloader can increase the efficiency and capacity of this unloading operation. Modern ocean-going vessels are often equipped with a bucket wheel for self-unloading.

Truck unloading

Trucks may dump coal through a grid into a storage hopper. This grid separates large pieces of wood and other trash from the coal. At some plants, the trucks are directed to a temporary storage area, where coal from various mines can be blended prior to crushing or feeding to the boiler.

An effective truck delivery and coal handling system for a small to medium size (30 to 300 t/d) stoker coal-fired boiler is illustrated in Fig. 15. The elevator and storage bunker are located outside and no provisions are made for crushing or tramp metal removal. Transfer chutes should be angled at least 60 deg from horizontal to minimize coal hangups.

Stockpile storage

Careful consideration should be given to storage pile location. The site must be conveniently accessible by barge, rail or truck. Frequently, provisions must be made for more than one method of coal delivery. The site should be free of underground power lines. Other underground utilities that would not be accessible after the storage pile is constructed must also be avoided. A thorough evaluation and environmental survey of the proposed site topography should include analysis of the soil characteristics, bedrock structure, local drainage patterns and the potential for flooding. Climatic data, such as precipitation records and prevailing wind patterns, should also be evaluated. Protection from tidal action or salt water

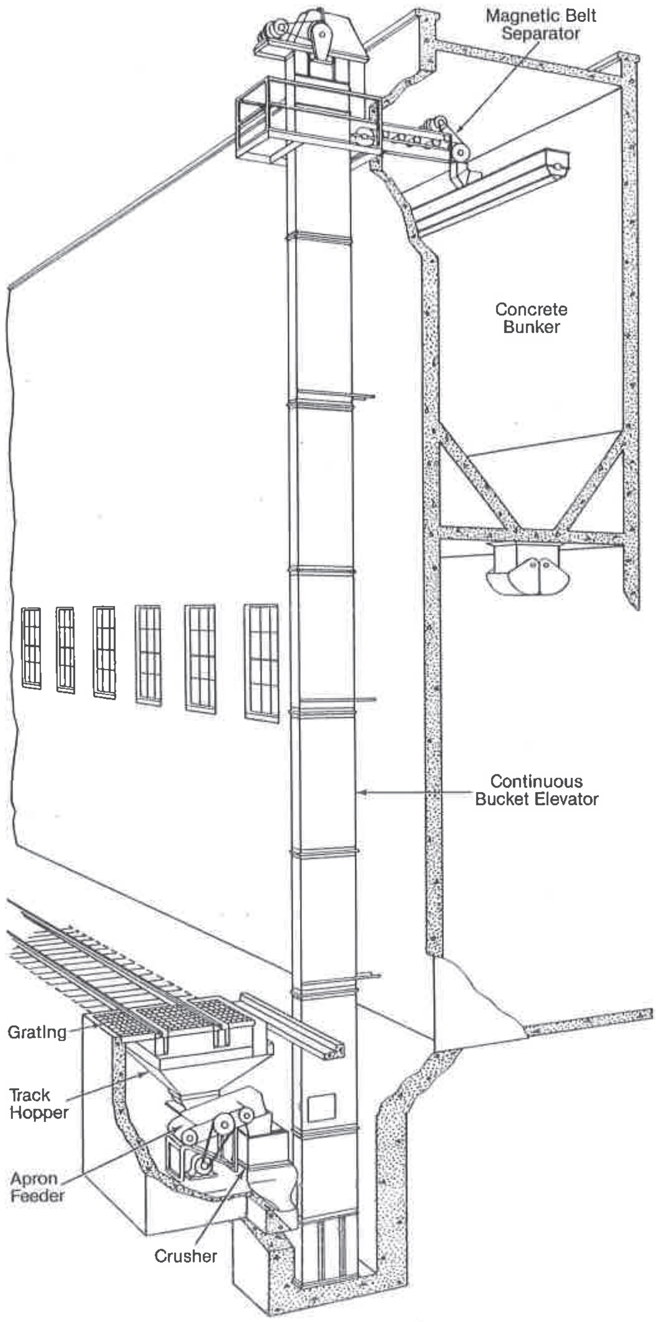


Fig. 13 Rail car dumping system for a small power plant.

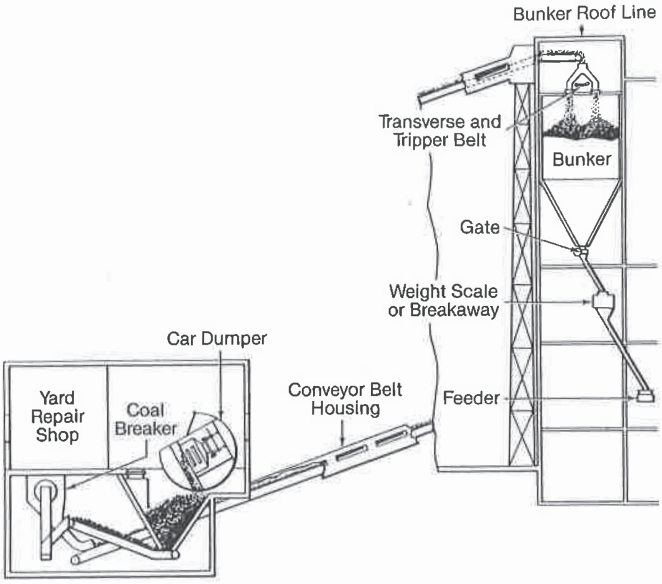


Fig. 14 Rail car unloading and coal handling system for a large power plant.

spray may be needed in coastal areas. The potential effects of water runoff and dust emissions from the pile must be considered. Site preparation includes removing foreign material, grading for drainage, compacting the soil and providing for collection of site drainage.

The shape of a stockpile is generally dependent on the type of equipment used for pile construction and for reclaiming coal from the pile. Conical piles are generally associated with a fixed stacker while a radial stacker generates a kidney shaped pile. A rail mounted traveling stacker can be used to form a rectangular pile. Regardless of the shape of the pile, the sides should have a shallow slope.

Bituminous coal, subbituminous coal and lignite should be stockpiled in multiple horizontal layers. To reduce the potential for spontaneous combustion, coal piles are frequently compacted to minimize air channels. These channels can function as chimneys which promote increased air flow through the pile as the coal heats. For bituminous coal, an initial layer, 1 to 2 ft (0.3 to 0.6 m) thick, is spread and thoroughly packed to eliminate air spaces. A thinner layer is required for subbituminous coal and lignite to assure good compaction. Care should be taken to avoid coal pile size segregation by blending coal during pile preparation.

For long term storage (see Fig. 16), the top of the pile may be slightly crowned to permit even rain runoff. All exposed sides and the top may be covered with a 1 ft (0.3 m) thick compacted layer of fines and then capped with a 1 ft (0.3 m) layer of screened lump coal. It is not practical to seal subbituminous and lignite piles with coarse coal because the coarse coal would weather and break apart to a smaller size in a short period of time. At smaller industrial plants, where heavy equipment for compaction can not be justified, a light coating of diesel oil can help to seal off the outer surface of the pile.

The quantity of coal stored in a stockpile can be estimated using geometry and some assumptions about the characteristics of coal. The volume of the pile can be estimated based on its shape. Approximate values for the material's bulk density and its angle of repose are required to complete tonnage calculations. Both of these parameters are particle size dependent. For typical utility storage pile applications, a loose coal bulk density of 50 lb/ft^3 (801 kg/m^3) and a 40 deg angle of repose may be used. For well compacted piles, a bulk density of 65 to 72 lb/ft^3 (1041 to 1153 kg/m^3) is more appropriate.

Storage pile inspection and maintenance Visual inspections for hot spots should be made daily. In wet weather, a hot area can be identified by the lighter color of the surface coal dried by escaping heat. On cold or humid days, streams of water vapor and the odor of burning coal are

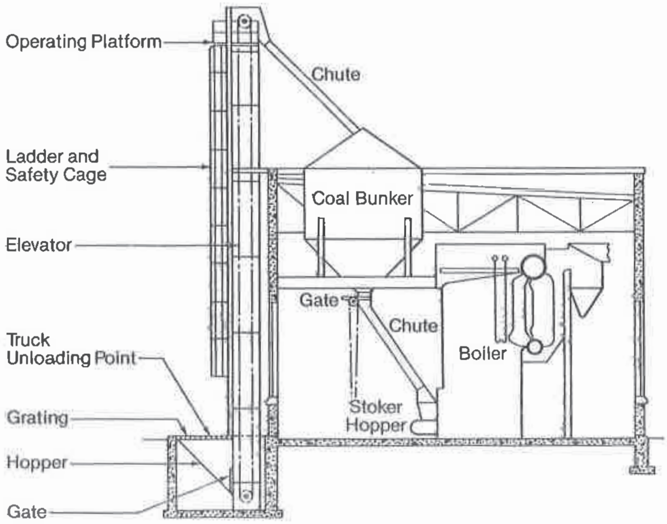


Fig. 15 Coal handling equipment for truck delivery.

Fig. 16 Long term coal storage — typical example of thorough packing with minimum size segregaton. This pile contains about 200,000 t of coal.

signs of heating or air flowing through the pile. Hot spots may also be located by probing the pile with a metal rod. If the portion of the rod in contact with the coal is too hot to be held as it is withdrawn, the coal temperature is dangerously high.

It is also important to rotate areas of the storage pile from long to short term storage on a planned schedule. This minimizes harmful degradation of the coal.

Bulk storage reclaim and transfer The specific system for reclaiming the stored coal depends upon plant size and economic tradeoffs between operating and capital costs. For higher capacity systems [150 to 4000 t/h (136 to 3629 t_m/h)], underground conveyors (Fig. 12) and bucketwheel reclaimers are used. As discussed earlier and shown in Fig. 12, coal is transferred to the in-plant silos or bunkers by inclined conveyors and, where needed, bucket elevators. Appropriate coal sizing and monitoring steps can be incorporated: crushing, magnetic tramp iron removal, screening, weighing and sampling. Bucket elevators (see Figs. 13, 15 and 17) are primarily used at small installations because of their limited capacity.

Silo storage

Fig. 17 illustrates a common silo design with an approximate storage capacity of 600 t (544 t_m). An internal shelf permits maximum use of the storage space. As coal is used from above the shelf, reserve storage can be reclaimed from the lower part of the silo. Silo storage requires less building volume and structural steel for a given capacity than bunker storage.

Bunker storage

Coal bunkers provide intermediate, short term storage ahead of the pulverizers or other combustion zone coal feed equipment. The complexity of bunker and chute design has increased as the size of individual boilers and consequently the rate of coal consumption have increased.

When the bunkers and transfer chutes have been properly selected and sized, the condition of the coal becomes the dominant factor in determining the effectiveness of the fuel supply system. Steady flow of fine coal can be difficult to maintain when the surface moisture is 5 to 10%. *Rat holes* or *pipes* can form in the bunker, resulting in intermittent flow or complete flow stoppage.

To assure a continuous flow of coal from the bunker, the design and construction must be integrated with the upstream bulk storage and handling techniques and the anticipated coal properties at the bunker inlet.

Bunker design Once constructed, coal bunkers are an integral part of the boiler house structure and are usually not modified significantly over the life of the plant. The required capacity, construction material, shape and location are important considerations in designing a bunker.

The capacity of a bunker or series of bunkers should normally be sufficient to provide 30 hours of fuel supply at maximum boiler operating load. The storage capacity must also be adequate to cover weekend or holiday periods during which coal handling labor or equipment may not be available. Storage bunkers provide flexibility to optimize plant operating labor requirements and to permit maintenance and repair of coal handling equipment independent of steam generator operation.

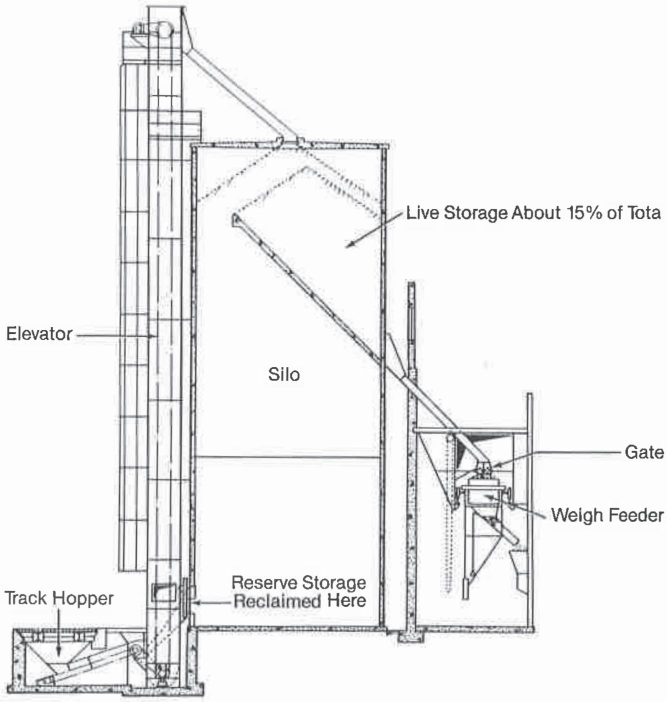


Fig. 17 Silo system for live and reserve storage.

Coal bunkers have been built of tile, reinforced concrete, carbon steel plate, stainless steel clad plate, steel plate lined with acid resistant concrete and steel plate lined with rubber. When unlined carbon steel plate is used, a periodic inspection program is required to monitor corrosion and to assure the safety of the structure.

The final shape of a bunker usually represents a compromise between space limitations and the optimum design for coal flow. Dead pockets, in which coal flow is restricted, should be avoided because of possible spontaneous combustion. Several common bunker shapes are shown in Fig. 18. The silo bunker is less susceptible to rat holing and hangups than other shapes. This design is equally suitable for small and large plants.

The bunker should be located so that coal flow to the pulverizer or furnace is nearly vertical. Generally, bunkers are located in the upper levels of the plant to permit gravity flow to pulverizer or furnace feeders underneath. Storage bunkers should be as far as possible from furnace exit gas flues, hot air ducts, steam pipes, or other external sources of heat which could contribute to spontaneous coal ignition. It may be necessary to insulate the bunker and provide ventilation to reduce heat transfer from nearby steam lines or breachings. Bunkers should also be designed to provide a means of emptying the coal for an extended forced outage.

Chute design Modeling of coal flow in transfer chutes has identified several design features which can minimize flow interruptions. Chutes should generally be circular, short and as steep as possible. Reductions in cross-sectional area and sudden changes in direction should be avoided. When two streams merge, a minimum angle of convergence should be used. Finally, except in pressurized systems discussed below, a *breakaway* (a vented sudden enlargement in diameter) should be used when significant changes in angle can not be avoided in order to relieve lateral pressure and pipe friction.

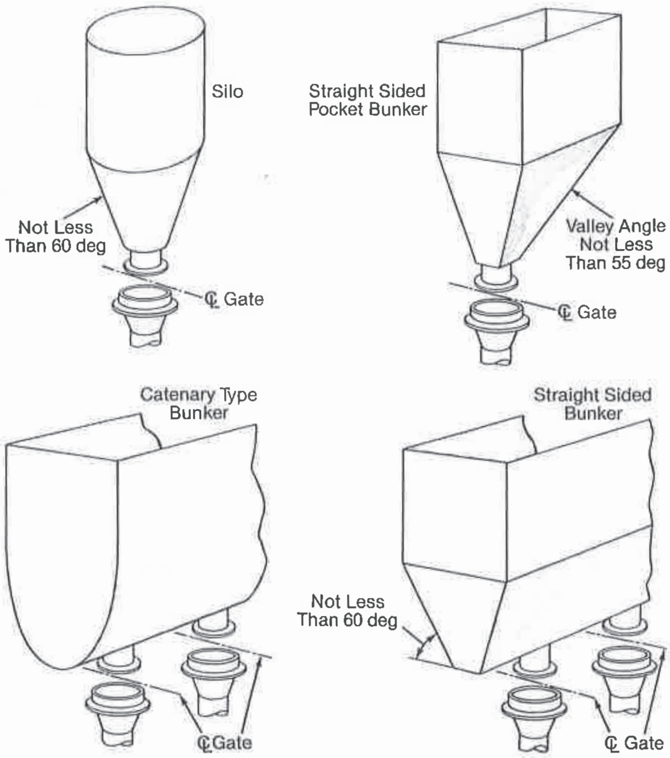


Fig. 18 Four commonly used shapes in coal bunker design.

In pressurized pulverizer feed applications, special consideration must be given to chute design because the coal inside the chute also serves as the seal to minimize air loss from the pressurized pulverizer to the bunker. A minimum required height (*seal height*) and a sealed chute/feeder system are required. Breakaways can not be used. A typical bunker to pulverizer system is shown in Fig. 19. Vertical, constant-diameter chutes connect the bunker to the feeder and the feeder to the pulverizer. Appropriate couplings and valves complete the system.

Feeder design

Feeders are used to control coal flow from the storage bunker at a uniform rate. Feeder selection should be based on an analysis of the material properties (maximum particle size, particle size distribution, bulk density, moisture content and abrasiveness), the desired flow rate and the degree of flow control required. A variety of feeder designs have been used for coal-fired applications with increasing sophistication over time as more accurate control of coal flow has become necessary. Feeders for modern pulverized coal applications can generally be classified as *volumetric* or *gravimetric*.

Volumetric feeders, as the name implies, are designed to provide a controlled volume rate of coal to the pulverizer. Typical examples include drag, table, pocket, apron and belt feeders. Belt feeders, perhaps the most accurate type, have a *level bar* to maintain the flow of coal at a constant height and width while the belt speed sets the velocity of the coal through the opening. As with all volumetric designs, however, the belt feeder does not compensate for changes in coal bulk density. This results in variations in the energy input to the pulverizer and ultimately to the burners.

Gravimetric feeders (see Fig. 20) compensate for variations in bulk density due to moisture, coal size and other factors. They provide a more precise weight flow rate of coal to the pulverizer and therefore more accurate heat input to the burners and boiler. Even variations in coal moisture have a larger relative impact on coal bulk density than on heating value. Therefore, modern gravimetric feeders offer an accurate, commercially accepted technology to control fuel and heat input to the burners and boiler. This can be a very significant issue where more accurate control of fuel/air ratios is needed to: 1) minimize the formation of nitrogen oxides (NO_x), 2) control furnace slagging, and 3) maximize boiler thermal efficiency by reducing excess air levels. (See Chapter 13.)

In the most common gravimetric feeder system, coal is carried on a belt over a *load cell* which monitors the coal weight on the belt. The feedback signal is used to maintain the weight flow by either: 1) adjusting the height of a leveling bar to control the cross-sectional coal flow area while the belt speed remains constant, or 2) fine tuning the belt speed while the cross-sectional area remains constant. The overall set point flow rate is adjusted by varying the base belt speed.

Coal blending

When coals from two or more sources fuel a single boiler, effective coal blending or mixing is required to provide a uniform feed to the boiler. The use of multiple coals can be driven by economics, coal sulfur content to

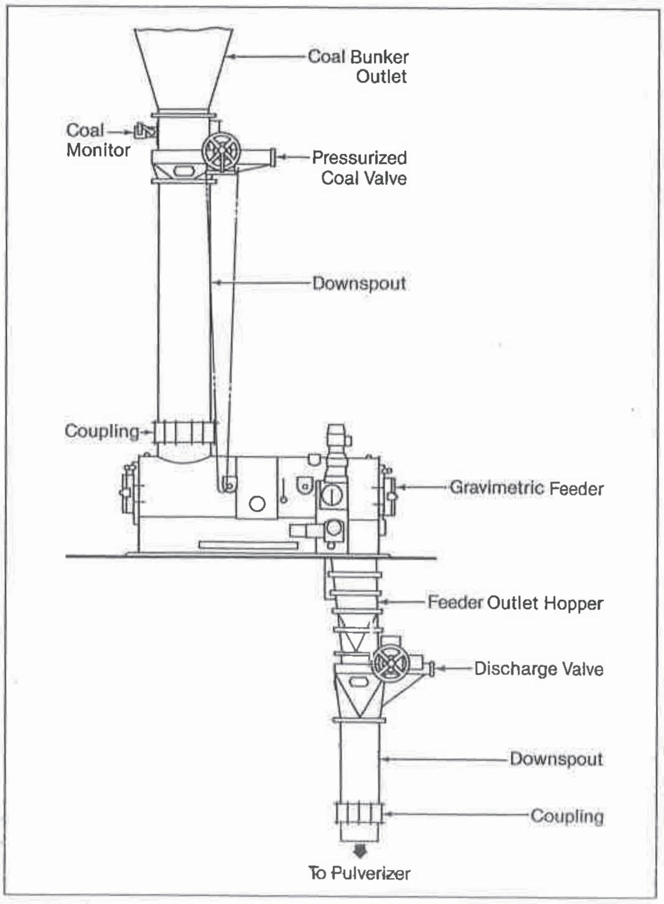


Fig. 19 Arrangement of bunker discharge to pulverizer showing typical feed system.

meet emission requirements and/or the effects of different coals on boiler operation. The goal of effective blending is to provide a coal supply with reasonably uniform properties which meet the blend specification typically including sulfur content, heating value, moisture content and grindability.

Coal blending may occur at a remote location or at the steam generating plant. Off-site blending eliminates the need for separate coal storage and additional fuel blending facilities. Steam plant on-site blending may be accomplished through a variety of techniques. It may be sufficient to provide separate stockpiles for each coal source and use front-end loaders to transfer the appropriate quantities to a common pile or hopper for blending prior to crushing. Coal may also be reclaimed from the various stockpiles using a boom or bridge-type reclaimer. Coal from the various sources may be stored in separate bins with a feeder from each bin used to meter the desired quantities onto a common transfer belt. On-site blending provides more flexibility in coal sourcing and in adjusting to actual on-site coal variations.

Particular care must be maintained to ensure proper and complete blending. Significant variations in the blended coal can have a major impact on operation of the pulverizers, burners, sootblowers and postcombustion cleanup equipment. If uniform blending does not occur, pulverizer performance can deteriorate (see Chapter 12), the boiler may experience excessive slagging and fouling, and electrostatic precipitator particulate collection efficiency may decline, among others.

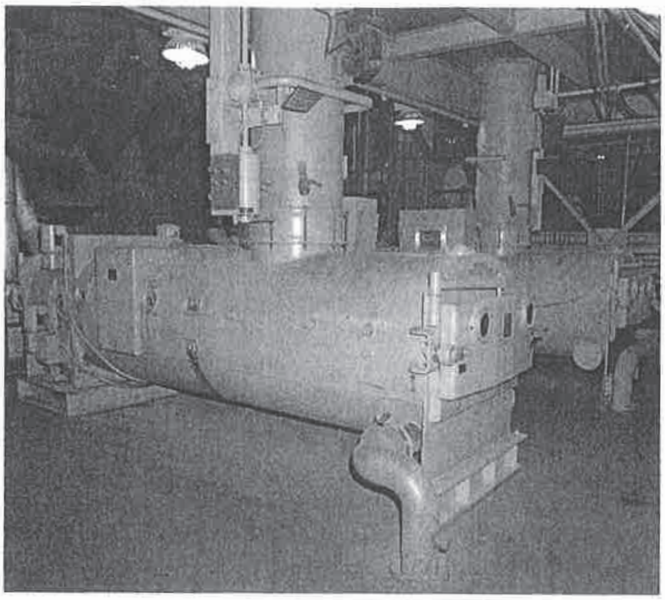


Fig. 20 Typical gravimetric feeder.

Resolution of common coal handling problems

Dust suppression

Water, oil and calcium chloride ($CaCl_2$) are common agents used to suppress dust emissions at coal handling and transportation transfer points. A water or oil mist may be sprayed onto a stream of coal falling from a chute or loading boom. The oil reduces dust emissions by causing the dust to adhere to larger pieces of coal and by forming agglomerates which are less easily airborne. Use of $CaCl_2$ should be limited because of its harmful side effects on boiler operation.

Oxidation

Coal constituents begin to oxidize when exposed to air. This oxidation may be considered as a very slow, low temperature combustion process, because the end products, carbon dioxide (CO_2), carbon monoxide, water and heat, are the same as those from furnace coal combustion. Furnace combustion of coal may be viewed as a very rapid oxidation process. Although there is evidence that bacterial action causes coal heating, the heating primarily occurs through a chemical reaction process. If spontaneous combustion is to be avoided, heat from the oxidation should be minimized by retarding oxidation or removing the generated heat.

Coal oxidation is primarily a surface action. Finer coal particles have more surface area for a given volume and, therefore, oxidize more rapidly. Freshly crushed coal also has a high oxidation rate. Coal's oxygen absorption rate at constant temperature decreases with time. Once a safe storage pile has been established, the rate of oxidation has been slowed considerably. Coal should be kept in dead storage undisturbed until an emergency requires its use.

The rate of oxidation also increases with moisture content. High moisture, western coals are particularly susceptible to self-heating.

Frozen coal

The difficulties associated with handling frozen coal may be avoided by thermally or mechanically drying the fines following coal preparation or by spraying the coal with an oil or anti-freezing solution mist. The cost of this oil spray treatment can be reduced by using waste oil. A heavy coat of oil may also be sprayed on the rail car hoppers to prevent the coal from freezing to the sides. The use of salt or $CaCl_2$ may result in accelerated ash deposition or boiler heating surface corrosion and therefore is generally not recommended.

Permanent installations for thawing frozen coal in rail cars include steam heated thawing sheds, oil-fired thawing pits, and radiant electric thawing systems. Steam heated systems are reliable and efficient, but are relatively expensive. Oil-fired systems, which prevent direct flame impingement on the cars, provide reliable operation and rapid thawing. Electric thawing systems are used at many plants that handle unit train coal shipments.

Coal pile fires

A primary concern in coal storage is the potential for spontaneous combustion in the pile as a result of self-heating properties.

A coal pile fire may be handled in several ways depending on its extent. The hot region should be isolated from the remainder of the pile. This may be accomplished by trenching and sealing the sides and top of the hot area with an airtight coating of road tar or asphalt. Caution should be used in working the hot area with heavy equipment as subsurface coal combustion can affect the stability and load bearing characteristics of the pile. Water should not be used unless it is necessary to control flames. Pouring water on a smoldering pile induces more pronounced channeling and promotes greater air flow through the pile. The use of asphalt or road tar for airtight sealing of the entire pile is not recommended.

Bunker flow problems

Hangups of fine coal are liable to begin when surface moisture reaches 5 to 10% by weight. Improved bulk storage techniques and careful coal reclaiming are the best preventive measures for reducing bunker flow problems.

Fine, wet coal feeding from a bottom outlet bunker tends to rat hole or pipe all the way to the top surface. When this occurs, coal flow to the feeders is intermittent and may be completely interrupted.

Bunkers may be equipped with ports located near the outlet. These ports permit the use of air lances for restoring flow. Air lances may also be effectively used from above. Small boring machines can be mounted above the bunker to loosen coal jams at the outlet. Service companies can be contracted to remove flow obstructions using boring tools. Air blasters or air cannons have been successfully used to promote flow of coal in bunker hoppers. If there is any possibility of fire, these devices must be charged with nitrogen or carbon dioxide to prevent triggering a dust explosion.

Castable polyurethane can be used for lining bunkers and chutes to improve abrasion resistance and reduce flow resistance. Bunker hoppers or silo cones are frequently lined with stainless steel sheet. The sheet is typically specified as cold-finished and all welds are ground and polished to an equivalent finish. This smooth and corrosion-resistant surface resists the formation of deposits which provide anchors for arches or stagnant coal masses.

Bunker fires

A fire in a coal bunker is a serious danger to personnel and equipment and must be dealt with promptly. The coal feed to the bunker should be stopped. An attempt should be made to smother the fire while quickly discharging the coal. Continuity and uniformity of the hot or burning coal discharge from the bunker is especially important; interruption of coal flow aggravates the danger. The bunker should be emptied completely; no fresh coal should be added until the bunker has cooled and the cause of the fire determined.

The fire may be smothered using steam or CO_2. CO_2 settles through the coal and displaces oxygen from the fire zone because it is heavier than air. Permanent piping connections to the bottom of the bunker may be made to supply CO_2 on demand. The CO_2 should fill the bunker, displace the air and smother the fire.

It is highly desirable to completely extinguish the fire before emptying the bunker. This is rarely possible because of boiler load demands and the difficulty of eliminating air flow to the fire. However, the use of steam or CO_2 to smother the fire can minimize the danger.

Bunker flow problems which result in dead zones may contribute to fires. Thermocouples installed in the bunker can monitor the temperature of the stored coal. The coal feed to the bunkers may also be monitored to prevent loading the bunker with hot coal.

Additional remarks on dealing with bunker fires in pulverized coal plants are provided in Chapter 12.

Environmental concerns

Water which percolates through the coal storage pile can become a source of acidic drainage which may contaminate local streams. Runoff water must be isolated by directing the drainage to a holding pond where the pH may be adjusted. (See also Chapter 32.)

Airborne dust from stockpiles creates a public nuisance, has potentially harmful effects on surrounding vegetation and may violate regulated dust emission standards. The potential for dust emissions is determined by the surface layer coal characteristics (particle size distribution, moisture), stockpile design (exposed area, height), and local climatic conditions (wind velocity, rainfall).[8]

Alternate solid fuel handling

Economic and environmental concerns have led to increasing steam generation from solid fuels derived from residential, commercial and industrial byproducts and wastes. Key among these are municipal solid waste (MSW), wood and biomass as discussed in Chapters 27 and 28. The properties of these solid fuels require storage, handling and separation considerations different from those applied to coal.

MSW can either be burned with little pre-combustion processing (mass burn) or as a refuse-derived fuel (RDF). As-received refuse for mass-burn units is delivered to the tipping area and stored in an open concrete storage pit. The refuse pit is usually enclosed and kept under a slightly negative pressure to control odors and dust emissions. The tipping bay is designed to facilitate traffic flow based upon the frequency of deliveries and the size of the delivery trucks or trailers. The pit is usually equipped with a water spray system to suppress fires which may arise in part due to heat generated from decomposition of the refuse. An overhead crane is used to mix the raw MSW in the storage pit, to remove bulky items and to transfer material to the boiler feed charging hoppers. Large objects and potentially explosive containers are located and removed prior to combustion. (See Chapter 27.) A full capacity spare crane is recommended. Storage capacity is typically three to five days in order to accommodate weekends, holidays and other periods when refuse delivery may not be available. Longer term storage of refuse is not normally recommended.

MSW may be processed to yield a higher Btu, lower ash RDF. The degree of processing required is determined by economics and by the fuel properties necessary for efficient boiler operation. MSW is usually delivered to an enclosed receiving floor. Front-end loaders can be used to spread the refuse, remove oversized and potentially dangerous items and feed the MSW to the RDF processing system as needed. RDF processing includes an integrated system of conveying, size reduction, separation, ferrous metal recovery, sizing and other equipment discussed in depth in Chapter 27. MSW may be processed into RDF at the power plant site or at a remote location. The selection is based upon a number of economic factors, but operation of the RDF processing system at the boiler site typically will enhance availability to support uninterrupted steam generation.

Wood waste generally consists of bark, sawdust, saw mill shavings and lumber rejects. Material is generally shipped by truck to the steam generator site near the source. Material can be dumped directly on the storage pile or an unloading facility can be used. The unloading and handling equipment must be designed to handle extremely dusty conditions with a very abrasive material. Wood products can be stored in large outdoor piles or inside bins or silos. Wood is not typically stored in piles for more than six months or in silos or bins for more than three to five days. This fuel is typically screened to remove oversized material for further size reduction. Oversized material is reduced by a shredding machine, or *hog*, and either returned to storage or sent directly to the combustor. Mechanical belt conveyors are the most popular method of transporting the fuel on site, although pneumatic systems can be effective with a finely ground, clean fuel such as sawdust. Tramp iron is usually removed by a magnetic separator. While most modern wood-fired boilers can burn materials with a moisture content of up to 65% as-received (see Chapter 28), pre-drying may be required. Mechanical hydraulic presses and hot gas drying, or both, are used.

Economics

The selection of the fuel source, degree of cleaning, and transportation system are closely tied to providing the lowest plant fuel cost. The selections must not be made in isolation, but in concert with evaluating the impact of the specific fuel on the boiler and bypass system operation. For example, use of a new less expensive fuel may result in significant deterioration in boiler performance and availability due to more severe slagging and fouling tendencies of the flyash. (See Chapter 20.) The relative contributions of coal cleaning, transportation and base fuel price vary widely.

References

1. Bessett, R.D., "Coal transportation," appearing in *Handbook of Energy Systems Engineering,* L.C. Wilbur, ed., Wiley, New York, 1985.
2. Schwieger, R.G., "Coal handling," appearing in *Standard Handbook of Powerplant Engineering*, T.C. Elliot, ed., McGraw-Hill, New York, 1989.
3. *Facts About Coal, 1989*, National Coal Association, Washington, D.C., 1989.
4. Mahr, D., "Coal transportation and handling," *Power Engineering*, pp. 38-43, November 1985.
5. Scott, R.H., "Competitive coal transportation," presented at the conference Coal Marketing Days: Is the Turnaround at Hand?, Pittsburgh, 1983.
6. Edgar, T.F., *Coal Processing and Pollution Control*, Gulf, Tulsa, Oklahoma, 1983.
7. Yu, A.T., "Transfer and storage," appearing in *Society of Mining Engineers Mining Engineering Handbook*, A.B. Cummins, and I.A. Given, eds., Vol. 2, Section 18.6, Society of Mining Engineers, New York, 1973.
8. Smitham, J.B., and Nicol, S.K., "Physico-chemical principles controlling the emission of dust from coal stockpiles," *Powder Technology*, Vol. 64, No. 3, pp. 259-270, February 1991.

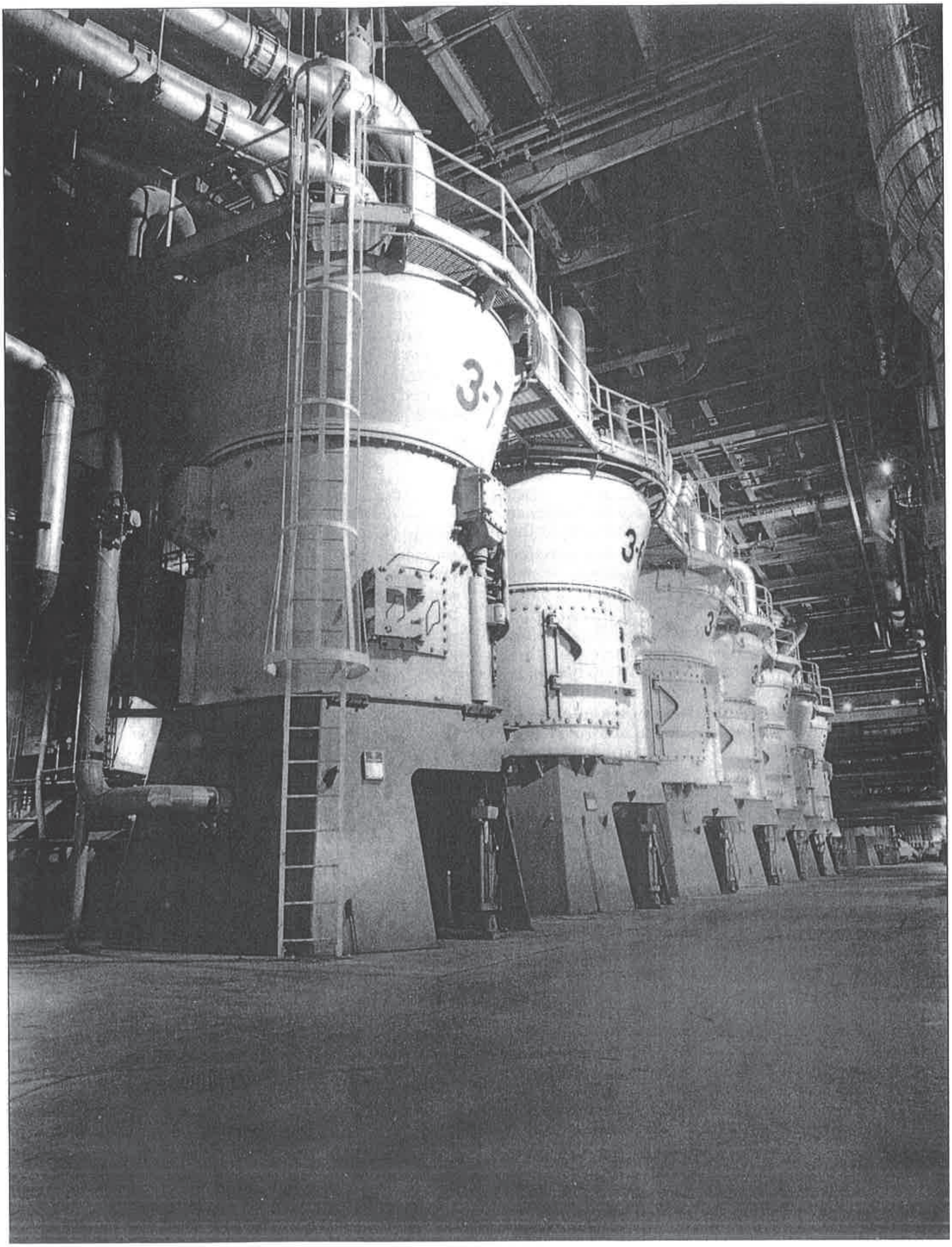
Bibliography

Pfleider, E.P., ed., *Surface Mining*, The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1968.

Leonard, J.W., ed., *Coal Preparation*, The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1979.

Lotz, C.W., *Notes on the Cleaning of Bituminous Coal*, West Virginia University, Charleston, West Virginia, 1960.

Given, I.A., ed., *Society of Mining Engineers Mining Engineering Handbook*, The American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1973.



Coal pulverizers at a modern power station.

Chapter 12
Coal Pulverization

The development and growth of coal pulverization closely parallels the development of pulverized coal-firing technology. Early systems used ball-and-tube mills to grind coal and holding bins to temporarily store the coal before firing. Evolution of the technology to eliminate the bins and direct fire the coal pneumatically transported from the pulverizers required more responsive and reliable grinding equipment. Vertical air-swept pulverizers met this need.

The first Babcock & Wilcox (B&W) vertical air-swept pulverizing mills were the E type design introduced in 1929 at Commonwealth Edison's Powerton Station in the United States (U.S.). Today, B&W offers a broad line of proven MPS pulverizer mills (see Fig. 1) to meet utility needs and EL type mills to meet lower load industrial requirements. Both use rolling elements on rotating tables to finely grind the coal which is swept from the mill by air for pneumatic transport directly to the burners.

Reliable coal pulverizer performance is essential for sustained full load operation of modern coal-fired electric generating stations. Also, an effective pulverizer must be capable of handling a wide variety of coals and accommodating load swings. The MPS pulverizer, through conser-

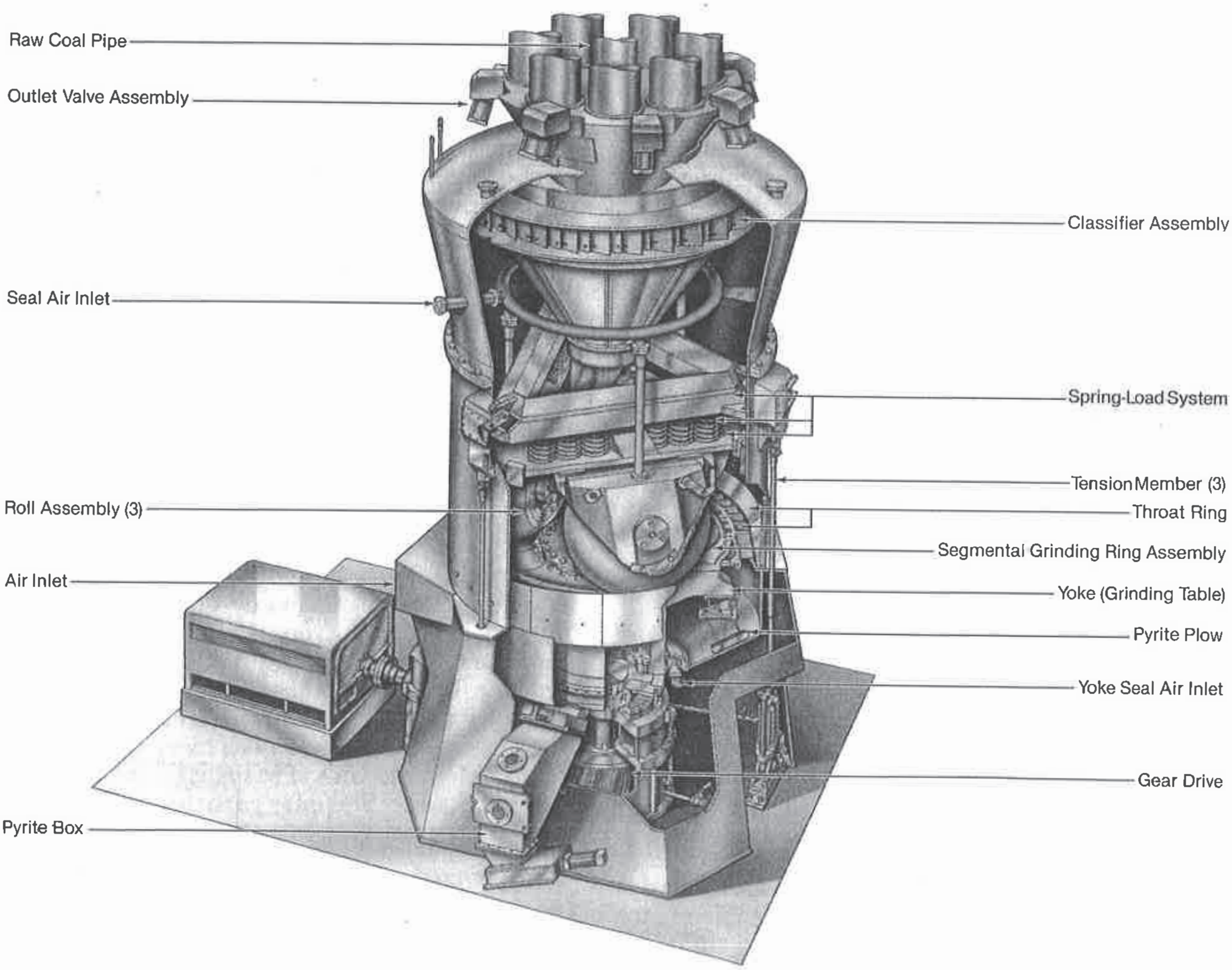


Fig. 1 Babcock & Wilcox MPS pulverizer.

vative design, reserve capacity and long grinding element life, has set the standard for high availability, reliability and low maintenance, contributing to stable boiler performance.

A key difference between much of the boiler system and the pulverizer is that the pulverizer is sized and operated as a mass flow machine while the boiler is a thermal driven machine. Therefore, the heating value of the fuel plays a key role in integrating these two components.

Vertical air-swept pulverizers

Principles of operation

The elements of a rolling action grinding mechanism are shown in Fig. 2. The roller passes over a layer of granular material, compressing it against a moving table. The movement of the roller causes motion between particles, while the roller pressure creates compressive loads between particles. Motion under applied pressure within the particle layer causes attrition (particle breakup by friction) which is the dominant size reduction mechanism. The compressed granular layer has a cushioning influence which reduces grinding effectiveness but also reduces the rate of roller wear dramatically. When working surfaces in a grinding zone are close together, near the dimensions of single product particles, wear is increased by three body contact (roller, particle and table). Wear rates can be as much as much as 100 times those found in normal pulverizer field experience. Wear from the three body contact has also been observed in operating mills when significant amounts of quartz bearing rock are present in sizes equal to or greater than the grinding layer thickness.

As grinding proceeds, fine particles are removed from the process to prevent excessive grinding, power consumption and wear. Fig. 3 presents a simplified MPS vertical pulverizer, showing the essential elements of a vertical air-swept design. A table is turned from below and rollers, called *tires*, rotate against the table. Raw coal is fed into the mill from above and passes between the rollers and the rotating table. Each passage of the particles under the rollers reduces the size of the coal. The combined effects of centrifugal force and displacement of the coal layer by the rollers spills partly ground coal off the outside edge of the table. An upward flow of air fluidizes and entrains this coal.

The point where air is introduced is often called the air port ring, nozzle ring or throat. Rising air flow, mixed with the coal particles, creates a fluidized particle bed just above the throat. The air velocity is low enough so that it entrains only the smaller particles and percolates with them through the bed. The air-solids flow leaving the bed forms the initial stage of size separation or classification. The preheated air stream also dries the coal to enhance the combustion process.

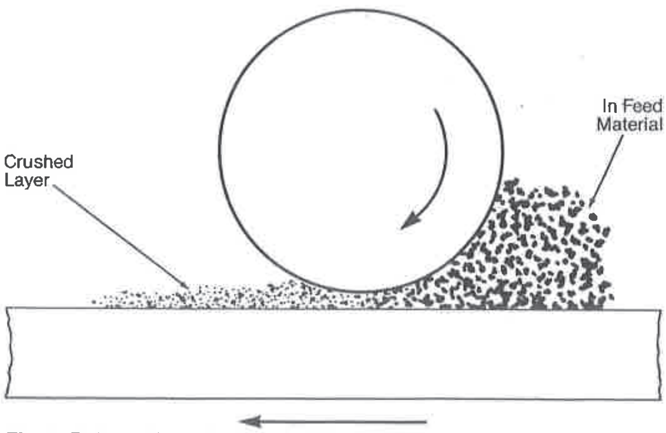


Fig. 2 Roller mill grinding mechanism.

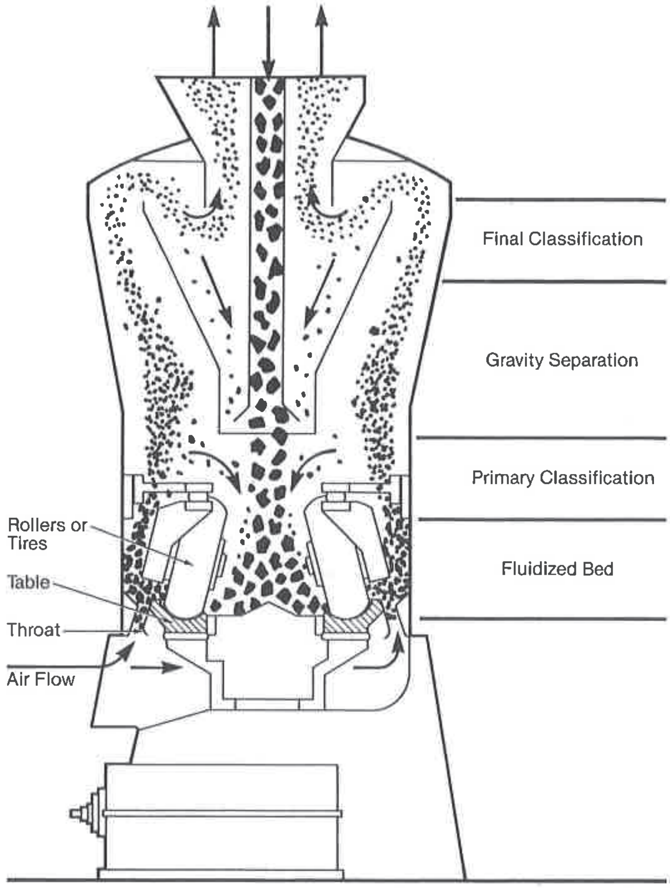


Fig. 3 Pulverizer coal recirculation.

Vertical pulverizers are effective drying devices. Coals with moisture content up to 40% have been successfully handled in vertical mills. Higher moisture levels are possible, but the primary air temperature needed would require special structural materials and would increase the chance of pulverizer fires. A practical moisture limit is 40%, by weight, requiring air temperatures up to 750F (399C).

As the air-solids mixture flows upward, the flow area increases and velocity decreases returning larger particles directly to the grinding zone. The final stage of size separation is provided by the classifier located at the top of the pulverizer. This device is a centrifugal separator. The coal-air mixture flows through openings angled to impart spin and induce centrifugal force. The coarser particles impact the perimeter, come out of suspension and fall back into the grinding zone. The finer particles remain suspended in the air mixture and exit to the fuel conduits.

Pulverizer control

There are two input streams into an air-swept pulverizer, air and coal. Both must be controlled for satisfactory operation. Many older methods of coal flow control are still used successfully. Either volumetric or gravimetric belt feeders are the currently preferred method of coal flow regulation. Accurate measurement of coal flow has allowed parallel control of air and coal (Fig. 4).

Pulverizer design requirements

Many different pulverizer designs have been applied for coal firing. Successful designs have met certain fundamental goals and requirements:

1. optimum fineness for design coals over the entire pulverizer operating range,
2. rapid response to load changes,
3. stable and safe operation over the entire load range,
4. continuous service over long operating periods,
5. acceptable maintenance requirements, particularly grinding elements, over the pulverizer life,
6. ability to handle variations in coal properties,
7. ease of maintenance (minimum number of moving parts and adequate access), and
8. minimum building volume.

Pulverizer designs

Mill development efforts by B&W were, for many years, based on variations of ball-and-ring (ball-and-race) grinding elements. In the late 1920s, B&W introduced the type E pulverizer. During the early 1950s, a redesign was installed and tested at Lancaster, South Carolina. This design, which uses two vertical axis horizontal rings, was

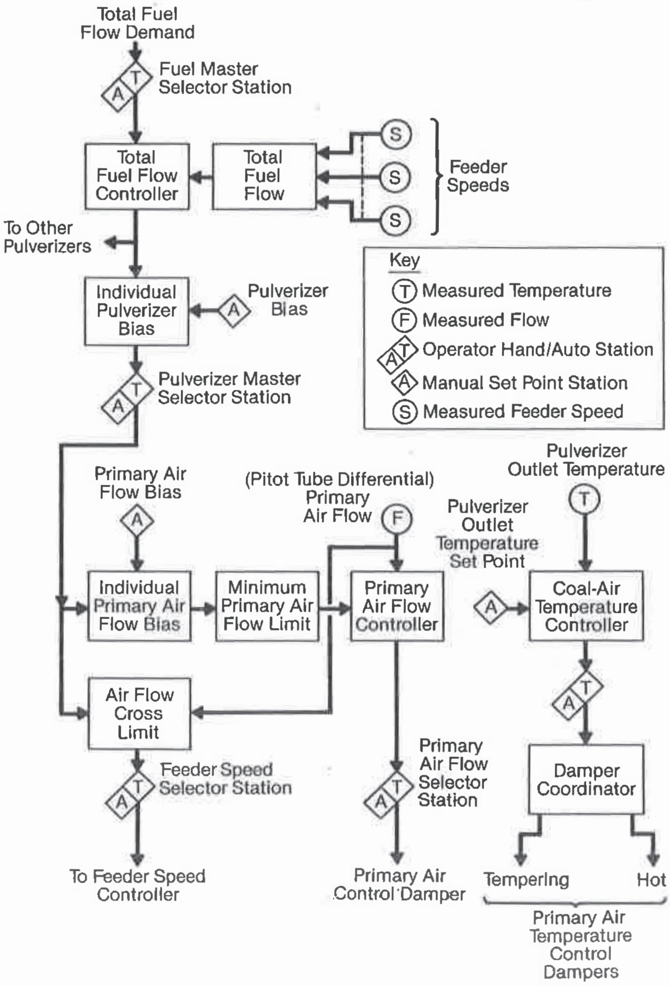


Fig. 4 Schematic of parallel cross limited pulverizer control system.

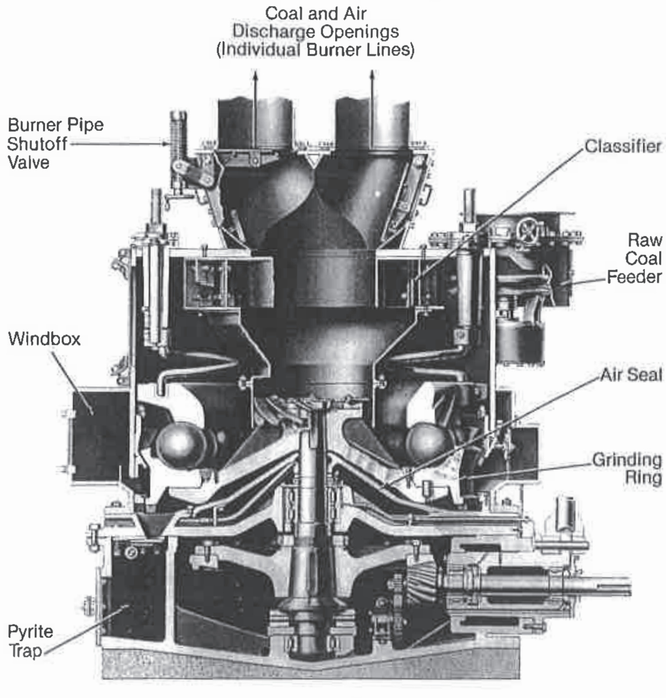


Fig. 5 B&W type EL ball-and-race mill.

designated E (Lancaster) or EL (Fig. 5). The lower ring rotates while the upper ring is stationary and is spring loaded to create grinding pressure. A set of balls is placed between the rings. The force from the upper ring pushes the balls against the coal layer on the lower ring.

Type E and EL mills have size designations which indicate the diameter, in inches, of the midline of the grinding track. Type E mills have been built as large as the E-70 with a capacity of 17 t/h (15 t_m/h). Type EL mills have been built as large as the EL-76 with a maximum capacity of 20 t/h (18 t_m/h). Approximately 1600 E and EL mills have been installed, with more than 1000 still in service. The major wear parts of E and EL pulverizers are the two rings and the balls which are made of abrasion resistant alloys and are easily replaced.

In 1970, B&W introduced the type MPS pulverizer to the U.S. market. A current MPS pulverizer design is shown in Fig. 1. The MPS pulverizer is an air-swept, roller type vertical pulverizer; however, it differs in significant ways from other roller mills. The rollers (tires) of the MPS are supported and loaded by a unique system which loads the three rollers simultaneously. The common loading system allows independent radial movement of each roller. This, in turn, allows continuous realignment with the grinding track as rollers wear. The rollers can also accommodate large foreign objects such as tramp iron or rocks which inadvertently enter the grinding zone. The MPS can maintain design performance with as much as 40% of its tires' weight lost due to wear.

MPS mills operate at speeds which produce centrifugal force at the grinding track midline of about 0.8 times the force of gravity. This very low speed contributes to low vibration levels and the ability to handle large foreign objects.

This mill also introduced a nonintegral gear drive to coal pulverizer design. This feature is now popular with most mill designers in the U.S. These drives allow the most complex and difficult to repair component to be removed in case of failure and exchanged with a standby unit. Repair can then be undertaken using a variety of options while the mill is back in service.

The major replaceable wear parts of MPS pulverizers include the tires and ring segments plus minor items such as wear guide plates, ceramic linings, and parts for the throat or air port ring. Wear life of all parts in contact with the coal is dependent upon the coal abrasiveness, and ranges from 8000 to more than 100,000 hours.

The B&W MPS mill size designations are also based upon the grinding track centerline diameter, in inches. Units have been furnished ranging from the MPS-56 to the MPS-118 with capacities ranging from 17 to 105 t/h (15 to 95 t_m/h) respectively. More than 1000 MPS mills have been sold with the MPS-89 being the most popular. There are more than 700 MPS-89 units currently in use.

Table 1 lists important features and characteristics of MPS and EL mills for comparison.

Horizontal air-swept pulverizers

High speed pulverizers

Horizontal pulverizers are categorized as either high speed or low speed. One high speed design which has been used in the U.S. serves the same applications as the vertical types. This machine operates at about 600 rpm and grinds by both impact and attrition. Coal enters at the impact section for initial size reduction then passes between moving and stationary parts for final size reduction (Fig. 6). At the final stage, an exhauster fan provides the air flow for drying and transport. There is no classifier and the design relies upon the action of the rotor and stator to achieve size control in a single pass of the coal. The coal passes through quickly so there is little storage in the mill. This pulverizer is limited to coals with moisture content of 20% or less because of the short residence time for drying.

Fan/beater mills are used outside North America (Fig. 7). These are similar in some respects to the attrition mills described above. These mills are used for grinding and

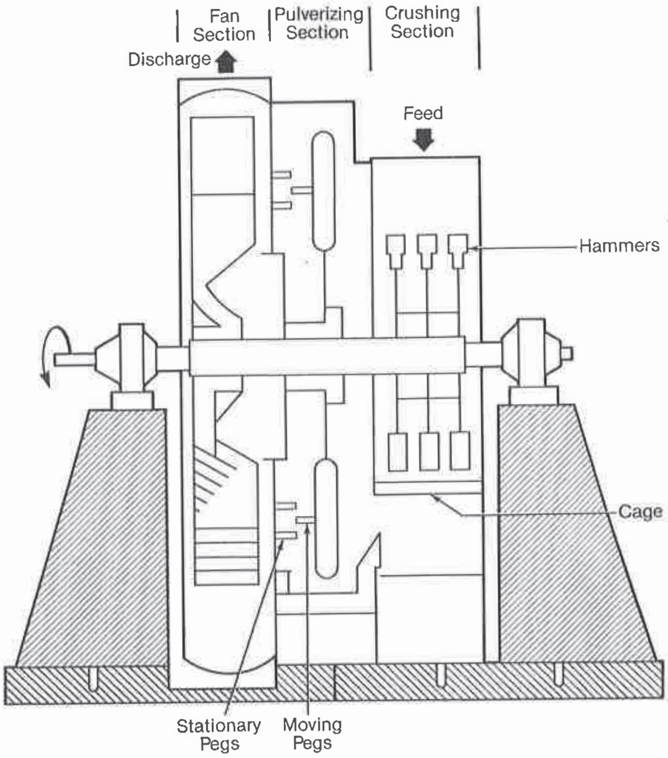


Fig. 6 Horizontal high speed pulverizer.

Table 1
Characteristics of B&W Type EL and MPS Pulverizers

	Type EL Ball-and-Race	Type MPS Roll-and-Race
Size range	EL-17 to EL-76	MPS-56 to MPS-118
Capacity, t/h (t_m/h)	1.5 to 20 (1.4 to 18)	17 to 105 (15 to 95
Motor size, hp (kW)	25 to 300 (18 to 224)	200 to 1250 (149 to 933)
Speed	Medium	Slow
Table, rpm	231 to 90	32 to 21
Operates under	Pressure	Pressure
Classifier	Internal, centrifugal	Internal, centrifugal
Classification adjustment	Internal	Internal (standard) External (special)
Drying limit	40% H_2O or 700F (371C) Primary air temperature	40% H_2O or 750F (399C) Primary air temperature
Moisture load correction	None up to temperature limit	Load correction above 4% surface moisture
Maximum exit temperature limit	250F (121C)	210F (99C)
Effect of wear on performance	None if fill-in balls added	Power increase up to 15% at fully worn condition
Air-coal control system	Mill level with table feeders, parallel control with belt feeders	Parallel coal and air flow control
Air/coal weight ratio	1.75:1 at full load	1.75:1 at full load
Internal inventory	Medium, 2 to 3 min of output	High, 5 to 6 min of output
Load response	>10%/min	>10%/min
Specific power, kWh/t (kWh/t_m)	Low, 14 (15) including primary air fan	Low, 14 (15) including primary air fan
Noise level	Above 90 dBA	Above 90 dBA, 85 dBA attenuated
Vibration	Moderate	Low

Note: Capacities are those for bituminous coal with a 50 HGI and 70% fineness passing through 200 mesh (74 microns). Specific power is that at full load. Externally driven variable speed rotating classifiers have been applied to EL and MPS pulverizers.

drying the fossil fuels referred to as brown coals. These are very low grade lignite type coals with high ash and moisture contents and low heating values. Moisture content of brown coal often exceeds 50% and combined ash and moisture contents may exceed 60%.

Beater mills grind by impact and attrition with very rapid drying. They achieve drying despite short residence time by replacing primary air with extremely high temperature gas extracted from the upper furnace at temperatures of about 1900F (1038C). Gas from a cooler location such as the air heater outlet may be mixed with the hot gas for mill outlet temperature control. Coal is mixed with the gas stream ahead of the mill for initial drying to reduce the inlet temperature. The final stage is the fan section which maintains a negative pressure in the mill at all times. Beater mills operate at variable speed to control grinding performance at varying coal feed rates. One and two shaft machines are used trading simplicity in the former for more flexibility in the latter. Because of the low coal quality, beater mills must handle huge amounts of coal and are made in very large sizes. There are very few coal deposits in North America which would require this grinding/drying technology. However deposits in Germany, Eastern Europe, Turkey and Australia make brown coal a very important fuel for power generation throughout these regions.

Low speed pulverizers

The oldest pulverizer design still in frequent use is the ball-and-tube mill. This is a horizontal cylinder, partly filled with small diameter balls (Fig. 8). The cylinder is lined with wear resistant material contoured to enhance the action of the tumbling balls and the balls fill 25 to 30% of the cylinder volume. The rotational speed is 80% of that at which centrifugal force would overcome gravity and cause the balls to cling to the shell wall. Grinding is caused by the tumbling action which traps coal particles between balls as they impact.

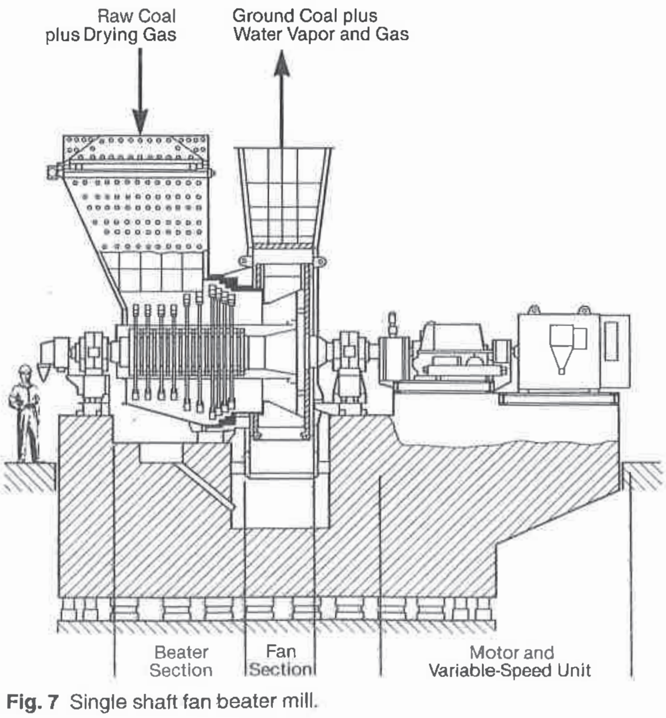


Fig. 7 Single shaft fan beater mill.

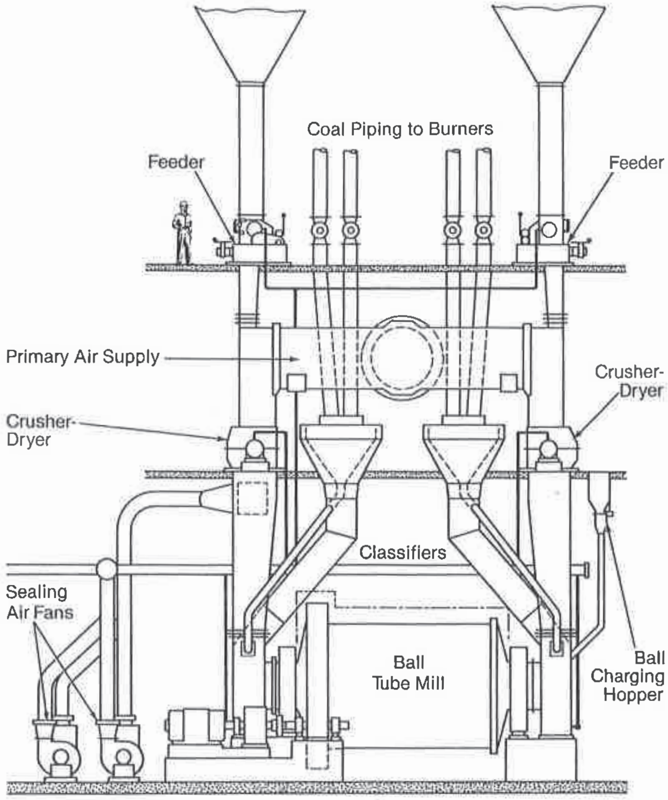


Fig. 8 Typical pressurized ball-and-tube coal pulverizing system.

Ball-and-tube mills may be either single or double ended. In the former, air and coal enter through one end and exit the opposite. Double ended mills are fed coal and air at each end and ground-dried coal is extracted from each end. In both types, classifiers are external to the mill and oversize material is injected back to the mill with the raw feed. Ball-and-tube mills do not develop the fluidized bed which is characteristic of vertical mills and the poor mixing of air and coal limits the drying capability. When coals with moisture above 20% must be ground in ball-and-tube mills, auxiliary equipment, usually crusher dryers, must be used.

Ball-and-tube mills have largely been supplanted by vertical air-swept pulverizers for new boilers. They typically require larger building volume and higher specific power consumption than the vertical air-swept pulverizers. They are also more difficult to control and have higher metal wear rates. They are, however, well suited for grinding extremely abrasive, low moisture, and difficult materials such as petroleum coke. Their long coal residence time makes them effective for fine grinding.

Application engineering

The arrangement of coal-fired system components must be determined according to economic factors as well as the attributes of the coal. The performance in terms of product fineness, mill outlet temperature, and air-coal ratio must all be determined as part of overall combustion system design.

Pulverizer systems

Pulverizers are part of larger systems, normally classified as either direct-fired or storage. In direct firing, coal leaving each mill goes directly to the combustion process. The air, evaporated moisture, and the thermal energy which entered the mill, along with the ground coal, all become part of the combustion process. Storage systems separate the ground coal from the air, evaporated moisture and the thermal energy prior to the combustion process. Stored ground coal is then injected with new transport air to the combustion process. Bin storage systems are seldom used in steam generation today, but are still used with special technologies such as coal gasification and blast furnace coal injection. Of the 1000 or so MPS pulverizers in service in the U.S. more than 99% are used in direct-firied systems.

The essential elements of a direct-fired system are:

1. a raw coal feeder that regulates the coal flow from a silo or bunker to the pulverizer,
2. a heat source that preheats the primary air for coal drying,
3. a pulverizer (primary air) fan that is typically located ahead of the mill (pressurized mill) as a blower, or after the mill (suction mill) as an exhauster.
4. a pulverizer, configured as either a pressurized or suction unit,
5. piping that directs the coal and primary air from the pulverizer to the burners,
6. burners which mix the coal and balance of combustion air, and
7. controls and regulating devices.

These components can be arranged in several ways based on project economics. With pressurized pulverizers, the choice must be made between hot primary air fans with a dedicated fan for each mill, or cold fans located ahead of a dedicated air heater and a hot air supply system with lateral branches to the individual mills. Hot fan systems have a lower capital cost because a dedicated primary air heater is not required. Cold fan systems have lower operating costs which, on larger systems, may offset the higher initial cost. Figs. 9 and 10 show these systems.

The terminology for air-swept pulverizers refers to the air introduced for drying and transport as primary air. Control of primary air is of vital importance to proper pulverizer system operation. For direct-fired or storage systems and for hot fan and cold fan systems, common control elements are found. Primary air must be controlled for flow rate and pulverizer outlet temperature. This control is achieved by three interrelated dampers.

Two of these, hot and cold air dampers, regulate air temperature to the mill and these dampers are usually linked so that as one opens, the other closes. The third damper is independent and controls air volume. Some manufacturers use only two dampers, but lack of stability or slow load change response can offset the cost advantages.

Because direct-fired pulverizers are closely linked to the firing system, system engineering must coordinate the design performance of the mills and burners. A set of curves can be used to relate important operating characteristics of volume flow, velocities at critical locations, and system pressure losses through the load range of the boiler. The curves consider numbers of mills in service and the output range of the individual mills. An example set of curves is shown in Fig. 11. Study of these curves provides

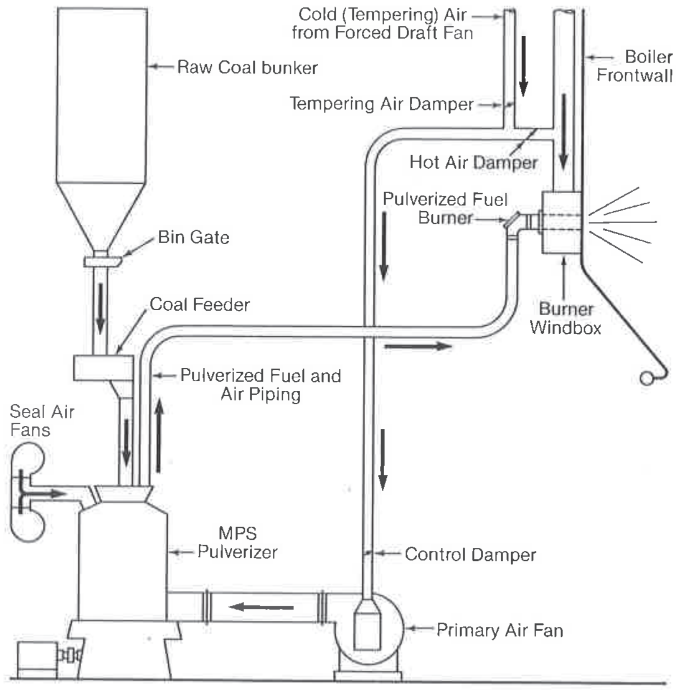


Fig. 9 Direct-fired, hot fan system for pulverized coal.

information on many aspects of pulverizer and system operation. The lower curve, labeled A, shows boiler steam flow versus coal output per pulverizer. The individual lines show the number of mills in operation. In this example, a full boiler load of 2.5 x 10^6 lb/h (315 kg/s) steam flow can be reached with five mills in service at about 89,000 lb/h (11.2 kg/s) each. The maximum load also can be reached with four mills at about 111,000 lb/h (14.0 kg/s) each. The maximum steam flow with three mills is just over 2.1 x 10^6 lb/h (265 kg/s). The minimum load line represents a typical limit of turndown based on coal properties, ignition stability and the onset of mechanical vibration. This

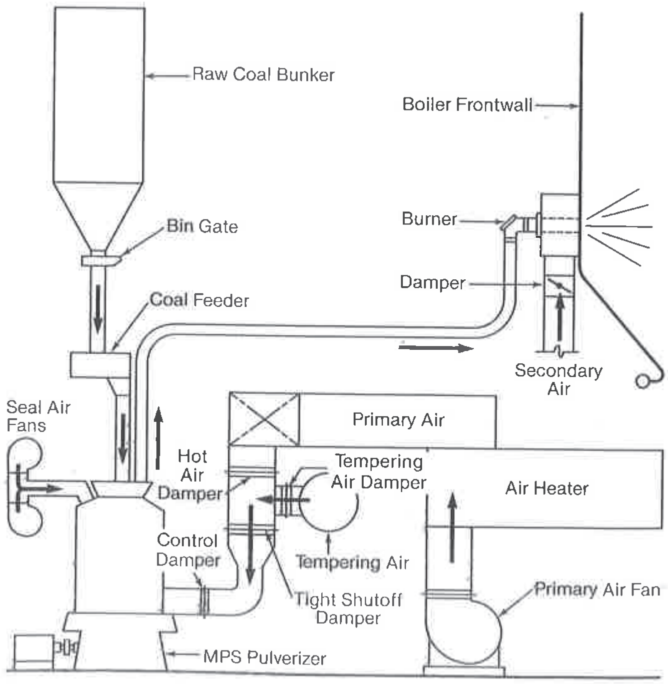


Fig. 10 Direct-fired, cold fan,fuel-air system for pulverized coal.

limit varies and the value shown of 30,000 lb/h (3.8 kg/s) of coal represents a relatively high turndown ratio.

Curve B shows primary air flow at mill exit conditions. Maximum flow is 55,800 ft^3/min (26.34 m^3/s) for an MPS-89N mill, corresponding to 124,000 lb/h (15.6 kg/s) coal flow. The minimum equipment design flow is approximately 55% of this or 30,700 ft^3/min (14.49 m^3/s). However, the exact minimum flow may need adjustment to permit stable burner operation. This is illustrated by 37,000 ft^3/min (17.46 m^3/s) minimum shown in Fig. 11, curve B, plus the minimum in curves D and E.

Curve C is the air/fuel ratio expressed in ft^3 of air per lb of coal. This ratio is critical to stable ignition at low loads and is influenced by coal rank and fineness. If the air flow indicated by curve B allows the air-fuel mixture to fall below the stability limit for the fuel being used, this limit will set the minimum coal flow.

Curve D is an internal velocity in the pulverizer. The velocity in the throat must be at least 7000 ft/min (35.56 m/s) to prevent spillage of coal into the mill windbox or air plenum. This velocity is calculated at mill inlet conditions. With high moisture coals, the required high drying temperature results in high specific volume and velocity is seldom a problem at low load. With very dry coal, it may be necessary to raise the minimum air flow or reduce the throat area and raise the velocity. However, throat restrictions can cause excessive pressure loss at high loads.

Curve E shows primary air velocity in the burner pipes versus pulverizer coal flow. This curve is plotted by dividing air volume at mill exit conditions by the total flow

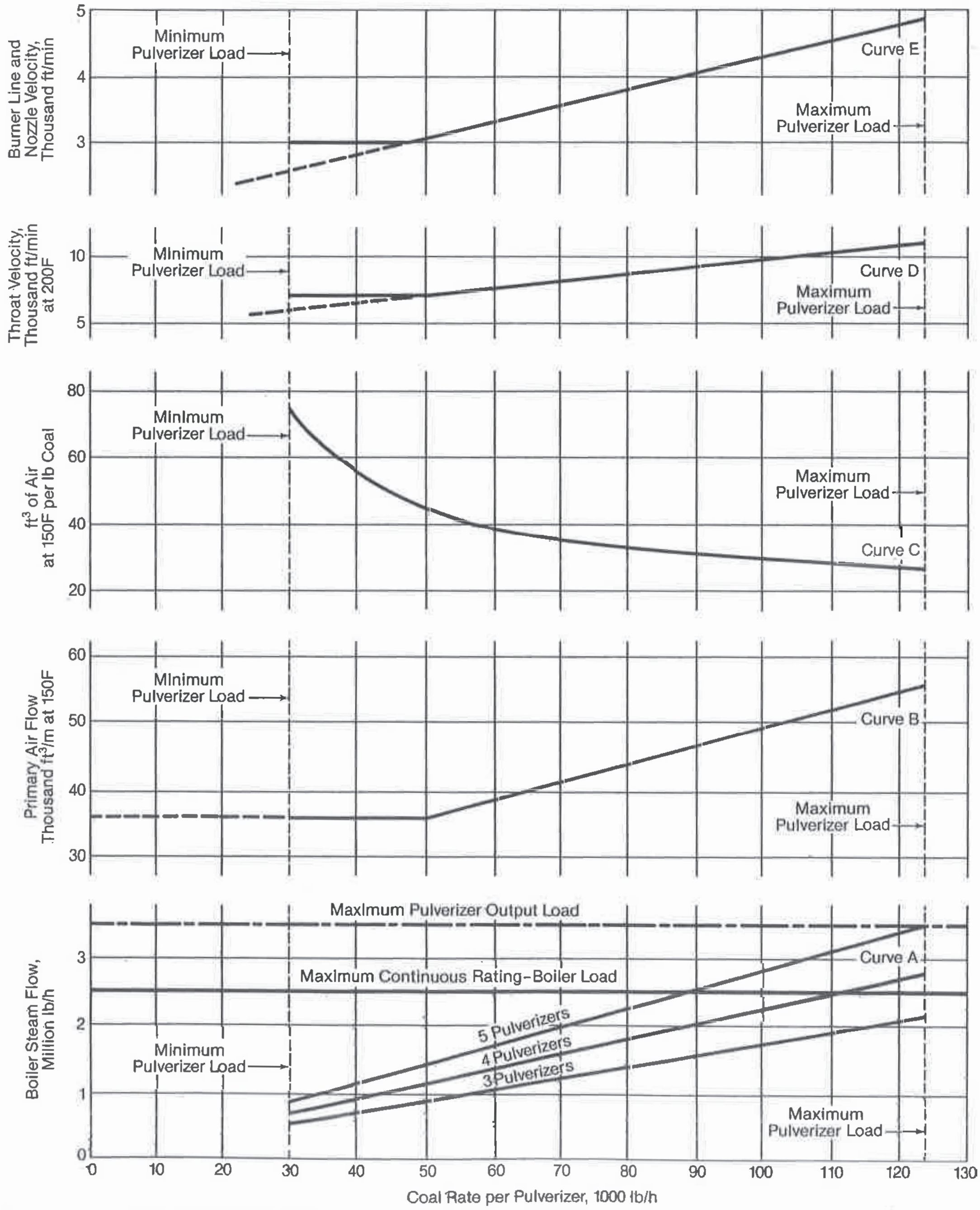


Fig. 11 MPS-89 pulverizer-burner coordination curves.

area of the pipes connecting the mill to the burners. The minimum velocity allowed is 3000 ft/min (15.2 m/s), at which the pulverized coal can be kept entrained in the primary air stream. The minimum, or saltation, velocity is particularly important in long horizontal spans of pipe. This velocity limit is influenced by air density and viscosity, particle loading and particle size. For the relatively narrow range of applications in burner pipes, the 3000 ft/min (15.2 m/s) limit is adjusted only for density and particle loading (air/coal ratio). Fig. 12 is a correction curve for minimum velocity.

An important pulverizer performance requirement is particle size leaving the mill. There is a mixture of particle sizes with any pulverizer because of the statistical distribution of particle sizes produced by the pulverizing process. The most frequently referenced size fraction for coal combustion is that portion smaller than a 200 U.S. standard sieve opening (mesh), or 74 microns. The portion passing this sieve size has been used as a gauge of pulverizer capacity as well as for assuring good combustion and good carbon burnout. The required particle size (fineness) is determined by the combination of coal combustion characteristics and the combustion chamber. Table 2 shows requirements used for various firing systems according to coal rank.

For bituminous coals burned in water-cooled enclosures, the required fineness is 70% passing through 200 mesh (74 microns) or better. The capacity rating of pulverizers in the U.S. is based also on 70% fineness. This value for good combustion characteristics has come under close scrutiny with the widespread use of low NO_x burners and the need for lower flame temperatures. Reduced flame temperature increases the required residence time in the combustion chamber. Coarse particles, those larger than 100 mesh (150 microns), contribute to high unburned carbon loss at traditional particle size distributions. The proven means to reduce the amount of plus 100 mesh (150 microns) product is to reduce the overall product size by increasing the amount passing through 200 mesh (74 microns) to 80%. Increasing the fineness from 70 to 80% causes a 20% pulverizer capacity reduction with stationary classifiers.

Outlet temperature

Coal with low volatile content may require higher air-coal temperatures to assure stable combustion, especially at lower burner inputs or low furnace loads. The usual pulverizer exit temperature is 150F (66C). Higher temperatures, up to 210F (99C) for coal, may be used if needed. Higher temperatures lead to lubrication problems in the grinding roller bearings. In addition, high outlet temperatures require high inlet temperatures which increase the risk of pulverizer fires. Some pulverizer applications, notably bin storage systems, will require higher temperatures to assure complete drying and prevent handling problems with fine coal. Usually, 180F (82C) is adequate to assure drying of coal having raw coal moisture up to 10%. For direct firing, the outlet temperature requirements are determined by volatile content and the need for stable combustion. Table 3 lists mill outlet temperatures for various coal types.

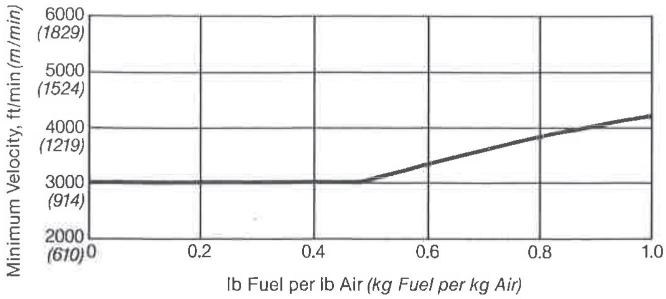


Fig. 12 Correction curve for minimum velocity.

Effects of coal properties

Grindability When determining pulverizer size, the most important physical coal characteristic to consider is *grindability*. This characteristic is indicative of the ease with which coal can be ground; higher grindabilities indicate coals which are easier to pulverize. The test procedure to determine the commonly used Hardgrove Grindability Index (HGI) is described in The American Society for Testing and Materials (ASTM) D 409. The operative principle with this procedure is the application of a fixed, predetermined amount of grinding effort or work on a prepared and sized sample. The apparatus shown in Fig. 13 is used to determine grindability. By rotating exactly 60 revolutions, this miniature pulverizer does a fixed amount of work on each sample. The amount of new, fine material produced is a measure of the ease of grinding. The index value of grindability used by B&W is HGI = 50, i.e., at HGI = 50, the capacity correction factor is 1.0. The index is open ended with no upper limit on the HGI scale.

Table 2
Typical Pulverized Coal Fineness Requirements — Percent Passing 200 U.S. Standard Sieve

	High Rank * Fixed Carbon,%			Low Rank (Fixed Carbon < 69%) Heating Value, Btu/lb**		
Furnace or process:	97.9 to 86.0	85.9 to 78.0	77.9 to 69.0	Above 13,000	13,000 to 11,000	Below 11,000
Marine boiler	—	85	80	80	75	—
Water-cooled	80	75	70	70	65	60
Cement kiln	90	85	80	80	80	—
Blast furnace	N/A	N/A	N/A	80	80	N/A

* ASTM classification
** Btu/lb x 2.326 = kJ/kg

Table 3
Typical Pulverizer Outlet Temperature

Fuel Type	Volatile Content, %*	Exit Temperature F (C)**
Lignite and subbituminous	—	125 to 140 (52 to 60)
High volatile bituminous	30	150 (66)
Low volatile bituminous	14 to 22	150 to 180 (66 to 82)
Anthracite, coal waste	14	200 to 210 (93 to 99)
Petroleum coke	0 to 8	200 to 250 (93 to 121)

* Volatile content is on a dry, mineral-matter-free basis.
** The capacity of pulverizers is adversely affected with exit temperatures below 125F (52C) when grinding high moisture lignites.

Grindability is not strictly a matter of hardness. Some materials, fibrous in nature, are not hard but are very difficult to grind. Sticky or plastic materials can also defy grinding.

The procedure described in ASTM D 409 was originally developed as a purely empirical method but provides a valid capacity calculation for vertical pulverizers when grinding bituminous coal. When lower rank coals are tested in the Hardgrove apparatus, the correlation between laboratory tests and field operating equipment is often quite poor. There is a strong but unpredictable effect of sample moisture on test results. A more accurate index of grindability for low rank coals is determined in a laboratory sized MPS-32 pulverizer. This equipment has all the features of a field installation and can emulate field conditions. The capacity of the mill is about 800 lb/h (0.10 kg/s) and a coal capacity test requires a 1000 lb (453.6 kg) sample. Fig. 14 is an arrangement diagram of this test apparatus. Results are interpreted as apparent grindability and the values are valid for capacity calculations.

Wear properties Wear in coal pulverizers results from the combined effects of abrasion and erosion. The mechanism which dominates in the wear of a particular machine component depends upon the designed function of the component and on the properties of the coal being ground. Abrasiveness and erosiveness are the important properties to be considered when evaluating the influence of a candidate coal on expected maintenance cost. Unfortunately, these two important properties are inherently difficult to measure, especially with a material as variable as coal.

Abrasiveness One indication of the likely pulverizer wear part life is abrasiveness. It is primarily related to the quantity and size distribution of quartz and pyrite found in the as-received coal, especially for particles larger than 100 mesh (150 microns). While standard and accepted procedures are available to determine the quantity of these two minerals in a sample (ASTM D 2492 and ASTM D 2799 for pyrite and quartz respectively), accepted procedures to establish quartz and pyrite particle sizes are not available.

Unfortunately, direct small-scale laboratory abrasiveness testing and correlation to field wear conditions are not satisfactory because of operating differences between small laboratory equipment and power plant pulverizers. However, satisfactory abrasiveness measurements have been made using the MPS-32 laboratory pulverizer with 3000 lb (1362 kg) samples. Although expensive, wear life testing with this procedure can typically predict field performance with an error of 10% or less. While other abrasiveness tests, such as the Yancey-Geer Price apparatus, are used to provide some insight into relative wear rates, they are of very limited value in predicting actual field wear rates.

Erosiveness Erosion is not the same as abrasion. It can be defined as the progressive removal of material from a target on which a fluid borne stream of solids impinges. For a given combination of particles and target material, wear rate increases with velocity, with particle size, and

Lead Weights	57.0	*(25.9)*
Shaft and Gear	4.5	*(2.0)*
Top Ring	2.5	*(1.1)*
Total	64.0 lb	*(29.0 kg)*

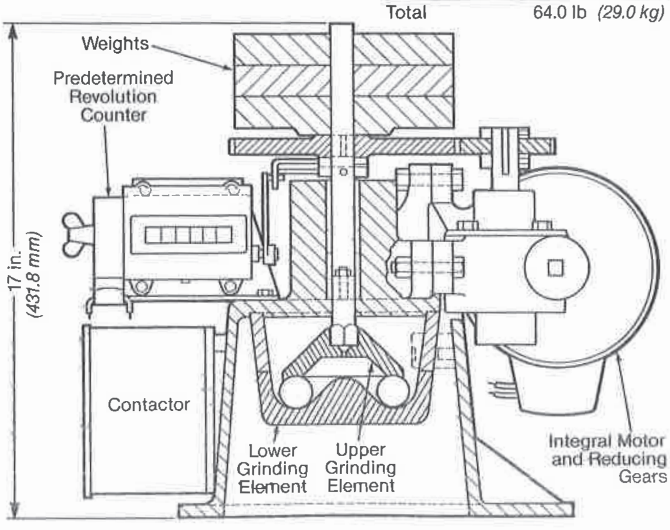


Fig. 13 Hardgrove grindability testing machine.

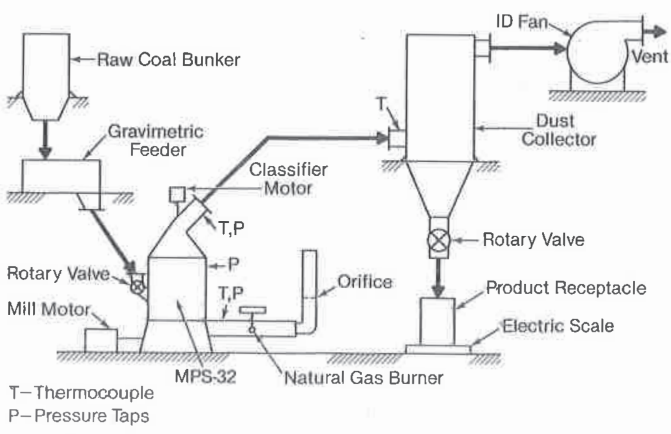


Fig. 14 B&W's MPS-32 test apparatus.

with the solids content of the stream. For ductile target materials, the wear rate increases up to an impingement angle of approximately 35 to 45 deg, at which point wear begins to decline.[1] For brittle materials, the rate of erosion increases up to the angle of approximately 70 deg, where rebounding material interferes with the impinging stream and measurement becomes erratic.

Moisture Moisture content in the fuel is a key design parameter. This inherent or fuel bound moisture can strongly influence grindability for subbituminous and lignite coals (Fig. 15). In addition, the surface moisture plus inherent moisture strongly influence the amount of drying needed and therefore strongly influence pulverizer air inlet temperature. Coal moisture is highly variable and depends more on coal type than on the amount of water introduced after mining. Moisture may be inherent, that which is present in the geological deposit, or may be surface moisture which is water introduced during handling, transport, processing or storage, or may be an artificial value called equilibrium moisture. This is the stable value reached after thermally dried coal reabsorbs atmospheric moisture. Coals used in the U.S. range from inherent moisture levels of 2% for Appalachian bituminous to near 40% for lignites. Brown coals may range up to 70%. Moisture in coal is determined according to the procedures in ASTM D 3302.

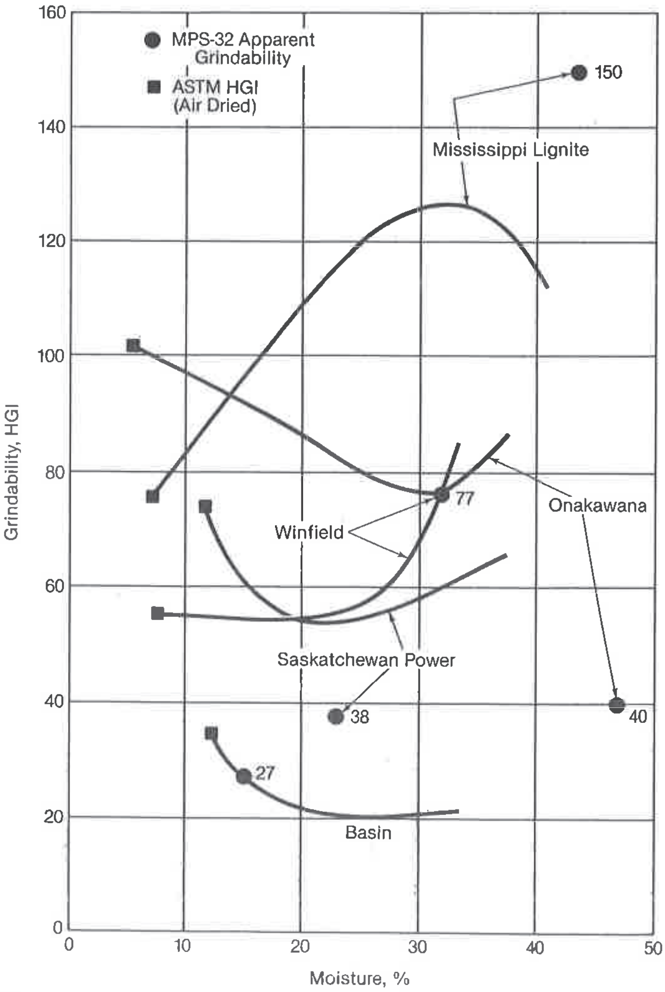


Fig. 15 Hardgrove Grindability Index versus fuel moisture.

Pulverizer size selection

The ultimate task in pulverizing application is the selection of the size and number of mills for the proposed project. The total boiler heat input and coal flow requirements are established from the combustion calculations (see Chapter 9) and the specified boiler steam flow requirements. The coal flow rate is then divided by the capacity correction factor to establish the equivalent required pulverizer capacity. The correction factor not only includes the fineness and grindability factors shown in Fig. 16, but also the appropriate fuel moisture correction. Most roller mills, including the MPS, require a moisture correction for capacity loss while the EL mills require no correction.

The number of pulverizers is then evaluated by dividing the equivalent required capacity by the unit pulverizer rated capacity based upon 70% passing through a 200 mesh (74 microns) screen and a grindability of 50. The unit pulverizer rated capacity is based upon pulverizer size, type and manufacturer. The tradeoff between fewer larger mills and more smaller mills is based upon balancing total capital cost with the proposed operating requirements such as boiler turndown. Frequently an extra pulverizer is specified to permit the boiler to operate at full load while one mill is out of service for maintenance.

Pulverizer selection and sizing are complicated by the frequent need to consider various coal sources and emission requirements. Computer programs can analyze pulverizer performance quickly, even for a large number of candidate coals, to learn which will govern mill selection. If the coal setting the pulverizer size is greatly different from the intended primary use coal, the result may be oversized mills and limits on turndown on the primary coal. In such a case, it may be necessary to reconsider whether this coal should remain on the list of possible fuels.

Performance testing

The most rigorous performance tests are done to assure compliance with the purchase contract. This acceptance testing will usually be guided by the procedures in The American Society of Mechanical Engineers (ASME) Performance Test Code, PTC 4.2 which references other applicable codes and standards. Testing may also be done as part of an overall boiler test, or simply to learn whether maintenance or adjustments are needed.

Fineness testing

Among the more daunting tasks in performance testing is the collection of valid fineness samples. The method of sampling is well described in PTC 4.2 and ASTM D 197. While this procedure has inherent weaknesses, it is the basis for measuring one of the fundamental performance parameters to verify pulverizer capacity. Periodically, alternative sampling procedures or new hardware are proposed to overcome the weaknesses in the ASTM method and apparatus. One such device is the ISO probe, also called the Rotorprobe. This well conceived device can sweep around circles that represent equal concentric areas of the pulverized coal pipe cross section. It is possible that the ISO probe may collect a more representative sample than the ASTM methods. However, the ASTM probe is currently the accepted standard on which capacity correction factors for fineness are based and whatever

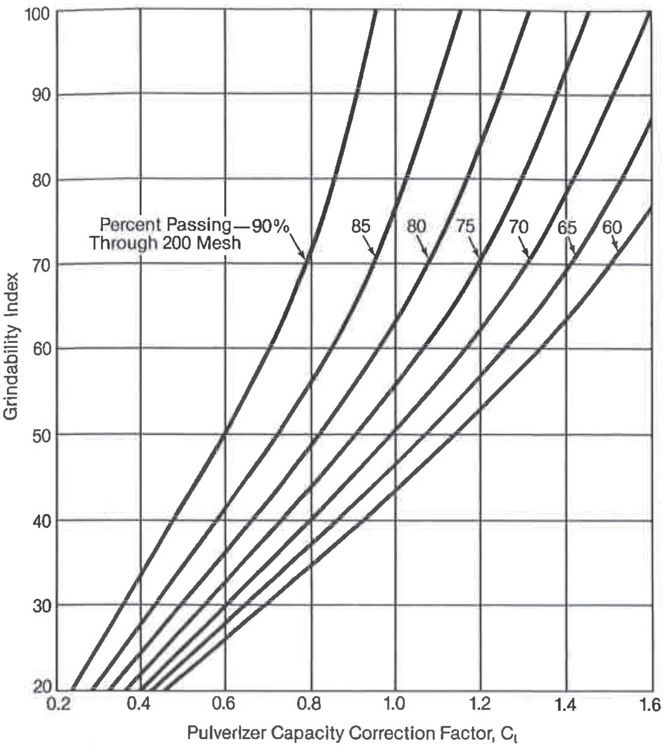


Fig. 16 Capacity correction factor.

errors are inherent in its application are included in its basis for use. It is important that new methods do not introduce new errors or controversies. They should produce results at least as consistent as the ASTM methods.

When tests are run to determine the condition of the pulverizer system or to evaluate a proposed new coal, comparative values between successive tests may be adequate. In such cases, alternatives, such as the ISO probe, may serve well if they provide acceptable repeatability and are not sensitive to variables such as velocity or temperature. Use of panel board instruments, if they can be read with sufficient precision, will serve as well as calibrated instruments for periodic testing.

Evaluating test results

The approach to evaluation depends on the purpose of the tests. If the parties have agreed upon test protocols as prescribed by PTC 4.2, results evaluation is simply a calculation process. When results indicate that the performance requirements have not been met but that the shortfall is slight, reference to the ASTM standards, D 409 and D 197, may show that the shortfall could lie within the limits of laboratory analysis repeatability. The protocols should provide for resolution of small deviations in the test results.

The more usual case of testing to evaluate the equipment or its systems requires a different approach. It is a mistake to try to read excessive precision into test results. It is more important to discover trends as guides to corrective action or the frequency of retesting. In such testing, it is useful to develop checklists or troubleshooting guides to note what each abnormality indicates. For example, acceptable fineness but excessive pressure differential probably indicates a need to adjust the pulverizer load springs. Acceptable fine fraction fineness but poor coarse fraction fineness indicates erosion damage and internal short circuiting of some air-coal flow. Also, it is common to discover that recalibration of primary measuring devices is needed on a regular schedule.

When equipment tests are first undertaken, it is important to collect all data which could possibly prove useful. As test experience grows, extraneous data can be removed. It is usually only a short time before standard data sheets evolve and testing becomes a routine task for an individual plant.

Operations

Power consumption

The main costs of coal pulverizer operation are capital, power consumption and maintenance. The capital cost is usually an annual levelized charge including capital, taxes and several other factors. Power and maintenance are often expressed as costs per ton of coal ground, and are influenced by operating plant practices.

When comparing pulverizer designs, it is common to combine primary air fan and pulverizer power consumption. The power consumption for B&W EL or MPS pulverizers and their respective fans is about 14 kWh/t (15 kWh/t_m) with coal at 50 HGI and 70% fineness, operating at rated output and with new grinding parts. These conditions seldom exist for any length of time during operation. Most modern installations include extra capacity for future coal variation. For most mills, there will be either a decline in capacity or an increase in power consumed as wear progresses. Therefore, because of the combined effect of pulverizer oversizing and wear, a realistic power value might be 20 kWh/t (22 kWh/t_m) for a well sized mill on a base loaded boiler or 22 kWh/t (24 kWh/t_m) on a load following unit.

There are various ways of calculating the cost of auxiliary power. The lowest cost which can be calculated is the cost of coal used to generate the power. This is a heat rate cost and, for a hypothetical boiler using coal with a 13,000 Btu/lb (30,238 kJ/kg) heating value and a thermal heat rate of 10,000 Btu/kWh (34.1% efficiency), 22 kWh/t (24 kWh/t_m) is about 0.85% of the fuel energy input to the boiler. As heating value declines, more power is spent grinding and moving material which does not produce thermal input, and the percentage represented by 22 kWh/t (24 kWh/t_m) increases.

Power can be expected to increase as the grinding parts wear. The depth of the grinding track may play a part in the power increase as well. There is little information to show whether power increases uniformly with time or if it takes place mostly at the end of wear life.

Maintenance

Costs for material and labor depend on wear life which varies with the abrasiveness of the coal. Wear life on MPS mills grinding U.S. coals ranges from under 10,000 to more than 100,000 hours, and normally between 25,000 and 60,000 hours. Therefore, average annual maintenance costs can vary widely. Costs will also vary by mill size, where part costs are proportionately higher for smaller MPS mills. For MPS-67 mills, taking all variables into account, maintenance will cost about 60% of the power costs cited above at a wear life of 25,000 hours and as little as 20% at 60,000 hours. Respective values for MPS-89 are 40% and 10%. For a very rough estimate, maintenance costs will be about one half the power costs for small mills and about one third for larger mills.

Maintenance and power costs are also influenced by operating practices. Experienced operators may notice that, for example, an increase in pulverizer pressure differential indicates a need for spring readjustment. There may be cost effective decisions between maintenance and operations regarding rebuild frequency to minimize the costly power increases near the end of wear life.

Ceramics

The use of ceramic tiles for erosion resistance has reduced repair costs. Erosion resistance of ceramic, 97% alumina, is at least eight times greater than an equivalent thickness of carbon steel. Ceramic lined panels are used in classifier cones, in the housing above the throat, and in the discharge turret in MPS mills. Ceramic lining is used extensively in burner pipe elbows and for wear shields on MPS roller brackets. When ceramic tiles are used, they must be carefully fitted to avoid undercutting and loss of the lining (Fig. 17). Ceramic tiles are not suitable for all forms of erosion protection. High angles of impingement are destructive to brittle materials.

Record keeping

Records are useful for pulverizer maintenance. Critical dimensions as recommended by the manufacturer should be taken and recorded during internal inspections. Suspicious wear data should be recorded and given special attention at the next inspection. When lubricants are drained, the amount should be noted and recorded and a sample obtained for analysis. Many owners are now including periodic vibration measurements in their data collection and record keeping. Such data may indicate impending bearing or gear failure.

Fires and explosions

It must always be remembered that a coal pulverizer grinds fuel to a form suitable for good combustion. Combustion can and does occur at unplanned locations with costly results. Pulverizer fires are serious and should be treated with preplanned emergency procedures. The surprising speed with which a fire can develop requires prompt action.

Pulverizer fires can develop in the so-called high temperature areas of mills or in the coal rich low temperature areas. Usually, there should be no coal in the areas upstream of the throat — the high temperature areas. Excessive spillage, because of insufficient air flow or throat wear, can cause coal accumulation in the plenum or windbox of the pulverizer. If this coal is not rejected promptly to the pyrite removal system, it will be ignited by the high temperature primary air. Coal will also enter this area when a mill is tripped or shut down in an abnormally fast mode. Coal in the windbox may burn out without damage and, indeed, this form of fire may go undiscovered. Fires in the cooler, fuel rich zones may develop more slowly, but these fires are fed by enormous amounts of coal and can quickly destroy the internal pulverizer parts.

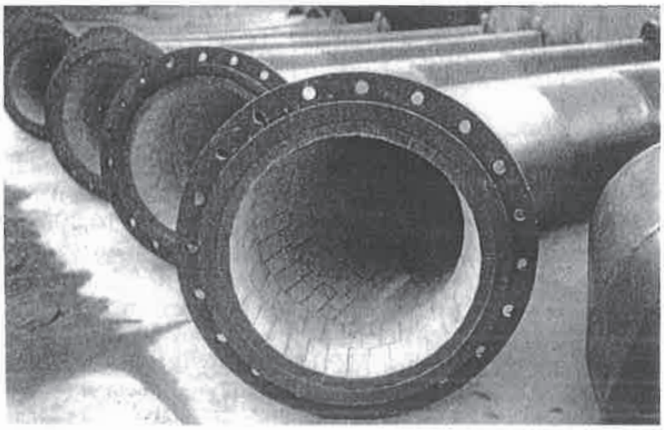


Fig. 17 Ceramic tile lining.

The most common fire indicator is mill outlet temperature. Temperature indicators are slow in response because they are sheltered by erosion protection, but they are inherently reliable and their indications should be taken seriously.

Control room operators can gain useful information about potential hazards by following consistent operating practices, especially on multiple mill installations. If, for example, all mills are at the same coal feed rate, and if primary air control is in the automatic mode, all mills should have the same air/coal ratio. Under these conditions, a significant temperature difference from inlet to outlet in one mill may indicate a fire and should be investigated immediately. Of course, there are other possible causes of inlet temperature differences such as faulty feeder calibration, faulty air flow calibration, or coal moisture variation between the respective mills. The significant point is that there is important information to be drawn from careful observation of the vital signs of pulverizer system performance. Use of all vital signs as leading indicators of potential hazards is important to safe operations.

Severe fire damage has also been caused by feeding burning coal from silos or bunkers. All pulverizer manufacturers prohibit this practice. Silo fires must be dealt with separately by emptying the fire through special diverter chutes or by extinguishing agents applied to the coal surface.

In mill trips, the sudden loss of air flow causes the collapse of the fluid bed above the throat; the coal then falls into the windbox and contacts the hot metal surfaces. Low rank coals can begin smoldering within a few minutes at temperatures of 450F (232C) or more, and, upon agitation, dust clouds can be created leading to explosions. The agitation may be from mechanical action of the pyrite plows upon restart, or from the start of primary air flow before restart. The danger of explosion is minimized by removing the coal under rigidly controlled conditions. It is first necessary to assure personnel safety by evacuating all workers from places which could be affected by an explosion if the enclosures of the mill, ducts or burner pipes are breached. The mill is isolated from all air flow and an inert internal atmosphere is created by injecting inert gas or vapor. Brief operation of the mill, while isolated, rejects the coal to the pyrite removal system. The inert atmosphere prevents any smoldering coal from igniting the dust cloud raised internally by mill operation.

When a mill explosion occurs it is nearly always during changes in operating status, that is, during startup and shutdown.[2] During startup, the air-coal mixture in the mill passes from extremely fuel lean to fuel rich. There is a transitional mixture which is ideal for a dust explosion if a sufficiently strong ignition source exists. One recurring source of ignition is smoldering fires which develop in the residual coal left in the hot zone of a mill following a trip. The coal removal procedure just described was devised to avoid or safely remove this ignition source.

Undiscovered fires can cause dust explosions during otherwise normal shutdowns. These are not common, but experience has led many operators to actuate audible and visible alarms before routine starts and stops. This is a recommended safety precaution for all coal pulverizer operators.

In general, operators have reported a declining rate of incidents since 1985 and those with formal event investigation procedures have reported the greatest decline. The clear message from recent industry surveys is that experience and constant review of safety and emergency procedures will pay dividends in preventing injury and equipment damage from pulverizer fires and explosions. Proper safety systems and procedures are reducing the frequency and damage.

Controls and interlocks

The most widely followed standard for design and application of coal pulverizer systems is the National Fire Protection Association Standard NFPA-8503 (formerly NFPA 85F). This sets the minimum standards listed below for safety interlocks to be used with coal pulverizers:

1. failure of primary air flow trips the pulverizer system,
2. failure of the pulverizer trips the coal feeder and primary air flow,
3. closing of all burner pipe valves trips the pulverizer, the feeder, and the primary air flow, and
4. primary air flow below the manufacturer's minimum trips the pulverizer.

Other interlocks not mandated by NFPA but required by B&W are:

1. loss of the lube oil pump, or low pressure, trips the pulverizer (MPS mill only), and
2. flame safety systems trip the pulverizer if minimum flame detector indications are not met.

Additional indications of malfunctions which may require manually tripping a mill include:

1. excessively high or rapidly rising mill exit temperature probably indicates a fire,
2. inability to maintain an exit temperature of at least 125F (52C) may lead to loss of grinding capacity,
3. loss of seal air pressure or flow will eventually lead to bearing failure, and
4. high lube oil temperature indicates a loss of cooling water flow which may lead to gear drive damage.

The faults indicated by numbers 3 and 4 above are not strictly safety related. They are, however, examples of designers' choices which avoid unnecessary mill trips and the special safety procedures which must be followed to restart tripped mills.

Special safety systems

The procedure for removing coal after a pulverizer trip requires a separate control system. This system must bypass the control logic which prevents operation of the pulverizer drive motor without adequate primary air flow. To prevent misuse of this bypass feature, the coal removal logic (referred to as inert and clear logic) is enabled by actuation of the mill trip logic. A schematic logic diagram is shown in Fig. 18.

Another special system has been developed to deal with a phenomenon which has been observed in ducts after trips. A fine layer of dust is often seen in the clean air portion of the primary air system. This is thought to be due to a turbulent dust cloud which persists after collapse of the fluid bed. An array of water fog nozzles under the throat will intercept this cloud if actuated with

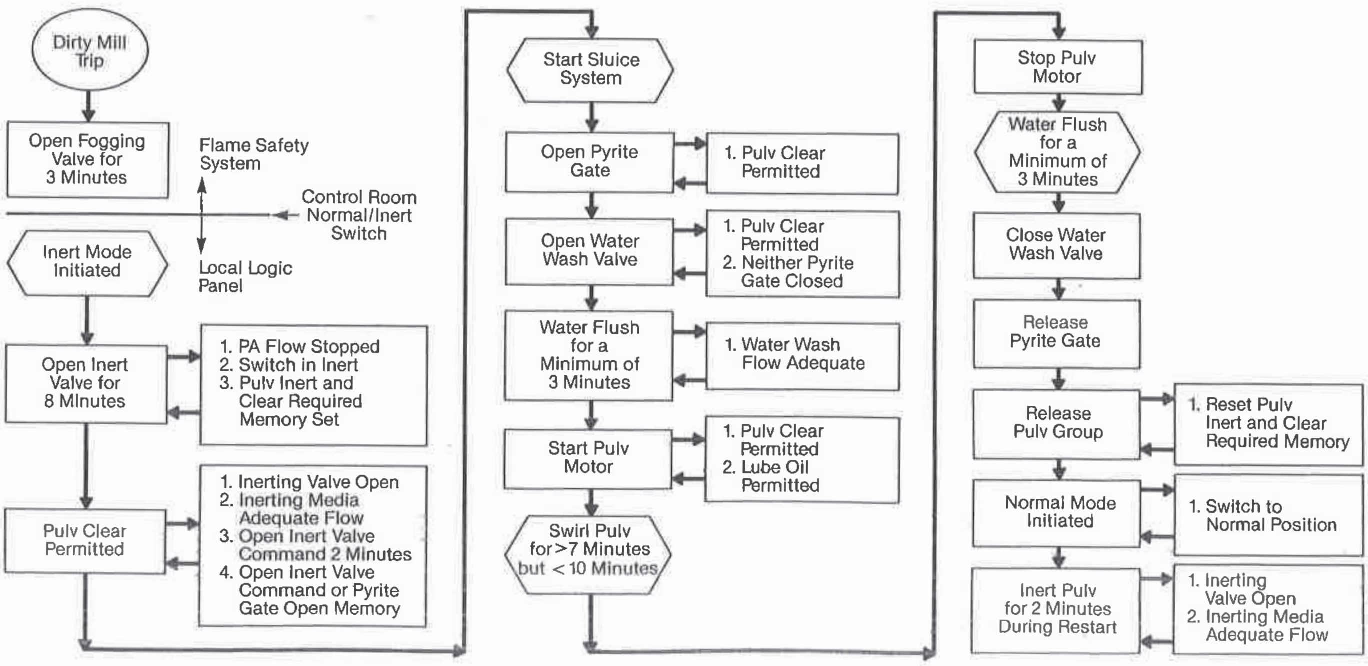


Fig. 18 Safety system logic diagram.

the mill trip signal. Applied along with the automatic spray system is hardware for tangential wash nozzles to enhance the coal removal action of the pyrite plows during the inert and clear cycle. The wash nozzles are actuated manually at the appropriate time in the cycle.

Advanced designs

Rotating classifiers

As noted under *Application Engineering*, product fineness is under review after being generally standardized at 70% passing through 200 mesh (74 microns) for direct firing of bituminous coal. Raising fineness to 80% will meet most early 1990s emission limits, but more demanding requirements are expected. Fineness values in excess of 95% passing through 200 mesh (74 microns) can be achieved with externally driven rotating classifiers. This is a recent development for coal pulverizers, emerging since the mid 1970s, although rotating classifiers have been applied to large vertical rock grinding mills for many years. The design developed for EL pulverizers is shown in Fig. 19. Interestingly, as shown in Fig. 20, this classifier is more effective at reducing percentages of coarse particles than finer particles. The value shown of 95% passing through 200 mesh (74 microns) may be near the practical limit for large vertical pulverizers. Other configurations for classifier rotors have been developed including squirrel-cage, various vane types and two-stage using a stationary first stage. Each of these represents the designer's solution to problems with retrofit, with particle size distribution, with drive power consumption or with overall pulverizer performance. Classifiers developed for MPS pulverizers have taken forms similar to that shown in Fig. 19 as well as two-stage and squirrel-cage designs.

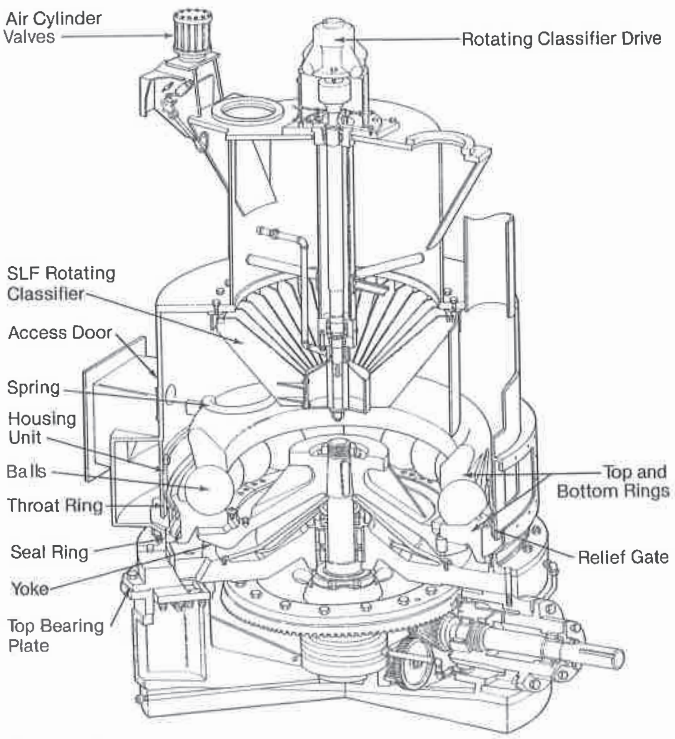


Fig. 19 Rotating classifier for EL mill.

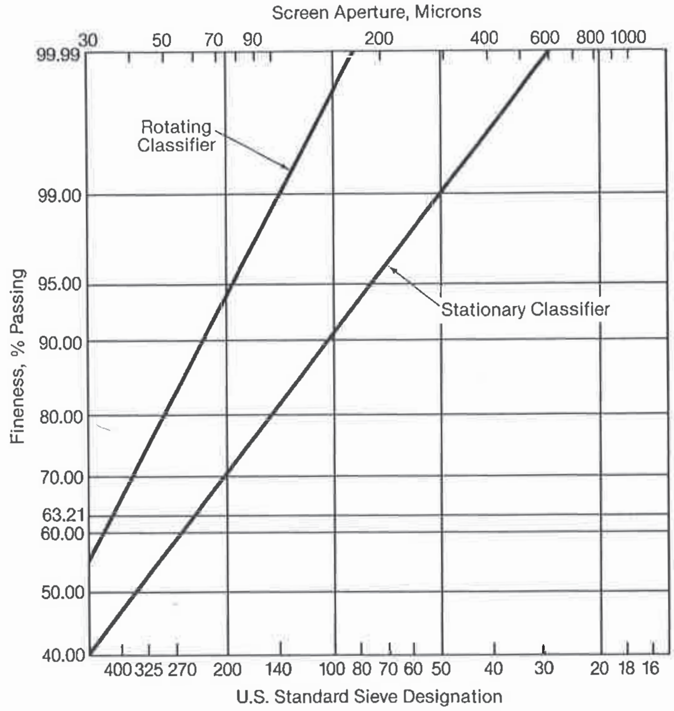


Fig. 20 Particle size distribution.

Product improvements

The 1980s was a period of refinement and product improvement for vertical pulverizers. One major improvement for MPS pulverizers was the introduction of rotating throat rings which improved performance and reduced erosive wear costs. A more subtle improvement was variable spring loading systems. It has been normal practice to operate vertical mill loading systems at constant preload. If, however, the spring preload is caused to follow coal feed rate, as illustrated in Fig. 21, the benefits will be reduced power consumption at low loads, ability to operate at lower output without vibration, and, in some instances, reduced pressure loss at high load by increasing preload above the previous fixed values.

Fine grinding

Vertical roller mills may have a practical limit of about 95% passing through 200 mesh (74 microns) for product fineness. As the product becomes finer, the recirculated material in the grinding chamber also becomes finer and the compressed layer becomes more fluid and less stable.

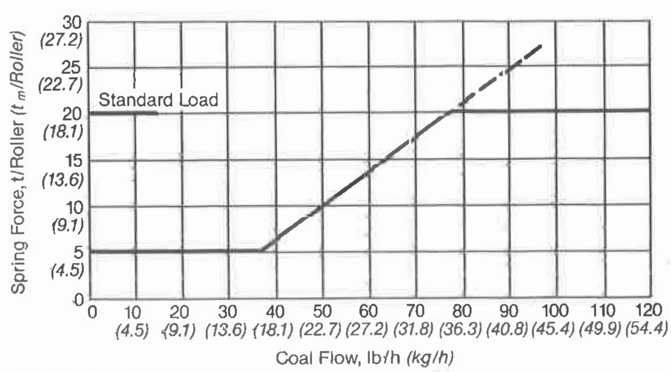


Fig. 21 MPS-89 spring load versus coal flow.

For very fine grinding other machines are needed. One of these is the ball-and-tube mill, offering the long residence time needed for an extremely fine product. In addition, ball-and-tube mills are built in the large sizes needed for direct firing.

It is not clear that the high capacity of ball-and-tube mill will be needed to meet foreseen fine grinding applications. An interesting application of fine grinding is to provide fuel for coal-fired lighters to reduce oil consumption for startup and low load flame stabilization. Smaller capacity mills could be used for this application.

Mills for fine grinding have been used to grind pigments, food and pharmaceuticals. These are small mills, generally 5 t/h (4.5 t_m/h) or less. Grinding principles include fluid energy, stirred ball, and high speed attrition. Fluid energy mills cause solids bearing fluid streams to impinge; particle impacts cause the size reduction. Stirred ball mills, usually wet grinders, use a charge of small balls in a cylindrical vessel which are agitated by a rotor, grinding the solids flowing through the charge.

High speed attrition mills grind by a combination of first stage impact and final stage attrition. It is these mills which have begun to attract some attention for preparation of oil replacement lighter fuel. Fig. 22 illustrates the grinding chamber of a high speed attrition mill. The rotor is a series of discs, each with impact bars, and each forming the driver for a grinding stage. The grinding stages are separated by diaphragms and coal must move inward against centrifugal force to pass from one stage to the next. Coal captured in each stage is said to provide an effective wearing surface to protect the mill shell from rapid wear. These mills are made in capacities up to about 5 t/h (4.5 t_m/h) and may be once-through or be equipped with external centrifugal classifiers for size control. Manufacturers of these mills refer to the product as micronized coal. When the term was adopted in the early 1980s, micronized coal referred to coal which was 100% finer than a 325 mesh (44 microns). The output of vertical high speed attrition mills is about 98% passing through 200 mesh (74 microns), 86% passing through 325 mesh (44 microns). However, this coal is reported to be fine enough to be easily ignited without the need for preheated primary or combustion air. These mills are high in power consumption and motor power is said to be sufficient to provide the necessary energy for drying most coals. The economic attractiveness of finely ground coal as a stabilizing and startup fuel depends on oil prices.

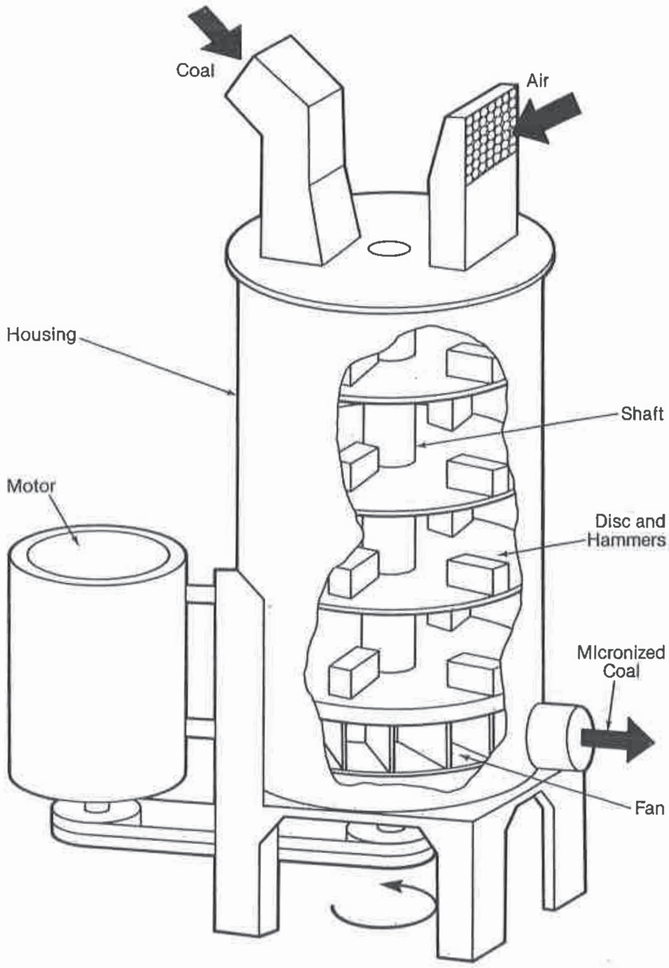


Fig. 22 High speed attrition mill.

References

1. Johnson, T.D., *et al.*, Central Electricity Generating Board, England, "Pulverized fuel system erosion," presented at EPRI Conference on Coal Pulverizers, pp. 18-22, 1985.

2. Zalosh, R.G., "Review of coal pulverizer fire and explosion incidents," ASTM STP 958, Cashdollar, K.L., and Hertzberg, M., eds., American Society for Testing and Materials, Philadelphia, p. 194, 1987.

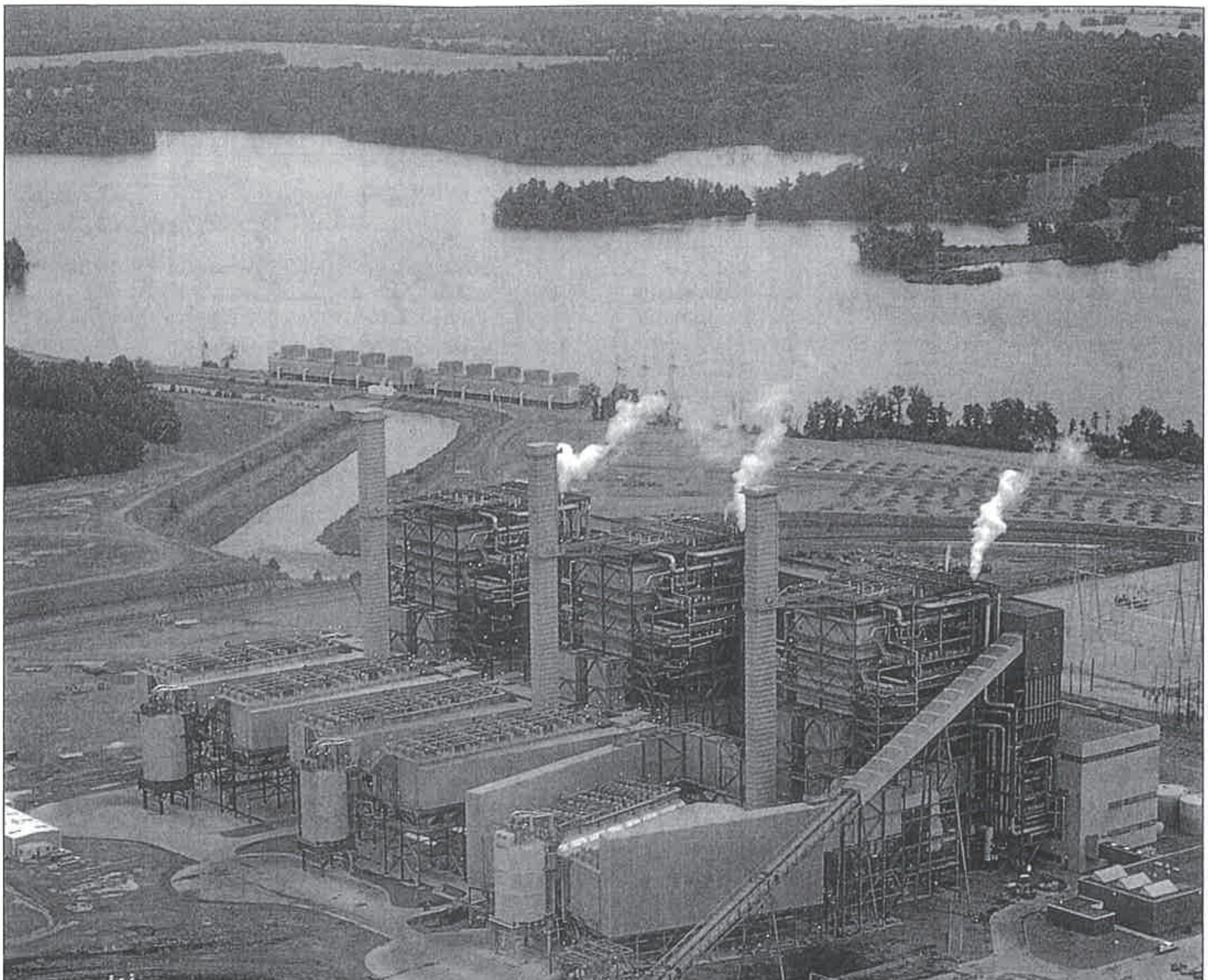
Bibliography

"Coal — Sampling of pulverized coal conveyed by gases in direct fired coal systems,' Draft International Standard ISO/DIS 9931, International Standards Organization, 1989.

Donais, R.T., Tyler, A.L., and Bakker, W.T., "The effect of quartz and pyrite on abrasive wear in coal pulverizers," *Proceedings of the International Conference on Advances in Material for Fossil Power Plants*, American Society for Metals, Metals Park, Ohio, p. 643, 1987.

Piepho, R.R., and Dougan, D.R., 'Grindability measurements on low rank fuels," *Proceedings, Coal Technology '81*, Vol. 3, pp. 111-121, 1981.

Wiley, A.C., *et al.*, "Micronized coal for boiler upgrade/retrofit," Proceedings of Power-Gen '90, PennWell, Houston, pp. 1155-1170, 1990.



These three 550 MW B&W boilers fire pulverized subbituminous coal.

Chapter 13
Burners and Combustion Systems for Pulverized Coal

Coal is an abundant and low cost fuel for boilers. It can be burned in a number of ways depending upon the characteristics of the coal and the particular boiler application. Cyclone, stoker, and fluidized bed firing methods are used for a variety of applications as discussed in Chapters 14 through 16. However, pulverized coal (PC) firing — burning coal as a fine powder suspension in an open furnace — is the dominant method in use today. PC firing has made possible the large, efficient utility boilers used as the base load capacity in many utilities worldwide. Modern PC burners provide high combustion efficiency and low emissions through full integration with the entire boiler design.

Pulverized coal firing differs from the other coal combustion technologies primarily through the much smaller particle size used and the resulting high combustion rates. The combustion rate of coal as a solid fuel is, to a large extent, controlled by the total particle surface area. By pulverizing coal to a nominal 50 micron diameter or smaller (see Chapter 12), the coal can be completely burned in approximately one to two seconds. This approaches the rate for oil and gas. In contrast, the other technologies discussed in subsequent chapters use crushed coal of various sizes and provide substantially longer combustion zone residence times (up to 60 seconds or longer).

Pulverized coal was first used in the 1800s as a cost effective fuel for cement kilns.[1] The ash content enhanced the properties of the cement and the low cost resulted in the rapid displacement of oil and gas as a fuel. However, early pulverizing equipment was not highly reliable and, as a result, an indirect bin system was developed to temporarily store the pulverized coal prior to combustion, providing a buffer between pulverization and combustion steps. Use in the steel industry followed closely. In this application, the importance of coal drying, particle size control and uniform coal feed were recognized.

Success for boiler PC firing applications required modification of the boiler furnace geometry to effectively use the PC technology. In the early 1900s, fireboxes and crowded tube banks had to be expanded to accommodate PC firing. By the late 1920s, the first water-cooled furnaces were used with advanced pulverized coal-fired systems, and burner design advanced to improve flame stability, provide better mixing, increase flame temperatures and improve combustion efficiency. Coupled with improvements in pulverizer design and reliability, improved PC burners permitted the use of direct firing with coal transported directly from the pulverizer to the burner. (See Fig. 1.)

The exponential increase in the United States (U.S.) electric power generation and the increase in boiler size from 100 MW to as large as 1300 MW could not have been achieved economically without the development and refinement of pulverized coal firing. Today, nearly all types of coal from anthracite to lignite can be burned through pulverized firing. Combustion efficiencies of most coals approach those of oil and gas. Current research is focusing on continuing reduction in emissions of nitrogen oxides (NO_x) for environmental protection without sacrificing boiler performance or availability. (See also Chapter 34.)

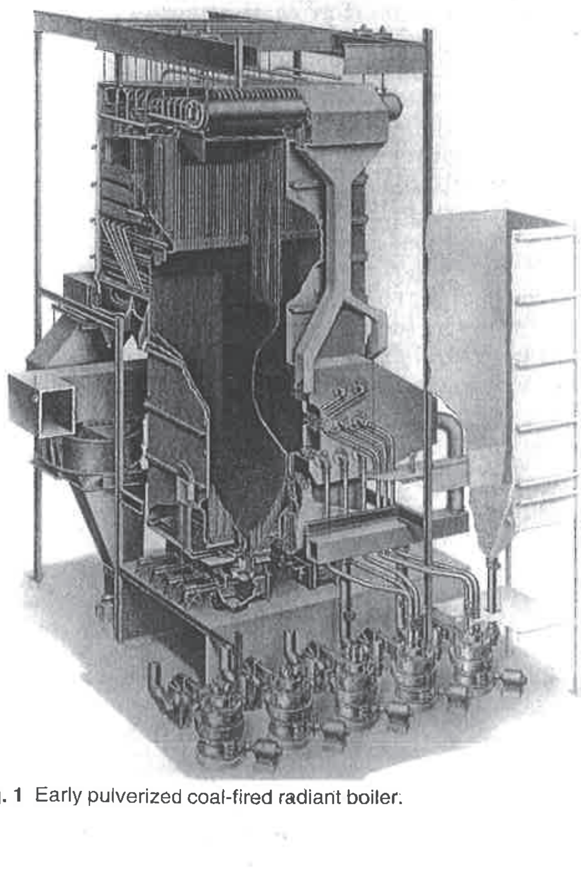


Fig. 1 Early pulverized coal-fired radiant boiler.

Combustion

The manner in which pulverized coal burns depends on its rank and properties as well as the furnace conditions. As a coal particle enters the furnace (see Fig. 2), its surface temperature increases due to radiative and convective heat transfer from furnace gases and other burning particles. As particle temperature increases, the moisture is vaporized and volatile matter is released. This volatile matter, which ignites and burns almost immediately, further raises the temperature of the char particle, which is primarily composed of carbon and mineral matter. The char particle is then consumed at high temperature leaving the ash content and a small amount of unburned carbon. The volatile matter, fixed carbon (char precursor), moisture and ash content of the fuel are identified on a percentage basis as part of the proximate analysis discussed in Chapter 8.

Volatile matter content

Volatile matter is critical for maintaining flame stability and accelerating char burnout. Coals with minimal volatile matter, such as anthracites and low volatile bituminous, are more difficult to ignite and require specially designed combustion systems. The amount of volatile matter evolved from a coal particle depends on coal composition, the temperature to which it is exposed, and the time of this exposure. The American Society for Testing and Materials (ASTM) Method D 3175 stipulates a temperature of 950 ± 20C for seven minutes for volatile matter content determination.[2] Raising the temperature would increase volatile yield with other factors held constant. Coals with higher volatile matter content also benefit from more effective NO_x control by combustion methods. Ignition is influenced by the quality and the quantity of volatile matter. Volatile matter from bituminous and higher rank coals is rich in hydrocarbons and high in heating value. Volatile matter from lower rank coals includes larger quantities of carbon monoxide and moisture (from thermal decomposition) and consequently has a lower heating value. Volatile matter from higher rank coals can provide twice the heating value per unit weight as that from low grade coals.

Char particles

The speed of the char particle combustion depends on several factors including particle size, porosity, thermal environment, and oxygen partial pressure. Char reactions often begin as the coal particle is heated and devolatilizes, but they continue long after devolatilization is complete. Devolatilization is mostly completed after 0.01 seconds but char-based reactions continue for one to two seconds. The char particle retains a fraction of the hydrocarbons. Small particles, with 10 to 20 micron diameters, benefit from high surface to mass ratios and heat up rapidly, while coarse particles heat more slowly. Many coals go through plastic deformation and swell by 10 to 15% when heated. These changes can significantly impact the porosity of the coal particle.

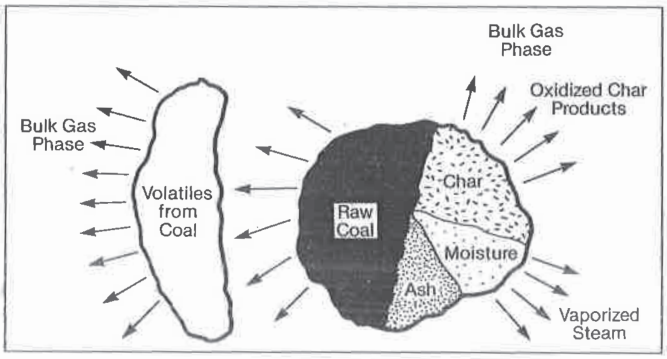


Fig. 2 Coal particle combustion.

Char oxidation requires oxygen to reach the carbon in the particle and the carbon surface area is primarily within the particle interior structure. Char combustion generally begins at relatively low particle temperatures. Reaction rates are primarily dependent upon local temperature as well as oxygen diffusion and char reactivity. For larger particles, the solid mass is reduced as carbon monoxide (CO) and carbon dioxide (CO_2) form, but particle volume is maintained. Coarse particles, more than 100 micron diameter, burn out slowly as a result of their lower surface to mass ratios. Longer burnout times cause these larger char particles to continue reacting downstream where the flame temperature has moderated.

Rapid heat transfer to and combustion of smaller particles lead to higher particle temperatures. Reaction rates increase exponentially with temperature, and oxygen (O_2) diffusion into the particle becomes the controlling parameter. Particle diameter and density change in the process. At higher particle temperatures, char reactions are so fast that oxygen is consumed before it can penetrate the particle surface. The particle shrinks as the outer portions are consumed, and transport of oxygen from the surroundings to the particle is the factor governing combustion rate.

Effect of moisture content

The moisture content of the coal also influences combustion behavior. Direct pulverized coal-fired systems convey all of the moisture to the burners. This moisture presents a burden to coal ignition; the water must be vaporized and superheated as the particles devolatilize. Further energy is absorbed at elevated temperatures as the water molecules dissociate.

Moisture content increases as rank decreases as discussed in Chapter 8. 15% moisture is common in high volatile bituminous coals, 30% is seen in subbituminous, and more than 40% is common in some lignites. Moisture contents in excess of 40% exceed the ignition capability of conventional PC-fired systems. Alternate systems are then required to boost drying during fuel preparation and/or divert a portion of the evaporated moisture from the burners. Char burnout is impaired by moisture which depresses the flame temperature. This is compensated for in part by the generally higher inherent reactivities and porosities of the higher moisture coals.

Effect of mineral matter content

The mineral matter, or resulting ash, of the coal is inert and dilutes the coal's heating value. Consequently, more fuel by weight is required as ash content increases in order to reach the furnace net heat input.

The ash absorbs heat and interferes with radiative heat transfer to coal particles, inhibiting the combustion process noticeably with high ash coals. The forms of mineral matter determine the slagging tendencies of the ash. These impact combustion by influencing the burner/furnace arrangement and the resulting flame temperatures and residence time. The additional effects of ash on overall boiler design are discussed in Chapter 20.

Pulverized coal combustion system

Effect of coal type

Conventional PC Pulverized coal firing is adaptable to most types of coal. Its versatility has made it the most prevalent method of coal firing for power generation worldwide. The majority of coals are PC-fired in conventional combustion systems as shown in Fig. 3. In these systems, the burners are located in the lower portion of the furnace, usually on one or two walls. Primary air typically at 130 to 200F (54 to 93C) conveys pulverized coal directly to the burners at a rate set by the combustion controls based on steam generation requirements. Secondary air is supplied by the forced draft fans and is typically preheated to about 600F (316C). All or most of the secondary air is supplied to the windboxes enclosing the burners. A portion of the secondary air may be diverted from the burners to NO_x ports (discussed later) in order to control the formation of NO_x. The secondary air supplied to the burners is mixed with the pulverized coal in the throat of the burner. This permits the coal to ignite and burn.

The combustion process continues as the gases and unburned fuel move away from the burner and up the furnace shaft. Final burnout of the char depends on the coal properties, particle fineness, excess air, air-fuel mixing, and thermal environment. The products of combustion eventually leave the furnace and enter the convection pass after being cooled sufficiently to minimize convection surface fouling.

Low volatile coals While the majority of bituminous, subbituminous, and lignite PC-fired units are arranged in this manner, alternate designs are required to accommodate other coals. Coals with low volatile matter content, particularly anthracites, are difficult to ignite. Their low levels of rapid burning volatiles limit this critical source of ignition energy. In addition, their advanced coalification (see Chapter 8) has reduced char reactivity, resulting in elevated char ignition and burnout temperatures. These factors require hotter furnaces to sustain combustion. A downshot firing system (see Fig. 4) accomplishes this in combination with an enlarged, refractory-lined furnace. The downshot arrangement causes the flame to travel down and then turn upward to leave the furnace. The char reactions, which build in intensity some distance from the burners, return their heat near the burners as the gases return and leave the furnace. This heat supplies energy to ignite the fuel introduced at the burners. The refractory lining in the furnace inhibits heat transfer and elevates gas temperatures to sustain combustion. The enlarged lower furnace also provides increased residence time to accommodate the slower burning char. In addition, very high coal fineness is used to accelerate char reactions and reduce unburned carbon loss. Growth in unit size and NO_x emission regulations have limited downshot fired units in the U.S. although they are applied internationally where low volatile coals are a fuel source.

High moisture coals The other major category of nonconventional PC-fired units is that used for lignites with very high moisture content. Moisture content in these coals typically ranges from 50 to 70% by weight, which is well beyond the level that air-swept pulverizers can adequately dry. (See Chapter 12.) Instead, hot gases, removed from the upper portion of the furnace, are used in combination with beater mills to dry and prepare the fuel. These hot gases, near 1832F (1000C), are more suitable for coal drying than preheated air, with a practical upper limit of 752F (400C). Furthermore, the low oxygen content of the flue gas provides a relatively inert atmosphere in the grinding equipment, lessening the threat of fire or explosion as the hot gas mixes with these reactive coals. The fuel is conveyed from the mills to the burners located on the walls, and combustion proceeds as secondary air mixes with the fuel in the furnace. Units of this design are prevalent in parts of Europe and Australia where high moisture brown coals are used.

Combustion system and boiler integration

The most fundamental factors that determine the boiler design are the steam production requirements and the coal to be fired. The thermal cycle defines the heat absorption requirements of the boiler which supplies the rated steam flow at design temperature and pressure. Gas side parameters, based on the design coal, are used to estimate boiler efficiency. Heat input requirements from the coal can then be determined, setting the coal firing rate at maximum load. The number and size of pulverizers are then selected. Frequently, the pulverizer

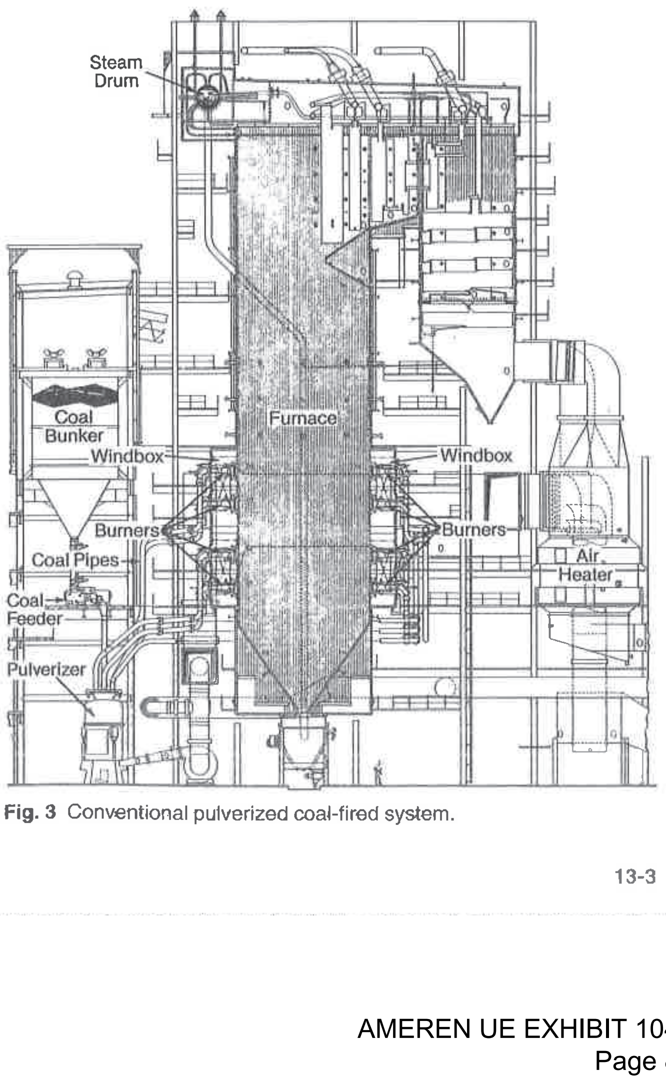


Fig. 3 Conventional pulverized coal-fired system.

selection is based on meeting maximum requirements with one mill out of operation. This permits maintenance on one pulverizer without limiting boiler load.

The size and configuration of the furnace are designed to accommodate the combustion and slagging/fouling characteristics of the coal as discussed in Chapter 20. NO_x emission control factors are also incorporated into the layouts of modern combustion systems. The number of burners and the heat input per burner are selected to minimize flame impingement on the furnace walls. Multiple burners at moderate inputs, in an opposed-fired arrangement, are favored to provide uniform heat distribution across the furnace. This reduces thermal gradients and helps prevent localized slagging, while improving NO_x emissions control and combustion efficiency. The burner design is based on fuel parameters and NO_x emission control requirements in order to provide complete combustion and minimum pollutant emissions.

Theoretical and excess air quantities are determined for the required coal input rate from combustion air calculations as discussed in Chapter 9. Fans, ductwork, air heaters, windboxes, and burners are sized to satisfy flow, pressure loss, air preheat and velocity requirements for the unit. If needed to meet emission requirements, separate staged combustion can be employed in the furnace through air injection after the burner zone (NO_x ports).

Burner fundamentals

Burners are the central element of effective combustion system designs which incorporate fuel preparation, air-fuel distribution, furnace design and combustion control. The burners provide for the introduction and mixing of the fuel and combustion air as shown in Fig. 5.

Control The quantity of pulverized coal and primary air supplied to the burners is set by the coal feed rate and primary air control dampers. Restrictors are usually included in the piping from the pulverizer to its burners to more evenly distribute coal among several burners. Secondary air flow is controlled by dampers at the forced draft fans to maintain excess air for good combustion and proper boiler operation. The distribution of secondary air among burners is accomplished by duct/windbox dampers and burner adjustments.

Flame stability A burner introduces the primary air and pulverized coal to the secondary air in a manner that establishes a stable flame. This involves producing a flame front close to the burner over the range of operating conditions. An ignitor or lighter is required to initiate combustion as fuel is first introduced to the burner and to sustain combustion when flames would otherwise be unstable. The burner normally sustains a stable flame by using heat from coal combustion to ignite the incoming pulverized coal. A flame safety system, included with modern burners, electronically scans the flame to verify stabilization and triggers corrective action if the flame becomes unstable.

Air-fuel mixing The burner also promotes local air-fuel mixing to completely burn the fuel. The overall mixing is a combination of burner-induced local mixing and the resultant more global furnace-induced mixing. Furnace mixing results from expansion of the air-fuel mixture in the furnace due to rapid temperature increase during combustion, from flow variations introduced by the burners, and from the size and shape of the furnace enclosure.

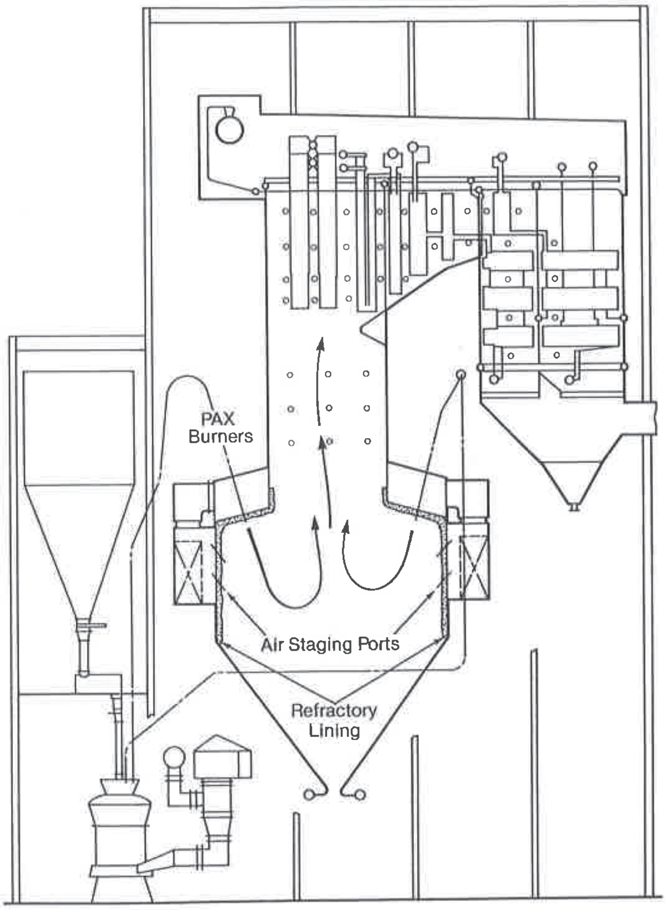


Fig. 4 Downshot-fired unit with refractory-lined furnace for low rank coals and PAX (primary air exchange) burners.

The amount of air-fuel mixing produced by the burner varies considerably with burner type. The simplest burners inject the fuel and air in parallel or concentric streams without the benefit of other burner-induced mixing. Entrainment of adjacent flow streams occurs as the jets develop and due to jet expansion from combustion. Tangentially-fired furnaces operate in this manner, as do some roof-fired designs. Flame length and combustion performance greatly depend on the effectiveness of furnace mixing. Mixing effectiveness decreases with boiler load as air-fuel flow rates drop. This can result in poor combustion performance at reduced boiler loads.

Modern wall-fired burners provide further controlled air-fuel mixing. The amount varies with the firing rate of the burners. Air-fuel mixing is achieved at reduced boiler loads by operating with fewer burners in service and by operating those burners at higher firing rates. Burner mixing can be induced by using the primary air/pulverized coal (PA/PC) stream, by using the secondary air, or by a combination of the two. Looking first at the PA/PC system, the most frequently used burner mixing devices are deflectors, bluff bodies, and swirl generators. Deflectors are frequently installed near the exit of the burner nozzle to cause the PA/PC stream to disperse into the secondary air. These deflectors, or impellers, also reduce axial momentum of the fuel jet, reducing flame length. Impellers may also induce radially-pitched swirl of the fuel jet to further accelerate mixing. Bluff bodies are sometimes used in or adjacent to the burner nozzle exit. Flow locally accelerates around the upstream side of the bluff body and recirculates on the downstream side. The recirculation promotes mixing. The bluff body can also be used to increase residence time for a portion of the fuel near the burner, thereby improving flame stability.

Secondary air swirl is the most common way to induce air-fuel mixing in circular throat burners. Swirl generators are used upstream of the burner throat to impart rotating motion to the secondary air. This air leaves the burner throat with tangential, radial and axial velocity components. Radial and axial pressure gradients form in the flow field downstream of the throat, with the lowest pressure being near the center of the throat.[3] As swirl is increased the pressure gradients increase. This causes the flow to reverse and travel along the axis of the flame toward the low pressure zone. A recirculating flow pattern is then generated near the burner.

Primary air and coal flow rates The primary air requirements are determined by the pulverizer, and the burner piping must be accommodated by the burners. Most pulverizers require 40 to 70% of their full load primary air requirements at their minimum output level. (See Chapter 12.) In addition, the PA/PC mixture traveling to the burners must be transported at a minimum of 3,000 ft/min (15 m/s). This velocity serves to prevent the coal particles from dropping out of suspension in horizontal runs of coal pipe. Minimum primary air flow is the greater of the minimum PA flow required for the pulverizer or the minimum required to satisfy burner line velocity limits.

The primary air and coal mixture conveyed to the burners reaches a maximum velocity and solids loading at full pulverizer load and follows the pulverizer output as mill loading is reduced. As the burner nozzle velocity increases, the ignition point gradually moves farther from the burner. At some point, continued increases in nozzle velocity lead to *blowoff* of the flame, a potentially hazardous condition where coal ignition and flame stability are lost. High burner nozzle velocities also result in accelerated erosion of burner hardware. The weight ratio of coal to primary air typically reaches a peak of 0.4 to 0.65 at full load and a minimum of 0.15 to 0.3 for minimum pulverizer load. Solid fuel loading reduction eventually leads to flame instability as the flame temperature drops.

Temperature The temperature of the PA/PC mixture supplied to the burners is based on the raw coal properties. A minimum of 130F (54C) is required with high moisture, reactive coals. A value of 150F (66C) is typical for high volatile bituminous coal. A maximum of 200F (93C), a result of pulverizer mechanical constraints, is used with low volatile coals to improve ignition.

Unburned carbon loss A small portion of the coal is not completely burned in the boiler, typically reducing efficiency by less than 1%. This unburned carbon loss is calculated based on the furnace-combustion system configuration, thermal environment in the furnace, coal reactivity, coal fineness and excess air levels. This unburned carbon level is included in the final determination of total boiler efficiency. (See Chapters 9 and 21.)

Performance requirements

Pulverized coal-fired equipment should meet the following performance conditions:

1. The coal and air feed rates must comply with the load demand over a predetermined operating range. For modern applications with high volatile bituminous or subbituminous coal, flames should be stable without the use of lighters from about 30% to full load. The minimum load depends on the coal, burner design, and pulverizer load; operation below this load is performed in combination with lighters in service.

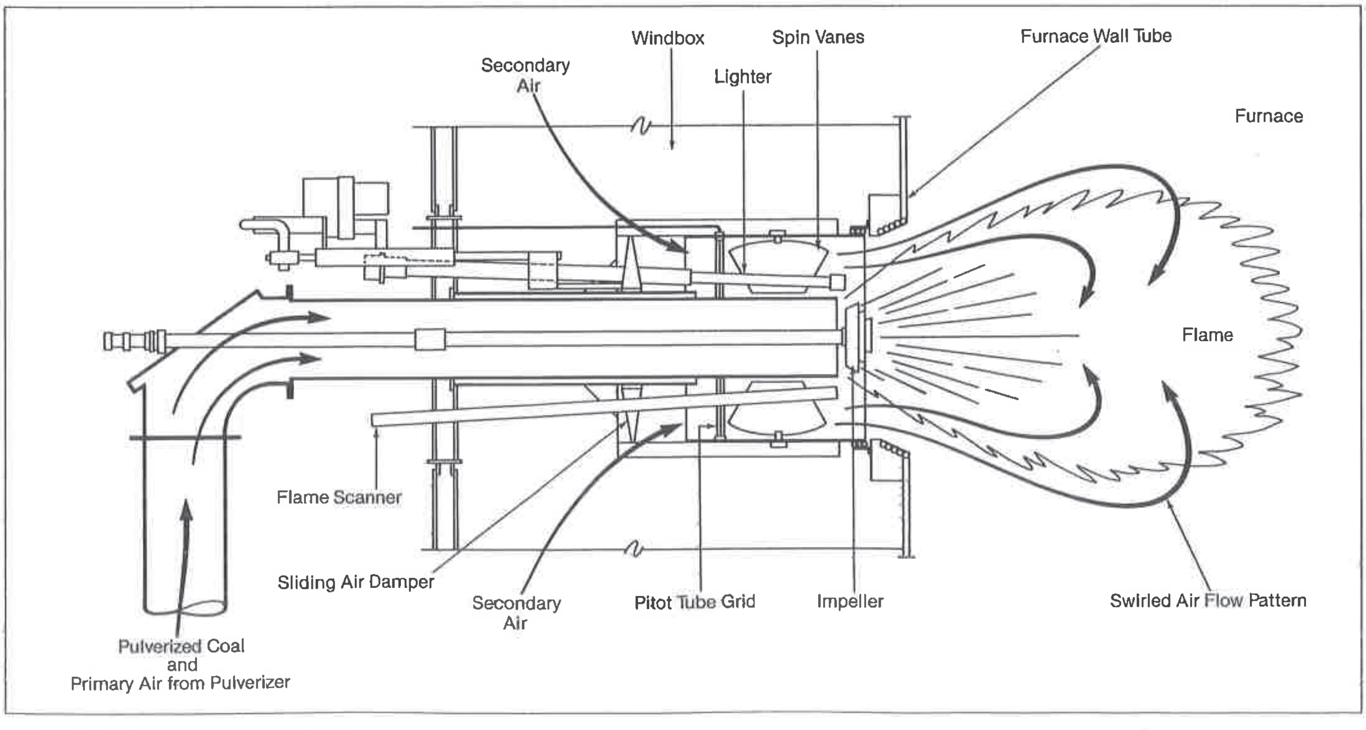


Fig. 5 S-type burner and components.

2. Unburned combustible loss (UCL) should reduce efficiency by less than 1%. UCL less than 0.2% should be expected with reactive subbituminous or lignite coals. UCL increases with less reactive bituminous coals and in boilers with less than 400,000 lb/h (50.4 kg/s) steam capacity.
3. The burner should not require continual adjustment to maintain performance. The unit should be designed to avoid the formation of localized slag deposits that may interfere with burner performance or damage the boiler.
4. Only minor maintenance should be necessary during the annual outage. To avoid high temperature damage, alloy steel should be used for burner parts exposed to furnace radiative heat transfer. Burner parts subject to PC erosion may require more frequent repair or replacement.
5. Safety must be paramount under all operating conditions. Automated flame safety and combustion control systems are recommended and required in many cases.

Conventional PC burners

Prior to 1971 in the U.S., the primary focus of combustion system development was to permit the design of compact, cost effective boilers. As a result, the burner systems developed focused on maximizing heat input per unit volume with small furnace volumes, rapid mixing burners, and very high flame temperatures. An unintended side effect was the production of high levels of NO_x. Many boilers with this technology remain in operation today. Burners used on such boilers include the conventional circular burner, the cell burner, and a more mechanically reliable version — the S-type burner.

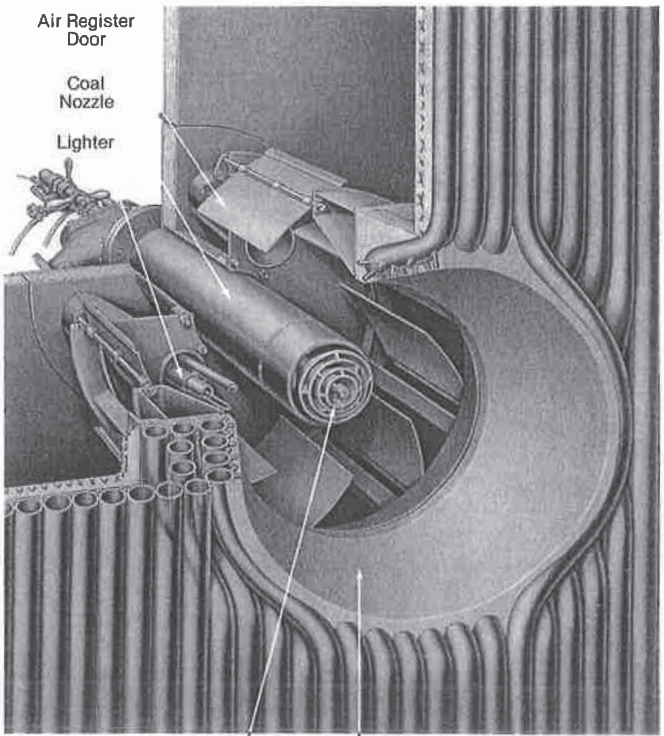


Fig. 6 Circular register pulverized coal burner with water-cooled throat.

Conventional circular burner

The circular burner (Fig. 6) was one of the earliest forms of swirl-stabilized PC-fired burners. Due to its success, this burner has been used for six decades firing a variety of coals in many boiler sizes. The circular burner may still be supplied for conventional use in selected cases. The burner is composed of a central nozzle to which PA/PC is supplied. The nozzle is equipped with an impeller at the tip to disperse the coal into the secondary air. Secondary air is admitted to the burner through a register. The register consists of interlinked doors arranged in a circular pattern between two plates. The doors are closed to cooling position when the burner is out of service, are partially open for lightoff and are more fully open for normal operation.

Opening the register doors allows more air into the burner but reduces swirl. Flame shape can also be adjusted using the registers. However, air distribution among burners is also impacted by register position, and high combustion efficiency depends on uniform air-fuel distribution.

The circular burner can fire natural gas, oil or pulverized coal. Simultaneous firing of more than one fuel is not recommended due to the potential for overfiring the burners and the resulting combustion problems. Variations of the circular burner are in operation at inputs from 50 to 300 $\times 10^6$ Btu/h (15 to 88 MW). Moderate input units provide more uniform heat distribution to the combustion zone, improving operation.

Cell burner

The cell burner combines two or three circular burners into a vertically stacked assembly that operates as a single unit (Fig. 7). In the 1960s and 1970s the cell burner was applied to numerous utility boilers which had compact burner zones. While highly efficient, the cell burners produced high levels of NO_x emissions.

S-type burner

The S-type burner shares the functional attributes of the circular burner in an improved configuration. (See Fig. 5.) The burner nozzle is the same as that in the circular burner. However, secondary air flow and swirl are separately controlled. Secondary air quantity is controlled by a sliding disk as it moves closer to or farther from the burner barrel. Secondary air swirl is provided by adjustable spin vanes positioned in the burner barrel. An air-measuring pitot tube grid is installed in the barrel ahead of the spin vanes. Secondary air can be measured for each burner to distribute the flow uniformly among burners using the sliding disks or other means. Swirl control for flame shaping is controlled separately by spin vanes. The S-type burner provides higher combustion efficiency and mechanical reliability than the circular unit and is a direct plug-in replacement.

Low NO_x combustion systems

NO_x formation

NO_x is an unintended byproduct from the combustion of fossil fuels and its emissions are regulated in the U.S. and many other parts of the world. (See Chapter 32.)

While a number of options are available to control and reduce NO_x emissions from boilers, as discussed in Chapter 34, the most cost effective means is the use of low NO_x combustion technology either alone or in combination with other techniques. The effectiveness of the pulverized coal NO_x control technology, however, depends upon the fuel characteristics and the overall system design. For pulverized coal wall-fired units, NO_x emissions from conventional combustion systems discussed above typically range from 0.8 to 1.6 lb/10^6 Btu (984 to 1968 mg/Nm^3: see Note below). Low NO_x PC combustion systems are capable of reducing NO_x to 0.2 to 0.7 lb/10^6 Btu (246 to 861 mg/Nm^3).

NO_x control by combustion

More than 75% of the NO_x formed during conventional PC firing is fuel NO_x; the remainder is primarily thermal NO_x. Consequently, the most effective combustion countermeasures are those limiting fuel NO_x formation. Fuel NO_x is formed by oxidation of fuel-bound nitrogen during devolatilization and char burnout. Coal typically contains 0.5 to 2.0% nitrogen bound in its organic matter. High oxygen availability and high flame temperatures during devolatilization encourage the conversion of volatile-released nitrogen to NO_x. Nitrogen retained in the char has a lower conversion efficiency to NO_x, primarily due to lower oxygen availability during char burnout. Reactive coals with high volatile matter and low fixed carbon/volatile matter (FC/VM) ratios have tended to be the most amenable to NO_x control by combustion modification. Coals with higher nitrogen content tend to produce higher NO_x emissions.

The most effective means of reducing fuel-based NO_x formation is to reduce oxygen (air) availability during the critical step of devolatilization. Additional air can then be added later in the process to complete char reactions and maintain high combustion efficiency.

Oxygen availability can be reduced during devolatilization in two ways. One method is to remove a portion of the combustion air from the burners and introduce it elsewhere in the furnace. This method is referred to as *air staging*. PC combustion systems typically operate with 15 to 20% excess air at maximum firing rate. (See Chapter 9.) In some staging situations, reducing the air flow by 10% at the burners is sufficient for a given level of NO_x emissions control. This permits the burners to continue to operate in an excess air condition. Reducing the air flow to less than stoichiometric (theoretically required for complete combustion air flow) conditions can further reduce NO_x emissions. However, further reductions in burner stoichiometry below 70% of the theoretical air requirements can cause NO_x to increase again. This is due largely to the significant fraction of combustion which is deferred and the high air flows and mixing rates necessary to subsequently complete this combustion. Burner operation below theoretical air requirements can also increase unburned carbon loss and slagging in the combustion zone with bituminous coals while increasing the risk of furnace corrosion. Unburned carbon loss

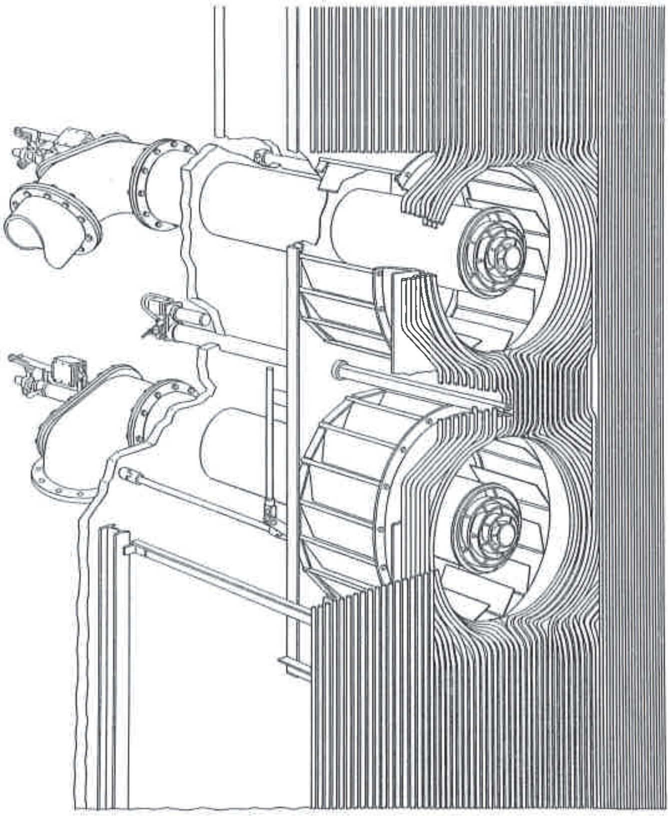


Fig. 7 Conventional cell burner.

can be controlled by increasing coal fineness and by careful management of air-fuel distribution among burners and air staging ports. Slagging can be minimized by proper arrangement of burners and by burner design. Tube corrosion damage by hydrogen sulfide (H_2S) attack is a concern when firing high sulfur coals under substoichiometric conditions. H_2S is formed during the combustion of sulfur bearing coals under oxygen deficient or reducing conditions. The resulting corrosion potential is dependent upon the H_2S concentration, tube material, tube temperature and operating conditions. This corrosion potential can be reduced by switching to low sulfur coal or by coating the burner zone tubes with a corrosion resistant material.

A second method of reducing oxygen availability during coal devolatilization is by burner design. The burner can be designed to supply all the combustion air but to limit its rate of introduction to the flame. Only a fraction of the air is permitted to mix with the coal during devolatilization. The remaining air is then mixed downstream in the flame to complete combustion. However, overall mixing is reduced and the flame envelope is larger compared to rapid mixing conventional burners. NO_x emission reduction using low NO_x burners ranges from 30 to 60% compared to uncontrolled levels. These burners can be used in combination with air staging through NO_x ports (discussed later) to satisfy emission limits. However, from a cost and performance perspective, the use of NO_x ports should be minimized where possible. Advanced low NO_x burners can frequently meet emission control requirements without the use of NO_x ports.

Another method of reducing NO_x emissions is referred to as reburning or fuel staging. This control technique

Note: The International Energy Agency conversion has been adopted for NO_x emission rates: 1230 mg/Nm^3 equals 1 lb/10^6 Btu for dry flue gas, 6% O_2, 350 Nm^3/GJ for coal.

destroys NO_x after it has formed. Fuel staging involves introducing the fuel into the furnace in steps. The bulk of the fuel is burned in the furnace at near stoichiometric conditions. The balance of the fuel with a limited amount of air is then injected to create a reducing zone part way through the combustion process. The reducing conditions form hydrocarbon radicals which strip the oxygen from previously formed NO_x, thereby reducing overall NO_x emissions. The balance of the air necessary to complete the combustion is then added. Some fuel-staged systems involve separate burners or fuel injectors followed by NO_x ports which supply the remaining combustion air. Some advanced low NO_x burners embody fuel staging while supplying all the fuel to the burners. A portion of the fuel is introduced in a manner to generate hydrocarbon radicals; the balance is mixed into the flame later to reduce previously formed NO_x. These burners can achieve NO_x reductions of 50 to 70% from baseline uncontrolled levels.

Dual register burner

B&W began experimenting with techniques to reduce NO_x from PC-fired burners in the 1950s. A slot burner, which incorporated controlled air-fuel mixing, was first developed.[4] Air introduced through the burner throat mixed rapidly in the flame while air diverted to the external slots mixed gradually. While effective, the design with slots external to the burner throat was difficult to apply to furnaces. In 1972, B&W developed the dual register burner (DRB) for firing pulverized coal. The DRB (Fig. 8) provided two air zones, each controlled by a separate register, around an axially positioned coal nozzle. A portion of the secondary air was admitted through the inner air zone to aid ignition and flame stability. The remainder passed through the outer air zone and was mixed downstream in the flame. Recirculation induced by the swirled outer air also improved flame stability. The burner nozzle was equipped with a venturi to disperse the primary air-coal mixture. The mixture was then injected into the throat without deflection. The results were a stable flame with a fuel-rich core and gradually completed mixing downstream. The first unit retrofit was completed in 1973 and achieved 50% NO_x reduction relative to prior circular burners. This retrofit required no modifications to boiler pressure parts, fans, or pulverizers, and NO_x ports were not used. The U.S. government granted a patent to B&W for the DRB in January 1974. Numerous variations have been used by B&W since its introduction.

The DRB is often used in combination with enlarged furnace combustion zones to reduce thermal NO_x and with a compartmented windbox to better control air distribution (Fig. 8). This design has the burners coupled with each pulverizer situated in an individual windbox compartment. Secondary air is metered and controlled separately for each compartment. This approach corrects much of the flow imbalance among burners that was experienced in open windbox designs. High combustion efficiency with minimal burner zone slagging results.

The DRB typically reduces NO_x 50 to 60% from uncontrolled levels. This efficiency enables its use on new boilers without NO_x ports or other air diversion systems. Utility boiler NO_x emissions with the DRB range from 0.27 to 0.70 lb/10^6 Btu (332 to 861 mg/Nm^3).

DRB-XCL™ burner

The dual register XCL burner is an advanced version of the original DRB. The DRB-XCL™ is reconfigured mechanically as shown in Fig. 9. A DRB-XCL™ burner being prepared for shipment is shown in Fig. 10. Air flow to the burner is regulated by a sliding disk similar to that used on the S-type burner. An impact/suction pitot tube grid is located in the burner barrel to measure secondary air flow. With this information, the secondary air can be uniformly distributed among all burners by adjusting the sliding disks or other means. Balanced air and

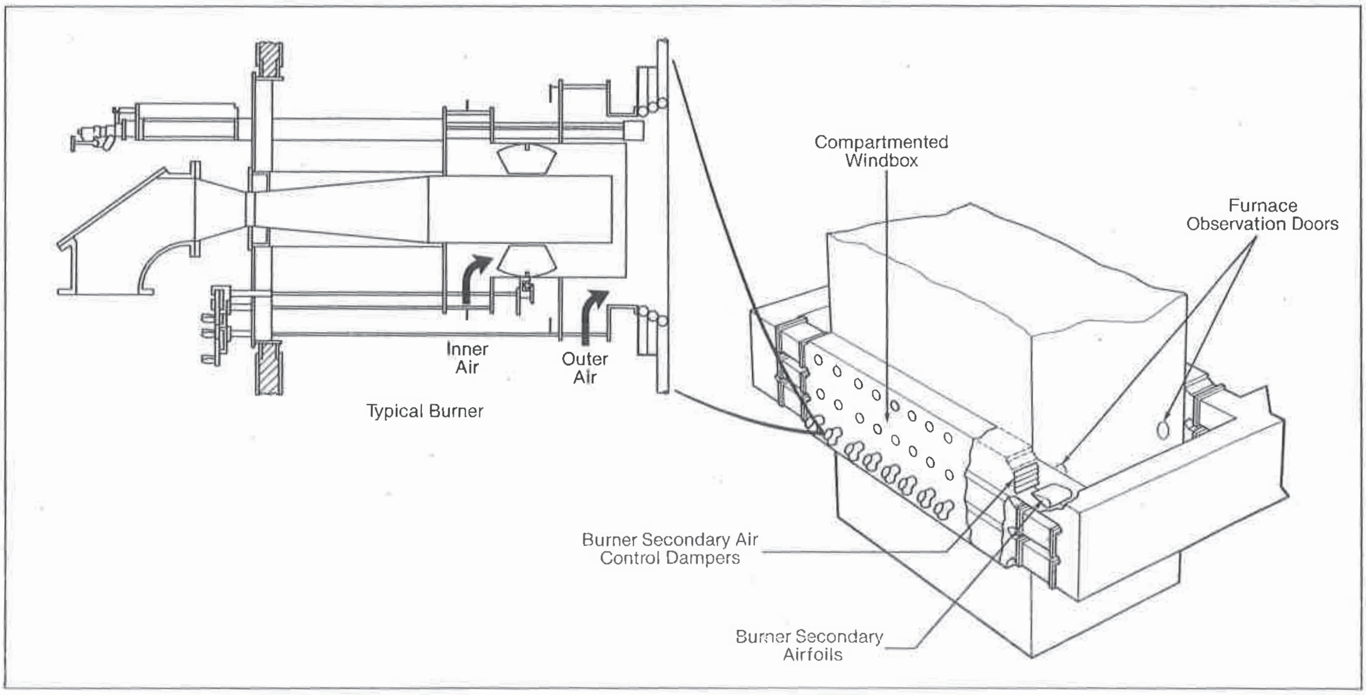


Fig. 8 Dual register burner and compartmented windbox.

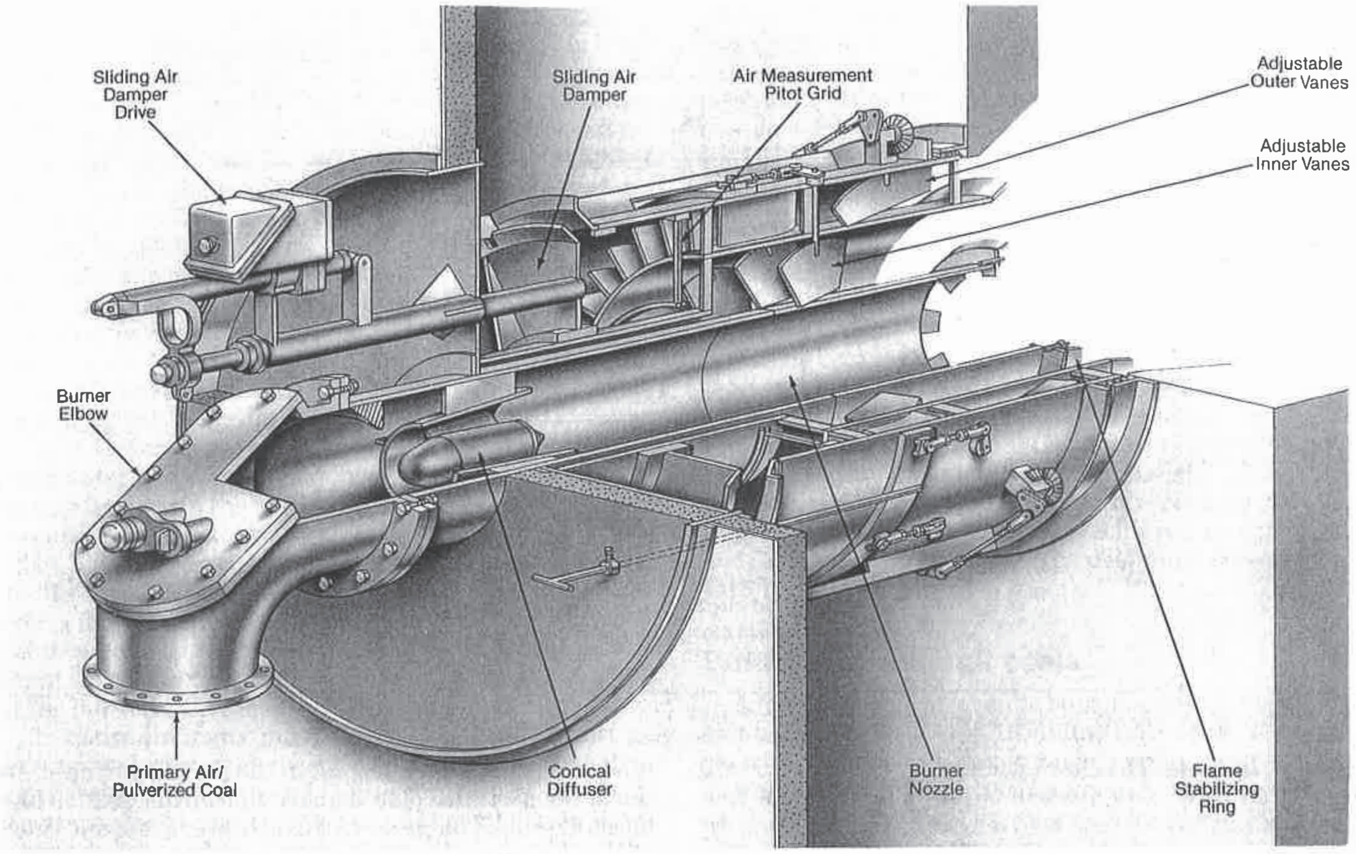


Fig. 9 DRB-XCL™ low NO_x burner for pulverized coal firing.

fuel distribution among all burners is critical to combustion efficiency, particularly with low NO_x systems. Downstream of the pitot tube grid are the inner and outer air zones. Adjustable vanes in the inner zone stabilize ignition at the burner nozzle tip. The outer zone, the main air path, is equipped with two stages of vanes. The upstream set is fixed and improves peripheral air distribution within the burner. The downstream set is adjustable and provides proper mixing of this secondary air into the flame. The burner nozzle is equipped with a conical diffuser and flame stabilizing ring. These combine to improve flame stability while further reducing NO_x by incorporating fuel staging technology. The DRB-XCL™ burner reduces NO_x 50 to 70% from uncontrolled levels without using NO_x ports. This level of NO_x reduction is possible through the creation of the flame combustion zones as shown in Fig. 11. The burner is specifically designed to generate rapid heating and high temperatures in the fuel rich flame core. This causes more of the coal to burn as volatile matter and releases a larger portion of the fuel nitrogen early in the combustion process, leaving less in the char. By limiting available oxygen in the flame core, NO_x formation is minimized. At the same time, reducing species are generated from the volatile materials. These propagate into the flame to aid in reducing NO_x formed in the later zones of the flame. Char oxidation occurs last at reduced temperature and oxygen concentrations, thereby limiting NO_x formation during char burnout. NO_x ports can be added when further NO_x reduction is required. In retrofit applications, the DRB-XCL™ burner can be equipped with modified coal impellers to shape the flame to existing furnaces.

The air and fuel staging technology of the DRB-XCL™ burner is also well suited for firing fuel oil or natural gas and for multi-fuel applications with pulverized coal. Chapter 10 discusses the oil and gas performance.

Low NO_x Cell™ burner

The cell burners discussed earlier produced high NO_x emissions, typically 1.0 to 1.8 lb/10^6 Btu (1230 to 2214 mg/Nm^3). The unique arrangement of the cell burner (Fig. 7) was incompatible with direct replacement by standard

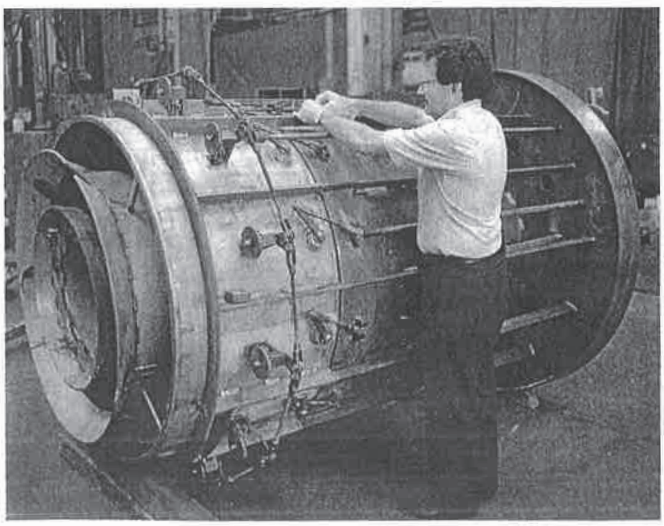


Fig. 10 DRB-XCL™ burner being prepared for shipment.

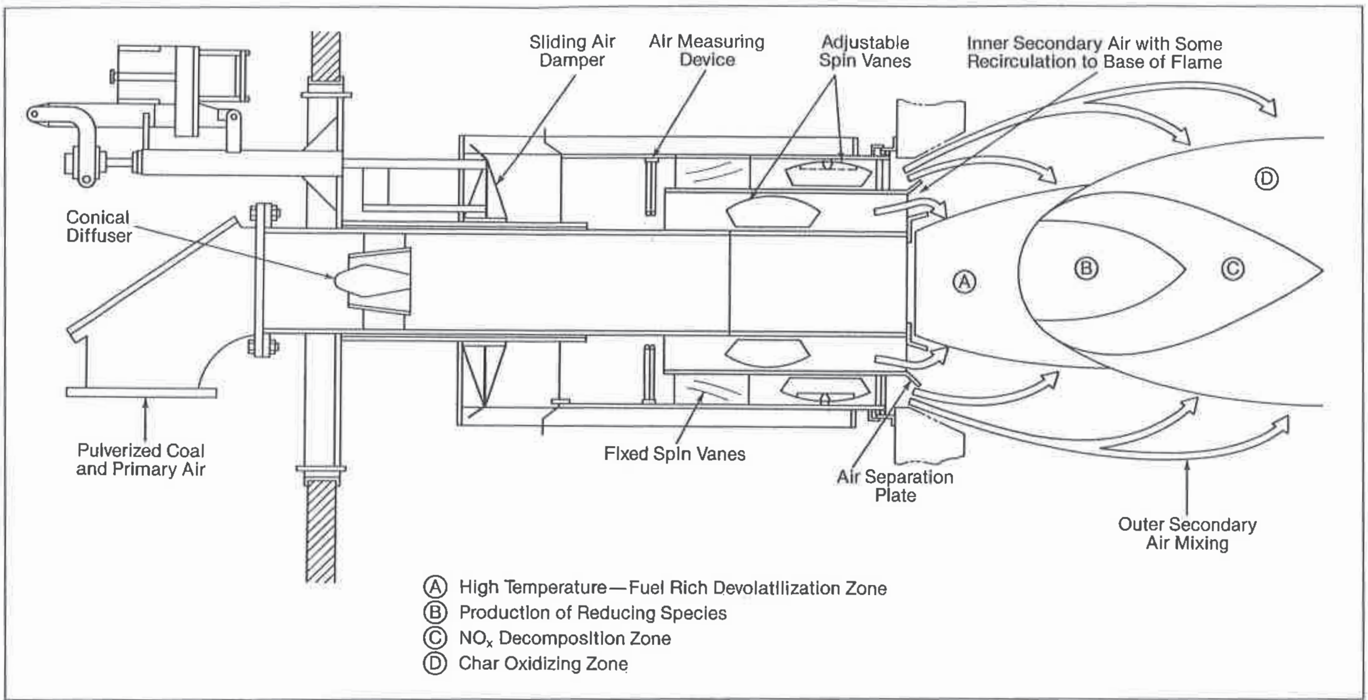


Fig. 11 DRB-XCL™ low NO_x combustion zones.

low NO_x burners. The close spacing of the burner throats prevented direct installation of larger, multi-zone low NO_x burners. One option is to rearrange the burners, increasing space between them and installing the DRB-XCL™ low NO_x burner. This solution is effective but costly. Costs increase due to the need for new boiler tube wall panels, coal piping, burners, ignition system plus windbox alterations. Another alternative is the Low NO_x Cell™ burner (LNCB™). (See Fig. 12.) This burner is designed to fit into existing cell burner locations and reduce NO_x. The LNCB™ was conceived by B&W and developed in cooperation with the Electric Power Research Institute. In essence, all of the coal is supplied to the lower burner throat with a portion of the secondary air. The balance of the secondary air is supplied to the upper burner throat. The upper throat serves as an integral NO_x port for each burner location. The coal piping is altered to supply all the coal to the lower throat, usually by joining the pipes in a Y connection. A larger burner nozzle is installed in the lower throat and can be equipped with an impeller to shape the flame. The lower throat burner assembly is essentially a conventional S-type burner with an oversized nozzle. The upper throat assembly is equipped with a sliding disk and pitot tube grid to set secondary air flow. It is also equipped with vanes to control mixing of this air into the flame. NO_x levels can be reduced by 50% with the LNCB™ while maintaining high combustion efficiency. Retrofit costs are reduced because wall panel and windbox alterations are avoided and because coal piping alterations are reduced.

NO_x ports

Removing a portion of the secondary air from PC-fired burners effectively reduces NO_x emissions as discussed above. The air is diverted to ports which introduce it later in the combustion process. These ports may be located close to the burners, as in the LNCB™, or at some distance from all of the burners. In the majority of applications, the ports are placed above the burner zone in furnaces arranged for gases to travel upward and out. Such ports are sometimes referred to as overfire air (OFA) ports. In some applications, ports are placed beneath or within the burner zone.

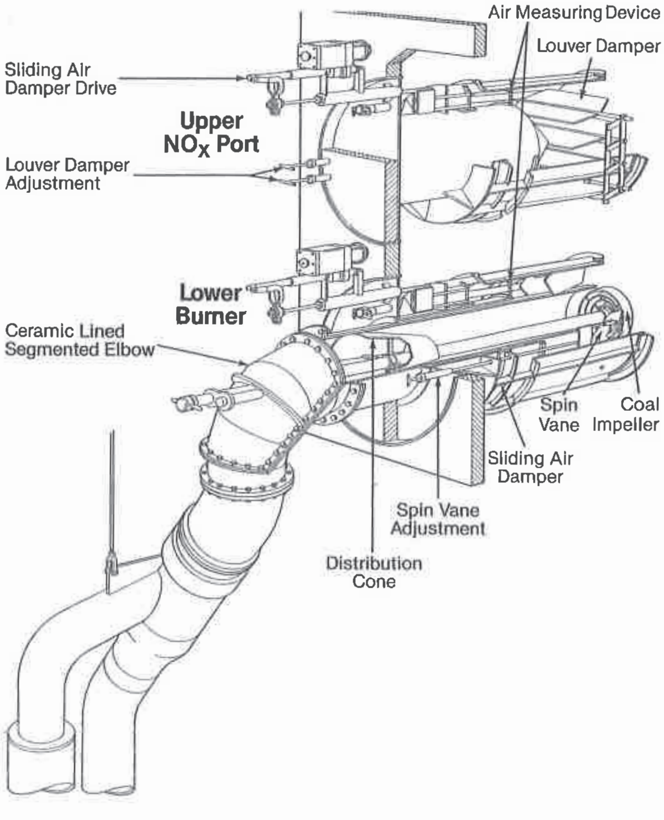


Fig. 12 Low NO_x Cell™ burner.

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B&W pioneered the development and application of NO_x ports and air staging as NO_x emission controls. This work, which began in the 1950s, was initially directed at NO_x reduction for oil- and gas-fired boilers in California. R.M. Hardgrove of B&W filed a patent for a *Method for Burning Fuel* on June 18, 1959, disclosing key aspects of air-staging influences on NO_x emissions. The patent was granted in 1962, and NO_x ports have been used subsequently by B&W.

Despite the proven effectiveness of NO_x ports, they are not always used with pulverized coal. This is due to the potential for increased slagging and corrosion in the furnace and the loss of combustion efficiency. The H_2S corrosion potential is a concern with higher sulfur coals, particularly those exceeding 2 lb/10^6 Btu (860 g/GJ) sulfur content. High and severe slagging bituminous coals are not suitable for NO_x ports due to the potential for wet or plastic slag forming in the furnace. This slag can block burner throats or the furnace hopper and can be corrosive to boiler tubes. Protective coatings of some stainless steels or aluminum can greatly reduce the corrosion potential. However, substoichiometric operation with high sulfur coals is not recommended. Low NO_x burners alone, or those with slight staging to maintain a stoichiometry of at least 1.05 at the burners, are better solutions with such coals.

To maintain high combustion efficiency, NO_x port jet size and velocity must be sufficient to provide penetration across the furnace and mixing with crossflow gases. However, high velocity jets can miss combustion product gases flowing between the ports. B&W developed the Dual Zone NO_x Port (Fig. 13) to address this problem. The inner zone of the port provides a jet to penetrate across the furnace. The outer zone has vanes to deflect air and entrain nearby gases. The ports have adjustable disks and vanes to permit tuning during commissioning. Each port is also equipped with pitot tubes to measure flow and to allow uniform air distribution among ports. Systems intended to operate at low burner zone stoichiometries, e.g., 0.70 to 0.85, benefit from two levels of NO_x ports. This better controls introduction of oxygen in the latter stages of combustion and minimizes associated NO_x formation. NO_x port system performance benefits from the inclusion of equipment to measure and regulate flow to both the burners and the ports through the boiler load range.

An emerging technology which facilitates this integration is numerical modeling. (See Chapters 3 and 4.) Computer programs provide detailed information about mixing effectiveness throughout the furnace. These programs can be used to optimize NO_x port size and placement, burner swirl orientation, and furnace geometry. Major improvements in mixing can be achieved by this parametric evaluation;[5] however, models must be validated with test data.

Burners for difficult coals

A few coals have proven to be considerably more difficult to burn than others, including unreactive coals and reactive coals which would burn readily except for an overabundance of moisture and/or ash. B&W has developed burners specifically for use with these problem coals. The selection of burner type is based on an empirical ignition factor derived from full scale experience with difficult coals. This factor relates variations in fuel ratio (FC/VM), moisture content, ash content, and coal heat-

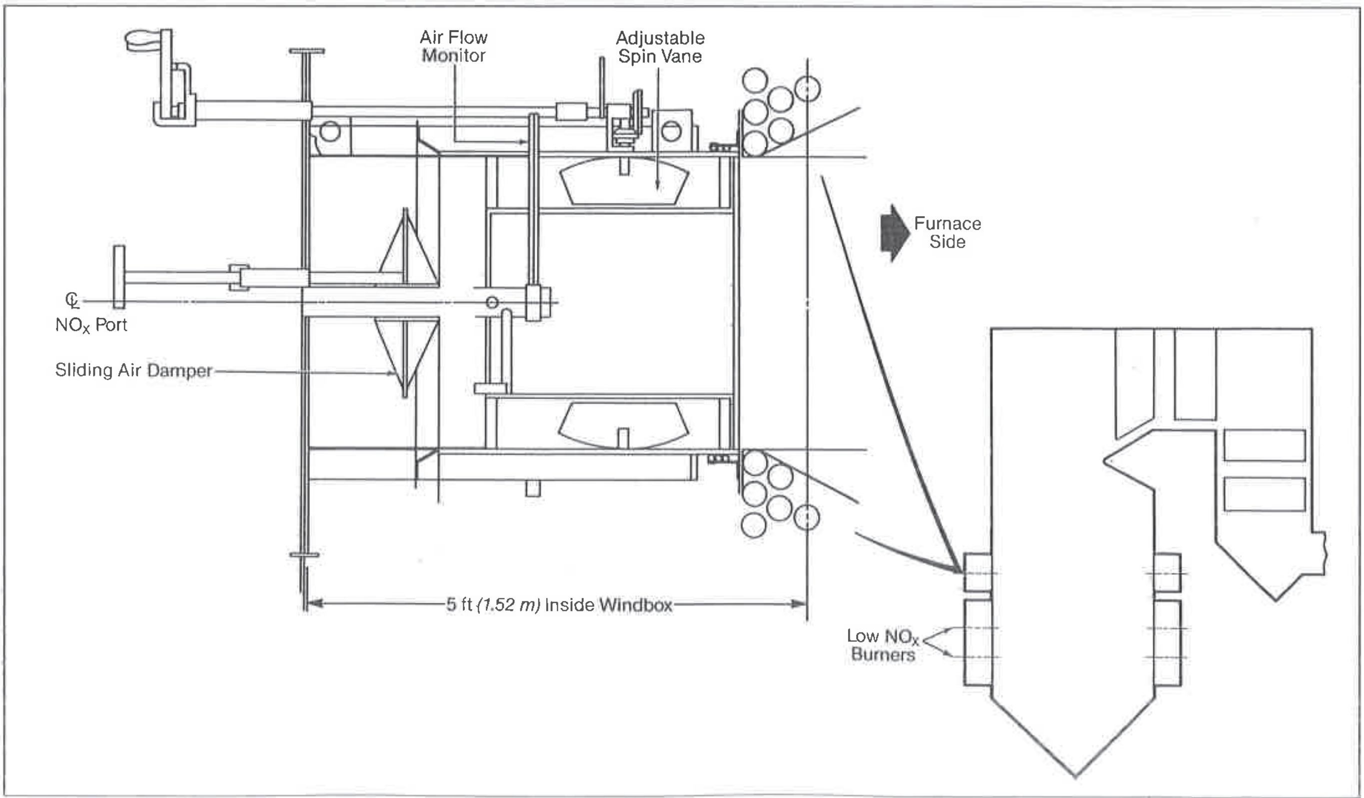


Fig. 13 Dual Zone NO_x Port.

ing value to ignition behavior. Burner choices for these applications include conventional and low NO_x burners discussed above, the enhanced ignition (EI) burner, and the primary air exchange (PAX) burner.

Enhanced ignition burner

The enhanced ignition (EI) burner resembles the DRB-XCL™ burner. However, the EI burner uses a larger coal nozzle to reduce the primary air and coal mixture velocity as it enters the furnace. The conical diffuser produces a fuel-rich ring and a fuel-lean core; at low velocity, this combination is readily ignited. The dual air zones are adjusted relative to the DRB-XCL™ burner to increase recirculation of hot gases along the fuel jet. The EI burner is well suited for firing high moisture (more than 35%) lignites and low volatile bituminous coal.

Primary air exchange burner

The primary air exchange (PAX) burner is designed to fire anthracite coals. Some anthracites can be wall-fired conventionally with the PAX burner, while those lowest in volatile matter must be fired in a downshot arrangement (Fig. 4). The register design for the PAX burner is similar to that of the EI burner. However, in the case of downshot firing, air staging ports direct air away from the burner to raise flame temperature.

The anthracite fineness is increased to improve combustion efficiency. In addition, mill exit temperature is increased to the maximum for the pulverizer, often limited to 200F (93C) for mechanical reasons. Tests have shown the benefit of higher temperatures on ignition performance. The PAX burner raises the primary air and pulverized coal (PA/PC) temperature by a patented design which separates half of the primary air from the PA/PC mixture and vents it into the furnace. This primary air is replaced by secondary air near 700F (371C), significantly raising fuel temperatures as it enters the furnace. The PAX nozzle tip is also sized for low velocity to further assist ignition. Even with these techniques, good combustion is dependent upon high furnace temperatures. Low load operation still requires lighters for flame stabilization.

Auxiliary equipment

Oil/gas firing equipment

In some cases, PC-fired furnaces are required to burn fuel oil or natural gas up to full load firing rates. These fuels can be used when the PC system is not available for use early in the life of the unit, due to an interruption in coal supply, or as a NO_x control strategy. Some operators avoid installing a spare pulverizer by firing oil or gas when a mill is out of service.

To fire oil, an atomizer is installed axially in the burner nozzle. Erosion protection for the atomizer is recommended. A source of air is needed when firing oil or gas to purge the nozzle and improve combustion. This air system must be sealed off prior to PC firing. Steam-assisted atomizers are recommended for best performance.

Gas elements of several designs can be used in PC-fired burners. The burner gas manifold can be inside or outside of the windbox. Installation in the windbox clears the burner front of considerable hardware but prevents on-line adjustment or repair of gas elements. Gas elements are equipped with flame stabilizing cans to protect the root of the flame at each spud. Retrofitting multiple gas elements into PC-fired burners can disrupt air flow in the throat and impair performance. Compatibility of the gas elements with the PC burner design is important. Retrofit of gas or oil elements increases the forced draft fan load in many cases. Primary air is eliminated which results in higher quantities of secondary air compared to PC. As a result, fan flow and static margins need to be considered.

See Chapter 10 for more information on oil and gas firing equipment.

Lighters

A lighter, or ignitor, is required to initiate combustion as pulverized coal is first introduced to the burner, as the burners are being normally shut down, and as otherwise required for flame stability. Lighters typically use an electrically generated spark to ignite a lighter fuel, which is usually natural gas or No. 2 fuel oil. Most modern units have automated controls to activate, operate, purge, and shut down the lighters. Lighter systems are described in Chapter 10.

Flame safety system

Modern PC-fired boilers are equipped with a flame safety systems (FSS). The FSS uses scanners at each burner to electronically monitor flame conditions. Flame scanners are used to evaluate the lighter and main flames for intensity and frequency. The lack of satisfactory flame signals causes the FSS to automatically take corrective action, which is to shut down the burner and its associated group. This prevents unburned fuel from entering the furnace and significantly reduces the risk of an explosion. See Chapter 41 for additional information on the FSS.

Safety and operation

Uncontrolled ignition of pulverized coal may result in an explosion which can severely damage equipment and injure personnel. Explosions result from ignition of an accumulated combustible mixture within the furnace or associated boiler passes, ducts, and fans.[6,7] The magnitude and intensity of the explosion depend on the quantity of accumulated combustibles and the air-fuel mixture at ignition. Explosions result from improper operation, design, or malfunction. The National Fire Protection Association (NFPA) publishes standards in the following areas: *Pulverized Fuel Systems* (NFPA 85F) and *Prevention of Furnace Explosions in Pulverized Coal-Fired Multiple Burner Boiler-Furnaces* (NFPA 85E). These are excellent sources of information concerning design and equipment issues, operation and control of PC-fired equipment.

Another key source of information is the operating instructions. Operators of PC-fired equipment should expect the instructions to provide specific information concerning the purpose, design, calibration and adjustment, startup, operation and shutdown of the various equipment. The instructions also provide maintenance and troubleshooting information.

Other PC applications

Pulverized coal in the metals and cement industries

The application of pulverized coal firing to copper- and nickel-ore smelting and refining has been standard practice for many years. With the use of pulverized coal, high purity metal can be obtained because the furnace atmosphere and temperature can be easily controlled. Pulverized coal may be favored over other fuels for several reasons: it may be less expensive, it offers a high rate of smelting and refining, and it readily oxidizes sulfur.

Copper reverberatory furnaces for smelting and refining are fitted with waste heat boilers for steam generation. These boilers supply a substantial portion of power for auxiliary equipment and also provide the means for cooling the gases leaving the furnace.

In producing cement, the fuel cost is a major expense item. Except in locations where the cost favors oil or gas, pulverized coal is widely used in the industry. Direct firing, with a single pulverizer delivering coal to a single burner, is common practice in the majority of U.S. cement plants. The waste heat air from the clinker cooler, taken from the top of the kiln hood through a dust collector, usually serves as the preheated air for drying the coal in the pulverizer.

Pulverized coal has recently been introduced in the steel industry where it is injected into the blast furnace tuyères. The pulverized coal replaces a similar weight of higher priced coke. Theoretically, 40% of the coke could be replaced by pulverized coal.

References

1. Orning, A.A., "The combustion of pulverized coal," Chapter 34, appearing in *Chemistry of Coal Utilization*, H.H. Lowry, ed., Wiley, New York, pp. 1522-1567, 1945.

2. "Standard test method for volatile matter in the analysis sample of coal and coke," D3175-89a, *Annual Book of ASTM Standards*, Vol. 5.05, American Society for Testing and Materials, Philadelphia, pp. 329-331, 1991.

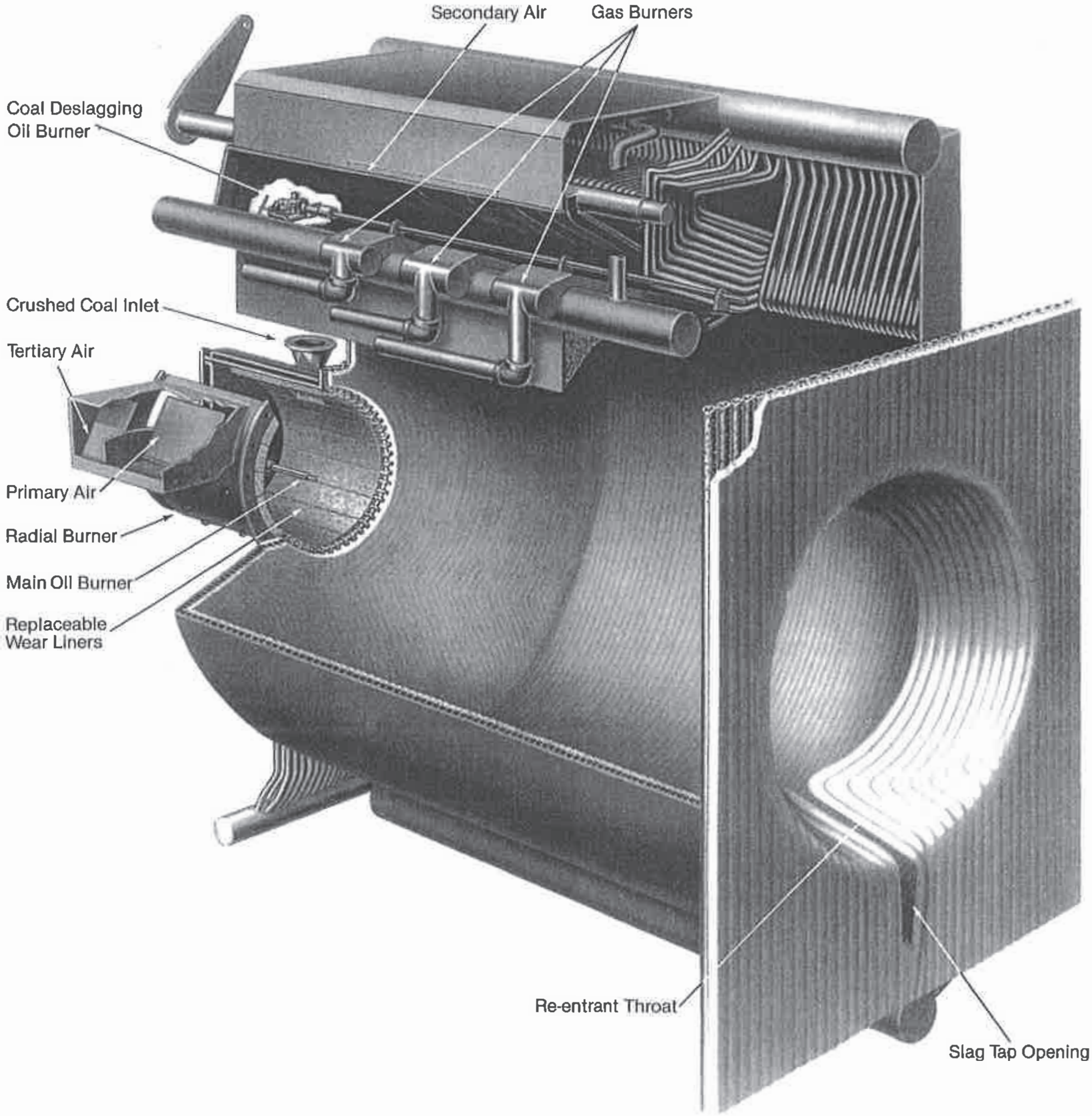
3. Beer, J.M., and Chigier, N.A., *Combustion Aerodynamics*, Chapter 5, Krieger Publishing, Malabar, Florida, 1983.

4. Brackett, C.E., and Barsin, J.A., "The dual register pulverized coal burner," presented at the Electric Power Research Institute NO_x Control Technology Seminar, San Francisco, February 1976.

5. Fiveland, W.A., Latham, C.E., and LaRue, A.D., "Combustion system optimization by advanced modeling technology," presented at the International Joint Power Generation Conference, Boston, October 1990.

6. *NFPA 85C — Prevention of Furnace Explosions / Implosions in Multiple Burner Boiler-Furnaces*, National Fire Protection Association, Quincy, Massachusetts, 1991.

7. *NFPA 85F — Installation and Operation of Pulverized Fuel Systems*, National Fire Protection Association, Quincy, Massachusetts, 1991.



Cyclone furnace.

Chapter 16
Atmospheric Pressure Fluidized-Bed Boilers

The fluidized-bed process

Fluidized-bed combustion (FBC) technology has distinct advantages for burning solid fuels and recovering energy to produce steam. The process features a mixture of particles suspended in an upwardly flowing gas stream, the combination of which exhibits fluid-like properties. Combustion takes place in the bed with high heat transfer to the furnace and low combustion temperatures. Key benefits of this process are fuel flexibility and reduced emissions. FBC is technically accepted for industrial sized units and is emerging as an accepted technology for electric power generation.

The following example will help visualize the fluidized-bed process. Fig. 1a shows a container with an air supply plenum at the bottom, a distributor plate that promotes even air flow through the bed, and an upper chamber filled with sand or other granular material.

If a small quantity of air flows through the distributor plate into the sand, it will pass through the voids of an immobile mass of sand. For low velocities, the air does not exert much force on the sand particles and they remain in place. This condition is called a fixed bed and is shown in Fig. 1b.

By increasing the flow rate, the air exerts greater forces on the sand and thereby reduces the contact forces between the sand particles caused by gravity. By increasing the air flow further, a point is reached where the drag forces on the particles counterbalance the gravity forces and sand particles become suspended in the upward flowing air stream. The point where the bed starts to behave as a fluid is called the *minimum fluidization condition*. As shown in Fig. 1c, the increase in bed volume is insignificant when compared with the nonfluidized case.

As the air flow increases further, the bed becomes less uniform, bubbles of air start to form and the bed becomes violent. This is called a *bubbling* fluidized bed which is shown in Fig. 1d. The volume occupied by the air-solids mixture increases substantially. For this case, there is an easily seen bed level and a distinct transition between the bed and the space above.

By increasing the air flow further, the bubbles become larger and begin to coalesce, forming large voids in the bed. The solids are present as interconnected groups of high solids concentrations. This condition is called a *turbulent* fluidized bed.

If the solids are caught, separated from the air and returned to the bed they will circulate around a loop. This type of system is defined as a *circulating* fluidized bed (CFB) and is shown in Fig. 1e. Unlike the bubbling bed, there is no distinct transition between the dense bed in the bottom of the container and the dilute zone above. The solids concentration gradually decreases between these two zones.

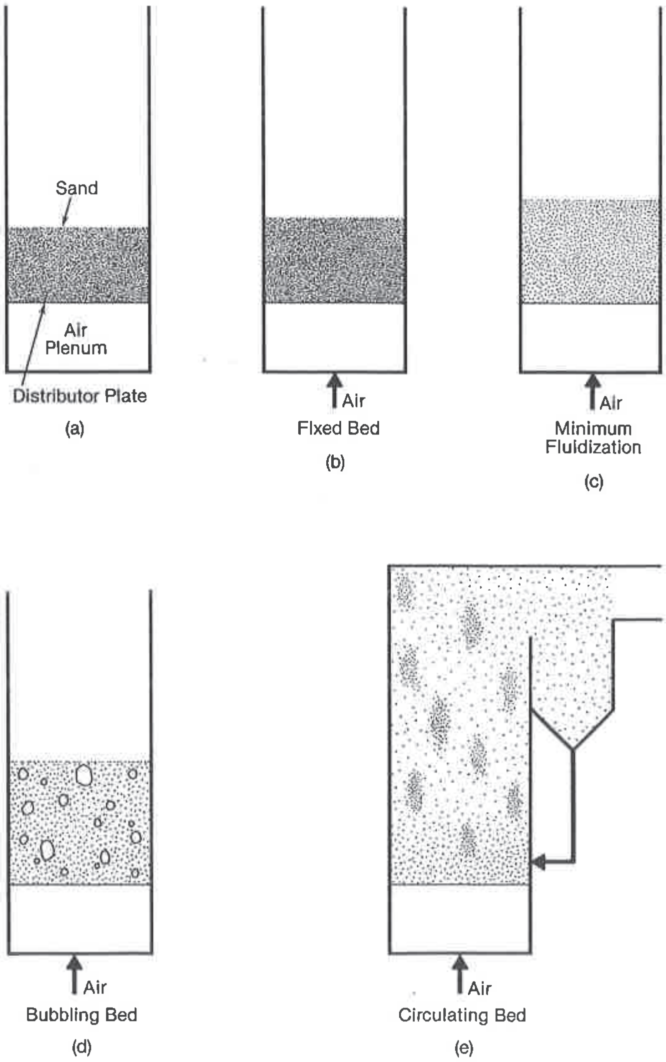


Fig. 1 Typical fluidized-bed conditions.

The weight of solids recirculated from the outlet back to the bed zone can be hundreds of times the weight of air flowing through the system, and the quantity of solids in the container is proportional to the amount of sand recycled from the collector. As a result, the pressure differential will increase to the value required to support the solids in the container.

The pressure differential between the top and the bottom of the container changes with air flow, as shown in Fig. 2. At low air flow rates, the pressure differential increases with flow until the minimum fluidization velocity is reached. At this point, the sand is supported by the air and the pressure differential is determined only by the mass of sand in the bed. The pressure differential is independent of further increases in air flow until the air velocity becomes high enough to convey the sand out of the container. At higher air flows, the pressure differential starts to decrease as mass is lost from the system.

Of the fluidization conditions just described, only bubbling and circulating beds are currently used by the power industry to generate steam.

Background and evolution

One of the earliest recorded applications of a fluidized bed used coal as the feed stock. In the mid 1920s, the fluidized-bed coal gasification process, invented by Fritz Winkler, was used commercially to generate gas from coal. (See also Chapter 17.) This gas was then used for fuel or as a feed stock for chemical syntheses. While there are a few Winkler gasifiers operating today, industry has found it both easier and less expensive to use natural gas or oil as fuels and for synthesis gas production.

During the late 1930s and early 1940s, a large research and development effort was directed to fluidized beds. This work identified the advantages of a fluidized bed as a solids-gas contacting device and led to development of the fluid catalytic cracker to produce gasoline and other petroleum based products. Today, fluidized beds are used worldwide for a variety of processes in many industries.

In the early 1960s, national attention turned to reducing sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from power plants. The fluidized-bed combustion process offered the potential for reducing these emissions. The effort to develop the coal-fired fluidized-bed boiler began.

In the early 1970s, Babcock & Wilcox (B&W) conducted an extensive study to evaluate the application of atmospheric pressure fluidized-bed combustion to large boilers. In 1977, B&W, in cooperation with the Electric Power Research Institute (EPRI), constructed and placed into operation a 6 × 6 ft (1.8 × 1.8 m) bubbling-bed test unit at the B&W Research Center in Alliance, Ohio. Test results from this facility have contributed significantly to the advancement of bubbling fluidized-bed boiler technology. Recent applications of large, coal-fired bubbling beds have included retrofits to existing boilers.

In the early 1980s, the market for coal-fired fluidized-bed boilers moved toward circulating beds. To meet this changing market, B&W used its knowledge of bubbling-bed technology and the technical concepts of Studsvik AB of Sweden to advance into the circulating-bed field. A schematic of a pilot-scale circulating fluidized bed built at B&W's research center is shown in Fig. 3.

Comparison with other combustion methods

The fluidized-bed combustion process, as with other firing methods, provides a means for mixing fuel with air to convert the chemical heat contained in the fuel into recoverable, sensible heat. Normally, fluidized-bed combustors are used to burn solid fuels.

In a pulverized coal-fired furnace, the combustion process consists of oxidizing fine (70% less than 200 mesh), widely dispersed fuel particles suspended in air and combustion gases. (See Chapter 13.) The volume around the burners is the hottest zone in the furnace with temperatures reaching 3000 to 3500F (1649 to 1927C). Also, the residence time of the particles in the furnace is close to the flue gas residence time.

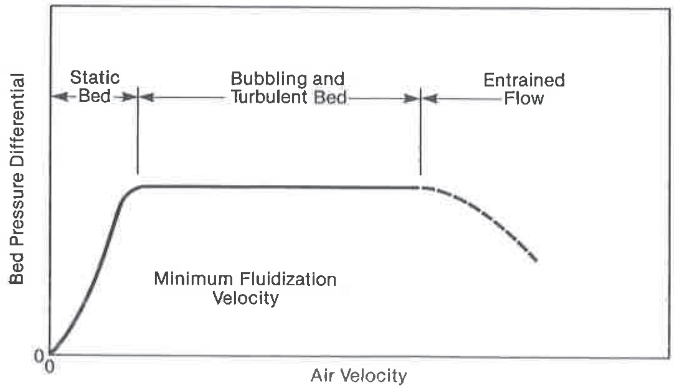


Fig. 2 Effect of velocity on bed pressure drop.

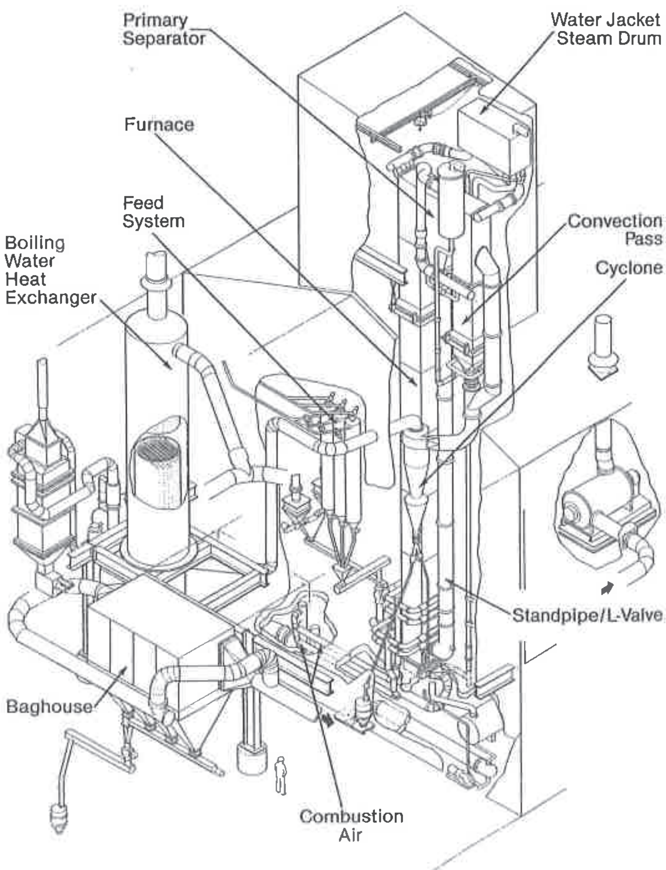


Fig. 3 2.5 MW_t CFB test facility by B&W.

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Stoker firing uses considerably larger fuel particles than pulverized coal firing. Fuel sizing is typically 1 to 1.25 in. (25.4 to 31.8 mm) top size for bituminous coal. Most of the fuel is burned as an immobile mass on some type of moving grate, with the air and combustion gas passing through the fixed bed of fuel. (See Chapter 15.) Temperatures in the fuel bed exceed 3000F (1649C) and the fuel residence time is determined by the grate speed.

The fluidized-bed combustion process falls in between pulverized coal and stoker firing with respect to the size of the fuel feed. Coal is typically crushed to less than 0.25 in. (6.4 mm). Depending on coal properties larger coal, 1.25 in. (31.8 mm), or smaller coal, 0.125 in. (3.18 mm), is used. Fuel is fed into the lower portion of a fluidized-bed boiler furnace. The bed has a density of approximately 45 lb/ft^3 (721 kg/m^3) for a bubbling bed and 35 lb/ft^3 (561 kg/m^3) for a circulating bed. The solids are maintained at a temperature of 1500 to 1600F (816 to 871C) in an upwardly moving stream of air and combustion gas.

When fuel is introduced into the bed it is quickly heated above its ignition temperature, ignites and becomes part of the burning mass. The flow of the air and fuel to the dense bed is controlled so that the desired amount of heat is released to the furnace on a continuous basis. Typically, the fuel is burned with 20% excess air. Due to the long fuel residence time and high intensity of the mass transfer process, the fuel can be efficiently burned in the fluidized-bed combustor at temperatures considerably lower than in conventional combustion processes.

The fuel particles remain in the dense bed until they are entrained by combustion gas or removed with the bed drain solids. As the fuel particles burn, their size falls below a given value where the terminal and gas velocities are equal, which allows them to be entrained. Therefore, the residence time is determined by the initial fuel particle size and by the reduction of the initial size resulting from combustion and attrition.

In bubbling fluidized beds, combustion occurs mostly in the bed due to lower gas velocity and coarser fuel feed size. The residence time of the fine fuel particles carried out of the bed with the combustion gas is, in many cases, increased by collecting and recycling the particles to the furnace.

In circulating beds, more particles are blown from the bed (elutriated) than for a bubbling bed. The particles are then collected by a particle separator and recirculated to the furnace. The residence time of the particles is determined by the collection efficiency of the particle separator and the solids circulation rate. As a result of the recirculation process, the effective particle residence time greatly exceeds the gas residence time.

The concentration of fuel in the dense bed is normally quite low. For a reactive fuel such as wood, it is difficult to find a measurable amount of carbon in the bed. Normally, the carbon content in a bed burning bituminous coal is less than 1%. The remaining portion of the bed is made up of fuel ash, lime and calcium sulfate when a sorbent is used for sulfur capture, and sand or other inert material when a sorbent is not used.

Overall carbon conversion efficiencies are near 100% for wood and highly reactive fuels, greater than 98% for bituminous coals, and slightly lower for less reactive fuels and waste coals.

Fluidized-bed combustion advantages

The primary driving force for the development of fluidized-bed combustors in the United States (U.S.) is reduced SO_2 and NO_x emissions. By implementing this technology, it is possible to burn high sulfur coals and achieve low SO_2 emission levels without the need for additional back-end sulfur removal equipment. As the technology developed, it also became apparent that the process could burn low grade fuels that are difficult or impractical to burn with other methods.

Designers of coal burning equipment have known for many years that coal properties vary depending on the fuel type and source and that the firing equipment must be compatible with the specific fuel. While fluidized-bed combustors are more tolerant of these variations, the same basic rules of combustion apply, so fuel type, chemical composition and heating value must be considered on each design.

Fluidized-bed boilers are designed so that the bed operating temperature is between 1500 and 1600F (816 and 871C); the ability to operate at this low temperature results in several operating advantages.

Reduced emissions — SO_2 and NO_x

Because of lower operating temperatures, it is possible to use an inexpensive material, such as limestone or dolomite, as a sorbent to remove SO_2 from flue gas. When limestone or dolomite is added to the bed, a reaction occurs in the furnace between the resulting calcium oxide (CaO) and the SO_2 in the gas. SO_2 emissions can be reduced by 90% or more depending on the sulfur content of the fuel and the amount of sorbent added.

Nitrogen and oxygen will react at high temperatures, above 2700F (1482C), to form nitric oxide. The rate of reaction decreases rapidly as the temperature is reduced from this value. With an operating bed temperature between 1500 and 1600F (816 and 871C), the amount of NO_x formed in the fluidized bed is less than in conventional units which operate at higher temperatures. For some bubbling-bed and all CFB boilers, additional suppression of NO_x formation is achieved by air staging. Fluidized beds can operate in this manner with less impact on combustion efficiency than in pulverized coal furnaces. With the addition of postcombustion reduction techniques, even lower NO_x emissions can be achieved.

Fuel flexibility

Fuel ash properties In addition to reduced emissions, the lower combustion temperatures permit burning high fouling and slagging fuels at temperatures below their ash fusion temperature. As a result, many of the boiler operating problems associated with these fuels are greatly reduced. However, care is still required as high alkali metal concentrations in the bed may cause sintering and in-bed tube bundle fouling. In addition, excessive amounts of above-bed burning may cause a significant increase in the furnace exit gas temperature and cause deposits to form in the superheater. For these reasons, bed temperatures around 1500F (816C) are normally chosen for fuels whose ash is high in alkali metals.

Low Btu fuels The fluidized-bed combustion process can also burn fuels with very low heating values. This capability results from the rapid heating of the fuel particles by the large mass of hot bed material and the long residence time that the fuel spends in the bed, both of which offset the effects of lower combustion temperatures. When burning high moisture fuels it is also necessary to consider the additional gas weight, resulting from water vapor, in the design of the convection pass and other related components.

Fuel preparation For high ash coals, the fluidized-bed boiler offers an advantage in fuel preparation over pulverized coal systems. These fuels require greater installed pulverizer capacity and the pulverizers generally require frequent maintenance. The crushed fuel, less than 0.25 in. (6.4 mm), required for a fluidized-bed boiler is easier and less costly to prepare.

A fluidized-bed boiler can be designed to burn a wider range of fuels than alternate firing methods. However, once the boiler is designed for a specified set of fuels there are limitations to the degree of deviation from the specified values that can be fired before design limits are exceeded. A CFB boiler has greater fuel flexibility than a bubbling bed.

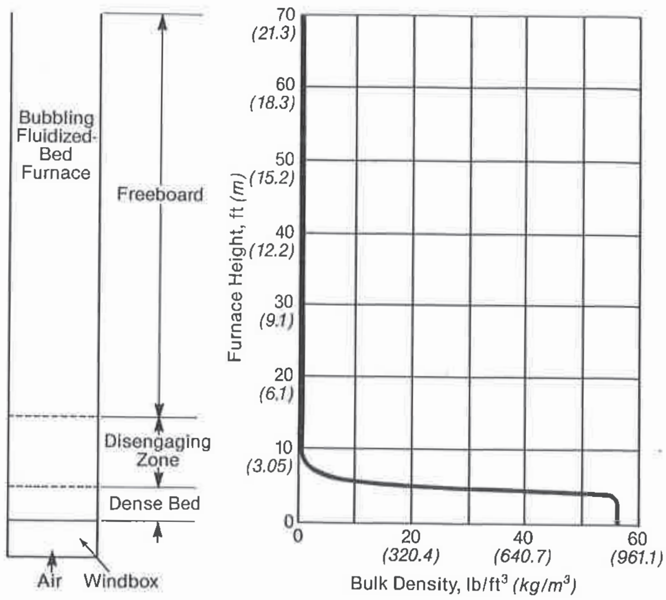

Fig. 5 Typical atmospheric pressure bubbling-bed furnace density profile.

Atmospheric pressure fluidized-bed boilers

Bubbling bed

Fig. 4 shows the main features of a bubbling fluidized-bed boiler. The bed itself is usually 4 ft (1.2 m) deep in its expanded or fluidized condition. Fig. 5 shows a typical furnace bulk density profile curve. The sharp drop in density indicates the top of the bed.

Normally, the heat transfer surface, which is in the form of a tube bundle, is placed in the bed to achieve the desired heat balance and bed operating temperature. For fuels with low heating values the amount of surface can be minimal or absent. In all cases, the bed temperature is uniform, plus or minus 25F (14C), as a result of the vigorous mixing of gas and solids.

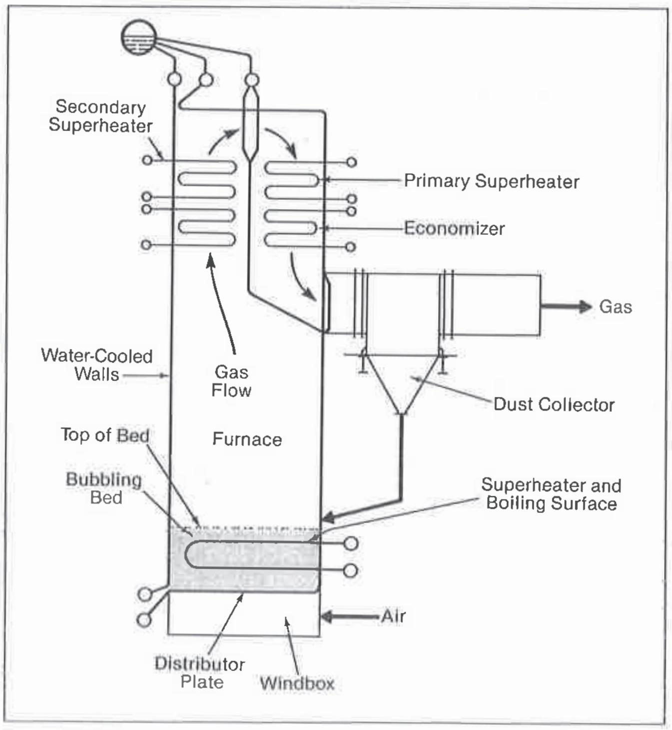

Fig. 4 Typical bubbling fluidized-bed boiler schematic.

Coal-fired bubbling-bed boilers normally incorporate a recycle system that separates the solids leaving the economizer from the gas and recycles them to the bed. This maximizes combustion efficiency and sulfur capture. Normally, the amount of solids recycled is limited to about 25% of the combustion gas weight. For highly reactive fuels this recycle system can be omitted.

Bubbling beds that burn coal usually operate in the range of 8 to 10 ft/s (2.4 to 3 m/s) superficial flue gas velocity at maximum load. The bed material size is 30 mesh (590 microns) and coarser, with a mean size of about 18 to 16 mesh (1000 to 1200 microns).

Circulating bed

Fig. 6 shows the main features of a circulating fluidized-bed boiler and Fig. 7 shows the furnace density profile. The dense bed does not contain any in-bed tube bundle heating surface. The furnace enclosure and internal division wall type surfaces provide the required heat removal. This is possible because of the large quantity of solids that are recycled internally and externally around the furnace. Because the mass flow rate of recycled solids is many times the mass flow rate of the combustion gas, furnace temperatures remain uniform. Also, the heat transferred to the furnace walls is adequate to provide the heat absorption required to maintain the target bed temperature of 1500 to 1600F (816 to 871C). B&W circulating fluidized-bed boilers usually operate at about 20 ft/s (6.1 m/s) superficial flue gas velocity at full load. The size of the solids in the furnace is usually smaller than 30 mesh (590 microns), with the mean particle size in the 150 to 200 micron range.

Emissions

U.S. federal and state governments have imposed limits on emissions from most large boilers and combustion processes. These emissions limits vary by region and gov-

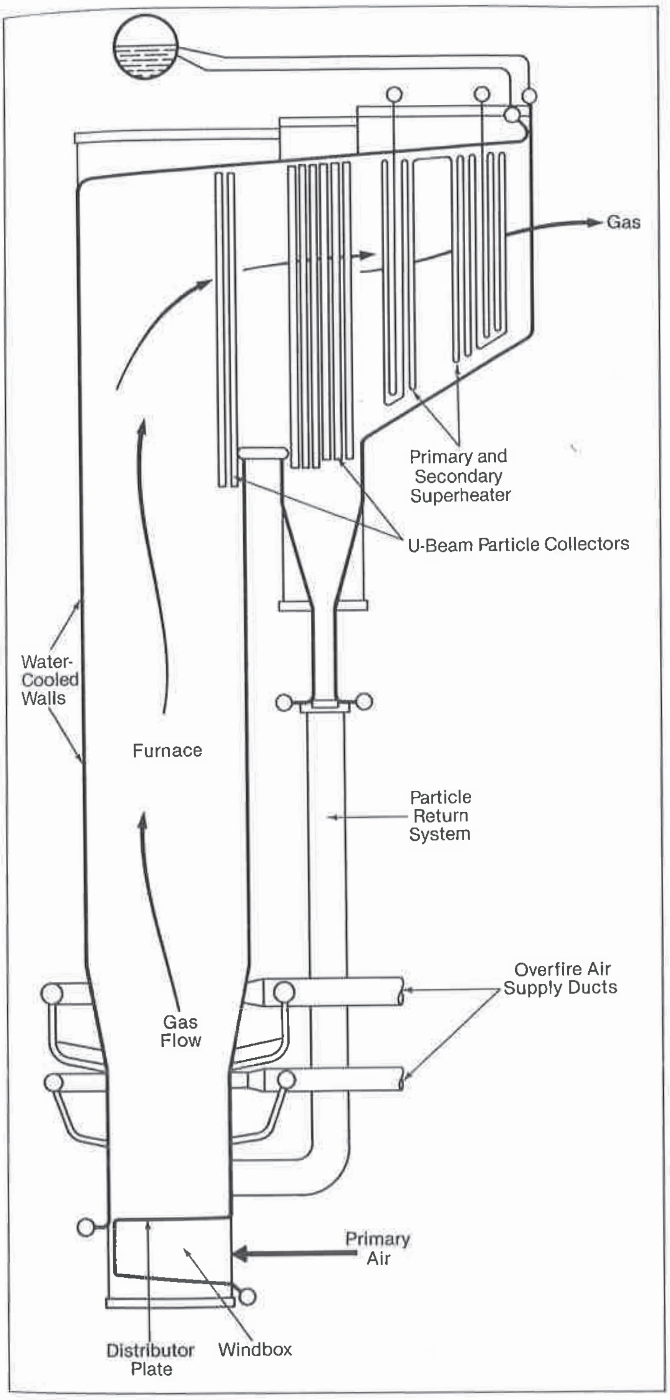

Fig. 6 Typical circulating-bed boiler schematic.

ernment, but the compounds and materials controlled are generally the same. These are SO_2, NO_x, carbon monoxide (CO), hydrocarbons and particulate matter. (See Chapter 32.) Fluidized-bed boilers are designed, primarily, to burn solid fuel while controlling many of these emissions.

Sulfur dioxide

When sulfur bearing fuels burn, most of the sulfur is oxidized to SO_2 which becomes a component of the flue gas. When limestone is added to the bed it undergoes a transformation called *calcination* and then reacts with the SO_2 in the flue gas to form calcium sulfate ($CaSO_4$). The calcining reaction is endothermic and is described by:

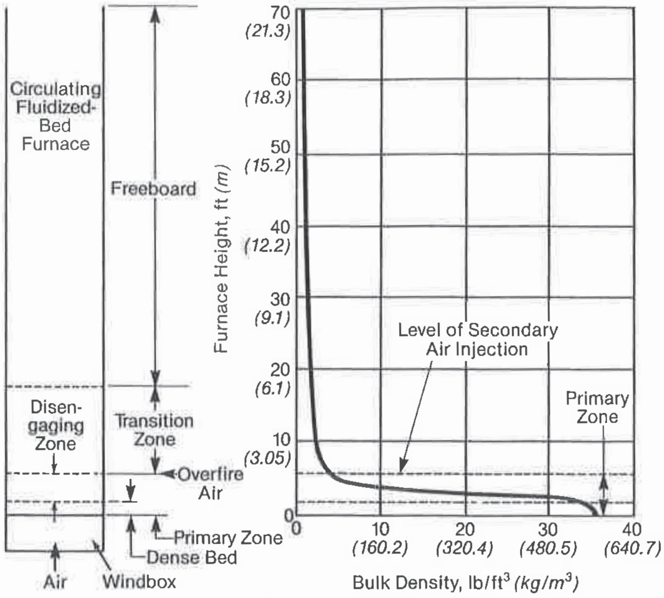

Fig. 7 Typical atmospheric pressure circulating-bed furnace density profile.

$$CaCO_3\ (s) + 766\ \text{Btu/lb (of } CaCO_3) \rightarrow CaO(s) + CO_2\ (g)$$

Once formed, solid CaO (lime) reacts with gaseous SO_2 and oxygen exothermically to form $CaSO_4$ according to the following reaction:

$$SO_2\ (g) + \tfrac{1}{2}\ O_2\ (g) + CaO\ (s) \rightarrow CaSO_4\ (s) + 6733\ \text{Btu/lb (of S)}$$

$CaSO_4$ is chemically stable at fluidized-bed operating temperatures and is removed from the system as a solid for disposal.

Early coal-fired fluidized-bed combustion work was carried out on a once-through principle. In this case, the coal and limestone were fed to the combustor, reacted and passed out of the system. Combustion efficiency and sulfur capture fell short of desired values. To overcome this, a portion of the solids leaving the furnace (flyash, $CaSO_4$, carbon and lime) is separated from the gas by a dust collector located between the economizer and the air heater and is recycled to the furnace for further reaction. Fig. 8 shows the effect of solids recycle on sulfur capture for a bubbling bed. Normally, recycle rates are limited to a maximum of 2.5 times the fuel feed rate which is a result of practical considerations of equipment size and arrangement.

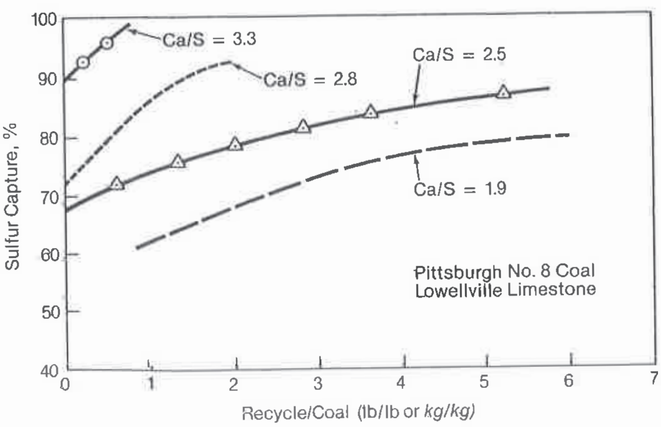

Fig. 8 Sulfur capture as a function of recycle ratio.