PRB COAL DEGRADATION – CAUSES AND CURES

By

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Introduction

The coals produced in the Powder River Basin (PRB) are environmentally and economically attractive to power companies. This type of coal has made enormous inroads to power plants due to these factors regardless of any difficulties plant personnel might experience. The difficulties in handling and storing PRB coal are due to fines generation and spontaneous combustion issues. Many [1-9] have worked on addressing these concerns and how we can improve our utilization of these fuels. Refer to APPENDIX A for basic bulk solids handling considerations for PRB coal.

PRB coal is extremely friable and will break down into smaller particles virtually independent of how the coal is transported or handled. PRB represents the extremes of handling problems: *dust* is an issue when the coal is fine and dry; *plugging* in bunkers and chutes is an issue when the same fine coal is wet. Once PRB coal is exposed by mining, the degradation process begins – the majority of the damage can occur in a very short time, even as short as a few days. The extent of the degradation that occurs depends in large part on the distance to the plant from the mine, i.e., how long the coal is exposed to the atmosphere during transportation. Additional factors such as crushed run of mine (CROM) size, and specific handling procedures also impact the degradation process. Additional decomposition occurs during handling and storage in a pile and bunker, bin or silo. We believe the root cause of the degradation is loss of moisture that impacts the coal both mechanically and chemically, through the generation of additional surface reaction area. The combination of the two is what makes PRB coal so difficult to handle.

This paper focuses on the mechanisms, both inherent and external, that cause this rapid degradation of the coal particles. Some of the questions are posed that could lead to preventing, or at least retarding the degradation of the particles, thus avoiding the results of the associated problems with handling and storage, such as dust, perceived loss of inventory, bunker hang-ups and especially spontaneous combustion.

What is PRB coal?

The Powder River Basin extends from Wyoming into Southeast Montana, with the bulk of the PRB coal being supplied from the Southern Powder River Basin (Wyoming). PRB is classified by the American Society for Testing and Materials (ASTM) as a sub-bituminous A or B [10] coal. Scientists report that these coals have been burning naturally for over 2 million years. Early Native Americans held these coal fired lands to be spiritual. Prehistoric inhabitants of the Powder River Basin used porcellanite as weapons and tools. Porcellanite is formed from the intensively coal baked shale or siltstone near or in the coal as it burned. We know this material today as *slag*. The fires are in part caused by the spontaneous combustion of coal. These same properties show up at the plant as hot coal, fires and explosions. While low in sulfur (0.4 to 1.4 LB/MMBTU), PRB coal is also low in heating value (8,000 to 8,800 BTU/LB, on an *as received* basis for Southern PRB, with one or two mines in the north going as high as 9,400 BTU/LB). Additionally, its friability results in fines and, when dry, the dust (Fig. 1) increases the explosion hazard potential. On the other hand, this same fine coal can be high in moisture content (Fig. 2), which increases its handling difficulty in equipment. Most of the plants currently burning or converting to burn PRB coal have difficulty with these characteristics.

Fig. 1 PRB coal – *dry*

Fig. 2 PRB coal – *wet*

The relatively low ranking of PRB coal means that the coal is relatively young. Specific ASTM ranking is just a laboratory method for drawing a line in the sand to differentiate different types of coals. It is basically describing the geological process of transforming plant material to anthracite. The first phase of coalification (fossilization) is to preserve the plant material from oxidation. This peat moss like material is still basically plant material. The first coal-like material formed is lignite, or brown coal. The coalification process basically squeezes out oxygen and water. As the plant material becomes less like wood and more like oil, the pore structure constricts, limiting the water retention capacity of a coal chemically; as the oxygen content decreases the coal becomes more hydrophobic or water repelling (water and oil don't mix). This water retention capacity is measured using the equilibrium moisture test. Sub-bituminous coals like the PRB coals are the next step up in the coal ranking system. Then comes the low ranked Bituminous C type coal. This is the ranking of many Illinois Basin coals. The higher ranked Bituminous B and C coals are generally found in the Appalachian coalfields. Most of the coal tests that ASTM has standardized were written around higher ranked bituminous and anthracite coals. The tight pore structures of these coals limit the amount of inherent moisture they can hold. Typically these high ranked coals have equilibrium moistures of between 1 and 10. The first step of determining coal quality in the lab is to air-dry the sample to near equilibrium with the laboratory humidity levels. This is done to minimize any impact on lab results of additional drying or absorption of water from the air. In high rank coals, the moisture lost in the air-drying step is near equivalent to the surface moisture.

The residual moisture is that moisture that is still locked up in the coal after air-drying. The higher ranked coals that ASTM standards were based on possess this well-defined split between the air-dried or surface moisture and the residual or near equilibrium moisture. This is not the case for low rank coals like PRB coal. The sponge-like or wood like nature of PRB coals make the split between surface moisture and inherent moisture a rather fuzzy line.

Most of the quality differences between PRB coal and the higher ranked coal are due to the PRB coal's looser pore structure and additional moisture retention capacity. PRB coal also has more oxygen chemically bonded to the coal, which makes the coal hydrophilic (water-liking). This helps explain why the PRB coal is likely to reabsorb water after it has dried and degraded.

Self-heating characteristics

Spontaneous combustion of coal is a well-known phenomenon, especially with PRB coal. This high-moisture, highly volatile sub-bituminous coal will not only smolder and catch fire while in storage piles at power plants and coal terminals, but has been known to be delivered to a power plant with the rail car or barge partially on fire.

An "explosive" case study [11] was presented at the PRBCUG (Powder River Basin Coal Users Group) Annual Meeting in Houston, March 2003 that is a case in point. The dust in a tripper room ignited, causing a major explosion (Figure 3) at Wisconsin Public Service J.P. Pulliam Generating Station in Green Bay Wisconsin in June 1991. At the time, the plant was burning a 50/50 blend of PRB coal and bituminous coal, and a fire existed in one of the coal bunkers. Dust within the atmosphere of the tripper room was ignited by a minor explosion, or *puff*, within the bunker, which triggered a massive explosion in the tripper room, blowing out the outer building walls and roof. While fires prior to this were not uncommon with bituminous coal in the bunker, this was the first serious dust explosion.

Figure 3. Tripper room after explosion at WPS J. P. Pulliam Generating Station

The coal properties that affect spontaneous combustion risk include [12]:

- Moisture content of the PRB coal - or how much drying and rewetting occurs during handling.
- Friability - or how much size degradation occurs.
- Particle size - or exposed surface reaction area.
- Rank - PRB coal contains a high percentage of reactive components that tend to decompose as a coal's rank increases to Bituminous and Anthracite.
- Pyrite concentrations greater than two percent - PRB coal is low in pyrite, so the risk due to this effect is low.

These properties primarily influence the rate of heat generation during the self-heating of coal. Since most of the combustible matter in coal is carbon, when coal is stored in an atmospheric environment, the carbon slowly oxidizes to form carbon dioxide and carbon monoxide. PRB coal is also one of the highest hydrogen content coals. The oxidation reaction with hydrogen forms water. The production of both water and carbon gases in the coal will not help the situation. These reactions produce heat; since coal is a relatively good insulator, much of this heat is trapped, increasing both the temperature and the rate of oxidation. Depending on how the coal is stored, heat production may substantially exceed heat loss to the environment, and the coal can self-ignite.

Self-heating occurs when the rate of heat generation exceeds the rate of heat dissipation. Two mechanisms contribute to the rate of heat generation, coal oxidation and the adsorption of moisture. The reactivity of coal is a measure of its potential to oxidize when exposed to air. The mechanism of coal oxidation is not completely understood. The coal's minimum Self Heating Temperature (SHT) is sometimes used as a relative indication of its reactivity. There are various methods used to determine a coal's minimum SHT, but they all require running a test in real time and monitoring the temperature of the coal as any reaction occurs. These tests are typically a relative measure of a coal's propensity to self-ignite. In general, a coal's reactivity increases with decreasing rank.

The moisture content of a coal is also an important parameter in the rate of heat generation of the coal. Drying coal is an endothermic process, in which heat is absorbed, and the temperature of the coal is lowered. The adsorption of moisture on a dry coal surface is an exothermic process, with a heat producing reaction. If it is partially dried during its mining, storage, or processing, coal has the potential to readsorb moisture, thus producing heat. Therefore, the higher the moisture content of the coal, the greater the potential for this to occur. The most dangerous scenario for spontaneous combustion is when wet and dry coals are combined; the interface between wet and dry coal becomes a heat exchanger [13]. If coal is either completely wet or completely dry, the risk is substantially reduced. In general, the moisture content of coal increases with decreasing rank. For example, PRB coal has a higher inherent moisture content than bituminous B type coal.

Friability and previous oxidation of the coal are also important factors in the self-heating process. The friability of the coal is a measure of the coal's ability to break apart into smaller pieces. This exposes fresh coal surfaces to air and moisture, where oxidation and moisture adsorption can occur. Previous oxidation makes coal more friable. Although the oxidized matter is less reactive, the porous nature of the oxidized coal makes the coal more susceptible to air and water leakage when exposed to higher pressure differentials, such as in a pile or bunker.

The oxidation of sulfur in pyrite is also a heat producing reaction. The heat generated can cause the temperature of the surrounding coal to increase, thus increasing the rate of oxidation. Also, as it oxidizes, the sulfur expands, causing coal degradation to occur. Fortunately, PRB coal contains less than the minimum two percent concentration of pyrite considered necessary for a reaction.

Causes of degradation

From the time it leaves the mine, PRB coal starts to degrade. The most dramatic result of this can be found by observing the top surface of an open railcar delivering PRB coal to the plant from the mine. The large particles have distinct cracks and will shatter into smaller pieces when dropped from a height of only 6 feet. Particles contained deeper in the bed of coal within the railcar do not appear to be similarly affected.

The root cause of this degradation of PRB is the drying and resultant cracking and particle size degradation and oxidation. There are many variables that are potential contributors to attrition of PRB coal once it is exposed to air: ambient temperature (heat), moisture (addition and loss), compaction, impact (drop height), interparticle motion (due to general handling), and time. It is felt that all of these variables impact the total degradation process, however the loss of moisture appears to dominate the process.

The moisture that contributes to the problem of spontaneous combustion comes from humidity and from other PRB coal. New PRB coal added over old PRB coal seems to create more heat at that interface. The fine particles typically have a higher total moisture content compared to the coarse particles, due to their larger surface area per unit volume. Generally, each time a particle diameter is reduced by half due to breakage, the surface area doubles. This is true for smooth surface spheres or cubes. Coals, especially those low in rank, have a significant amount of surface area that resides *within* the pore structure. This would indicate there is a potential for significantly more surface area being available when fines are generated. Also, this available surface area increases as the particle becomes drier, and the pores that were filled with moisture become available for oxygen adsorption.

Test program

The test program investigated the influence of one variable on the degradation process – *time*. In a relatively dry environment, as time proceeded, the coal dried out. As it dried out, the coal cracked and broke down into smaller particles. The role that particle size plays in this process can be investigated by exposing both large and small particles to a controlled environment (temperature and moisture), and monitoring the weight loss (moisture and/or volatiles loss) over time.

Two different types of tests were run.

Test Program 1. Large PRB coal particles were exposed to ambient conditions (inside a building) for 6 days.

Test Program 2. Both fines (-1/4 in. particles) and coarse (3 inch particles) were placed in an environmental chamber at controlled conditions (72°F and approximately 45% Relative Humidity, with some excursions) for 16 days.

Results of Test Program 1

The first test simply allowed large PRB coal particles to sit at ambient conditions (inside a building) for 6 days while photos were taken. Figures 4a–4f show a series of photos of one particle over time.


Figure 4a. PRB coal at start of test.


Figure 4b. PRB coal after 5 hours.


Figure 4c. PRB coal after 2 days.


Figure 4d. PRB coal after 4 days.


Figure 4e. PRB coal after 6 days.

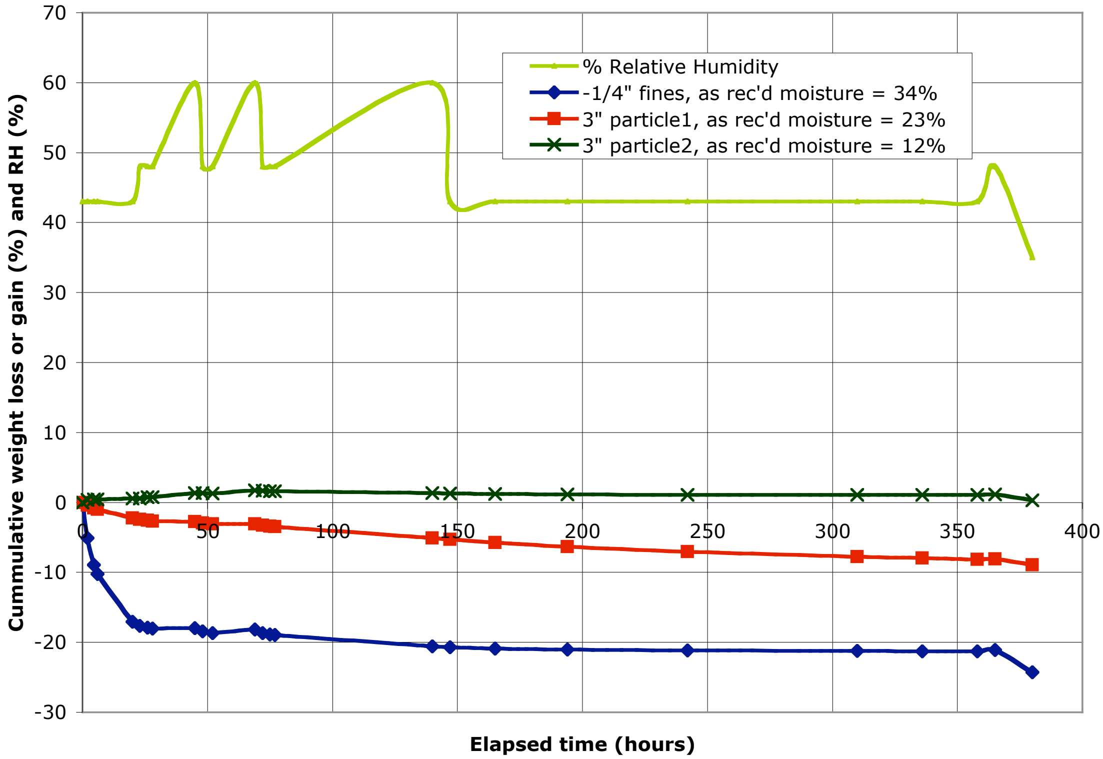

Figure 4f. PRB coal after 6 days.

As is evident from the photos, degradation of the coal starts immediately upon exposure to the environment. In fact, cracks started to appear within one hour after the start of the test!

Results of Test Program 2

Three samples of fines (-1/4 in. particles) and three samples of coarse (3 inch) particles were placed on individual trays and placed in an environmental chamber. The temperature was kept constant at 72°F and the Relative humidity at approximately 45% RH (with some excursions). The test was run over a period of 16 days. The weight of the samples was monitored and recorded over that time period. The temperature of the coal was monitored also, using multiple thermocouples, but no change in temperature of the samples was noted. It was not anticipated that any heat would be generated because drying of coal (loss of moisture) is an endothermic reaction. It is likely that even if any small amount of heat were generated due to the slight gain in moisture (exothermic reaction) on one of the large particles, the heat would quickly dissipate because the coal surface area was relatively small compared to the environmental room. The effect of moisture addition on heat generation would be a good candidate for further study. The test results are shown in Figure 5.

Figure 5. Cummulative % Moisture/Volatiles Loss/Gain for PRB Coal exposed to atmosphere



The moisture values were determined by drying small samples at 107°C in a forced convection oven and recording the weight change, until no additional weight loss was recorded. The loss in weight of each sample, divided by its original weight before drying, is denoted as the *moisture*. The fines, with an *as received* (starting) moisture of 34%, lost the largest percentage of weight (18%) during the first 24 hours compared to the coarse particles. One coarse particle (particle2) with a starting moisture of 23%, lost only 3% of its weight during the first 24 hours and 9% over 16 days; another coarse particle (particle1) with a starting moisture of only 12%, actually *gained* weight (0.75% in 24 hours, with a net gain of 0.3% over 16 days). The *equilibrated* moisture content of the samples at the end of the test was determined to be approximately 10% for the fines and 13% for the coarse particles. As shown in Figure 5, the *rate* of moisture loss (or gain) decreased well before the test ended. For example, both the fines and coarse particle2 approached their *equilibrated* moisture content after 7 days. However, particle1 still had not reached its *equilibrated* moisture by the end of the test (16 days).

Test conclusions

One of the six samples, particle2, showed an indication of the potential for coal to adsorb more moisture. If more moisture, i.e., humidity, were available, it is likely that particle2 had the potential for adsorbing more moisture, setting up the conditions for self-heating. As discussed previously, the adsorption of moisture on a dry coal surface is an exothermic process, with a heat producing reaction. A Wyoming University/Wyoming State Geological Survey [5] study found that larger, partially dried particles produce heat as they adsorb moisture. However, as was the case with our tests, the Wyoming study dealt mostly with dry coal, so data on this effect is limited.

Preventing and/or retarding degradation

Some of the same procedures that are followed to minimize the potential for spontaneous combustion can be followed to prevent particle attrition:

Coal Handling (in general)

- Incorporate any process that can minimize additional drying of the coal
- Use larger, slower moving belts
- Minimize drop heights to control drying, especially in open air in windy conditions
- Minimize drop heights to control attrition due to impact.

Coal pile

- Seal the pile to minimize air ingress and air movement in the pile. This also helps prevent moisture loss and size degradation.
- Protect the pile from the wind. A steeper slope creates greater wind resistance, forcing air into the pile; protecting the pile from the wind (e.g., wind screens) minimizes air movement through the pile.

Coal bunker

- Design for a mass flow pattern [3, 4, 11] (see APPENDIX A).
- Provide an inerting agent or atmosphere (not recommended on a normal basis)

Considerations for further study

The following are areas of study that the authors feel may assist in our further understanding of PRB coal degradation:

- The effect of moisture addition on heat generation. Particles that are partially dried could be subjected to varying levels of increased relative humidity, while monitoring the internal temperature of the large coal particle or bed of coal fines.
- Particle porosity vs. particle size; particle porosity vs. moisture content.
- Moisture gain and loss due to changes in relative humidity.
- How various substances/additives retard the loss and adsorption of moisture.

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APPENDIX A
BASIC BULK SOLIDS HANDLING CONSIDERATIONS FOR PRB COAL

MASS FLOW: ESSENTIAL FOR SAFE COAL STORAGE

Common flow problems

Two of the most common flow problems experienced in an improperly designed silo are no-flow and erratic flow.

No-flow [Fig. A1] from a silo can be due to either arching (bridging) or ratholing.

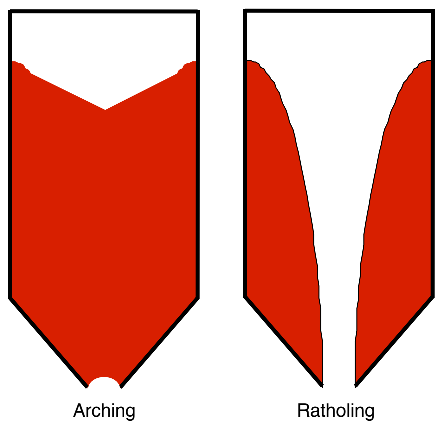

Figure A1. No Flow

Arching occurs when an obstruction in the shape of an arch or bridge forms above the outlet of a hopper and prevents any further discharge. This cohesive arch occurs when particles pack together to form such an obstruction.

Ratholing can occur in a silo when flow takes place in a channel located above the outlet. If the coal being handled has sufficient cohesive strength, the stagnant material outside of this channel will not flow into it. Once the flow channel has emptied, all flow from the silo stops.

Erratic flow is often the result of an obstruction alternating between an arch and a rathole. A rathole may fail due to an external force, such as ambient plant vibrations, vibrations created by a passing train, or vibrations from a flow aid device such as an air cannon, vibrator, etc. While some coal discharges as the rathole collapses, falling material often gets compacted over the outlet and forms an arch. This arch may break due to a similar external force, and material flow resumes until the flow channel is emptied and a rathole forms again.

Results of flow problems

Delayed startup time caused by problems related to fuel handling can add significantly to the cost of a plant. While flow stoppages alone can be very costly problems, any stagnant region in a silo can be dangerous, especially when handling coals that are prone to spontaneous combustion. If flow takes place through a channel within the silo, the material outside of this channel may remain stagnant for a very long time (depending on how often the silo is completely emptied or refilled), increasing the likelihood of fires.

Collapsing ratholes and arches can cause silos to shake or vibrate [A1]. They can also impose significant dynamic loads that can result in structural failures of hoppers, feeders or silo supports. In addition, non-symmetric flow channels alter the loading on the cylinder walls and can lead to silo deformation or buckling [A2, A3].

Flow patterns

There are two basic types of flow [A4]: *funnel flow* and *mass flow*. In *funnel flow*, some material moves while the rest remains stationary during discharge from the silo (see Fig. A2).

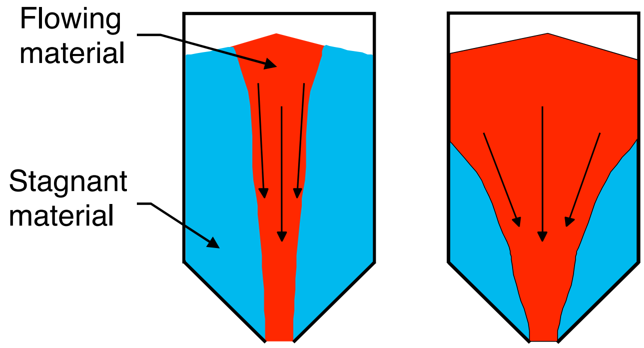

Fig. A2: Funnel Flow Pattern

Funnel flow occurs when the sloping hopper walls of a silo are not steep enough and sufficiently low in friction for material to flow along them. Under these conditions, particles slide on themselves rather than the hopper walls, and an internal flow channel develops.

Mass flow is defined as the flow pattern where upon withdrawal of any material, all of the material in a silo moves (see Fig. A3).

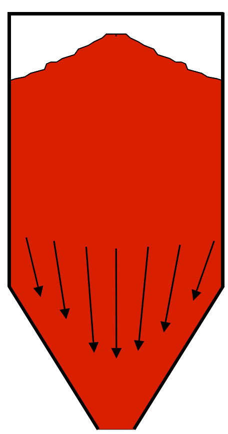

Fig. A3: Mass Flow Pattern

Mass flow occurs when particles slide along sloping hopper walls during discharge. Mass flow eliminates ratholing, stagnant material and the associated problem of spontaneous combustion, and maximizes the usable (live) capacity of the silo. In order to achieve mass flow, two conditions must be met: the sloping hopper walls must be steep enough and low enough in friction for the particles to slide along them; and the hopper outlet must be large enough to prevent arching.

TYPICAL SOLUTIONS

The key to reliability is to design the handling system equipment based on the measured flow properties of the coal being handled. As discussed above, given the variability of coals, it is essential to test samples from multiple sources over the expected range of moisture contents.

However, if the plant is already built, there are three methods available to address the types of problems mentioned here - change the material, change the operating procedures or change the equipment. The methods described here also apply to new plant design.

Change the material

The material can be changed by any of the following methods. The moisture of the coal can be lowered by covering the storage pile, by mechanical drying, or by blending wet and dry materials. Increasing the particle size by screening lowers the cohesive strength (arching/ratholing tendency); however, this is not always a practical consideration, especially for plants that use finer coal for greater boiler efficiency. The composition of the coal can be changed by finding another source of coal or by blending coal from different sources.

Change the operating procedures

Often changing the operational procedures is extremely effective in reducing handling problems, and in many cases is the most economical solution. If the coal gains cohesive strength after being stored at rest for extended periods, limiting the time of storage at rest can reduce its arching or ratholing tendency. If the combination of the silo design and the coal flow properties result in stagnant material, reducing the amount of material being stored (limit silo capacity and thus reduce head pressure) can reduce the amount of material remaining stagnant. Frequently drawing the material down to low levels, or emptying the silo on a regular basis, can help with clean-off and reduce the amount of stagnant material.

Flow aids can be very effective in breaking arches when used only after an arch has formed (due to material impact upon filling or after storage at rest) and turned off once flow has resumed; however, if material flow has not resumed and the flow aids are used repeatedly, the coal will become more compacted, and restarting flow with these devices will be futile.

If the coal silo has multiple outlets, all outlets must be used simultaneously. Use of only one outlet will likely result in severe eccentric silo wall loading and compacted, stagnant material over the non-flowing outlet(s).

Change the equipment

Consideration should be given to changing the equipment only after measuring or confirming the flow properties of the coal to be handled, thus eliminating guesswork. This is particularly wise given the significant capital investment that was laid out for this equipment in the first place. Thus, unnecessary changes should be avoided, if at all possible; however, changes to the equipment may be the most effective and long-term economic solution. Based on the measured flow properties of the coal being handled, the required modifications can range from simply lining the existing hopper with a less frictional liner to changing the hopper geometry more significantly by such measures as enlarging the outlet, steepening the angle of the lower hopper section, and/or adding an insert. Changes to the feeder, standpipe and/or the feeder interface may also be required.

The chutes at belt conveyor transfer points may need modifications as well, ranging from simple liners to a complete change in geometry to minimize impact points, while ensuring a consistent velocity to prevent adhesion to the chute surface.

HOW TO DESIGN EQUIPMENT FOR RELIABLE COAL HANDLING

To be confident that the coal storage and handling equipment will operate with few or no problems due to solids flow, the handling system should be designed utilizing a proven scientific and practical method.

Achieving mass flow

In order to achieve mass flow, two conditions must be met: the sloping hopper walls must be steep enough and low enough in friction for the coal particles to slide along them; and the hopper outlet must be large enough to prevent the coal from arching.

Hopper angle and smoothness. How steep and how smooth must a hopper surface be? This answer depends on the friction that develops between the particles and the hopper surface. This friction can be measured in a laboratory using an ASTM test method [A5]. A small sample of coal is placed in a test cell and slid along wall surfaces of interest (*e.g.* stainless steel with #2B, #1 or mill finish, and polyethylene liners). As various forces are applied normal (perpendicular) to the cell cover, the shear force is measured. These measurements are used to calculate the wall friction angle, which also can be expressed as a coefficient of friction. From the wall friction angles, limiting hopper angles for mass flow can be determined using a method developed by Dr. Andrew Jenike [A4]. These angles are used as design criteria for achieving mass flow in new silo installations, and are invaluable when considering retrofit options using liners, coatings and polished surfaces with existing designs [A6].

In general, a number of factors can affect wall friction for a given coal, such as:

- *Wall material*. Generally, smoother wall surfaces result in lower wall friction (there are exceptions), thus allowing shallower hopper angles to be sufficient for mass flow to take place.
- *Bulk solid condition*. Moisture content, variations in material composition and particle size can affect wall friction.
- *Time at rest*. Some coals adhere to a wall surface if left at rest in a hopper. Wall friction tests can be performed to measure the increase in wall friction (if any) due to storage at rest. If adhesion takes place, steeper hopper angles are required to overcome it.
- *Corrosion*. Wall materials that corrode with time generally become more frictional.
- *Abrasive wear*. Often, abrasive wear results in smoother wall surfaces; therefore, designs based on an unpolished surface are usually conservative. However, abrasive wear can occasionally result in a more frictional surface, which can disrupt mass flow. When handling abrasive materials, wear tests can be performed to determine the effect on wall friction, as well as calculate the amount of wear expected. A patented wear tester developed by Jenike & Johanson, Inc. can be used to estimate the amount of abrasive wear in a particular silo due to solids flow [A7]. These tests allow for a prediction of the useful life of a liner or surface based on its thickness, which can be an important economic consideration.

Hopper outlet size. The second requirement for mass flow is that the outlet must be large enough to prevent arching. Two types of arches are possible. Interlocking arches can be overcome by ensuring that the outlet diameter is at least six to eight times the largest particle size in a circular opening, or the width is at least three to four times the largest particle size in a slotted opening. (Slotted outlets must be at least three times as long as they are wide for such conditions to apply.)

The second type of arch, namely a cohesive arch, can be analyzed by determining the cohesive strength of the material. First the flow function of the coal (*i.e.,* its cohesive strength as a function of consolidating pressure) is measured through laboratory testing. Tests are conducted using an ASTM described direct shear tester [A5]. In this test, consolidating forces are applied to material in a test cell, similar to the wall friction test, and the force required to shear the material is measured. The measured property directly relates to a coal's ability to form a cohesive arch or a rathole. Once the flow function is determined, minimum outlet sizes to prevent arching or ratholing (in funnel flow) can be calculated through a series of design charts also published by Jenike [A4].

A number of factors affect the minimum outlet sizes required, including:

- *Particle size*. Generally as particle size decreases, cohesive strength increases, requiring larger outlets to prevent arching.
- *Moisture*. Increased moisture content generally results in an increase in cohesive strength, with the maximum typically occurring between 70% and 90% of saturation moisture. At moistures higher than these, many bulk solids (including coal) tend to become slurry-like and their cohesive strength decreases.
- *Time at rest*. Similar to wall friction, some coals exhibit an increase in their cohesive strength if left at rest for some period of time. Cohesive strength can be measured using a direct shear tester simulating storage time at rest.

Waste coals (such as bituminous gob and anthracite culm) are inherently difficult to handle because they are high in everything that contributes to flow problems: high fines, high ash (much of which is clay in waste coals), high moisture and storage time at rest. PRB and lignite, while low in ash, are high in just about everything else that contributes to handling difficulties. A robust design requires testing samples from multiple sources over a range of moisture contents.

Feeder design

In addition to ensuring that reliable flow takes place in the silo, it is also necessary for the entire cross-sectional area of the outlet to be active. A restricted outlet, such as due to a partially open slide gate, will result in funnel flow with a small active flow channel regardless of the hopper design. It is therefore imperative that a feeder be capable of continuously withdrawing material from the entire outlet of the hopper [A8]. This feature allows mass flow to take place in the silo above, if it is so designed. It also reduces the potential for ratholing in funnel flow by keeping the active flow channel as large as possible.

A hopper with an elongated, or slotted, outlet is often the preferred geometry due to its effectiveness in preventing arching compared to a circular outlet. When using a slotted outlet, it is essential that the feeder capacity increase in the direction of flow. As an example, when using a belt feeder, this increase in capacity is achieved by using a tapered interface as shown in Fig. A4.

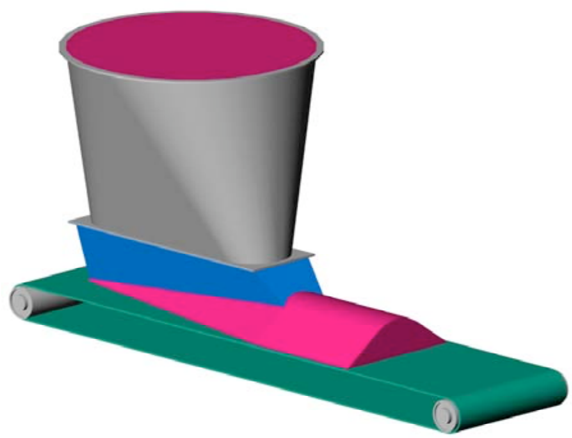

Figure A4. Mass Flow Belt Feeder Interface

Standpipe design

There are two purposes for a standpipe: to minimize the amount of gas leakage into the silo from a pressurized boiler and/or mill, and to minimize the upward (positive) gas pressure gradient that can in turn actually increase the arching potential of the coal, depending on the permeability of the coal. The finer the coal, the more adverse this latter effect will be - this applies to atmospheric boilers as well, if the seal air is supplied by positive pressure fans. Proper analysis must be used to determine the minimum height requirement for the standpipe.

When dealing with the high cohesive strength associated with waste coals and other fine, high moisture coals, the use of slotted outlets is becoming more common. This type of outlet requires a rectangular shaped standpipe (Fig. A5) between the hopper and feeder. The long slot makes the feeder interface design even more critical, compared to a typical round standpipe, to ensure a fully active flow channel within the standpipe and to avoid belt slippage, as well as minimize belt wear, by reducing the material head pressure on the belt. To provide additional stress relief, alternate design concepts may be needed.

Figure A5. Rectangular standpipe

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