IMPROVING FUEL HANDLING WITH PRB COAL BY CONVERTING A BUNKER FROM FUNNEL FLOW TO MASS FLOW

Wisconsin Public Service J.P. Pulliam Plant (*photo courtesy of WPS*)

By

Kerry L. McAtee
Poly Hi Solidur, Inc.
2710 American Way
Fort Wayne, IN 46809
260.479.4100 (voice) 260.478.1074 (fax)
tivar@polyhisolidur.com

Roderick J. Hossfeld
Jenike & Johanson, Inc.
1 Technology Park Drive
Westford, MA 01886-3189
978.392.0300 (voice) 978.392.9980 (fax)
rjhossfeld@jenike.com

Bruce Dantoin
Wisconsin Public Service Corporation
1530 N. Bylsby Ave.
Green Bay, WI 54303
920.436.5419 (voice) 920.436.5440 (fax)
bdantoi@wpsr.com

Presented at the Electric Power 2003 Conference & Exhibition
PRB Coal Users Group Annual Meeting, Houston, Texas
March 5, 2003

Improving Fuel Handling with PRB Coal by Converting a Bunker from Funnel Flow to Mass Flow

Foreword

Wisconsin Public Service (WPS) Corporation, an investor-owned electric and natural gas utility, serves more than 700,000 customers in northeast and north central Wisconsin, as well as an adjacent portion of Upper Michigan. Wisconsin Public Service has been serving residential, farm, commercial and industrial customers for more than a century. Approximately 65 percent of the electricity used annually by WPS customers is generated at their coal-fired power plants. The total generating capacity of these coal-fired plants is 1,270 MW. WPS owns 100 percent of two stations, Weston and J.P. Pulliam, with a total generating capacity of 830 MW. They are joint owners of two other stations, Columbia and Edgewater, with a total generating capacity of 440 MW.

Poly Hi Solidur, Inc., (PHS), headquartered in Fort Wayne, Ind., with manufacturing, fabricating and sales facilities worldwide, is the world's largest manufacturer of sheet, rod, tube and custom components from specifically formulated grades of polyethylene sold under the TIVAR® brand name. For the bulk material handling market, Poly Hi Solidur offers companies and industries TIVAR® 88 products that exhibit a low coefficient of friction, and high abrasion, corrosion, and impact resistance – and more than 30 years of experience in solving a wide variety of material flow problems using a solutions-oriented approach.

Jenike & Johanson, Inc. (J&J), with offices in Westford, Mass., and San Luis Obispo, Calif., is world-renowned as the leading expert in the flow of bulk solids, helping companies improve the efficiency, reliability, and safety of their operations by reducing or eliminating storage or processing problems. This involves finding economical, practical and often innovative solutions. Jenike & Johanson is recognized worldwide for its expertise in determining a material's handling characteristics by evaluating flow properties using the Jenike Shear Tester covered under the ASTM designation D 6128-00. Much of their engineering research focuses on providing the tools for solving real world bulk solids handling problems, bridging any gaps between science and practice.

Introduction

Many coal-fired utilities built between 1930 and 1970 were constructed using bins, bunkers and silos designed for a funnel flow discharge pattern. Storing Powder River Basin (PRB) coal in funnel flow bunkers creates a new set of fuel handling challenges for these facilities, particularly because funnel flow results in stagnant coal whenever any coal is discharged – and stagnant coal increases the potential for spontaneous combustion and explosions. Utilizing a case study involving Wisconsin Public Service Corporation's Pulliam Station, this paper discusses funnel flow challenges and explores options for alleviating those challenges.

Shortly after switching to PRB coal in 1991, the plant experienced a tripper floor explosion that was triggered by fires in bunkers with a funnel flow pattern. How WPS addressed this problem by converting their bunkers from a funnel flow to a mass flow pattern is the focus of this paper.

J. P. Pulliam Station's Coal Handling System

Wisconsin Public Service: J. P. Pulliam Station

Wisconsin Public Service's J. P. Pulliam Generating Station is located in Green Bay, Wis., overlooking Lake Michigan. The Pulliam Station consists of six active generating units, which are coal-fired. The original plant was built in 1926, with coal-fired generating Units 1 & 2. Both of these generating units have since been retired. Construction began on Units 3 through 8 in 1943. That project was completed in 1964. All of the plant's boilers, supplied by Babcock & Wilcox, provide steam power to three (3) Allis Chalmers and three (3) Westinghouse turbines. The total generating capacity of the Pulliam Station is 375 MW.

Coal

The Pulliam Station burns 1.5 million tons of Powder River Basin (PRB) sub-bituminous coal per year, primarily supplied by North Antelope Mine. The plant has also received fuel from Jacob's Ranch, Rochelle and North Rochelle mines. Specifications for the coal are 80% 1-1/2" minus with 20% 3/4"minus, with a moisture content of 26% or less and an ash content of 8%.

Transportation

Coal is transported to the Pulliam Station by Wisconsin Public Service's own railcar fleet, consisting of three (3) unit trains of 120 railcars each. These unit trains shuttle back and forth from the Wyoming coal fields on a continuous basis, fulfilling the fuel requirements of both the Pulliam and Weston Stations. Pulliam is also capable of receiving coal via self-unloading ship through its deep-water harbor terminal adjacent to the plant. The option of receiving coal via waterway transportation is only possible during non-winter months when the lake is not frozen.

Fuel Delivery System

Railcars are a bottom dump style and feed in-ground reclaim hoppers. Railcars are run through a thaw shed during the winter months to de-ice coal following the journey across the northern half of the United States. Coal received by ship is off-loaded onto the ground and then fed into the plant via reclaim hoppers, using dozers and scrapers.

Coal received from either the rail dump facility or outdoor ground storage is fed into the plant by 48" wide belt conveyors, which in turn feed a 60" wide belt conveyor. The 60" wide belt conveyor brings coal to the tripper above the bunkers at a feed rate of 1,500 tons per hour. The rail-mounted tripper feeds coal into the storage bunkers through the concrete floor slots running perpendicular to the tripper car travel. Each boiler is fed by two coal bunkers. The average storage capacity of each of these bunkers is 650 tons.

Units 3, 4, 5 & 6 bunkers are conical shaped, with 24" diameter discharge outlets. Unit 7 bunkers are conical with a split pant leg hopper. Unit 8 has two pyramidal bunkers with split pant leg hoppers. Each bunker discharges into 24" diameter standpipes that feed a rotary table. The coal storage bunkers are constructed of steel with an interior surface coating of gunite.

Gunite

Gunite is a sprayed concrete that is bonded to the steel substrate by a wire mesh grid connected to stud-welded fasteners. The typical thickness for gunite when combined with the wire mesh is 2-1/2". The surface finish of gunite is irregular, porous, and rough (Fig. 1).

The architecture of bunkers, silos and hoppers built during the 1930s through the early 1960s included gunite as an interior surface. Design factors centered around abrasion and corrosion protection. Limited consideration was given to bulk material flow since the majority of coal burned during this time was bituminous.

The defining characteristics of bituminous coal were consistent particle sizes ranging between 1-1/2" and 2", minimal fines, low inherent moisture, resistance to friability and high sulfur content.

Figure 1. Typical gunite coating portion

With the enactment of Clean Air Legislation, new boiler technology, synfuels and fuel blending strategies, the properties of today's fuels have changed dramatically. Powder River Basin coal, pet coke, synfuel, bituminous gob and anthracite culm all have a particle size range of 1-1/2" minus, high concentration of fines, are friable and exhibit high inherent moisture. These properties, combined with clay and other additives, make these fuels extremely cohesive. Storing and conveying these types of fuels on gunite surfaces is very problematic. The flow properties of these fuels and surface texture of the gunite provide an almost perfect attraction between these bulk materials and the wall surface. The most detrimental area for a gunite lining in coal bunkers is the sloping wall surfaces where bulk materials converge toward the discharge outlet. Sticking and hang-up of coal in this region of bunkers and silos can cause numerous problems. The coal must sometimes be re-mined from the bunker in order to capture the fuel for burning. This is often done through the use of bin whips, drills and blasting caps, or with pick and shovel.

Explosion

Cause

In June 1991, the Pulliam Station experienced a tripper room explosion which destroyed part of the roof and end wall. At the time of the explosion, the plant was test burning PRB coal as a possible alternative fuel in order to comply with the Clean Air Act. Test burns were being run on a 50/50 blend of PRB coal and bituminous coal.

An analysis of the accident led plant personnel to the conclusion that the explosion occurred as a result of a bunker fire. The investigation also revealed the following sequence of events:

(1) a coal fire existed in a Unit 5 bunker;
(2) a minor explosion or "puff" occurred within the bunker.;
(3) dust entrained within the atmosphere of the tripper floor room was ignited by the minor explosion within the bunker, which then triggered a massive explosion within the tripper floor room.

Fires in the coal bunkers at the Pulliam Station were not uncommon, occurring prior to the burning of PRB coal. However, according to coal yard supervisor, Bruce Dantoin, "when bituminous coal is ignited, it burns. On the other hand, PRB coal, under the right circumstances, can be explosive when ignited." In this particular situation, the conditions were right for an explosion. The minor "puff" in the bunker was believed to have increased atmospheric dust in the tripper floor room by dislodging coal dust from roof trusses and conveyor rails.

Figure 2. Looking from the boiler room into the conveyor room at 5B bunker drop chute. The three people injured were at this point when the conveyor room "lit-up".

Costs

Three shift operators were injured in the explosion. Two of the individuals were seriously hurt due to burns, requiring up to three months of recovery time before returning to work.

The estimated dollar cost of the explosion was in excess of $4 million. Generating revenue on 375 MW of electricity was lost for a period of three days due to damage to the tripper delivery system that provides coal to all the generating units. The tripper conveyor system sustained heavy damage, most notably, the conveyor belt that completely burned. Structurally, the roof and wall of the tripper floor building were blown off, necessitating complete replacement (Fig. 2).

Explosion Prevention Action Plan

Plant personnel implemented a series of changes to prevent a recurrence of this type of accident. These included: improved housekeeping, a fire watch program directed toward monitoring and extinguishing all bunker fires, the installation of fire suppression systems on all bunkers (F-500 chemical and CO_2 gas), and operational procedures that call for complete inventory turnover in the bunkers every two weeks.

A more challenging question, though, was how to prevent bunker fires. Operationally, the coal bunkers were routinely emptied to prevent coal from remaining in the vessels for more than a two-week period. What plant personnel quickly learned was that when the bunkers were drawn down, a significant portion of the coal remained along the side walls of the bunker. It was this coal that raised concerns about continued problems with spontaneous combustion and bunker fires. Plant engineers sought the advice of an industry consultant versed in knowledge about bunker geometry and bulk material flow to help them develop a solution for achieving complete bulk material discharge.

WHY MASS FLOW?

Mass Flow Versus Funnel Flow

Jenike & Johanson, Inc. of Westford, Mass., was hired to evaluate the fuel handling system at the Pulliam Station. Jenike & Johanson engineers revisited the site to review the operations with plant personnel and take samples of the blended fuel for testing in the Jenike Direct Shear Tester®[1]. The Jenike Shear Tester® is recognized by the ASTM as a means for establishing the inherent cohesive strength[1] of bulk materials, as well as the wall friction angle for various wall surfaces. The information generated from this testing provides insight into the flow pattern of bulk materials, outlet dimensions required to prevent arching or bridging, and the type of feeder necessary to deliver uniform withdrawal.

After a review of the fuel handling system and an analysis of the test data provided by the Jenike Direct Shear Tester®, J&J engineers concluded that in order to eliminate bunker fires, the stagnant material would have to be eliminated – mass flow discharge would be required. The flow pattern during discharge of bulk material from bunkers (storage bins, hoppers and silos) can be classified into two categories, *funnel flow* or *mass flow*[1]. Funnel flow is defined as a first-in, last-out flow pattern, having a flow region located directly over the discharge outlet and some stagnant material remaining in the bunker during discharge. Mass flow is defined as a first-in, first-out flow pattern, with all the material in motion whenever any is discharged. Mass flow discharge is the most effective way to handle non-free flowing bulk materials like PRB coal. A mass flow discharge pattern prevents cohesive bulk materials from degradation (if time sensitive), from cross-batch contamination, from segregation (if mixture consistency is critical), and from spontaneous combustion (if susceptible to self-ignition when left at rest).

The following three elements are critical to the design of a bunker to achieve mass flow:

(1) hopper walls need to be sufficiently steep and smooth for bulk material to flow along the wall;
(2) discharge outlets need to be large enough to prevent materials from bridging or arching over the discharge outlet;
(3) feeders need to be to designed to provide uniform withdrawal of material across the entire outlet area.

Mass flow discharge can be developed in existing funnel flow bunkers with the proper modifications. A flow study is required to understand what type of modifications are needed. The return on investment generally justifies performing a flow study because it clearly outlines the changes required, removing the element of guess-work and unnecessary capital expenditures. A cost effective mass flow modification plan can be developed to fit the unique requirements of existing applications.

In new construction, mass flow discharge can be incorporated into the initial design, yielding significant cost advantages. Plant availability guarantees can be provided which assure owners that fuel delivery from storage bunkers will be reliable and without interruption.

Cost Savings Realized from Mass Flow Discharge

Justifying the costs of a mass flow conversion are based on a number of variables:

(1) increased plant availability due to reductions in coal pluggages and no-flow conditions;
(2) reduced labor costs associated with operational procedures that call for frequent emptying and re-filling of storage bunkers;

---

[1]Refer to the appendix, *Bulk Materials Handling Basic Principles*, for more information on flow patterns and testing

(3) reduced equipment and conveyor maintenance costs associated with frequent emptying and re-filling of storage bunkers;
(4) reduced labor and equipment costs associated with routine bunker clean-out programs;
(5) reduced fuel costs by preventing the consumption of coal through spontaneous combustion and bunker fires;
(6) reduced costs for fire suppression chemicals and nitrogen purging;
(7) reduced maintenance costs for bunkers damaged by fires;
(8) cost savings driven by reductions in safety related issues.

Bunker fires and explosions pose a serious risk to employees and the overall plant. One accident can take a generating station off-line for days, cause serious damage to fuel delivery systems and create the potential for life-threatening situations.

UNIT 5 CORRECTIVE ACTION PLAN

Implementation

Following the completion of the flow study on the Unit 5 coal bunkers, the recommendation was made to convert the existing funnel flow bunkers to mass flow, thereby eliminating stagnant coal and decreasing the potential for bunker fires, as well as preventing future explosions. Each of the two existing Unit 5 bunkers consisted of a steel cylinder with an asymmetric conical hopper (Figs. 3 & 4). The sloping wall angles of the hopper section varied due to the off-center 24” diameter discharge outlet, resulting in the following approximate wall angles, at four equidistant points around the cone: 58° & 67° in one view and 53° & 74° in the other view. The interior surface of each bunker, including the cone, was coated with gunite.

Figure 3. Unit 5 bunker before modification

Converting the bunkers from funnel flow to mass flow involved removing the entire conical hopper section and installing a new symmetric two-stage conical hopper, with a wall angle of 68º from the horizontal in the upper cone section and 73º from the horizontal in the lower cone section (Fig. 5). The outlet size of the hopper was increased from 24” diameter to 36” diameter, exceeding the minimum arching dimension of the coal based on the Jenike Shear Tester® data. A new 36” diameter standpipe feed chute was recommended to connect the hopper to the rotary table feeder, corresponding with the enlarged discharge outlet.

The final part of the recommendation involved lining the interior surface of the new mass flow hopper sections with 304 stainless steel sheet with a 2B finish, and mounting vibrators in the lower cone area to be used after the coal has been stored at rest to restart coal flow.

The mass flow hopper modification for the Unit 5 bunker was completed in 12 weeks during the spring outage of 1993 at a cost of approximately $1.2 million for the two bunkers.

Performance Results

By modifying the Unit 5 bunkers, the flow pattern was changed from funnel flow to mass flow. The Pulliam plant has not experienced any fires or explosions in the Unit 5 bunkers. Coal flow has been reliable and the fuel switch to PRB coal has been successfully implemented.

It should be noted that an alternative solution using TIVAR® 88[2] as the lining material could have been implemented. This industrial polymer lining material has an extremely low coefficient of friction is abrasion- and wear-resistant and has been successfully installed over gunite and stainless steel.

In most cases, using a TIVAR® 88 liner to achieve mass flow of coal and blended coal also eliminates the need for active flow promotion devices such as vibrators which can – and have – caused structural damage to bunkers and silos.

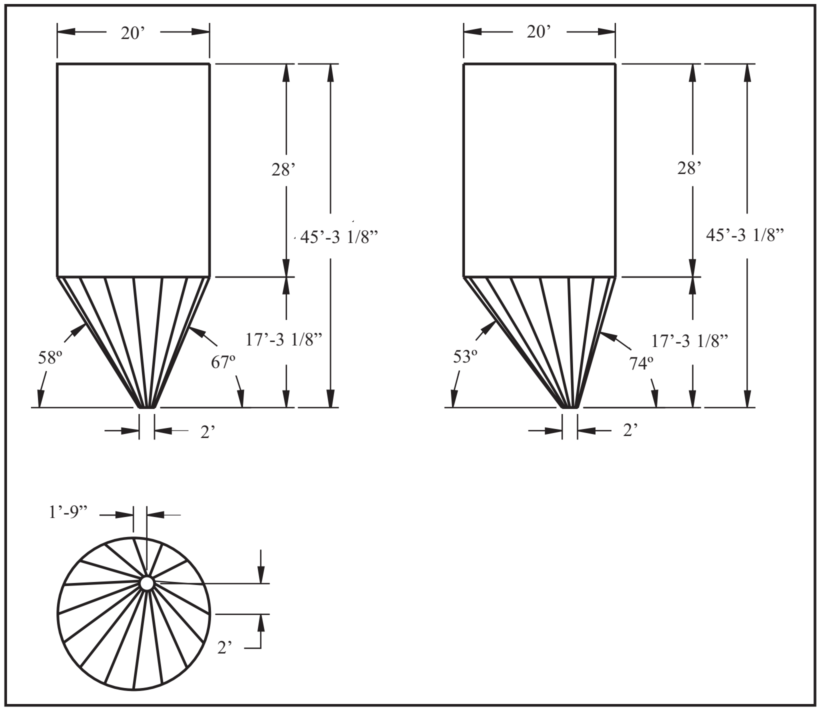

Figure 4. Dimensional layout of original Unit 5 bunker

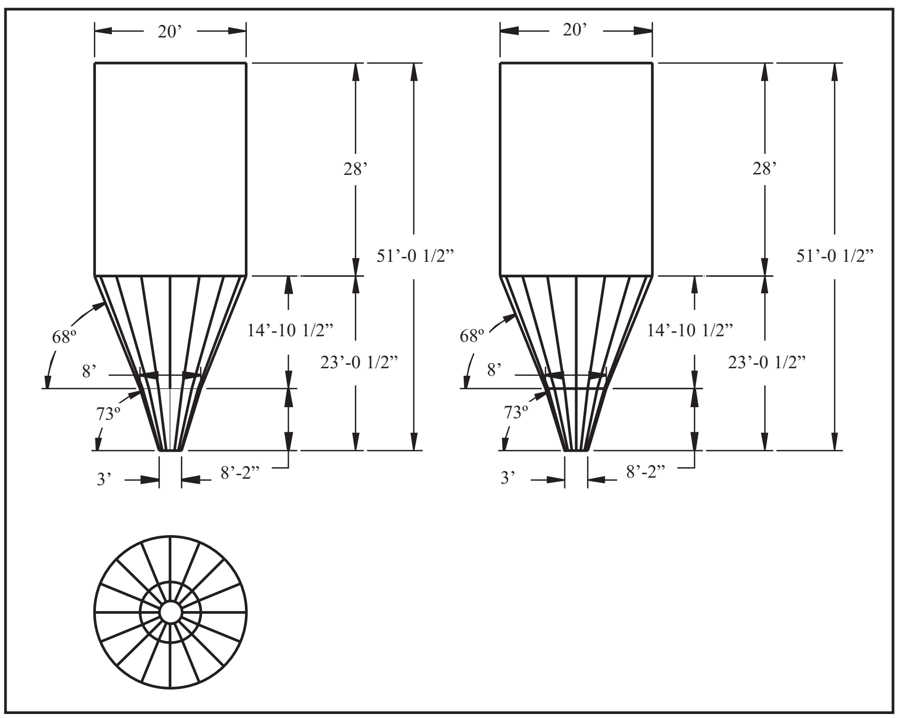

Figure 5. Unit 5 bunker modification with symmetric two-stage conical hopper.

---

[2]TIVAR® 88 is manufactured by Poly Hi Solidur, Inc.

UNIT 8 CORRECTIVE ACTION PLAN

Implementation

In 1994, Pulliam management decided to initiate a corrective action plan to reduce fires in Unit 8 coal bunkers. Jenike & Johanson was again hired to conduct a flow study and recommend a course of action for developing mass flow.

Unit 8 has two coal bunkers feeding the boiler, which are pyramidal shaped with a double pant leg hopper (Fig. 6). The bunkers are constructed of steel with a gunite coating on all interior surfaces. The sloping wall angles of the double pant leg hopper were 66º and 67º respectively. Valley angles in the pant leg hopper were and 58º and 60º. The discharge outlet of each pant leg hopper was 22-3/4" square as measured from an inside dimension. In the mid-80s, problems with coal stagnation and bunker fires led plant personnel to install 8 large capacity air cannons in the pant leg region of each bunker to facilitate flow (Fig. 7). Success with this approach was limited.

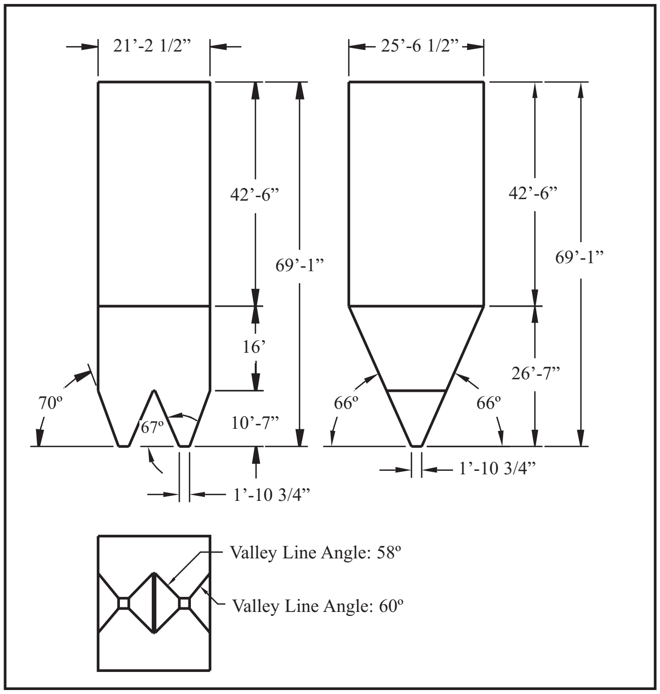

Figure 6. Unit 8 bunker dimensional layout

The Unit 8 fuel was 100% PRB coal. An analysis of the bunker geometry, based on the bulk material flow properties tests, showed that mass flow discharge could be developed in the Unit 8 bunkers by adding valley angle clean out plates (Fig. 8) and lining the sloping wall surfaces with one of the low friction materials tested, such as 304-2B stainless steel or TIVAR® 88. Field study research has shown that bulk material flow in valley angles is restricted due to shallower wall angles in this area and the ability of bulk materials to compact and adhere to wall surfaces in box corners.

Figure 7. Unit 8 bunker pant leg air cannons

Less than a year earlier, Wisconsin Public Service modified a fuel storage bunker with a gunite coating at its Weston station. The Weston facility had previously removed the gunite in the hopper section to accommodate the installation of 304-2B stainless steel liners. This approach proved to be very expensive and dirty because the gunite had to be jackhammered from the wall surfaces to allow for the installation of the stainless steel liners. As a result, corporate engineering for WPS decided an alternative approach was necessary.

Referencing information obtained from a project at Xcel Energy's (formerly Northern States Power) Riverside Plant concerning the successful use of a low friction polymer liner – TIVAR® 88 – the WPS engineering staff consulted with Jenike & Johanson and Poly Hi Solidur about using this material to solve the flow problems in the Unit 8 bunkers. Jenike & Johanson's prior experience with TIVAR® 88, and their flow study data on the WPS plant's PRB coal showed that TIVAR® 88 would offer an even lower surface friction than 304-2B stainless steel in the Pulliam Unit 8 bunker applications. Based on TIVAR® 88's past performance in coal handling applications, WPS decided to install TIVAR® 88 liners in the bunkers.

During the spring outage in 1995, the Pulliam plant made the recommended modifications to the Unit 8 bunkers. Steel clean out plates were installed in the valley angles to increase the slope of the walls in this region (Fig. 9) and TIVAR® 88 was placed over the existing gunite coating and valley angle plates (Fig. 10). The total cost for this mass flow modification was approximately $500K. The time required for modification was four (4) weeks.

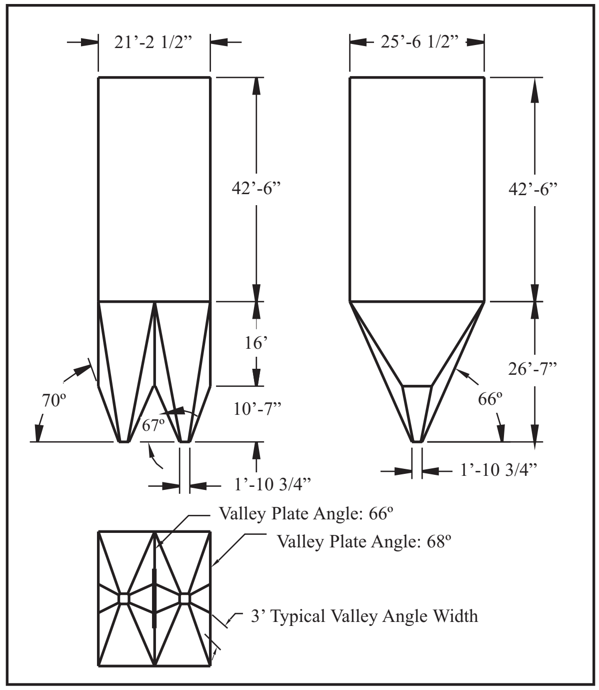

Figure 8. Dimensional layout for Unit 8 bunker valley angle clean out plate modification


Figure 9. Unit 8 bunker clean out plate installation

Performance Results

The flow pattern was changed from funnel flow to mass flow in the Unit 8 bunkers. According to Bruce Dantoin, mass flow is "absolutely what happens" when coal is withdrawn from the bunkers. There are no more stagnant regions of coal in the bunker. The Pulliam plant has not experienced any fires in the Unit 8 bunkers since the 1995 modification. The air cannon ports in the pant leg hoppers were covered over and haven't been used since.

Questions concerning the attachment of TIVAR® 88 liners to the existing gunite surface have also been answered. During the past seven years of operation, no liner panels have come loose from the gunite substrate, and only minor maintenance has been required.

Figure 10. TIVAR® 88 liner installed on clean out plates and gunite sloping wall surfaces

Conclusions

Handling PRB coal in a funnel flow bunker creates handling challenges for older power plants due to stagnant coal remaining in the bunker whenever any coal is discharged. Eliminating stagnant coal in a bunker is essential to preventing spontaneous combustion of coal that is prone to self-ignition. This requires a mass flow pattern of discharge in the bunker (or complete emptying of the bunker on a regular basis). Mass flow can *only* be assured by basing the modifications on the *measured* flow properties of the coal, as determined by testing the coal being handled. In many instances, lining an existing silo's geometry with TIVAR® 88 can reduce the wall friction sufficiently to induce mass flow.

Experimenting with the bunker can be costly and dangerous. The minimum outlet size to prevent arching and ratholing is determined by running a cohesive strength test on the coal. The hopper angles for the various liner options are determined by running wall friction tests. Using ASTM test methods[1], hopper angles for mass flow can be determined by measuring wall friction, and the minimum outlet size to prevent cohesive arching can be calculated by measuring the cohesive strength of a material.These measured flow properties are directly related to the fines content, moisture content and bunker storage time at rest of the coal being handled.

The only three methods available to alleviate coal-handling problems in an existing plant are:

(1) change the coal (dry it, screen it, blend it with something else or burn something else);
(2) change the operating procedures (store the coal for shorter times, empty the bunker more frequently);
(3) change the equipment (replace it, make the outlet larger, make the hopper steeper or install a less frictional liner).

Once a problem does occur and the crises have been dealt with, test the coal to determine the flow properties and use those test results to make informed decisions about corrective action.

APPENDIX – BULK MATERIALS HANDLING BASIC PRINCIPLES

Flow Problems

Two of the most common flow problems experienced in an improperly designed silo (also called bunker, bin, hopper) are no-flow and erratic flow. No-flow (Fig. A) from a silo can be due to either arching (bridging) or ratholing. 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 (Fig. A).

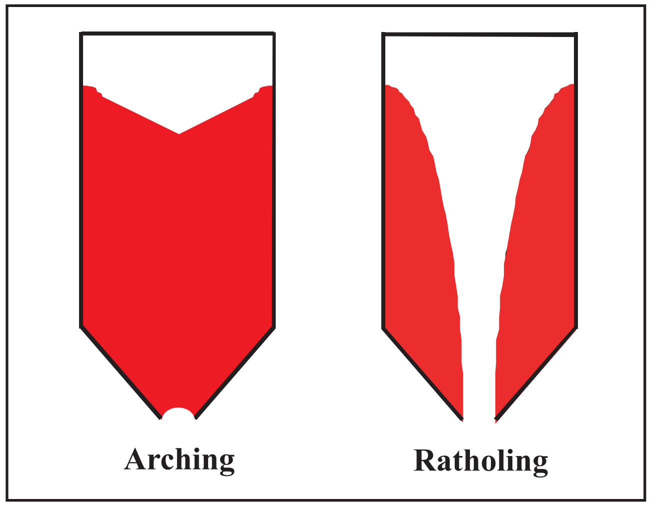

Figure A. No-flow problems – arching and ratholing

Arching occurs when an obstruction in the shape of an arch or a bridge forms above the outlet of a hopper and prevents any further discharge. It can be an interlocking arch, where the particles mechanically lock to form the obstruction, or a cohesive arch. An interlocking arch occurs when the particles are large compared to the outlet size of the hopper. A cohesive arch occurs when particle-to-particle bonds form an obstruction (Fig. B).

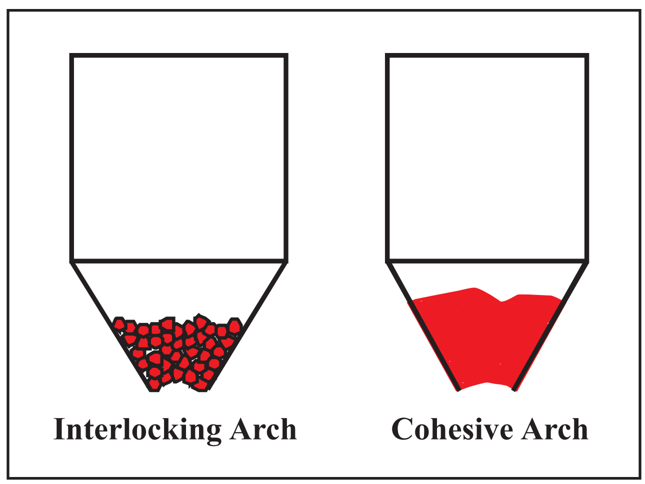

Figure B. Arching in a silo – interlocking or cohesive

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), increasing the likelihood of fires.

Collapsing ratholes and arches can cause silos to shake or vibrate.[2] 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 wrinkling or buckling.[3, 4]

Flow Patterns

Material flow (and the potential for flow problems) in a silo is a function of the silo geometry, in addition to the flow characteristics of the material being handled. Basically, there are two primary flow patterns: *funnel flow* and *mass flow* (Fig. C).

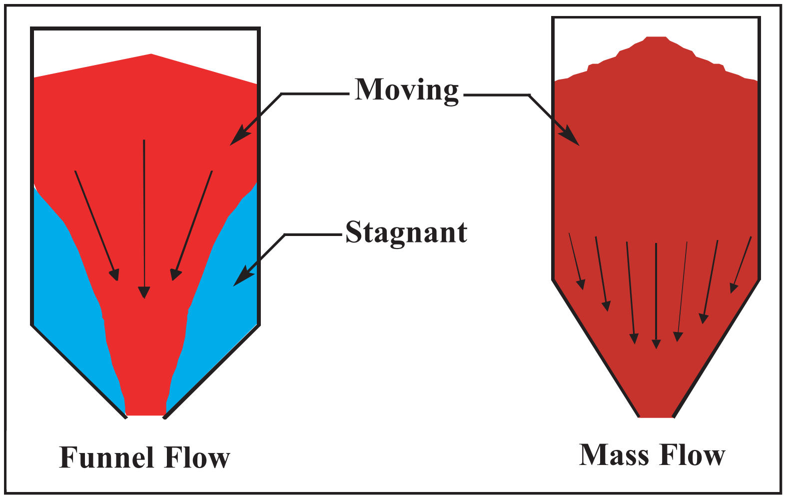

Figure C. Funnel flow and mass flow

In *funnel flow*, an active flow channel forms above the outlet, with non-flowing material at the periphery. As the level of material in the silo decreases, layers of the non-flowing material may or may not slide into the flowing channel, which can result in the formation of stable ratholes. In addition, funnel flow provides a first-in, last-out flow sequence and increases the potential for spontaneous combustion in stagnant regions.

In *mass flow*, all of the material is in motion whenever any is withdrawn from the hopper. Material from the center as well as the periphery moves toward the outlet. Mass flow hoppers provide a first-in, first-out flow sequence, reduce the potential for spontaneous combustion, reduce sifting segregation and provide a steady discharge with a consistent bulk density and a flow which is uniform and well-controlled. Requirements for achieving mass flow include sizing the outlet large enough to prevent arching, and ensuring the hopper walls are sufficiently smooth and steep enough to promote flow at the walls.

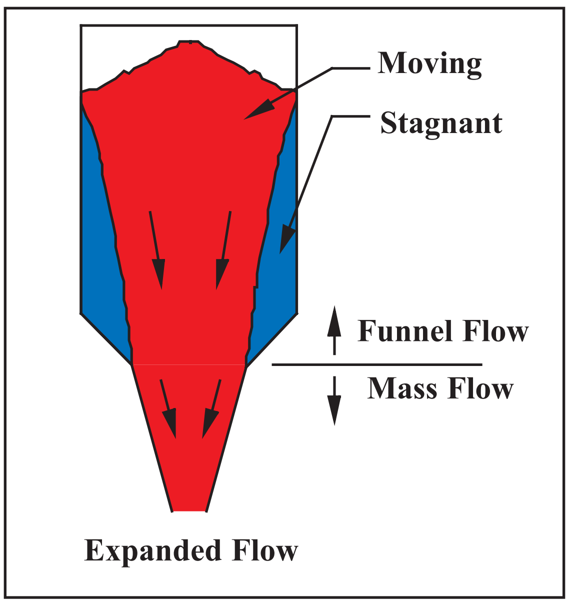

Figure D. Expanded flow pattern in a silo

A third type of flow pattern, called *expanded flow*, can develop when a mass flow hopper (or hoppers) is placed beneath a funnel flow hopper (Fig. D). In this embodiment of the basic flow patterns, the mass flow hopper is designed to activate a flow channel in the conical funnel flow hopper, which is sized to prevent the formation of a stable rathole. The major advantage of an expanded flow silo discharge pattern is the savings in headroom. The wall angles of the funnel flow hopper are more shallow than the angles necessary for a mass flow hopper; therefore, the height of the funnel flow hopper section is decreased.

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 particles to slide along them; and the hopper outlet must be large enough to prevent 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.[1] 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 TIVAR® 88). As various forces are applied normal (perpendicular) to the cell cover, the shear force is measured (Fig. E). These measurements are used to calculate the wall friction angle, ϕ', which also can be expressed as a coefficient of friction, μ. From the wall friction angles, limiting hopper angles for mass flow can be determined using a method developed by Dr. Andrew Jenike.[5] These angles are used as design criteria for achieving mass flow in new hopper and bunker installations, and are invaluable when considering retrofit options for liners, coatings and polished surfaces with existing designs.[6]

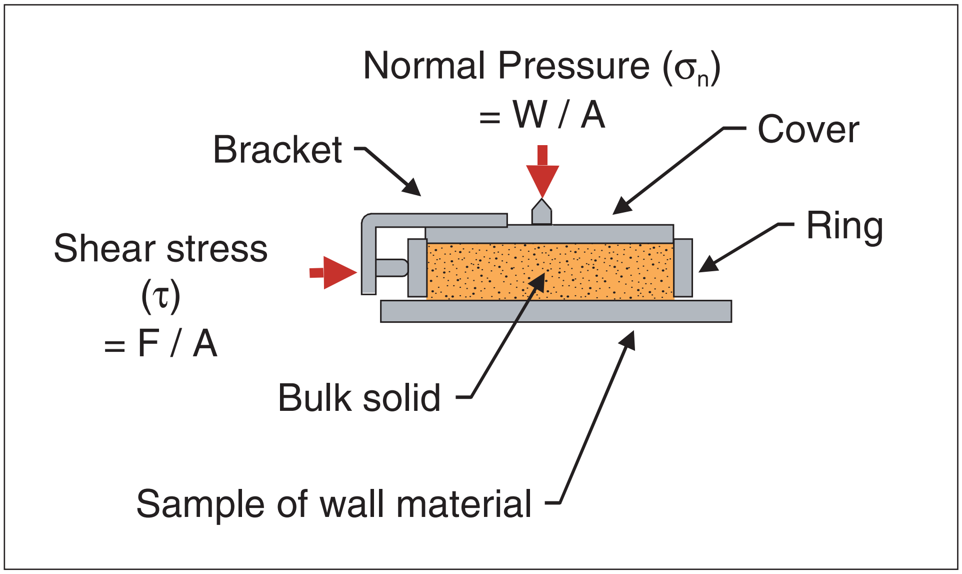

Figure E. Wall friction test

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, shallower hopper angles are 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 or a lower friction wall material 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.[7] 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. As discussed previously, 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.[1] 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 (Fig. F). 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.[5]

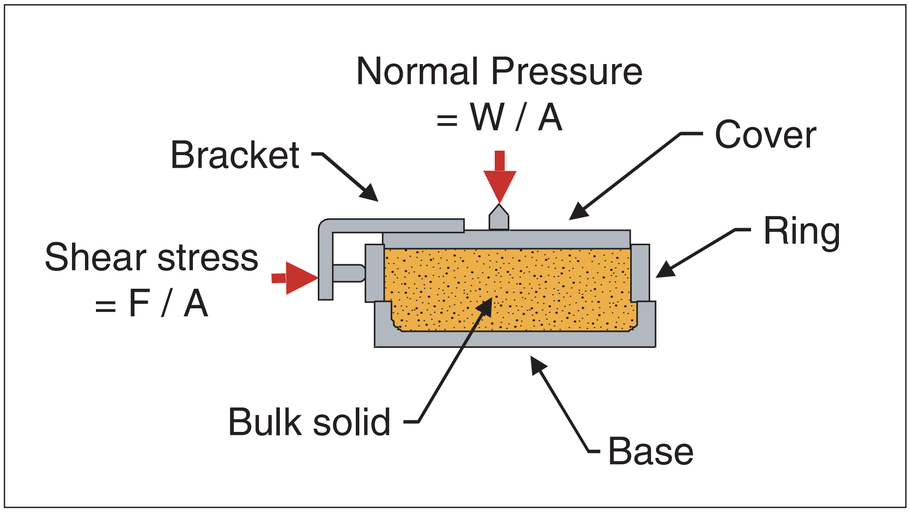

Figure F. Shear test

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 moisture 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.

Many of the coals, like sub-bituminous PRB, are high in fines and moisture, which when stored at rest, adversely affects the arching potential. Also, most of the waste fuels being used today in industry, such as bituminous gob and anthracite culm, are inherently bad actors because they are high in everything: high fines/high ash (much of which is clay), high moisture (due to open stockpiles and ponds), and storage time at rest. A robust design requires testing samples from multiple sources over a range of moisture contents.

Other Design Considerations to Achieve Mass Flow

Feeder Design

In addition to ensuring that reliable flow takes place in the hopper previously described, it is necessary for the entire cross-sectional area of the outlet to be active. A restricted outlet, such as 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.[8] This feature allows mass flow to take place in the hopper 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.

Standpipe Design

There are two purposes for a standpipe: to minimize the amount of gas leakage into the silo from a pressurized boiler, and to minimize the upward (positive) gas pressure gradient that can actually increase the arching potential of the coal. The finer the coal, the more adverse this latter effect will be. Proper analysis and design are required to determine the size and height requirements for the standpipe.

Typical Solutions

The key for reliable handling of coal is to design the handling system equipment based on the measured flow properties of the type of coal to be handled. Given the variability of coals, it is imperative 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. Coal moisture levels can be lowered by using covered storage, by mechanical drying, or by blending wet and dry materials. Increasing the particle size by screening lowers the cohesive strength (arching/ratholing tendency). Blending coal from different sources can change the composition of the coal.

Change the Operating Procedures

Often, changing fuel handling operational procedures is extremely effective in reducing handling problems, and in many cases, it 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 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 head) can reduce the amount of material remaining stagnant. Frequently drawing the material down to a low level, 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 down arches, but only after an arch has formed (due to material impact upon filling or after storage at rest) and they should be 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 trying to restart flow with these devices will be futile.

If the coal silo has dual outlets, both outlets must be used simultaneously. Use of only one outlet will probably result in severe eccentric silo wall loading and compacted, stagnant material over the non-flowing outlet.

Change the Equipment

Consideration should be given to changing the equipment only after confirming the handling properties of the coals to be handled, thus eliminating the guesswork. After all, a significant capital investment was laid out for this equipment in the first place. But changes to the equipment may be the most effective and long-term economic solution. Based on the measured flow properties of the coals being handled, the modifications required can range from lining the existing hopper with a less frictional liner, like TIVAR® 88, to enlarging the outlet and steepening the angle of the lower hopper section. Changes to the feeder, standpipe and/or the feeder interface may also be required.

References

[1] "Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell," American Society for Testing and Materials (ASTM), D 6128-00, 2000.

[2] Purutyan, H., Bengston, K.E. and Carson, J.W.: *Identifying and Controlling Silo Vibration Mechanisms: Part I,* Powder and Bulk Engineering, 1994, pp. 58-65.

[3] Carson, J.W. and T. Holmes: *Why Silos Fail*, Powder and Bulk Engineering, November 2001, pp. 31-43.

[4] Carson, J.W. and Jenkyn, R.T.: *Load Development and Structural Considerations in Silo Design,* Presented at Reliable Flow of Particulate Solids II, Oslo, Norway, 1993.

[5] Jenike, A.W.: *Storage and Flow of Solids*, University of Utah Engineering Experiment Station, Bulletin No. 123, 1964.

[6] Purutyan, H., Pittenger, B.H. and Carson, J.W.: *Solve Solids Handling Problems by Retrofitting*, Chemical Engineering Progress, Vol. 94, No. 4, 1998, pp. 27-39.

[7] Johanson, J.R. and Royal, T.A.: *Measuring and Use of Wear Properties for Predicting Life of Bulk Materials Handling Equipment*, Bulk Solids Handling, Vol. 2, No. 3, 1982, pp. 517-523.

[8] Carson, J.W. and Petro, G.J.: *Feeder Selection Guidelines*, Chemical Processing, Powder Solids Annual, 1997, pp. 40-43.

Bibliography

Steppling, K.P., McAtee, K.L. and Huggins, J.: Case Study: *How Northern States Power Company Solved Handling Problems Associated with Sub-Bituminous Coal*, Presented at Power-Gen Americas '94 Conference, Orlando, Florida, December 7-9, 1994.

Steppling, K.P., Hossfeld, R.J., Chakraborti, S.K. and Mesing, R.A.: Case Study: *How to Achieve Reliable Coal Flow and Maintain Plant Availability*, presented at Power-Gen International, Orlando, Florida, December 10-12, 2002.

About the Authors

Kerry L. McAtee
Sales Engineer, SystemTIVAR® Engineering
Poly Hi Solidur, Inc.
2710 American Way, Fort Wayne, IN 46809
Tel: (260) 479-4206 Fax: (260) 478-1074
E-mail: tivar@polyhisolidur.com
Mr. McAtee received his BS in business management from Purdue University in 1978. Over the past 15 years, he has been involved in the bulk material handling industry with Poly Hi Solidur. He has served in various roles ranging from project management to sales engineer. Mr. McAtee has authored several papers on the proper use and application of polymer liners in fuel storage bunkers.

Roderick (Rod) J. Hossfeld
Senior Consultant
Jenike & Johanson, Inc.
1 Technology Park Drive, Westford, MA 01886-3189
Tel: (978) 392-0300 Fax: (978) 392-9980
Email: rjhossfeld@jenike.com
Mr. Hossfeld received his BS in mechanical engineering from the University of Massachusetts in 1972 and MS in 1974, joining J&J in 1978. He consults with clients in all industries, with focused specialization on energy. Mr. Hossfeld has worked with hundreds of clients, solving problems ranging from minimizing particle attrition with special letdown chutes (food and energy industries) to ensuring reliable flow in large solid fuel bunkers.

Bruce Dantoin
Coal and Yard Group Supervisor
Wisconsin Public Service Corporation
1530 N. Bylsby Ave., Green Bay, WI 54303
Tel: (920) 436-5419 Fax: (920) 436-5440
Email: bdantoi@wpsr.com
Mr. Dantoin joined Wisconsin Public Service Co. in 1981 as a mechanic in the maintenance department. In 1999, he moved into the position of Outage Planner/ Scheduler and became Coal & Yard Group Supervisor in 2002.