Module 4: Thermal power plant fuel and milling systems

4.1. Objectives

On completion of this module the student should be able to:

- explain the processes associated with coal flow from bunker to furnace
- understand the plant options available to perform the various functions and the reasons for selecting particular equipment
- determine the changes in pulveriser performance with changing coal quality
- be aware of the potential dangers for personnel and plant from plant malfunctions in the coal processing area.

4.2. Furnace explosions

In considering boiler safety, it must be recognised that fuel processing and combustion conditions are only two areas where care needs to be taken to ensure that dangerous operating conditions are avoided. Discussions on other areas such as high-pressure and temperature steam and water systems and heavy rotating equipment are not included in this module.

Major furnace explosions have resulted in the deaths of personnel, extremely expensive repair costs and, in most cases, loss of revenue during the repair period. For a large power station boiler the total cost of a furnace explosion could easily be in the $10M to $20M range. The protection systems fitted to a modern boiler have been developed to the stage where boiler explosions are a rare occurrence today, but the operator and maintainer must be aware of the causes and results of boiler explosions particularly when any plant modifications are being considered.

The design and operation of combustion systems generally follow the guidelines contained in various available codes. The American National Fire Prevention Association Code, *NFPA 85: boiler and combustion systems hazards code* is used extensively in Australia. This code is available for free viewing at:

www.nfpa.org/freecodes/free_access_documents.asp?id=8504

4.2.1. Compliance with the relevant codes is essential

The following is an extract from NFPA 85 (2007) and highlights the likely causes of furnace explosions and applies to all fuels not just black coal:

- The basic cause of furnace explosions is the ignition of an accumulated combustible mixture within the confined space of the furnace or associated boiler passes, ducts and fans that convey the gases of combustion to the stack
- A dangerous combustible mixture within the boiler enclosure consists of the accumulation of an excessive quantity of combustible mixed with air in proportions that result in rapid or uncontrolled combustion where an ignition source is supplied. A furnace explosion can result from ignition of this accumulation if the quantity of combustion mixture and proportion of air to fuel are such that an explosive force is created within the boiler enclosure. The magnitude and intensity of the explosion depends on both the relative quantity of combustibles that has
accumulated and the proportion of air that mixes with the combustibles at the moment of ignition. Explosions, including “furnace puffs” are the result of improper operating procedures by personnel, improper design of equipment or control systems, or malfunction of equipment or control system malfunction.

Numerous conditions can arise in connection with the operation of a boiler that produce explosive conditions. The most common are:

- An interruption of the fuel or air supply or ignition energy to the burners, sufficient to result in momentary loss of flames, followed by restoration and delayed re-ignition of an accumulation.
- Fuel leakage into an idle furnace and the ignition of the accumulation by a spark or other source of ignition.
- Repeated unsuccessful attempts to light-off without appropriate purging, resulting in the accumulation of an explosive mixture.
- The accumulation of an explosive mixture of fuel and air as a result of loss of flame or incomplete combustion at one or more burners in the presence of other burners operating normally or during lighting of additional burners.
- The accumulation of an explosive mixture of fuel and air as a result of a complete furnace flameout and the ignition of the accumulation by spark or other ignition sources, such as could occur when attempting to light a burner(s).
- Purging with an airflow that is too high, which stirs up combustibles smoldering in hoppers.

The conditions favourable to furnace explosions described above are typical examples, and an examination of numerous reports of furnace explosions suggest that the occurrence of small explosions. Furnace puffs, or near misses, has been far more frequent than usually recognised. It is believed that improved instrumentation, safety interlocking and protective devices, proper operating sequences and a clearer understanding of the problem by both designers and operators can greatly reduce the risks and actual incidence of furnace explosions.

In a boiler, upset conditions or control malfunctions can lead to an air-fuel mixture that could result in a flameout followed by re-ignition after a combustible air-fuel ratio has been re-established. Dead pockets might exist in the boiler or other parts of the unit, where combustibles mixtures can accumulate under upset conditions. These accumulations could ignite with explosive force in the presents of an ignition source.
Figure 1 below shows the range of fuel-air mixtures for natural gas, vaporised oil and a typical black coal where an explosive condition exists. It should be noted that it takes as little as 1.5 Kg of coal in about 30 cubic metres of air to form an explosive mixture. In a 350 Mwe boiler coal flow of around 50 Kg/sec is required at full load, so the necessity for caution in design and operation of these systems is paramount.

Figure 1 Explosive mixtures for oil, gas and typical coal
(Source: Power Engineering 1962, p. 60)
4.3. Description of typical plant

Figure 2: Typical pulveriser plant layout
(Source: Babcock-Hitachi 1980, p. 32)

This section describes the typical plant used in the milling and combustion system, their function and outlines the reasons for selection. One of the many requirements of this milling system is that the coal flows smoothly and continuously while the plant is in service and that no coal hang-ups or coal accumulations occur. When the plant is out of service positive isolation from the furnace is required to prevent any extraneous coal from entering the furnace. Figure 2 above shows a typical layout of this area of plant.

4.3.1. Bunker to pulveriser

4.3.1.1. Bunkers

Generally modern boiler have cylindrical bunkers with an inverted conical bottom and a 600 mm or 900 mm diameter outlet. The size of the outlet is determined by the coal throughput, top size and flow characteristics. The design is chosen on the basis that the worst coal will start flowing of its own accord after a period of time out of service. Three days is the normal selected period.

In special cases, larger outlet is called for in order to cater for coals with handling difficulties. The boiler at Kogan Creek PS is a good example where the bunker outlet has been designed with a rectangular opening of 800 mm wide and 2000 mm long. This large opening is required to reduce the chances of bridging across the bunker outlet due to the bentonite in the ash, at certain moisture levels, producing poor coal flow properties.

The cylindrical bunkers designs have been adopted as they produce plug flow and all the coal is available. In earlier boilers inverted pyramidal bunker were supplied (Swanbank ‘B’ is an example of this design). This design suffered from coal accumulating in the corners, which reduced the effective storage of useable coal and lead to major coal hang-ups.
Bunker size is determined by the coal plant characteristics. With a 100 percent reliable and available coal plant, bunkers could be only a small surge bin of, say, one hour capacity. However, given the costs of providing and operating such a coal plant the designer will usually have a coal bunker with a capacity to allow the pulveriser to operate for twelve hours at full output.

For isolation purposes in order to allow work on the feeder or pulveriser, a knife gate valve is normally provided at the bunker outlet. Note that Figure 2 shows this valve close to the feeder and this has the advantage that the coal chute doesn’t need to be emptied to work on the coal feeder. Having the valve at the bunker outlet allows any necessary work, or replacement of the coal chute, without emptying the bunker and also the opening of the valve can help to re-establish coal flow when the feeder is returned to service.

4.3.1.2. Coal chutes

The coal chute connects the bunker outlet to the feeder and is normally vertical with a cross-section similar to the bunker outlet. This chute operates full of coal and this coal forms a seal to reduce the primary air from the pulveriser (pressure in the pulveriser could be 4 to 8 Kpa) leaking to the coal surface in the bunker. To achieve this seal the chutes are normally about 3 metres long. This chute can be fitted with a sensor to give an alarm for a loss of coal flow when the pulveriser is in operation.

4.3.1.3. Coal feeders

There are two types of feeders, volumetric and gravimetric.

Volumetric feeders

As the name implies these feeders are not designed to weigh the coal throughput but work as a volumetric device. They have a basic characteristic that volume feed to the pulveriser is proportional to the speed of the feeder. These feeders have the disadvantage that the density of coal varies with moisture level, particle size distribution and compaction. This means that for the same feeder speed a variation in the mass of coal being delivered to the pulveriser will occur with the variations in these coal parameters. This could lead to some control issues.

The advantage of these feeders is they are simple and relatively low cost. Examples of this type of feeder are a simple belt feeder, chain flight feeder or rotating table and plough. Figure 3 shows typical volumetric feeders.
Gravimetric feeders

Gravimetric feeders are belt feeder with a weighing station built in. The main advantage is that the mass flow to the pulveriser can be controlled accurately and also the mass flow can be use for performance monitoring. While the manufacturers claim mass flow accuracies of $\pm \frac{1}{2}$ percent in reality this is very difficult to check and some doubt exists about their accuracy. However, their repeatability is good and this removes variables from the control of mass coal flow to the boiler. While mass flow control is probably better than just volume flow control, it must be recognised that because of the variations in the coal supply properties mass flow does not equate to energy flow, which is the parameter that needs to be controlled. Figure 4 shows a typical gravimetric feeder.
4.3.1.4. Feeders casings

The *NFPA Code* requires that the casing of coal feeder be designed for an internal pressure of 350 Kpa. This pressure is the highest pressure expected from a coal explosion in the milling system. Generally feeder casings are cylindrical as this is the most economic enclosure to withstand internal pressure.

For feeders connected to pressurised pulverisers a cold air supply is connected to the casing. This air supply is necessary to match the leakage through the coal seal in the coal chute and prevents hot air from permeating into the bunker, which could possibly causing bunker fires.

4.4. Primary air

The main functions of primary air (PA) supplied to the pulveriser is to dry and heat the coal during the grinding process and to transport the product, pulverised fuel (PF) from the grinding zone through the classifier, PF pipes and on to the burners and furnace.

4.4.1. Drying the coal

The total moisture in coal is comprised of surface moisture and inherent moisture. Surface moisture is the moisture that can be removed by drying the coal in air. Inherent moisture (AKA residual moisture) is the moisture that remains after the air drying of the coal sample and is determined by heating the sample to above the boiling point of water. These tests are carried out in accordance with AS1038.

In the drying process where the PF/air mixture leaving the pulveriser is generally in the range of 60 to 85 °C not all the inherent moisture is evaporated from the coal. For all practical purposes it is assumed that 50 percent of the inherent moisture is removed from the coal during the grinding process.
Calculating the PA temperature requirements:

**Design data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed coal temperature</td>
<td>30 °C</td>
</tr>
<tr>
<td>Coal surface moisture</td>
<td>8%</td>
</tr>
<tr>
<td>Coal inherent moisture</td>
<td>3%</td>
</tr>
<tr>
<td>Fuel air ratio</td>
<td>1.4</td>
</tr>
<tr>
<td>Pulveriser outlet temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Specific heat of air</td>
<td>1 kJ/kg/degree C</td>
</tr>
</tbody>
</table>

On a per Kg of coal basis:

Energy to evaporate moisture = Mass of water* (sensible heat + latent heat)

\[
= (0.08 + 0.5*0.03)*(2643.8 - 125.7) \text{ kJ}
\]

= 239 kJ

Energy balance:- energy required = mass of Air*specific heat* temp.difference

\[
239 = \{(x - 80)*C_p*1.4\} \times \text{ x = temp. of inlet PA)
\]

\[
x = \{239/(C_p*1.4)\} + 80
\]

= 251C

Note: the above ignores the energy to raise the temperature of the coal from 30 to 80 °C and any system energy losses to the atmosphere.

The supply of hot PA is taken from after the air heater. There are several types of air heater arrangements utilised in PS boilers. These range from separate PA heater, either tubular or regenerative, hot PA extracted from the exit of a regenerative or tubular main air heater or regenerative air heaters with a dedicated section for PA, such as the ‘Howden Trisector’. In the latter case this allows for higher PA temperatures as the PA section usually has the first use of the heated air heater elements.

In the above example the hot PA design temperature would be much higher than the calculated 253 °C in order to maintain pulveriser outlet temperature when coal moisture levels are higher than design, for example, after rain on the stockpile coal. To enable control of the pulveriser outlet temperature some PA (cold PA) bypasses the air heater and is mixed with the hot PA to achieve the necessary inlet temperature in order to maintain the pulveriser outlet temperature at the design value. The design of the hot and cold PA mixing area of the ductwork needs careful attention to ensure adequate mixing of the two air streams, otherwise stratified flow can result in problems with the accuracy of temperature measurements and also localised hot spots in the system. The cold PA bypassing the air heater causes a slight increase in the final flue gas temperature and hence a slight efficiency penalty.
4.4.2. Pulverised fuel transportation

The designer establishes the quality of PA required for 100 percent output from the pulveriser. The pulveriser will be selected with a capacity margin above that required for full unit output. This margin is normally in the 10 to 20 percent range and is required to allow for over firing necessary during load changes, general controllability margins, worse than design coal properties and reducing pulveriser output as the grinding components wear. The minimum PA flow is set by the minimum allowable velocity in the PF pipes. A velocity of not less than 15 m/sec is required to prevent accumulation of PF in the bottom of the PF pipes. Any accumulation of PF in the pipes is dangerous as an increase in PA flow will re-entrain this PF and transport this extra PF to the furnace, resulting in fuel air mismatch and a rapid rise in energy release.

Figure 5 shows a typical PF pipe velocity characteristic and assumes a minimum controlled coal firing of the pulveriser of about 45 percent of full pulveriser output or about 50 percent unit load with the full compliment of pulverisers required for full unit load in service. This value is established by assuming the pulverisers have a 10 percent capacity margin. The reason for using 45 percent pulveriser output as the starting point is to allow for some negative modulating capability of the PA for firing control. PA is one of the variables used for short-term changes to firing rate. If 40 percent had been chosen as the minimum firing rate then the PA couldn't be decreased below 15 m/s and PA flow action to reduce the firing rate would not be available.

The components of the pulverising plant system must be designed to perform their functions with in the maximum and minimum PA flows established by the above procedure.

It should be noted that the pipe velocity finally chosen at commissioning for full load is often a compromise between coal fineness, controllability and component life. The effectiveness of the mill classifier and erosion becomes worse the higher the PA flow, and the control engineer often wants a steep line so that dynamic boiler control is improved. Usually there is a compromise between the boiler mechanical engineer and the control system engineer. In Figure 5 the 15 m/s line is the fixed minimum velocity while the two variables are the points where the velocity starts to increase and the final velocity (shown in the curve as 30 m/s). This section of the curve is normally a straight line. As a general rule the final velocity can be lower for a base loaded boiler while a plant operating in a system load following role may have a higher final velocity to enhance firing control. In the load following mode there is less time at full load so erosion is less of an issue for this plant.

The case for having velocities as low as possible is compelling as wear is recognised as being proportional to velocity raised to the power of 3 to 3.5.
4.5. Pulverisers and classifiers

The function of the pulveriser is to reduce the incoming coal to a size that is suitable for efficient and stable combustion in the boiler furnace. A typical feed coal may have a top size of 50 to 60 mm and have less than 20 percent smaller than 3 mm. The percentage below 3 mm is important as the higher this fraction, the more moisture will be retained by the coal and it is more likely to have handling problems. A typical output from a pulveriser (after the classifier) will have 70 percent of the product less than 75microns in size.

4.5.1. Pulveriser types

There are three basic types of pulverisers and they are classified as:
1. high speed
2. medium speed
3. low speed.

Medium speed pulverisers are more common in large, recently constructed power stations and this direction is simply based on economics. The high speed pulverisers are ruled out on the basis of throughput limitations so the decision on the type of pulveriser to install lies between medium and low speed pulverisers. Because of the higher capital cost and the higher auxiliary power requirements of the low speed pulveriser, when compared to medium speed pulverisers, it is difficult to justify their installation.

Some boiler suppliers have a preference for a particular type of pulverisers based on their experience and are reluctant to, or won’t offer to, supply other pulveriser options. This means that the type of pulveriser supplied is heavily influenced if not determined by other considerations in the purchase of a boiler.
4.5.1.1. High speed pulverisers

A typical high speed pulveriser is shown in Figure 6. The main components of these pulverisers are a hammer crusher, an attrition section, a classifier and an exhaust fan all mounted on a horizontal shaft. Both Callide ‘A’ and Gladstone have this type of pulveriser installed. The pulveriser maximum throughput at Gladstone is about 28 TPH and this is about the limiting upper size of these types of pulverisers. The Gladstone Pulverisers operate at 960 RPM.

Another example of this type of pulveriser is the ‘Beater Mill’, which is basically a large diameter, high speed rotor with impact bars on the periphery and the coal is reduced in size by the bars moving at high velocity colliding with the incoming coal. These pulverisers are more common where brown coal is utilised. Beater Mills are more commonly installed on brown coal fired boilers; however, some are installed on the boilers at Queensland Alumina, which fire the relatively soft Callide coal.

These types of pulverisers have some advantages over the other types of pulverisers:

- The mill outlet coal flow has a quicker response to changing inlet coal flow.
- They have an inbuilt exhauster fan so that the extra ducting, power supplies, control and footprint of primary air fans are eliminated.
- By having an exhauster fan the pulveriser works with a negative pressure and coal leaks are less of a problem.
- For regenerative air heater there is a much lower differential pressures across the seals and leakage is reduced thereby improving efficiency and reducing auxiliary power.

The main disadvantages are that they are limited in size to about 28 TPH for black coal and are only suitable for very low abrasive coals.

The overall maintenance costs of the Gladstone PS type are reasonable even though to extend the life between overhauls, the components in the attrition section are heavily protected by tungsten carbide inserts.

This type of pulveriser will not be discussed further in this course.
4.5.1.2. Medium speed pulverisers

These pulverisers also probably better described as vertical spindle pulverisers as the speed difference between low and medium speed pulverisers diminishes as throughputs increase. Earlier smaller versions of the vertical spindle pulveriser operate at speeds up to around 70 RPM while the larger size (40 to 80 TPH) operate in the 25 to 40 RPM range. While there are variations in the detail there only two types of crushing components in vertical spindle pulverisers. These are either ring and ball (like an oversized ball thrust bearing) or a roller and table. In Queensland PS the former is used at Tarong, Callide ‘B’ and Stanwell (Figure 7) while the latter type is installed at Callide ‘C’, Tarong North, Kogan, and Millmerran. Figure 8 shows a Foster Wheeler MBF pulveriser, which is typical of the larger medium speed roller and table pulverisers.

On these pulverisers the PA is introduced under the rotating table while the coal is gravity feed from the feeder through a central coal chute to the centre of the table. Figure 7 shows typical coal and PA flow patterns in the pulveriser. The velocity of air entering the grinding area from under the table must be sufficient to prevent coal falling through the gap and becoming reject coal and an energy loss. The area around the table for PA entry is normally a series of nozzles that rotates with the table. Some rejects are expected but the nozzles should be tuned to restrict the reject material to the heavier non-energy components of the fuel.

Ground coal is thrown from the table into the PA stream by centrifugal force and carried up to the classifier, which is an integral component of this type of pulveriser. Oversize particles are rejected by the classifier and returned to the table to be mixed with the new coal for another pass through the grinding section. Some primary classification also occurs above the table before the classifier. The velocity of the PA in the area above the table is...
insufficient to carry the larger and denser particles to the classifier and these particles fall back to the grinding area.

For these pulverisers, the coal is crushed between the rollers and table (or balls and the rotating lower grinding ring) and the pressure on the roller necessary to perform the crushing is supplied by an external force and the mass of the grinding components. The external grinding pressure applied to the rollers in earlier pulverisers was provided by coil springs. The characteristic of a spring made to fit into the small space available meant the spring needed to be pre-tensioned, so that the pressure necessary for full throughput performance could be achieved when the roller moved vertically upwards due the thickness of the coal bed on the table. The coal bed thickness at full throughput varies for different designs of pulverisers, but a typical bed thickness would be about 30 mm. With this arrangement the spring loading for low coal throughputs, and hence low coal bed thickness, remains very high and this leads to pulveriser vibration and other difficulties in operating at low coal throughputs and when starting up the pulveriser. Worn grinding elements, particularly near the end of their life, exacerbated these problems. For very low coal throughputs, of say 5 percent, the weight of the grinding elements is sufficient to supply the grinding pressure. The necessary grinding pressure over the operating range is approximately linear and is a function of coal throughput. The problems with spring characteristics and the increasing size and capacity of pulverisers have lead to the current pulveriser designs where grinding loads are supplied by either hydraulically loaded spring systems, hydro-pneumatic or straight hydraulic loading systems. Larger MPS pulverisers also have the facility to hydraulically lift the rollers slightly above the table to assist at start up.

A final benefit of these modern loading systems is that the load pressure characteristic can be changed on line via the control system. This allows optimum pressure characteristics to be used if the station has multiple coal suppliers and a significant variation in coal properties.
Figure 7: Babcock and Wilcox ring and ball pulveriser
(Source Babcock-Hitachi 1980, p. 37)
Table 1: Size and detail of the range of ring and ball pulverisers supplied by Babcock and Wilcox
(Source: Re-drawn from Babcock-Hitachi 1980, p. 38)

<table>
<thead>
<tr>
<th>Mill size</th>
<th>7E10</th>
<th>8.5E10</th>
<th>8.5E9</th>
<th>10E10</th>
<th>10.9E11</th>
<th>11.9E11</th>
<th>12E10</th>
<th>13E11</th>
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<tbody>
<tr>
<td>Base capacity (Ton/h)</td>
<td>17.3</td>
<td>27.4</td>
<td>30.5</td>
<td>40.6</td>
<td>45.7</td>
<td>56.9</td>
<td>64.0</td>
<td>71.1</td>
<td>76.2</td>
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<tr>
<td>Mill motor (KW)</td>
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<td>205</td>
<td>230</td>
<td>305</td>
<td>345</td>
<td>425</td>
<td>480</td>
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<td>570</td>
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<td>Main shaft speed (r.p.m.)</td>
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<td>40</td>
<td>37</td>
<td>37</td>
<td>34</td>
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<tr>
<td>Track diameter (mm)</td>
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<td>2160</td>
<td>2540</td>
<td>2768</td>
<td>3023</td>
<td>3050</td>
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<td>Track diameter (inch)</td>
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<td>85</td>
<td>100</td>
<td>109</td>
<td>119</td>
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<td>Mill ball diameter (mm)</td>
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<td>10</td>
<td>11</td>
<td>11</td>
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<tr>
<td>Fill-in ball diameter (mm)</td>
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<tr>
<td>Loading unit</td>
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<td></td>
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</tbody>
</table>

Note: The above base capacities are based on the grindability of Hardgrove Index 50 and the fineness of 70 percent through 200 B.S. mesh.

While the smaller capacity ring and ball pulveriser are very common around the world, the larger pulverisers, above 50 TPH capacity, are rare with some 12E10 pulveriser in South African power stations. The modern trend is towards roll and table pulveriser for these higher capacity requirements.
4.5.1.3. Low speed pulverisers

Low speed pulverisers (AKA Ball Tube Mills) are basically a rotating cylinder containing a charge of small diameter balls (50 to 100mm diameter). See Figure 9. The larger coal particles are crushed by the balls dropping onto the coal, which is floating on the sea of balls after being lifted by the action of centrifugal force and the corrugated wear liners of the internal surface of the cylinder. The smaller coal particles are ground to the required product size by the action of the mass of balls rubbing together with the fine coal in the void. Figure 10 shows a typical cross-section of this type of pulveriser and the grinding process can be visualised.
Coal and PA can be either feed in at one end and the product extracted from the opposite end (typical for throughputs up to about 20TPH) or the coal and PA can be feed and the product extracted from the same end. For larger throughput pulverisers the latter approach is normal and feeding the coal and extracting the PF at both ends of the pulveriser is usual. Ball tube mills with capacity over 100 TPH are available.

The main cylinder is supported at each end on hollow trunnions, which allow the ingress and egress of the coal and PA and have solid end plates. Sometimes on smaller pulverisers solid trunnions are used and the coal and PA is feed in-between the spokes that support the cylinder. Swanbank ‘B’ uses this type of pulveriser.

Low speed pulverisers have external classifiers which are positioned above the pulveriser, so that over-sized particles rejected by the classifier can be returned to the pulveriser by gravity.

As mentioned in the introduction of the section this type of pulveriser has high initial capital, a relatively large footprint, has high auxiliary power requirements and has some control issues relating maintaining the correct amount of coal in pulveriser.

However their advantages are significant:

- very high reliability—a standby pulveriser may not be necessary
- robust and few working parts—just add new balls (on line)
- long life before a major overhaul—up to 15 years or longer to a major replacement of liners
- good dynamic response because of the large amount of semi-processed coal contained in the pulveriser.

![Figure 9: Typical hollow trunnion double ended tube mill](Source: Riley-Stoker n.d.)
Figure 10: Typical cross section of a ball tube mill
(Source: Riley-Stoker n.d.)
Note the crusher dryers shown in Figure 11. These are used to improve the performance of the tube ball mill. The crushers are hammer mills, which have high efficiency when reducing coal with a top size of about 50 mm to 5 to 10 mm. Ball tube mills are much less efficient at reducing size in this range. This allows a smaller ball tube mill to be installed, reducing capital costs and auxiliary power consumption. Hot PA air is also passed through the crusher, which reduces the surface moisture, and also enhances the ball tube mill performance.
4.5.2. Classifiers

The classifier role is to allow the product of the pulveriser that meets the particle size distribution requirements through to the furnace and reject the balance. These rejects are returned to the pulveriser for further size reduction. The principal method of separation of the oversized particles from the acceptable product is particle directional change. The associated centrifugal forces cause the larger particles to be thrown outwards to the walls of the reject hopper, while the acceptable size particles remain entrained in the PA and pass out the top of the classifier. For some smaller installations the directional change is achieved by simple baffle arrangements.

This method is relatively inefficient and some acceptable product is returned with the rejects and effectively reduces the capacity of the system. For larger throughput installations the classifier is a cyclone type device with variable angle inlet vanes that can be adjusted to change the size profile of the PF leaving the classifier. The classifier has a conical reject hopper that collects the reject size particles. For vertical spindle pulverisers some manufacturer fit non-return valves at the bottom of the reject hopper. This is the preferred approach to this area as there is a differential pressure between the grinding area and the reject hopper and with an open annulus at the outlet of the reject hopper, which some manufacturers employ, to allow the rejects to return to the grinding area can result in some PA flow by-passing the classifier inlet vanes. This can lead to unstable operation of the pulveriser particularly at low coal flows.

Figure 12 shows a typical integral cyclone classifier with an open annulus reject hopper outlet. Figure 8 shows a non-return valve arrangement. Feed coal enters through the central coal tube while the final PF product passes vertically out of the top of the classifier.

40 TPH vertical spindle pulverisers are at about the limit in capacity where the classifier can be fitted into the same diameter as the grinding elements. This is because the grinding capacity is proportional to diameter squared while the classifier performance is proportional to diameter. On the larger vertical spindle pulverisers at the newer stations in Queensland the classifier section are larger in diameter than the grinding section. Typical arrangement is shown in Figure 8.

The classifiers of ball tube mills are basically the same as for the vertical spindle pulverisers except that it is a separate device. The output of the ball tube mill is piped to the classifier, the rejected oversize component is piped back to the mill and the final product passes out the top of the classifier on its path to the furnace.
4.5.2.1. Powered classifiers

Closer control of product size can be obtained using powered (AKA rotating) classifiers, where the centrifugal effect applied to each particle is achieved by passing the coal and PA through an inward-flowing rotor. This then makes the rejecting effect independent of PA flow. The rotor has its own variable speed motor, allowing great flexibility to control product fineness according to need, simply by changing the speed of the drive motor.
This type of classifier is gaining popularity, and is often used in conjunction with vertical spindle mills. While not generally practiced this type of classifier could also be applied to the external classifier of low speed pulverisers.

The main advantage of this classifier is that the larger particles normally present after a cyclone type classifier are rejected and returned to the grinding zone. As the larger particles are mainly responsible for unburnt carbon in refuse an efficiency gain is available. This type of classifier is more easily justified where coal is either expensive and/or has a high fuel ratio. The finer product will help combustion stability. Figure 13 shows the performance difference between static and rotating classifiers.

Their main disadvantages is that they are more expensive to maintain and the time between maintenance work is much shorter when compared to a static classifier.

![Figure 13: Comparison of product size—static v/s rotary classifiers](Source: Babcock & Wilcox 2005, p. 12-14)
4.6. Pulverised fuel distribution and pipes

For good burner performance it is important that each burner in a pulveriser group receives a similar mass flow of PF and PA (PA to a lesser degree). In practice this is difficult to achieve and a difficult and dirty job to measure. PF sampling is inexact because of the nature of the flow. PF tends to form concentrated streams within the overall flow in the PA/fuel mixture (known as roping) and this can lead to some significant errors in sampling. Sampling at the end of a long vertical PF pipe is desirable but generally not available in a commercial power station. Poor distribution can lead to higher Nox production, lower burner turn down or burner instability and increased carbon in ash losses.

Separate PF pipes from the top of a cyclone type classifier to each burner is one method used to distribute the PF evenly and relies on equal PA flow in each of the pipes equalling equal PF flow in the pipes. To compensate for different length and configurations of PF pipes cold air flow tests are carried out to determine clean air flow in each pipe and pipes are then fitted, where necessary, with orifices to balance the flows. This assumes that the PF burden in the PA flow at the top of the classifier is uniform. This uniformity can be upset by upstream configurations. For example in early Raymond Bowl pulveriser there were three dominant streams of PF from the grinding area and four outlets at the top of the classifier. This led to one pipe having lower PF concentration than the other three pipes. The pipe with the lean mixtures changed with load to further complicate the problem. This problem was largely overcome by reconfiguring the PA entry to the grinding zone by fitting a nozzle to the outside of the table, rather than having a large fixed PA inlet ports and deflecting devices after each of the three rollers.

Another method is to have a single outlet from the pulveriser and divide the flows with riffle boxes. This is used on some tangentially fired boilers where each level of firing is supplied by its own pulveriser and has a fuel injection nozzle at each corner of the furnace. In this case the flow is initially divided into two flows and each of these flows is again divided into two flows. A riffle box divides the inlet area into multiple passes with alternate passes flowing to each of the downstream pipes. This technique has been used satisfactorily in many installations, but can suffer from the same PF roping problem mention in PF sampling. This approach is also be adopted for some wall fired boiler.

The internal surfaces of PF pipes are in a high wearing environment and can require regular maintenance during boiler overhauls. Bend areas are subjected to high local velocities due to uneven velocity profiles and higher concentrations of PF on the outside of bends. This leads to high erosion rates at the bend and also downstream of bends. In earlier power stations to overcome this problem, bends and about three diameters down stream were manufactured from cast Ni-hard material. This material while long-lasting and relatively low cost resulted in some spectacular failures due to temperature and pressure excursions that occurred during pulveriser upsets/explosions and this material is only now used in conjunction with an external cage to contain the material should an explosion occur. Most common material for PF pipe today is a mild steel casing either fully lined with a ceramic or similar material or partially lined in areas of the high wear. For boilers operating with low capacity factors and with low abrasive coals mild steel pipes could prove satisfactory.

Fittings on PF pipes are normally a classifier outlet valve, PF sampling ports and an isolating valve next to the burner. Some manufacturers use simple non-return valves at the classifier outlet, while others use a flap valve fitted with a actuator with high speed closing capability. The valve will close in one to two seconds in the event of a pulveriser trip. This closing speed is considered necessary to ensure that unwanted fuel does not enter the furnace. Opening rates should be slower. In the case of simple non-return valve the
manufacturer relies on fast acting PA inlet dampers to close and prevent any unwanted PF flowing to the furnace.

PF sampling ports are normally 25 to 50 mm screwed sockets welded to the PF pipe at a suitable location with personnel access and at least 10 diameters straight pipe upstream. Typically, on each pipe two ports with isolating valves would be fitted at right angles and in the same plane.

The isolating valves at the burners are normally manual operated gate knife valves and are only closed for maintenance isolations.

4.7. Process product requirements

The following is a typical size analysis of PF out of a static classifier:

- 70% passing through a 75 micron screen
- 90% passing through a 150 micron screen
- 99% passing through a 300 micron screen.

The smaller fractions, i.e. around the 75 micron size, are important for burner flame stability. Free burning coal, such as Callide (fuel ratio about 2) or Tarong (fuel ratio about 1.5) can tolerate a coarser grind than a coal such as Curragh, which has a fuel ratio of about 3.4. This is the reason for the changes to the classifiers in the pulverisers at Stanwell PS when compared to the classifiers on the similar pulverisers at Tarong PS and Callide PS.

4.7.1. Comminution theory

For a given size reduction device, the following general observations can be made:

- The capacity of the device decreases as the product size decreases.
- The energy required per unit mass of material increases as the product size decreases.

Various attempts have been made to describe the energy required for size reduction. They can be summarised by a general equation:

\[ dE = -C \cdot dX / X^n \]

where,

- \( E \) = work done
- \( X \) = particle size
- \( C \) and \( n \) are constants.

When \( n = 1 \), the solution to the above equation becomes Kick’s law (1885).

\[ E = C \cdot \log(X_F / X_P) \]

where,

- \( X_F \) = feed particle size
- \( X_P \) = product size.
- \( X_F / X_P \) = reduction ratio.

When \( n > 1 \), the solution is

\[ E = \left( \frac{C}{n-1} \right) \left( \frac{1}{X_P^n - 1} - \frac{1}{X_F^n - 1} \right) \]
For \( n = 2 \) this become Rittinger's law (1867), which states that the energy is proportional to the new surface area produced.

For \( n = 1.5 \), this is equivalent to the Bond law (1952)

\[
E = 100 \cdot E_i \cdot \left( \frac{1}{\sqrt{X_P}} - \frac{1}{\sqrt{X_F}} \right)
\]

where,

\( E \) = Bond work index, or the work required to reduce a unit mass from a theoretical infinite size to 80 percent passing 100 microns. The work index has received considerable research attention and has been used to predict mill sizing.

The theories described above have little relevance to real-life milling, because there are many other effects in operation, which are not considered. Some of these are that:

- it can be difficult to determine the surface energy for a material
- many materials such as coal may already contain numerous internal fracture surfaces
- energy can be absorbed in many ways other than in creation of new surfaces.

4.7.2. Grinding efficiency

Grinding efficiency is usually the result of comparing a theoretical energy for a size reduction operation with the practical energy. On this basis, grinding efficiency rarely exceeds 1 percent.

4.7.3. Practical energy efficiency

Practical energy efficiency is defined as the ratio of the efficiency of a size reduction operation to the efficiency of a laboratory size reduction experiment. Practical energy efficiencies of 20–60 percent can be achieved.

4.7.4. The size reduction process

Brittle materials tend to fail during milling as the result of compressive stresses, whereas ductile materials fail by shear. A single particle may be brittle, but large numbers of the same particles in a bed may behave collectively as a ductile mass because of all the surface interactions between the particles.

Some of the most advanced crushers exploit this effect by causing intense shear in an extruding flow between two rolling surfaces, causing size reduction in the softest of the feed components, leaving harder feed particles untouched. The harder particles, being of larger size, can then be rejected easily.

4.8. Coal properties affecting processing

The three main coal properties affecting the performance of pulverisers are hardness or ease of reducing the size, moisture content and abrasiveness. Moisture has been mentioned earlier in these notes and will be raised again in Module 6.

4.8.1. Coal hardness

The most commonly used indicator of the ease of grinding a coal to PF size is the Hardgrove Grindability Index (HGI) and is named after the developer of this index. The test apparatus is shown in Figure 14.
The Hardgrove grindability test is not energy based, but instead measures the fraction of product passing a standard sized sieve (74 microns) from an initial 50 gram sample of the coal initially sized to –1190 microns + 595 microns. The sample is processed for 60 turns in a standardised ring and ball testing apparatus. The equipment can be calibrated against standardised coals.

As the Hardgrove test is a small-scale crushing test and the coal that is crushed to PF size is not removed it does not truly represent the process in a large pulveriser. Therefore, the results are not necessarily accurately transferable directly to full-size pulveriser or other types of crushing mills. However, manufacturers do tend to quote mill capacities for full-size machines against HGI.

Other testing devices have been developed which more closely represent the grinding process in a pulveriser but the HGI remains dominant as an indicator, probably because of the experience with the index and the simplicity of the machine and the test.

**Note, that the lower the HGI is the harder the coal is to grind.**

### 4.8.2. Coal abrasiveness

For pulveriser plant the most commonly used indicator of abrasiveness is the Yancey-Greer-Price Index (YGP). This index is determined in accordance with British Standards BS1016: Part 19 where the apparatus is shown.

The apparatus consists of a four-armed rotor mounted in a drum. The sample of coal is loaded and the rotor is run at 1470 RPM for 12000 revolutions and the loss of weight of the...
metal coupons on the rotor is determined. The index is expressed as mg of coupon weight loss per Kg of coal.

Extreme care must be taken when using this index and it should be used as a guide only. While it probably reflects the abrasiveness of the coal it does not necessarily relate to the overall wear rate in a pulveriser. A good example of this is the comparison of the life of the grinding components in the Tarong and Callide 350MWe pulverisers. These pulverisers are identical. Tarong coal has a YGP of about 50 while Callide coal has a YGP of less than 10. On this basis it would be reasonable to assume that the Callide pulverisers would have grinding component life many multiples of Tarong’s life. The real-life experience was that Callide pulverisers only had a marginally better life from it grinding components. The reason is believed to be because the metal to metal contact between the balls and the upper ring.

Some manufactures prefer to examine the coal sample microscopically and determine the various components and their structure in the coal and ash. This data is then compared with previous analytical data and plant history to determine the likely wear rate for the particular pulverisers being considered.

4.9. System performance

The overall objective for the Fuel and Milling systems is to safely provide the furnace with the appropriate quantity and quality of fuel in a ‘well controlled’ manner. Power station coal supply will vary with time because of coal property variation within a mining area or because coal is sourced from different suppliers or mines over the life of the plant. The following Figures, 15–19 and 21, show the relationships between the life and performance of the ring and ball pulveriser with varying coal properties.

Figures 20 and 22 are the manufacturer’s correction curves for Swanbank ‘B’ ball tube mills. These curves are typical for pulverisers and should be used as a guide to pulveriser performance. Similar performance curves should be available from the manufacturer for any specific pulverisers being investigated.

![Graph](image-url)  
Figure 15: Predicted ball life of ring and ball pulveriser based on coal with average abrasiveness  
(Source: Babcock-Hitachi 1980, p. 39)
Figure 16: Predicted ring life of ring and ball pulveriser based on coal with average abrasiveness
(Source: Babcock-Hitachi 1980, p. 39)

Figure 17: Early 10E10 pulveriser life history at Tarong and Callide
(Redrawn from: Queensland Electricity Commission n.d.)
The 10E10 pulverisers are fitted to Tarong, Callide and Stanwell 350MW units and, using Tarong as the example, the life expectancy of these curves was not realised. See Figure 17. The manufacturer guarantee was for certain throughput of coal before the grinding components required replacing. The equivalent time of this guarantee was much less than the Figures 15 and 16 above would indicate. The two main reasons for this were that the Tarong coal was more abrasive than their average abrasiveness coal (average abrasiveness is not clearly defined by the manufacturer), and to match the coal throughput guarantees required the speed of the pulverisers to be increased to 42 RPM compared to their normal of 37 RPM as shown in Table 1. Extensive work on the materials of the wear components and a reduction in speed has increased the service hours between major overhauls.

The extra life of the 10E10 when compared to the 8.5E10 in Figures 15 and 16 is a reflection of the lower quantity of metal in the rings and balls of the smaller pulveriser.

As can be seen in Figure 18 the throughput of a pulveriser is sensitive to the size of the product. In this case a relaxation of the PF fineness from the normal 70–60 percent passing 75 microns results in a 20 percent increase in coal throughput. This is one of the options available to the station engineer to counter coals being supplied with either lower HGI or lower heating value. The penalty for adopting this approach is that the carbon in ash losses will increase, but this will be a relatively low cost when compared to the cost of reduced output of the unit due to pulveriser constraints on unit output.

Figure 18: Change in pulveriser throughput with product fineness
(Source: Babcock-Hitachi 1980, p. 40)
Figure 19 demonstrates that the pulveriser throughput is sensitive to HGI. A reduction of the coal’s HGI from 50 to 40 results in a 20 percent reduction in throughput for a 10E10 pulveriser. If the milling capability is limited then any reduction in HGI may result in unit output restrictions, but this could be compensated by increased heating value. A classic example of this is the Walloon Series coal, which is burnt at Swanbank, Millmerran and Kogan PS. The ash associated with these coals is very soft when compared to the coal and if the coal is beneficiated then the HGI will fall from around 45 with about 25 percent ash to around 35 with 10 percent ash. While this would initially raise concerns about pulveriser throughput, the improvement in heating value resulting from the ash removal means that the energy throughput is maintained relatively constant.
This curve (Figure 21) is mainly for interest as the power consumption is generally not a problem from an operational perspective. However, if a station is considering lower HGI coal supplies without offsetting heat value increases then the power capability of the pulveriser drive could become a constraint or require a new drive train. Moving from 50 to 40 HGI with the same coal throughput increases the power requirement by some 25 percent, which is significant.

4.9.1. Pulveriser capacity v/s time in services

As the grinding components of a pulveriser wear there is generally a reduction in the capacity of the pulveriser. This is not always apparent as the pulveriser may have significant margin over its name plate rating when in the new conditions. For the 10E10 pulverisers at Tarong the reduction in performance was stated as about 5 percent from the new condition to the fully worn condition. Theory shows that the 42 TPH quoted for the new condition is very conservative and the grinding capacity is much higher. The constraint in the new condition is the classifier working within the available PA pressure drop.

Generally pulverisers are designed for an ‘average’ coal with a 50HGI. This determines a throughput for a particular grinding element arrangement and the PA flow. The classifier is designed to operate with this coal throughput and PA with some margins. For situations where a pulveriser is processing high HGI coal, (example is Callide with a HGI above 80) the classifier becomes the limiting throughput component. Because of this the Callide pulveriser speed has been able to be reduced by 25 percent from the installed speed and still meet coal throughput requirements. This speed reduction has improved the life of the wear components.
4.9.2. Effect of water

Increasing moisture content of coal reduces the capacity of dry grinding operations. This is only one of the reasons for the coal supply to boilers to be as dry as possible before pulverising. Increasing moisture content also tends to make the coal particles adhere and agglomerate, making the product difficult to transport including build-ups and blockages in the coal chutes in the pulverising plant. It must also be remembered that low surface moisture can lead to dust problems in the coal plant and bunker areas.

Increasing moisture content reduces the heating value of the coal and increases wet flue gas losses and as a result, a higher throughput of coal is required to compensate for these losses.

The performance reduction of ball tube pulverisers with increasing moisture levels is very pronounced. See Figure 22. Vertical spindle pulverisers are far less sensitive to moisture content because of the rapid coal drying occurring in the grinding zone.

![Figure 22: Throughput v/s moisture for a ball tube mill (Swanbank ‘B’) (Source: Mitchell Engineering 1969)](image)

4.9.3. Pulveriser performance prediction

The following data is for Swanbank ‘B’ and is used to illustrate the use of correction curves.

Swanbank B Data
Turbo Alternator full load output 120 MWe
Turbo Alternator full load heat rate 8500 kj/kwh
Boiler efficiency 88.5 %
Heating Value of coal 24 kj/kg
HGI 60
Surface moisture 5 %
Inherent moisture 2 %
Number of pulv. I/S for full load 3
Using Figures 20 and 22 determine the over firing capability or firing margin at full load:

**Fuel input required** = \( \text{output} \times \text{heat rate} / (\text{Blr. Eff.} \times \text{HV of coal}) \)

= \( 120000 \times 8500 / 0.885 \times 24 \times 1000 \text{ TPH} \)

= 48 TPH

From Figure 20 & 22, at 60HGI and 7 percent moisture, the pulverisers can process 22 TPH

Over firing capability = (22*3 – 48)*100/48 = 37.5%

This is a very comfortable situation.

The coal quality changed

Surface moisture increased to 7%

And HGI reduced to 54

Establish the new over firing capability:

Pulveriser base throughput = 22 TPH

From Figure 20, pulveriser throughput at 54 HGI is 20.25 TPH

From Figure 22, pulveriser throughput at 9 percent moisture is 21.2 TPH

New pulv. throughput = \( 22 \times (21.2/22) \times (20.25/22) \)

= 19.5 TPH

New heating value of coal = \( 24 \times 0.91 / (1 - 0.93) \times (1 - 0.91) \)

= 23.48 kj/kg

Pulv. total energy throughput capability = \( 3 \times 19.5 \times 23.48 \)

= 1373.5 Mj/hr

Unit energy input at 120 MW = \( 120 \times 8500 / 0.885 \)

= 1152500 kj/hr

= 1152.5 Mj/hr

Over firing capability = \( \{(1373.58 / 1152.5) - 1\} \times 100 \)

= 19.2%

This is a far less comfortable position than the previous situation with the original quality coal but a workable margin.

The supply of the above coal was ended and the new coal supply had the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Value of coal</td>
<td>23.5 kj/kg</td>
</tr>
<tr>
<td>HGI</td>
<td>39</td>
</tr>
<tr>
<td>Surface moisture</td>
<td>5 %</td>
</tr>
<tr>
<td>Inherent moisture</td>
<td>5 %</td>
</tr>
</tbody>
</table>

From Figure 20, pulveriser throughput at 39 HGI is 15.85 TPH.

From Figure 22, pulveriser throughput at 10 percent moisture is 20.1 TPH.
New pulv. throughput \[= 22 \times \frac{20.1}{22} \times \frac{15.85}{22} \]
\[= 14.5\text{TPH}\]

Pulv. total energy throughput
\[= 3 \times 14.5 \times 23.5 \]
\[= 1022.2\text{Mj/hr}\]

Unit energy input at 120 MW
\[= 120 \times 8500 / 0.885 \]
\[= 1152500\text{kJ/hr} \]
\[= 1152.5\text{Mj/hr} \]

Over firing capability
\[= \frac{(1022.2 / 1152.5) - 1}{} \times 100 \]
\[= -11.3\% \]

Unit maximum output
\[= 120 \times (1 - 0.113) \]
\[= 106.4\text{MW} \]

Full load capability with a small over firing capability was restored by relaxing the fineness of PF grind and accepting higher carbon in ash for the relatively short time the units operated at full output.

Note that the above calculations ignore the slight increase in firing needed to compensate for the decrease in boiler efficiency due to the extra moisture in the coal.

### 4.9.4. Optimising the fuel and milling plant

The major priority when considering any changes to the milling plant area is that the ability to be able to operate the plant safely is paramount. The cost for the milling plant to process the quantity of coal consumed by a large power station is an important component in the operating and maintenance budget. Typically this will be around $1 per tonne of coal processed. Any improvement in this cost is a bonus.

Don’t believe the manufacturer has ‘got it right’ at the design stage and always look for opportunities to improve the plant. Significant modifications have been made to the milling plants at Swanbank, Gladstone, Tarong, Callide and Stanwell and these have resulted in either improved operational performance or reduced costs or both, however, care is required. For example, a proposed modification to the grinding area may result in some maintenance savings but could cost significantly more than the savings by:

- limiting the electrical energy sent out of the station
- causing higher PF pipe and burner erosion
- increasing carbon in ash losses
- causing higher NOx emissions
- causing low load flame stability problems
- causing higher furnace slagging
- reducing the furnace absorption and increase metal temperatures
- causing higher erosion of boiler heat exchange area
- changing the precipitator/fabric filter performance
- reduce the dynamic load changing capability of the boiler
- etc.

The message is that care is required and you should consult with other personnel involved in the areas of plant where performance could be changed should your proposal proceed.
Summary

When you finish this module you should understand the processes involved and be able to analyse problems associated with the Fuel and Milling Plant of a coal fired boiler. You should be able to predict the performance of your milling plant for changing coal properties. You will understand the inherent explosion dangers associated with the operation and maintenance of milling and firing systems.

The learning objectives at the start of this module provide a detailed breakdown of the task described above. Make sure that you can do each activity listed in the learning objectives.

If you feel that you cannot achieve the learning objectives for this module, work through this Study Guide again and read the relevant sections from recommended books.

Remember that if you need assistance in your study, the lecturer and other University staff are there to assist you. We are only a phone call away.

Checklist

Use the following checklist to identify whether you achieved the essential elements of each of the enabling objectives and learning objectives in this module.

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**Performance criteria ✓**

**Furnace explosions**
- Describe an explosive mixture
- Why do furnace explosions occur
- What national or international codes are relevant

**Milling plant**
- Describe the coal flow from bunker to furnace
- Describe the differences and advantages of various types of coal feeders
- Describe the three types of pulverisers in common use and their comminution processes
- Calculate the required primary air temperature for a particular coal and a given pulveriser outlet temperature
- describe how a classifier works
- Explain how primary flows are selected

**Pulveriser performance**
- Describe how various coal properties affect the performance of pulveriser
- Calculate the change in performance for changes in coal properties

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**References**


