Babcock Power

Technical Publication

Pulverized Coal Explosions in the U.S. Utility Industry

by

R. C. Carini
Manager, Engineering Administration
RILEY POWER INC.
a Babcock Power Inc. company
(formerly Riley Stoker Corporation)

K. R. Hules
Senior Staff Engineer
RILEY POWER INC.
a Babcock Power Inc. company
(formerly Riley Stoker Corporation)

Presented to
Winter Annual Meeting
of the American Society of Mechanical Engineers
Anaheim, California
December 1986

RPI-0061

PULVERIZED COAL EXPLOSIONS IN THE U.S. UTILITY INDUSTRY

by

RICHARD C. CARINI
Manager, Engineering Administration
and
K.R. HULES
Senior Staff Engineer

INTRODUCTION

During 1981 the Electric Power Research Institute (EPRI) began a research project to study pulverized coal fires and explosions in the U.S. utility industry via an industry wide survey and explosion experiments.

The survey indicates that explosion events are occurring at a rate of approximately one every three years for each boiler. The trends show that although coal type has a positive correlation to explosion frequency, it is not the only significant factor in setting explosion hazard levels.

Laboratory experiments were performed in full scale test rigs that allowed triggering and monitoring coal system explosions on demand. Ignition events remaining within the coal pipe created only weak pressure rise, while ignition events within a simulated pulverizer volume created explosions exceeding 70 bar gage (1015 psig). These experiments showed that explosion characteristics depend on dust concentration, ratio of pulverizer volume to coal pipe area, as well as coal type.

THE SURVEY APPROACH

The survey used a questionnaire, together with telephone conversations and plant visits to gather data and observations from utility personnel. The survey asked for a description of pulverizer systems, unit hardware and characterization of the coal as well as fire and explosion experience. In this paper the term "explosion" encompasses both severe puffs (structure deformation) and true explosions (containment breaching). The term "unit" designates a utility steam generator and its auxiliaries.

The results of the survey materials indicate that the frequency of explosions is increasing. The survey average value of 0.31 explosions per year per unit shows a rise over previous averages[1]. Adjusted for the entire pulverized coal fired utility industry, there is almost one explosion event each day. Even though a small percentage are of the containment breaking type, the other events have the potential of being true explosions. In addition, there is a wide range of explosion frequencies from plant to plant. A number of units reported explosion free operation while a few units reported as high as three explosions per year.

SURVEY DATABASE

The database consists of data for 1678 pulverizers at 361 steam generating plants belonging to 76 separate utilities. Table I shows some sample data and statistics for the database.

SAMPLE DATABASE POPULATION STATISTICS

Item	Min.	Max.	Average
Pulverizer Age (Years)	1	44	19.
Pulverizer Capacity (Metric Tons/Hour)	3	91	28.64
Pulverizers per Boiler	2	12	4.75

Table I   Sample Database Population Statistics

Analysis followed a statistical approach to correlate a plant's particular configuration with explosion frequencies. The categories of plant configuration cover the following areas:

Pulverizer System Characteristics
- Pulverizer system operation mode
- Pulverizer generic type
- Pulverizer operation mode
- Pulverizer capacity
- Number of pulverizers per unit
- Pulverizer Age

Fuel Characteristics
- Coal type
- Coal volatile content
- Coal moisture content
- Coal ash content

SURVEY TRENDS

The analysis shows that the explosion hazard level of a plant is not simply a function of small numbers of plant characteristics. If all units in the industry are viewed as a single group, there are no single parameters or group of parameters that distinguish the high risk units from the low[2]. For all utility units, the categories noted above are statistically equivalent and equally poor for differentiation. Thus, viewing explosion susceptibility as a function of a single category is ineffective.

In spite of the poor correlations, understanding the interaction of plant characteristics at a simple level of analysis is of value for a discussion of trends at a higher level of analysis. Figure 1 shows the summary data for the four characteristics which take on only discrete values. Figure 2 shows the data for one of the other six characteristics which are continuous in nature. Recognizing that not all units will follow the overall tendencies, the following trends were observed:

1. Pulverizer System Operation Mode: Bin storage units have twice the explosion frequency of direct fired units. Differentiation of the direct fired units by coal type shows that subbituminous fired units have explosion frequencies twice as high as those of the bituminous fired units.

2. Pulverizer Generic Type: The explosion frequency for vertical spindle pulverizers is about twice that of ball tube pulverizers and about five times that of attrition pulverizers. Subbituminous grinding vertical spindle pulverizers have about twice the explosion frequency of bituminous grinding vertical spindle pulverizers. For both ball tube and attrition pulverizers the explosion frequency is higher with bituminous coals.

3. Pulverizer Operation Mode: Suction operation pulverizers have a slightly higher explosion frequency than pressurized pulverizers. Subbituminous coals accentuate the difference.

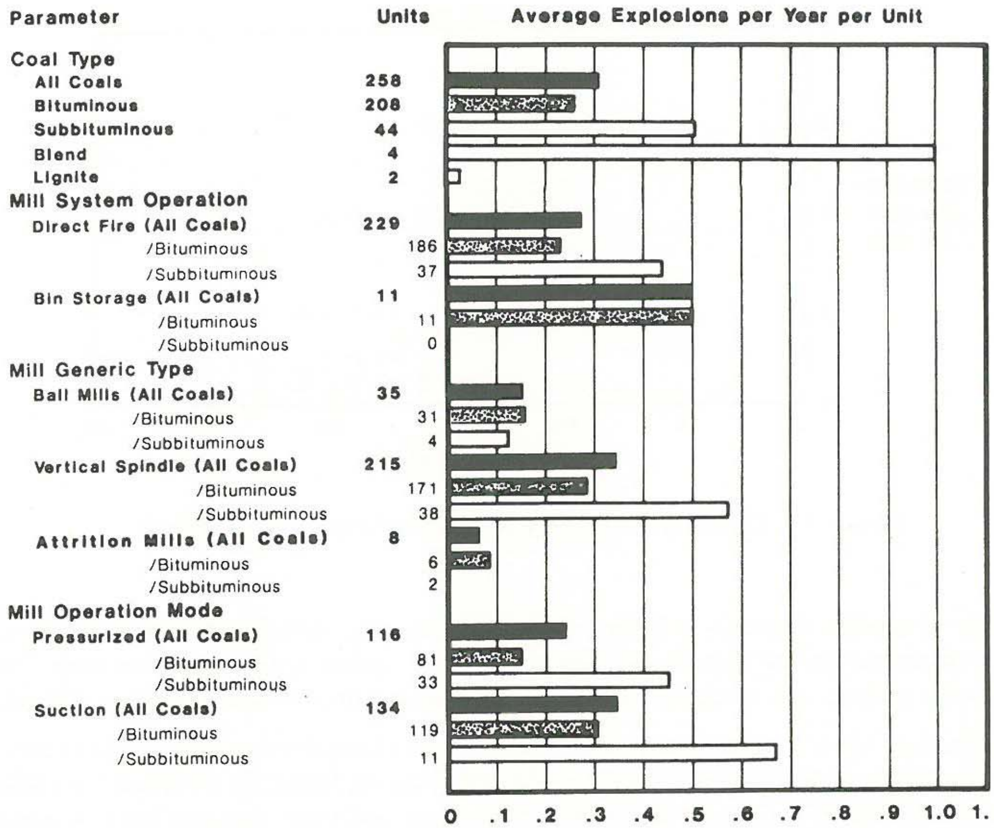

Figure 1 Explosion Fequencies for Class-type Characteristics

4. Pulverizer Capacity: Generally, explosion frequency is independent of pulverizer capacity. However, by separating bituminous and subbituminous coal fired systems a slight trend is observed. Pulverizers on bituminous coals show a reduction in explosion frequency with an increase in pulverizer capacity. Pulverizers on subbituminous coals experience an increase in explosion frequency with an increase in pulverizer capacity.

5. Number of Pulverizers per Unit: Initially, explosion frequency increases with an increasing number of pulverizers per unit. Once again coal type produces two opposing conditions. Bituminous coal fired units show a slight decrease in explosion frequency with increasing number of pulverizers per unit. However, subbituminous fired units show a sharp increase in explosion frequency with increasing number of pulverizers per unit.

6. Pulverizer Age: Without the coal type distinction explosion frequency appears to be independent of pulverizer age. Explosion frequency has a slight decrease with pulverizer newness for bituminous coals. Conversely, explosion frequency increases with pulverizer newness for subbituminous coals.

7. Coal Type: The subbituminous coals have explosion frequencies of about twice those of bituminous coals. The explosion values of lignite coals were ignored due to the extremely small population.

8. Coal Volatility: Explosion frequency increases with an increase in volatility content, but this trend is as weak statistically as the others. These statements and the appearance of Figure 2 remain unchanged even if a dry, ash free basis is used for volatility.

9. Coal Moisture: Explosion frequency remains unchanged with increasing coal moisture. Overall, there is a connection between moisture and pulverizer age. The newer units have a trend toward using higher moisture coals.

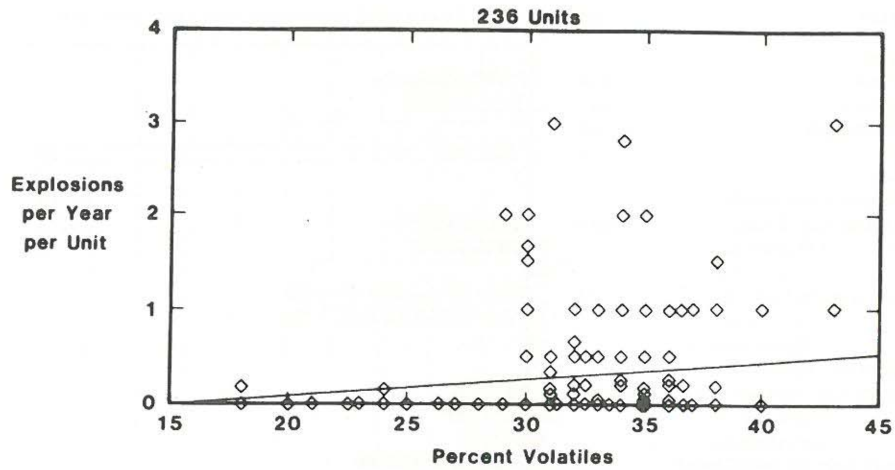

Figure 2 Explosion Frequency for a Range-type Characteristic

10. Coal Ash: Explosion frequency is higher for medium ash coals than for low and high ash coals. This trend is dominated by the units firing high volatile, low moisture subbituminous coals. These coals fall into the medium ash group and appear to have higher than normal explosion frequency.

The trends discussed above are statistically weak and should be considered as introductory material to fire and explosion problems. A better level of analysis does not focus on frequency of events but rather focuses on the common membership traits connecting fires, explosions, and plant characteristics. A major finding is that explosions do not occur in proportion to the number of fires at a unit as has been thought in the past. Rather, a unit falls into one of four modes.

Mode 1, low fire and low explosion frequency (78% of units), the desirable pattern, contains units with all types of plant characteristics indicating that there are no intrinsic barriers to safe operation for any plant. However, this mode does contain a significantly higher proportion of the database's oldest units. The trend that older units have fewer fires and explosions than newer units is interpreted as indicating that longer periods of operating and maintenance experience with a particular unit produce a safer facility. Thus, more attention to improved operating procedures and maintenance practices can make any plant safer.

Mode 2, high fire and low explosion frequency (9% of units), tends to be characterized by base loaded units; middle aged, large capacity, pressurized mills; and medium volatile, high ash, subbituminous coals.

Mode 3, low fire and high explosion frequency (7% of units), tends to be characterized by base loaded units; newer units; suction mills and vertical spindle mills in general; medium volatile coals, high moisture coals, low ash coals, and subbituminous coals.

Mode 4, high fire and high explosion frequency (6% of units), smallest of the groups, tends to be characterized by units with a larger number of mills; vertical spindle mills; medium volatile coals, high moisture coals, high ash coals, and subbituminous coals.

Less than one-fifth of the units reported using one or more of the three inerting agents named by any of the respondents. Figure 3 shows the explosion frequency for "CO_2", "N_2", and "Steam", as well as the groups "None" and "Unknown". The group "None" contain units clearly reporting no inerting agents in use. The group "Unknown" are the units that left the entry blank. Both "Unknown" and "None" contain units of low and high frequencies. Almost 90% of the "None" and "Unknown" categories are units firing bituminous coals, while the "Steam" group is almost 95% subbituminous coal users. Historically, the steam group is experiencing approximately 1.5 times as many explosions as the group that is doing nothing. The group using CO_2 is similar to "None" and has half the explosion frequency of steam[3].

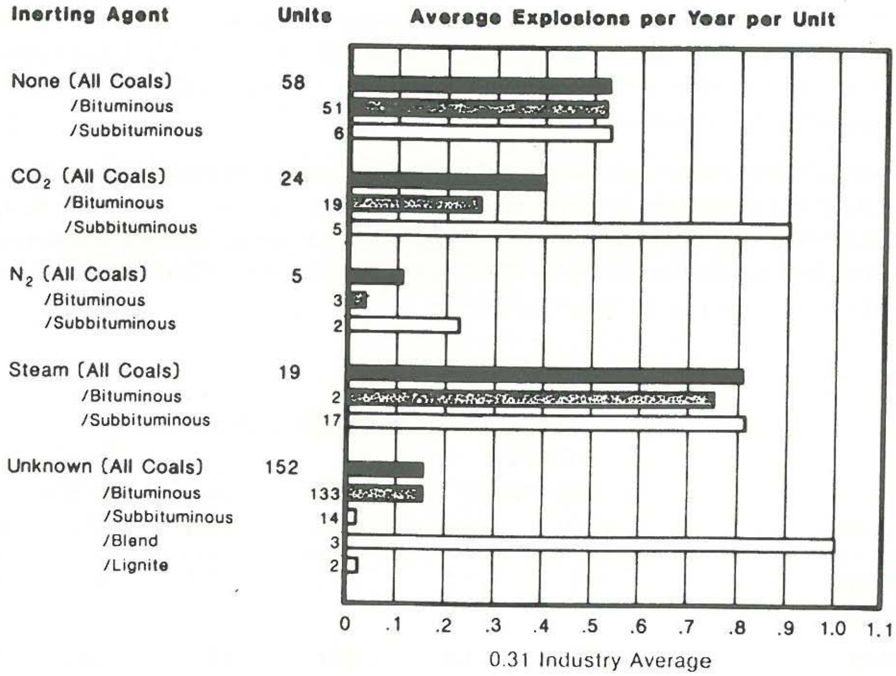

Figure 3 Average Explosion Frequency Versus Common Inerting Agents

LABORATORY EXPERIEMENTS

In order to obtain an understanding of explosion origin and growth, full scale coal pipe and simulated pulverizer tests were conducted at the Central Electricity Generating Board's (CEGB) Explosion Test Facility in Foulness, England[4]. The controlled conditions kept the interaction of variables at a manageable level while simulating field conditions which would produce damaging or lethal explosions in field hardware. The laboratory setting permitted detailed measurements to be made for understanding growth mechanisms of pulverized coal system explosions. Additional experiments were conducted at Fenwal, Incorporated in Ashland, Massachusetts, with explosion inerting agents[5]. Inerting is the release of an agent into a region with explosive conditions in order to render the environment non-explosive. The process is distinct in methods and goals from suppression and extinguishing. All pressures reported in the text, tables and figures are gage.

FULL SCALE EXPLOSION TESTS

The CEGB explosion test facility was built to focus on the origin and propagation of detonations in coal pipes. The test program carried out at CEGB divided into three series. The first two series concerned pipeline fires as possible trigger ignitions for detonations using intense, localized fire sources and large, persistent fire sources. The third test series used the combined pulverizer volume/coal pipe geometry with the ignition source within the pulverizer volume. The 0.6 m (24 in) diameter straight pipe of the apparatus reduced the number of interacting parameters influencing the initial testing. The test rig had a maximum instrumented length of 41 m (135 ft) when the simulated pulverizer was used. Four coals covering a wide range of characteristics were selected for testing[5]. Table II gives the proximate analyses and Table III gives the size distributions.

EXPLOSION TESTING USING PIPELINE FIRE IGNITION SOURCES

The T-injector ignition source was a 0.45 m^3 (16 ft^3) side chamber attached to the coal pipe and charged with a mixture of propane/air or pulverized coal/air mixture set off by an electrically fired ignitor. The expanding mixture burst a light diaphragm and entered the test pipe as a jet of flame. Figure 4 plots the maximum pressure recorded at a transducer versus the location of the transducer and includes tests with and without suspended coal dust in the main pipe for the same strength of the T-injector source. The figure shows that the observed low pressure levels are the result of the T-injector charge bursting into the pipe rather that any combustion of the coal dust mixtures in the main pipe. Since these tests provide a good simulation of actual coal pipe conditions, it is possible to conclude that vigorous but short lived fire events originating in the coal pipe would not trigger a detonation in that coal pipe.

A "burning bed" ignition source was used to simulate large, persistent pipeline fires. This gas fired ignitor is 25 cm (10 in.) wide and adjustable in length up to a maximum of 2.5 m (8.37 ft). The firing rate produced a heat flux of 363 kW/m^2 (0.115 $MMBtu/hr/ft^2$) which was sufficient to keep the stainless steel grate covering the burners at surface temperatures between 700°C (1300°F) and 900°C (1650°F). This condition corresponds roughly to a bed of coke burning at 1000°C (1830°F)[4].

Coal	Moisture Content (Raw/Pulv) (%)	(%)	Pulverized, Dry Basis Volatile (%)	Ash (%)	Fixed Carbon (%)	Coal Heating Value (kJ/kg)
Pennsylvania Bituminous	4.3	1.5	18.2	18.8	63.0	23,020
Oklahoma Bituminous	3.8	1.5	38.6	12.1	49.3	30,620
North Dakota Lignite	32.8	13.1	41.5	10.5	48.0	24,400
Wyoming Subbituminous	27.9	17.3	41.3	7.1	51.6	28,030

Table II Coal Characteristics of the Explosion Test Coals

Coal	British Grind	Mass % Through Sieve %-18	%-35	%-60	%-140	%-200
Pennsylvania Bituminous	SF250	100.	100.	100.	98.6	88.1
Oklahoma Bituminous	SF250	100.	100.	100.	97.4	88.9
North Dakota Lignite	SF250	100.	100.	100.	98.9	89.7
Wyoming Subbituminous	SF250	100.	100.	100.	97.1	85.8
Wyoming Subbituminous	M190	100.	99.8	96.2	69.1	52.4
Wyoming Subbituminous	CM100	99.9	85.7	55.5	24.5	15.9

Table III Size Distribution of Coals Used in the Explosion Tests

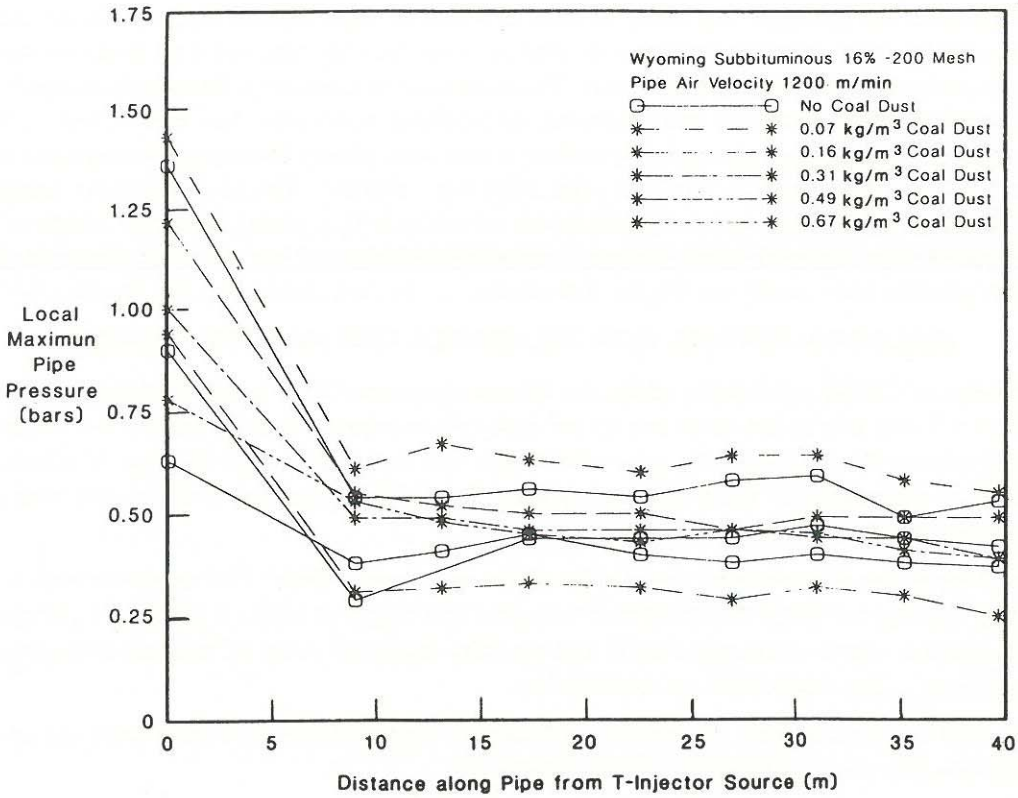

Figure 4 T-injector Source Pipeline Fire Results

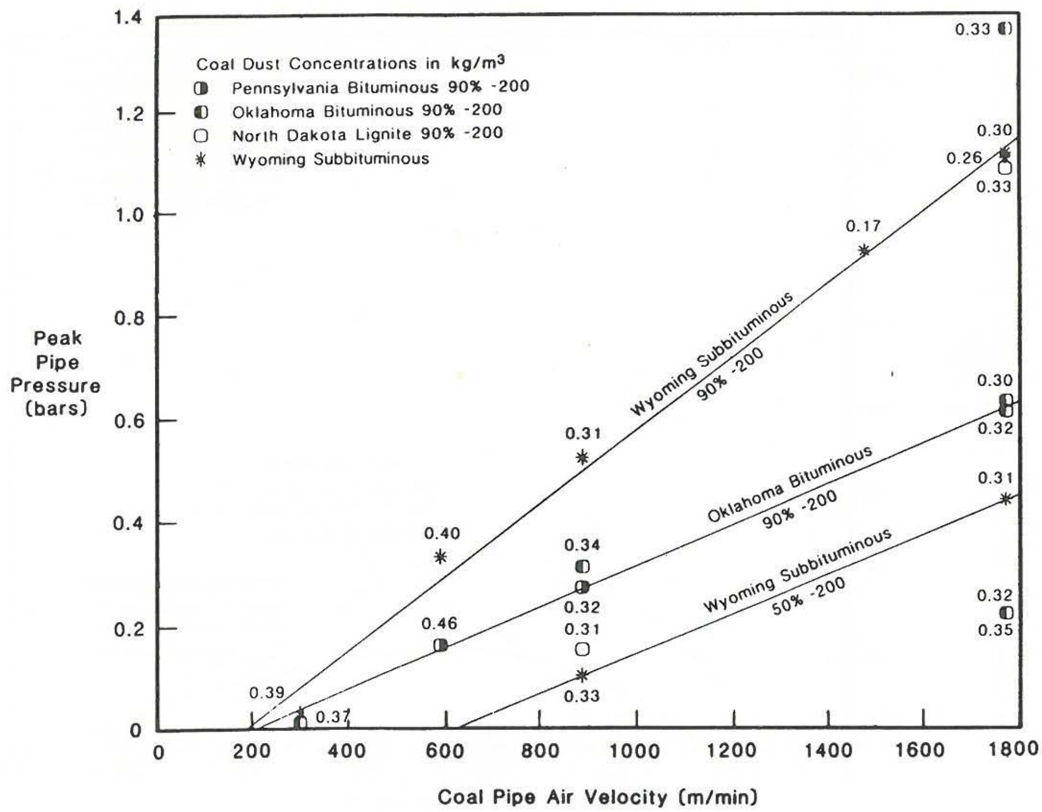

Figure 5 Burning Bed Source Pipeline Fire Results

Figure 5 presents the results of this series of tests as a plot of peak pipeline pressure versus coal pipe air velocity. The figure shows a strong influence of pipe air velocity, coal type and coal grind on the relatively low pressures created by the burning bed ignitor. The most reactive coals were fine grinds (roughly 90% -200 mesh) of the Oklahoma bituminous and Wyoming subbituminous samples. The lines in Figure 5 for these two coals indicate that pressures generated by coal pipe fires were almost linearly proportional to air velocity for a given coal type. The coal type fixed the proportionality constant[5]. The peak pressures remained small over the wide range of velocities tested. Typical design velocities in U.S. plants fall in the middle of the range shown in Figure 5 where the peak generated pressures would be below 0.7 bar (10 psig). Again the test results indicate that pipeline fires would not trigger detonations in the pipe containing the pipeline fire.

EXPLOSION TESTING WITH PULVERIZER FIRE IGNITION SOURCES

The last series of CEGB experiments added the volume representative of a full sized pulverizer. The vessel volume of 21 m^3 (742 ft^3) in full form and 15 m^3 (530 ft^3) in reduced form preserved the vessel/coal pipe interface and venting characteristics of a generalized pulverizer rather than a specific type. The ignition source was moved back upstream into the pulverizer volume. Two types of ignition sources were used in various locations relative to the pulverizer coal pipe interface:

1. The T-injector was attached to the middle of the vessel and charged with approximately 0.1 kg (0.22 lb.) of finely ground coal dispersed in the injector and triggered with a 5 kJ (5 Btu) chemical ignitor. This ignition source represents a small but vigorous dispersed cloud of burning coal particles which could enter a pulverizer from an external fire.
2. Two 5 kJ chemical ignitors, the energy equivalent of approximately 0.4 gram (0.01 oz) of coal, gave a reproducible source of modest energy release rate.

Figures 6, 7 and 8 plot the maximum pipe pressure, maximum vessel pressure, and maximum flame velocity respectively as functions of coal concentration. Prominent are high values for peak pressure in the pipe (up

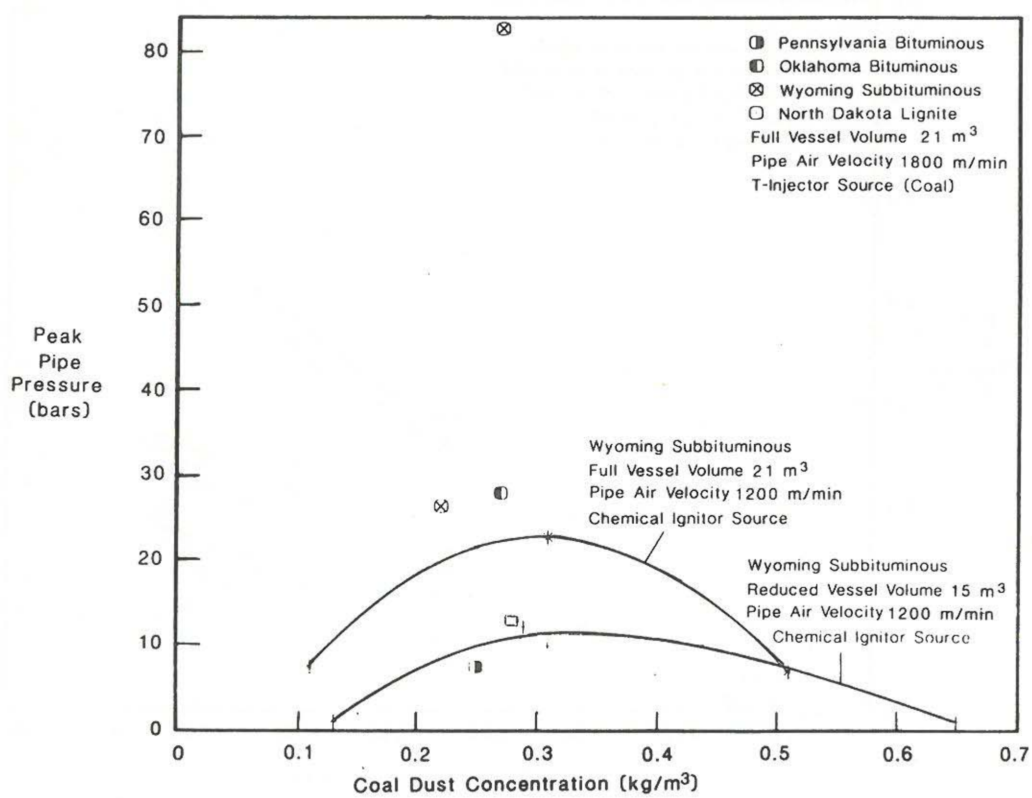

Figure 6 Mill Fire Results — Pipeline Pressures

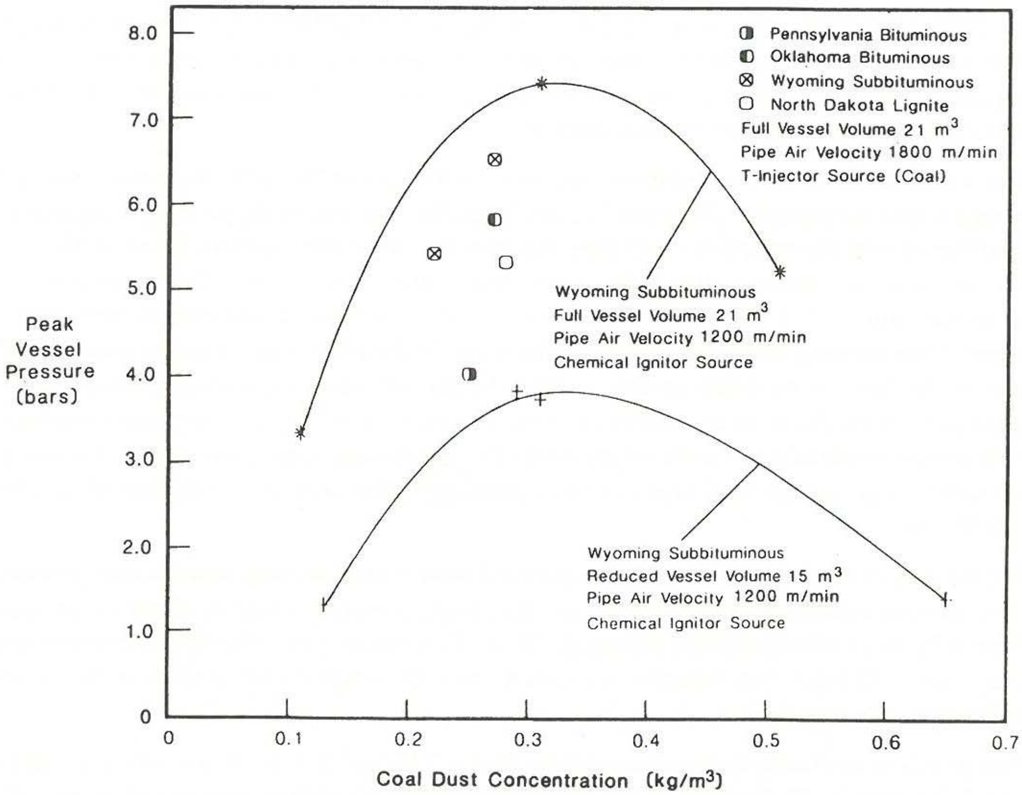

Figure 7 Mill Fire Results — Vessel Pressures

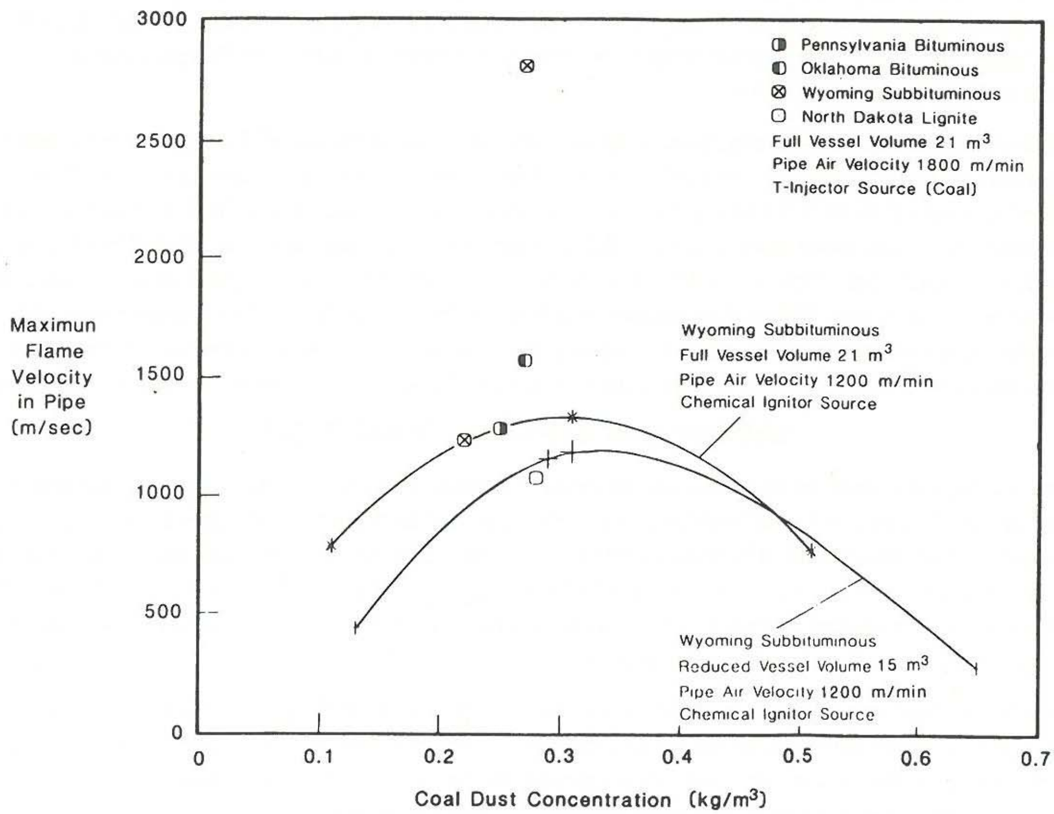

Figure 8 Mill Fire Results — Pipeline Flame Speeds

to 82 bar, 1190 psig), peak pressure in the pulverizer (up to 7.4 bar, 107 psig), and flame speed in the pipe (up to 2850 m/sec, 9350 ft/sec). These results are impressive because energy sources are small as a teaspoonful of burning coal triggered a detonation force while large pipeline fires produced low level pressure events. The vessel/pipe explosion tests may be summa rized as:

1. The origin and growth of an explosion requires the interaction of events in a vessel/pipe geometry containing a dust suspension. The word "vessel" signifies that any properly sized volume (i.e. pulverizer, classifier or fan) connected to a coal pipe may host the originating ignition event. A fire of even modest size and intensity enters a dust laden vessel and ignites the contents. The vessel pressure and flame front vent into a dust laden coal pipe. Pressure wave turbulence and compression effects appear to enhance the burning and speed of the flame front in the pipe. Pipe pressure rises above 10 bar (145 psig) as the flame front speeds up and narrows the gap between itself and the pressure wave downstream in the pipe. If the flame front catches up to the pressure wave, they coalesce into a burning shock front with almost instantaneous rates of pressure rise, supersonic speed, and pressure levels exceeding 70 bar (1015 psig). Longer coal pipe runs may produce higher pressure levels than these observed in the CEGB tests.

2. The buildup of the burning flame front/pressure wave system moving downstream generates a pressure front moving upstream toward the vessel. This rising pressure is held in check by an expansion wave created by the coalescence into the shock front. This return wave system can pressurize the vessel to over 7 bar (100 psig) even though the pressure from the original deflagration in the vessel was vented safely into the coal pipe.

3. Fine grinds of coal with dust concentrations near 0.3 kg/m^3 (0.3 oz/ft^3) produce the largest pressures and flame speeds. Higher and lower dust concentrations produce weaker explosions when all other conditions are held constant.

4. A reduction in the ratio of vessel volume to coal pipe area reduces the peak values of pressure and flame speed in an event. As vessel volume decreases, the venting of vessel pressure and flame from a trigger fire is less intense producing a less intense detonation force. A 28% reduction in vessel volume reduced peak pressures 50%.

The data shown in Figures 4 to 8 represent the appropriate maximum values from each test condition. Considerably more data are available for each test run. Fast response pressure transducers and flame detectors were stationed every 2 m (6.5 ft) along the test pipe and every 1 m along the final 4 m (13 ft). The signals were recorded on a high speed magnetic tape drive. After a test run the tape was played back at a very slow speed to drive a multi-pen chart recorder. This technique produced detailed space-time pressure and flame front histories for each run. Figure 9 is the detailed history for one of the mill fire source runs which turned out to be the most dramatic event observed during the testing. The figure shows the flame front speeding up and catching the pressure wave to coalesce into a burning shock with a dramatic change in the pressure trace.

LABORATORY STEAM INERTING TESTS

Fenwal conducted a series of experiments on steam inerting. The goal was to determine the minimum quan tity of steam need to prevent a detonation in a pulverizer isolated from coal pipes and air ducts and filled with a reactive coal dust cloud. Oklahoma bituminous coal ground to 75% -200 mesh was injected into a 1.90 m3 (67 ft^3) vessel to form a uniform cloud of 0.40 kg/m^3 (0.40 oz/ft^3) coal concentration in the 120°C (250°F) vessel air. Controlled amounts of steam were bled into the vessel. A nitrocellulose ignitor was triggered 0.3 seconds after the steam was introduced into the vessel.

The results of these tests are given in Table IV. Repeated tests at 18% steam by volume failed to produce an event, whereas lesser amounts of steam failed to inert the vessel. It was concluded that a minimum steam volume of 18% provided a non-explosive environment in the simulated isolated pulverizer. However, under-inerting with steam appears to lead to a more explosive condition in the mill. If a heat source is present, small amounts of steam may participate in gasification reactions with coal to produce highly combustible and explosive gaseous species. The 18% minimum value is related specifically to this experiment and further testing is necessary to determine a correlation for field application.

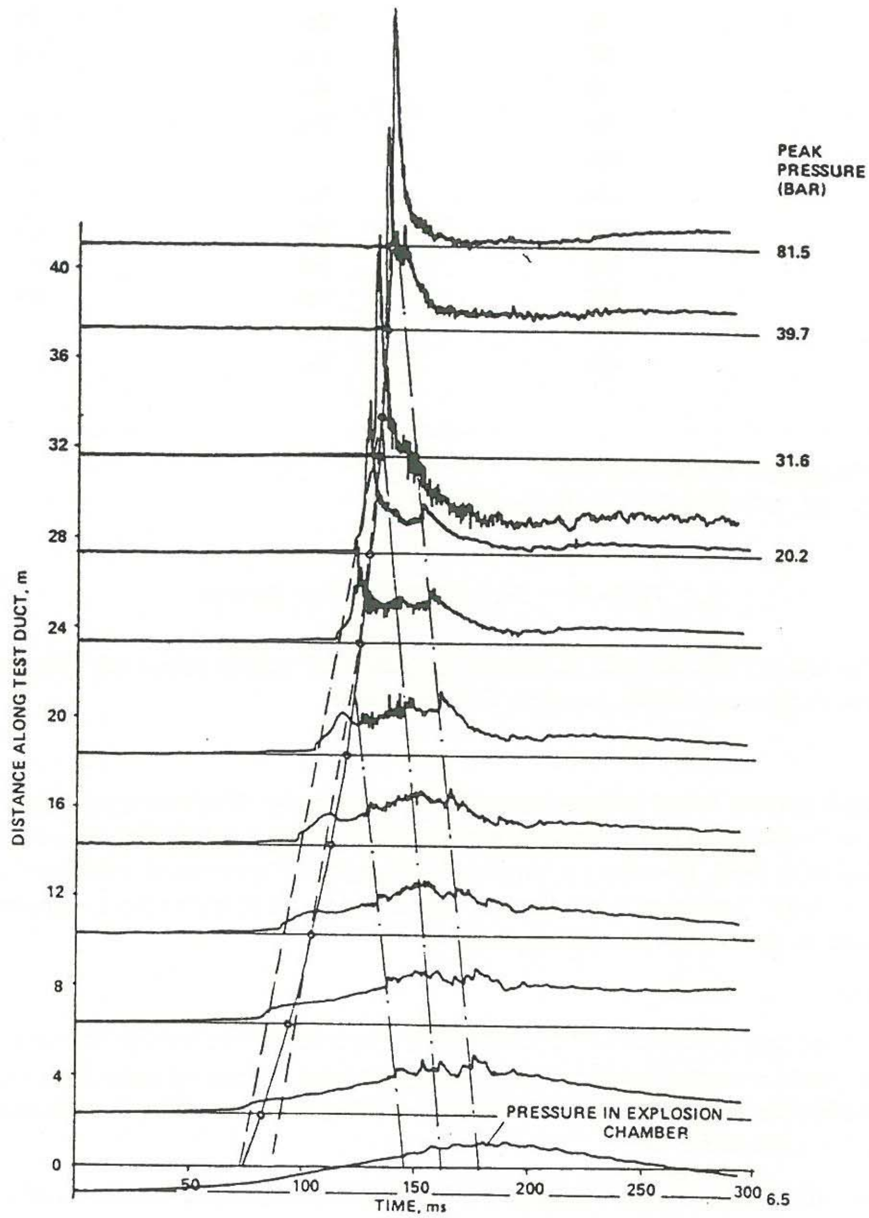

Figure 9 Sample Detailed Pressure Transducer and Flame Detector Traces

CONCLUSIONS

The survey results indicate that there is no single condition or combination of conditions that is always present in explosion situations. The laboratory test results are to be considered general in nature and are not directed at any specific plant. The creation of explosions evolves from a complicated interaction of variables. The conclusions drawn from the results are not absolute and contain exceptions. Therefore initiation of any pulverizer system modifications without a thorough analysis may produce results directly contrary to those desired.

There were two general conclusions reached in the study. First, not all fires cause explosions, however all

% Steam by Vol	Steam Pressure (mm Hg)	Explosive Event	Maximum Pressure (bar)
5	38	Yes	57
10	76	Yes	57
12	91	Yes	58
13	99	No	—
13	99	Yes	65
14	106	Yes	68
15	114	No	—
15	114	Yes	67
16	122	No	—
16	122	Yes	68
18	137	No	—
18	137	No	—

All tests with Oklahoma bituminous coal
98% -5, 72% -20, at 0.40 kg/m^3 (0.40 oz/ft^3)

Table IV Steam Inerting Test Results

explosions were caused by fires. Second, transients in a pulverizer system operation, planned or unexpected, represent the most dangerous periods for explosion formation.

Coal Type

The type of coal is a major factor influencing explosion frequencies. Units using subbituminous coals show twice the explosion frequency of units with bituminous coals. Firing a subbituminous coal does not indicate a hazardous situation by itself. However, when joined with other characteristics, subbituminous coals appear to exaggerate any sensitive condition. Fuel changes should not be made until after a complete analysis of the fuel has been made to determine the coal's reactivity.

Pulverizer Systems

Direct fired systems have exhibited half the explosion frequency of bin storage systems. Because flue gas is used as the pneumatic transport medium in bin storage systems, personnel assume an inert gas is present. However, load changes, leakage in the system, or malfunctioning dampers can increase oxygen concentrations to levels suitable for explosions.

The experiments show that the size relationship of pulverizer, classifiers, crushers and fans to coal pipes is crucial in explosion origin and growth. The relative sizes determine whether or not a detonation can occur as well as the magnitude of the resultant forces. Detonation evolution requires a change in volume and must originate in a pulverizer system component other than a coal pipe. While a fire is located in a coal pipe, it can not trigger a detonation. However, if the fire moves and enters a piece of equipment of different size and venting characteristics, then the probability of an explosion increases. The relocation of a fire from one component of a pulverizer system to another can create a detonation.

Pulverizer Age

The more experienced plants have lower explosion frequencies. However, complicating this statement are the fact that unit capacity, number of pulverizers, and pulverizer capacity are smaller for older units than newer units. The type of coal and type of operation are additional factors affecting experience. Because there is a correlation of lowered explosion frequencies with improvements in maintenance and operating procedures, it is important that procedures be reviewed periodically.

Pulverizer Type and Operation Mode

The historical trends show vertical spindle pulverizers have experienced twice the explosion frequency of ball tube pulverizers and five times the frequency of attrition pulverizers. Pressurized pulverizer operation shows a lower frequency of explosions than suction pulverizer operation for all pulverizers. Characteristics beyond the pulverizer type are involved, making it difficult to determine exact sensitivity of pulverizers to coal types.

Inerting Systems

The survey results show that the frequency of explosions is higher at units firing subbituminous coals whether or not an inertant was in use. The data does indicate problems with steam inerting systems. Inerting is no guarantee of explosion elimination and if it is determined that it is necessary, extreme care must be exercised. Additional instrumentation and controls are required. Extensive training is important to as sure full understanding of the system by operational and maintenance personnel.

Summary

The experiments confirm that explosions can not occur in equipment in a fuel rich state. This implies that, at full fuel capacity flow conditions, an explosion can not occur. However, unnoticed disruptions in fuel flow can reduce the fuel rich condition in one or more of the system components. In addition, testing indicates that the more powerful the ignition source the richer the mixture that can support an explosion. Detection and control of small fires reduces the risks of explosions for all operating conditions.

REFERENCES

1. R. C. Carini, K. R. Hules, and D. R. Broske, "Coal Pulverizer Fires and Explosions: Detection, Prevention, and Control", preliminary draft, Electric Power Research Institute (EPRI), October 1984.
2. R. C. Carini, K. R. Hules, and D. R. Broske, "Historical Trends In The Occurrence Of Fires And Explosions In The United States Pulverized Coal Fired Utility Industry", EPRI Symposium on Coal Pulverizers, Denver, CO, November 1985.
3. R. C. Carini, K. R. Hules, C. B. Santanam, D. R. Broske, and J. P. Gillis, "The Relative Effectiveness of Different Agents In Dealing With Coal Pulverizer Fire and Explosion Prevention", Coal Technology Conference, Houston, TX, November 1984.
4. B. R. Gardner, R. J. Winter, M. J. Moore, D. R. Broske, and R. C. Carini, "Some Explosion Tests On Typical American Coals", EPRI Symposium on Coal Pulverizers, Denver, CO, November 1985.
5. R. C. Carini, K. R. Hules, and D. R. Broske, "Experimental Results of Pulverized Coal System Fire and Explosion Testing", EPRI Symposium on Coal Pulverizers, Denver, CO, November 1985.