Technical Publication

Coal Pulverizer Explosions

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ABSTRACT

During 1981 the Electric Power Research Institute (EPRI) began a research program to study pulverized coal fires and explosions in the U.S. utility industry. Historical trends resulting from an industry wide survey and experimental results of explosion related testing are discussed. The survey indicates that explosive events are occurring at a rate of approximately one explosion for each unit every three years. The historical trends show that although coal type has a large influence on 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 that remained within the coal pipe created only weak pressure rise, while ignition events within the simulated pulverizer volume created explosions exceeding 1000 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. A description of pulverizer systems, unit hardware and characterization of the coal was sought by the survey. 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 average survey value of 0.31 explosions per year per unit shows a rise over previous averages.[1] Adjusted for the entire pulverizer coal fired utility industry, there is almost one explosive 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. It must be emphasized that the survey reflects the situation at the end of 1981 and some of the values may no longer apply. Since the survey, many plants have made modifications which have lowered their problem occurrences.

SURVEY DATABASE

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

Item	No. of Pulv.	Min	Max	Average
Pulverizer Age (Years)	1684	1	44	19
Pulverizer Capacity(Tons/Hour)	1678	3	100	31.50
Pulverizers per Boiler	1678	2	12	4.75

Table I Sample Database Population Statistics

Analysis of the database used a statistical approach to categorize a plant's particular configuration with respect to explosion frequencies. Categories useful for industrial applications 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 of the database shows that the explosion hazard level 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. Therefore, 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. Figures 1 and 2 show the data for each of the characteristics. It is important to note that, because of the general nature of this phase of the discussion, not all units will follow or agree with the overall trends. Recognizing the statistically weak influence of these parameters, the following trends were observed:

1. Pulverizer System Operation Mode: Bin storage units have twice the explosion frequency as 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 the ball pulverizers and about five times that of the attrition pulverizers. With bituminous coals the vertical spindle pulverizers show a higher explosion frequency while the ball and attrition pulverizers

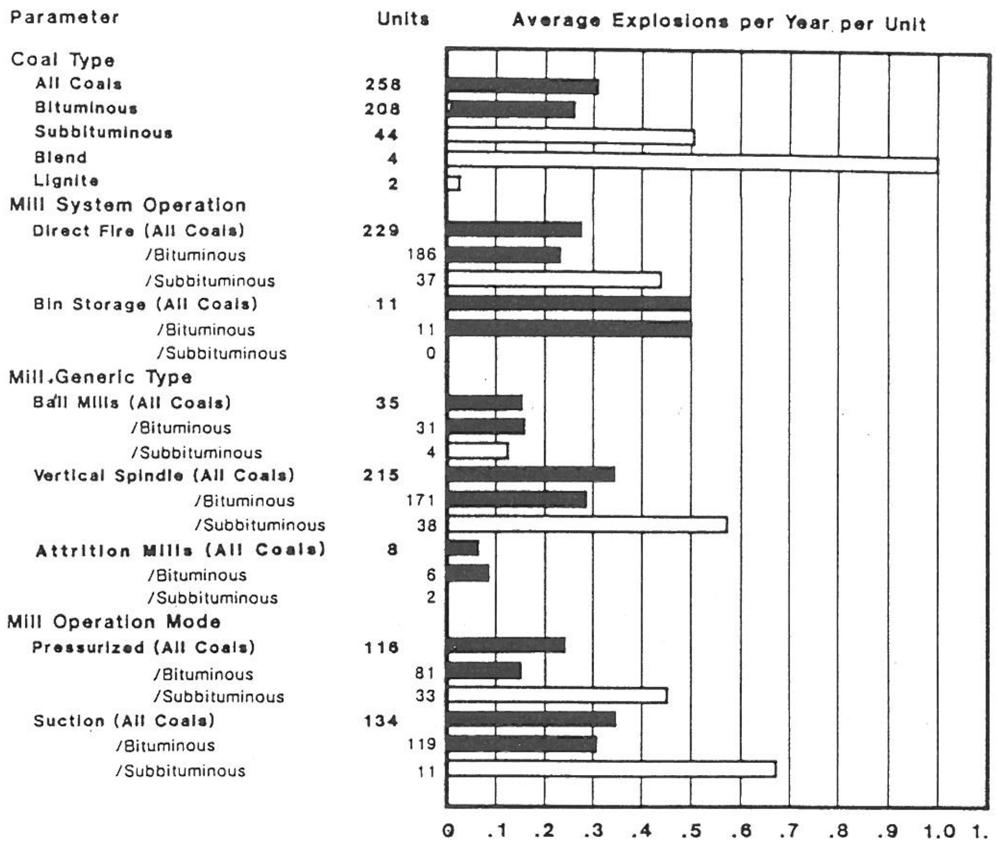


Figure 1 Average Explosions per Year per Unit for Four Classification Type Parameters

have equivalent lower frequencies. Also, subbituminous grinding vertical spindle pulverizers have about twice the explosion frequency of bituminous grinding vertical spindle pulverizers.

3. Pulverizer Operation Mode: The suction operation pulverizers have a slightly higher explosion frequency than pressurized pulverizers. The trend is re-emphasized by the coal type. Subbituminous coals accentuate the difference.

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. Units firing bituminous coals have a reduction in explosion frequency with an increase in pulverizer capacity. Units firing subbituminous coals experience an increase in explosion frequency with an increase in pulverizer capacity.

5. Number of Pulverizers per Unit: Explosion frequency increases with an increasing number of pulverizers per unit. Once again coal type produces two opposing conditions. Units firing bituminous coals 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: 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.

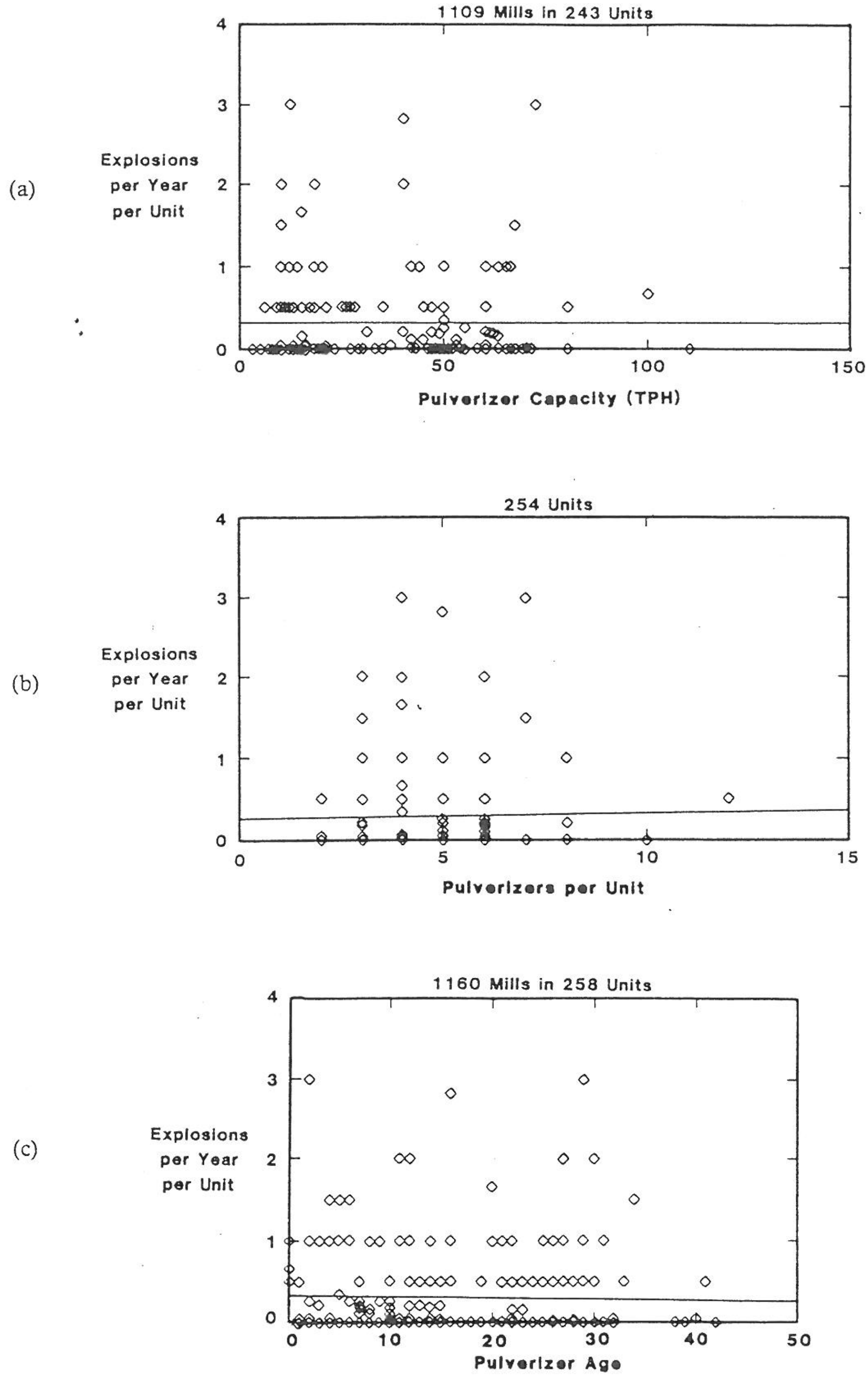
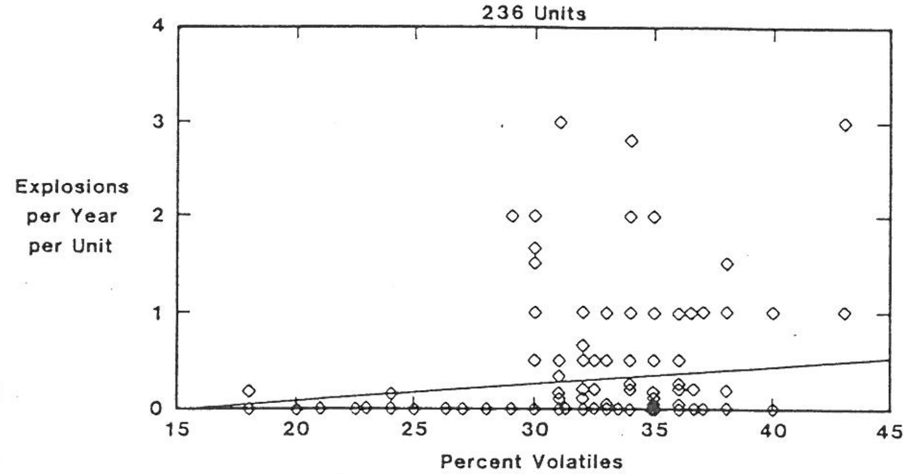
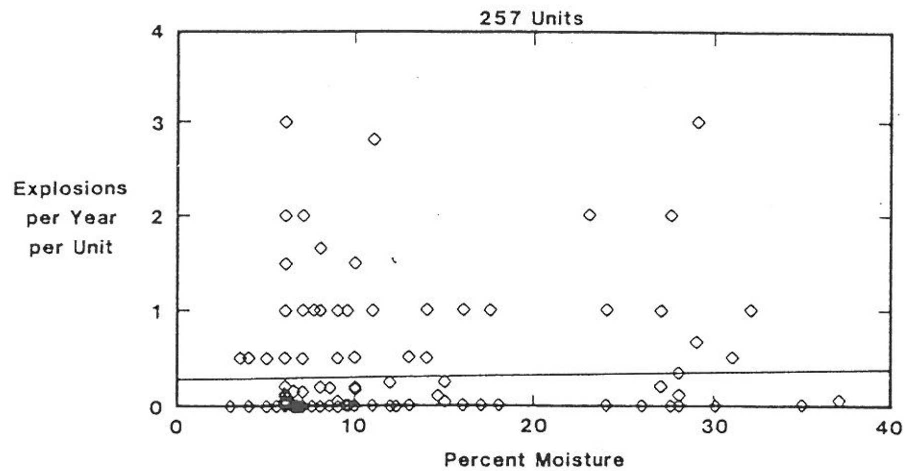


Figure 2 a, b, c   Explosions per Year per Unit for Six Range Type Parameters

(d)



(e)



(f)

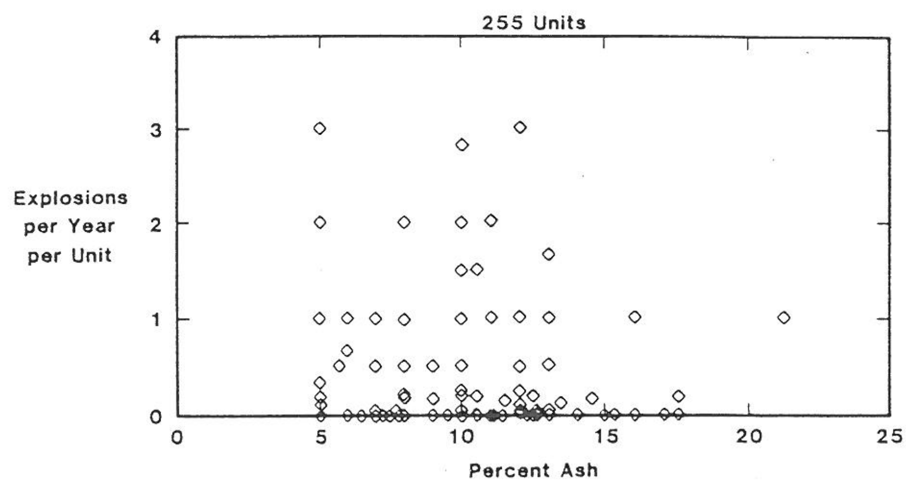


Figure 2 d, e, f   Explosions per Year per Unit for Six Range Type Parameters

8. Coal Volatility: Explosion frequency increases with an increase in volatility content, but this trend is as weak statistically as the other categories.

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.

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 the frequency of events but rather focuses on the interrelationship of fires, explosions, and plant characteristics. A major finding is that explosions do not occur in proportion to the number of fires at a unit. 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), the 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.

Because inerting agents are used to prevent something from happening, explosion frequency can be used to gauge the effectiveness of inerting agents in preventing explosions. Four inerting agents including "None" were identified in the survey. Figure 3 shows the explosion frequency for "CO_2", "N_2", and "Steam", as well as the groups "None" and "Unknown". The group "None' are units reporting no inerting agents. 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 comprised of units firing bituminous coals, while the "Steam" group contains 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. The survey does not distinguish between explosion experience before or after the installation of inerting systems.[3]

LABORATORY EXPERIMENTS

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, regarding 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.

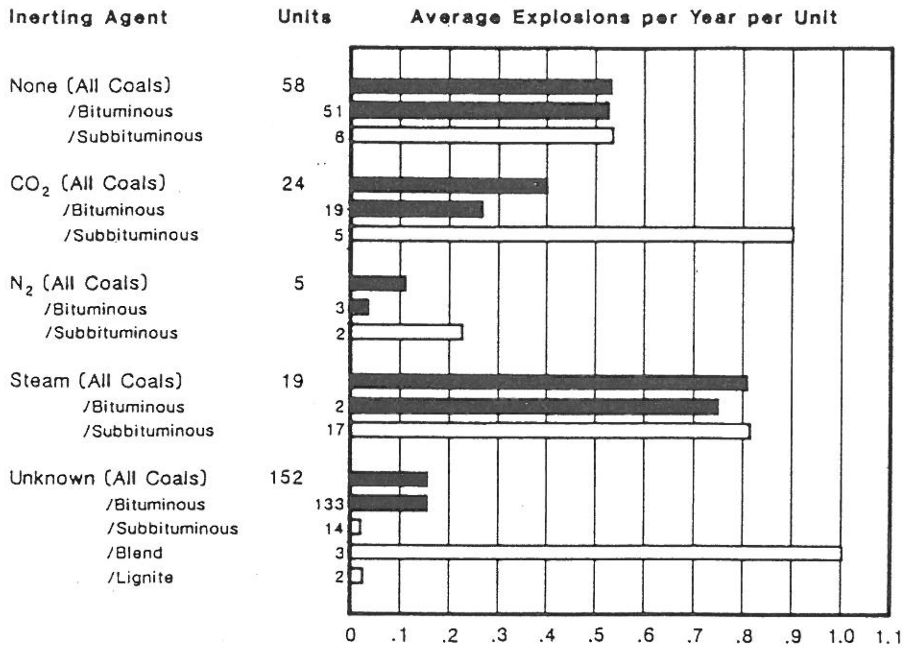


Figure 3 Average Explosions per Year per Unit Versus Three Inerting Agents Used by U.S. Utilities

FULL SCALE EXPLOSION TESTS

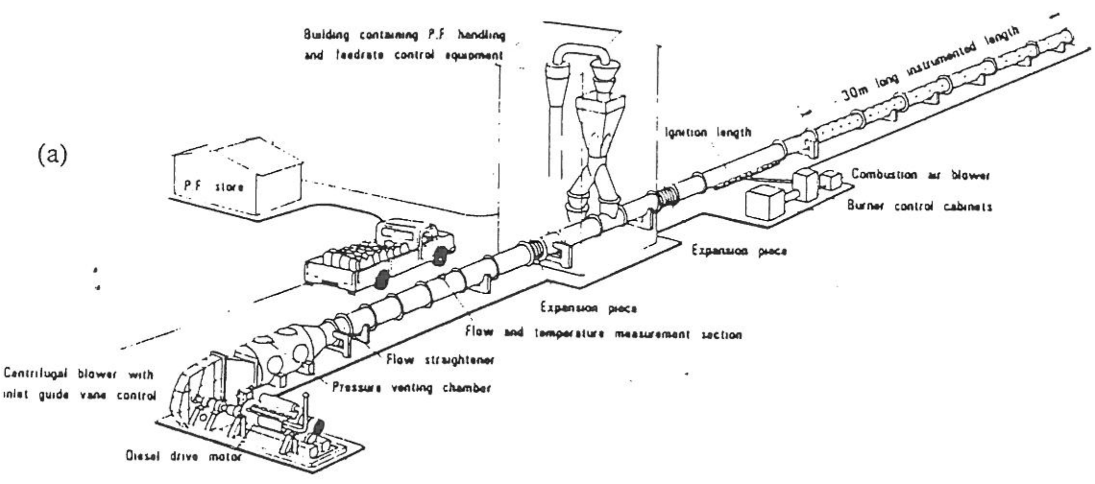
Figure 4 is a schematic of the CEGB explosion test facility built to focus on the origin and propagation of explosions in coal pipes. The test programs carried out at CEGB divided into three series. The first two series concerned pipeline fires as possible trigger ignitions for explosions using intense, 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 simple straight pipe layout shown in the figures reduced the number of interacting parameters influencing the initial testing. The program apparatus had a maximum instrumented length of 134.5 feet when the simulated pulverizers were used as shown in Figure 4b. 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 of the pulverized coals.

EXPLOSION TESTING USING PIPELINE FIRE IGNITION SOURCES

The 16 cubic foot T-injector shown in Figure 5 simulates a sudden eruption of a coal pipe fire when used in the Figure 4a arrangement. Figure 6 plots the maximum pressure recorded at a transducer versus the location of the transducer and includes tests with and without suspended coal dust 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 than any combustion of the coal dust mixtures. 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.

THE CEGB EXPLOSION TEST FACILITY, PIPELINE FIRE CONFIGURATION

(a)



THE CEGB EXPLOSION TEST FACILITY, MILL FIRE CONFIGURATION

(b)

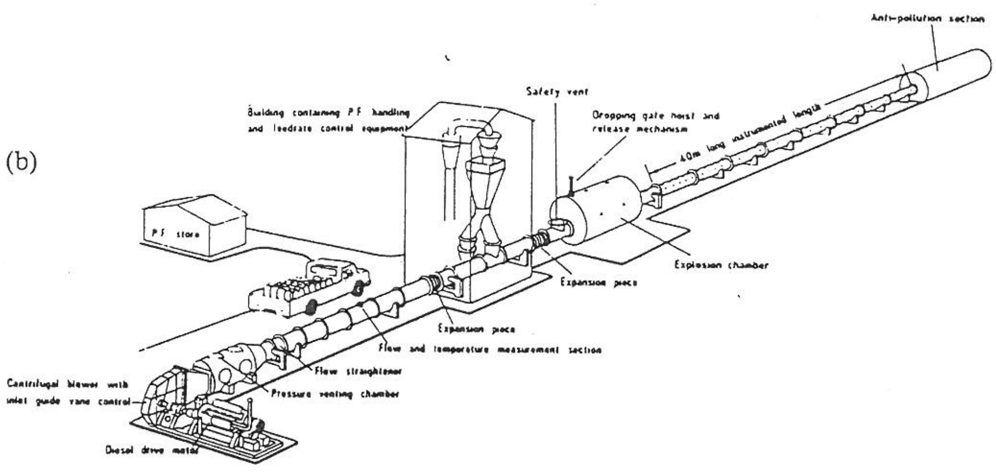


Figure 4 a, b The CEGB Explosion Test Facility

Coal	Moisture Content (Raw/Pulv.) (%)	(%)	Pulverized, Dry Basis Volatiles (%)	Ash (%)	Fixed Carbon (%)	Coal Heating Value (Btu/lb)
Pennsylvania Bituminous	4.3	1.5	18.2	18.8	63.0	12,046
Oklahoma Bituminous	3.8	1.5	38.6	12.1	49.3	13,164
North Dakota Lignite	32.8	13.1	41.5	10.5	48.0	10,490
Wyoming Subbituminous	27.9	17.3	41.3	7.1	51.6	12,051

Table II Coal Characteristics for Coals Used in the Explosion Tests

Coal	Grind	Mass % Through Sieve %-18	%-35	%-60	%-140	%-200
Pennsylvania Bituminous	SF 250	100.	100.	100.	98.6	88.1
Oklahoma Bituminous	SF-250	100.	100.	100.	97.4	88.9
North Dakota Lignite	SF 250	100.	100.	100.	98.9	89.7
Wyoming Subbituminous	SF 250	100.	100.	100.	97.1	85.8
Wyoming Subbituminous	M 190	100.	99.8	96.2	69.1	52.4
Wyoming Subbituminous	CM 100	99.9	85.7	55.5	24.5	15.9

Table III Size Distribution of Coals Used in the Explosion Tests

Figure 7 is a schematic of the "burning bed" ignition source used to simulate large, persistent pipeline fires. This gas fired ignitor is one foot wide and adjustable in length up to a maximum of 8.37 feet. The firing rate produced a heat flux of 0.115 MBtu/hr/ft^2 which was sufficient to keep the grate at surface temperature between 1300°F and 1650°F. This condition corresponds roughly to a bed of coke burning at 1830°F.[4]

Figure 8 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 8 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 8 where the peak generated pressures would be below 10 psig. The test results indicate that pipeline fires will not trigger detonation in the pipe. However, Figure 8 does indicate that pipeline fires may give rise to low level pressure events which may reach the burners and furnace.

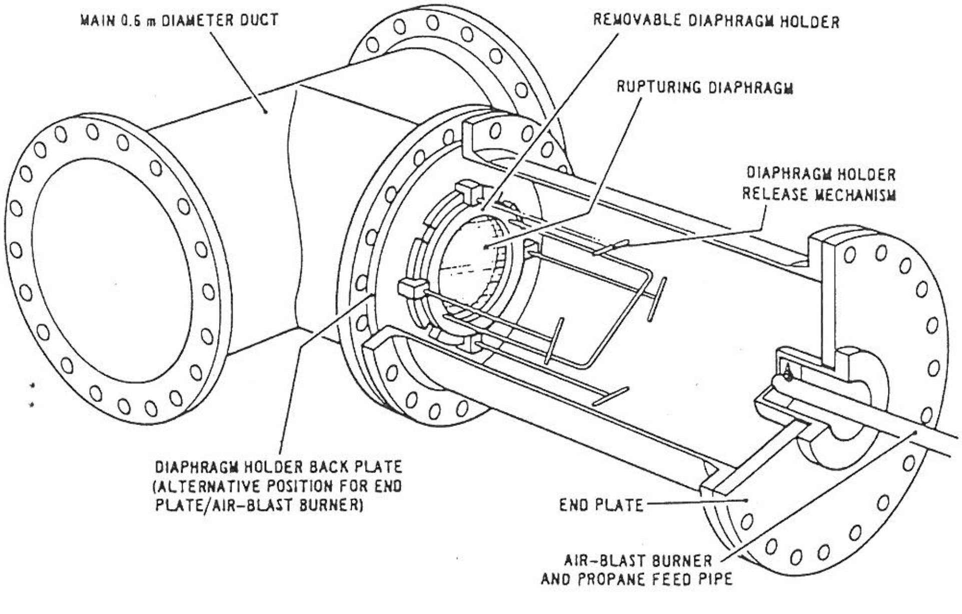


Figure 5 The CEGB "T-Injector" Flame Ignition Source

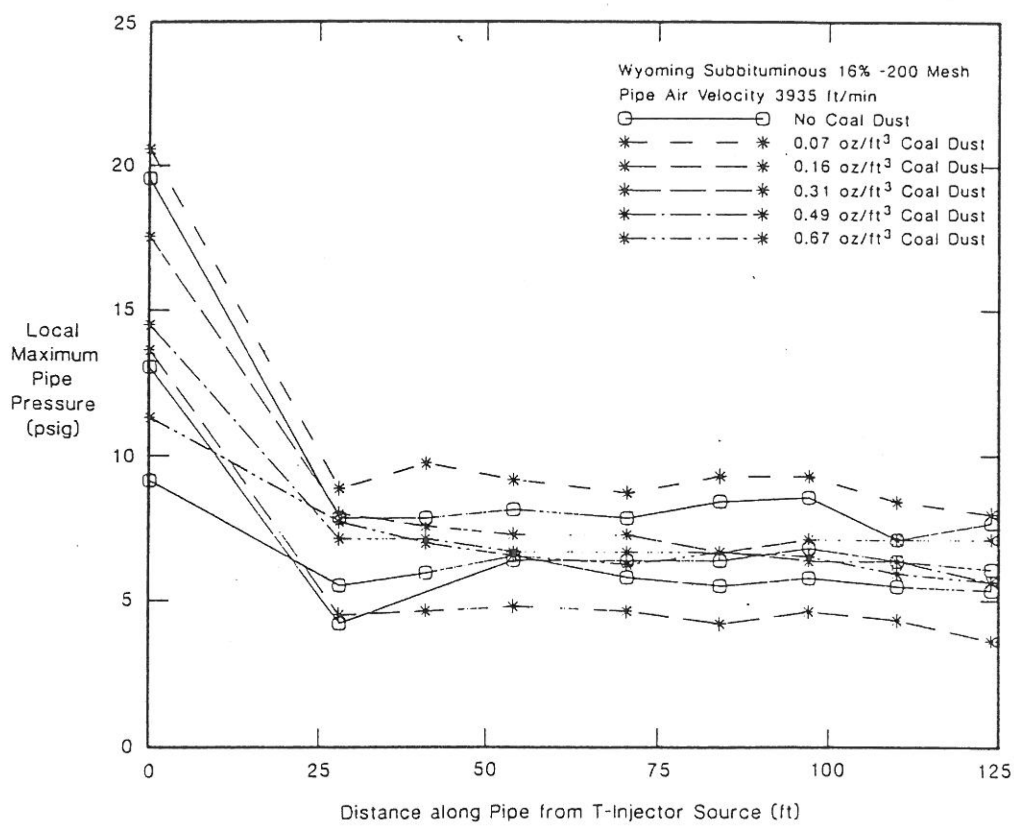


Figure 6 Local Maximum Pipe Pressure Versus Position Along the Coal Pipe for Explosion Testing Using the T-Injector Source in the Coal Pipe

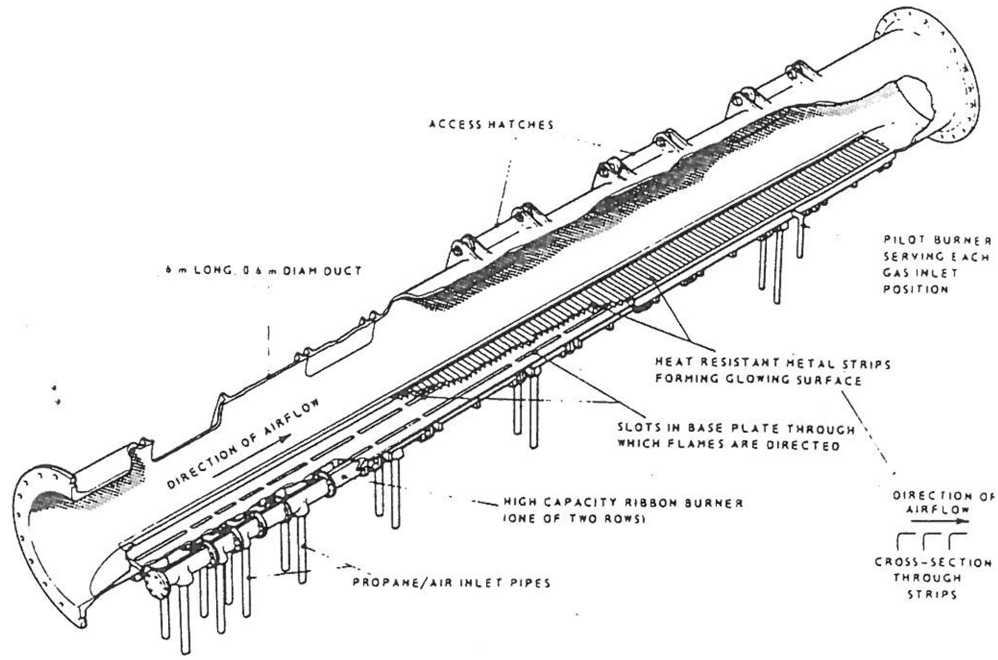


Figure 7 The CEGB "Burning Bed" Ignition Source

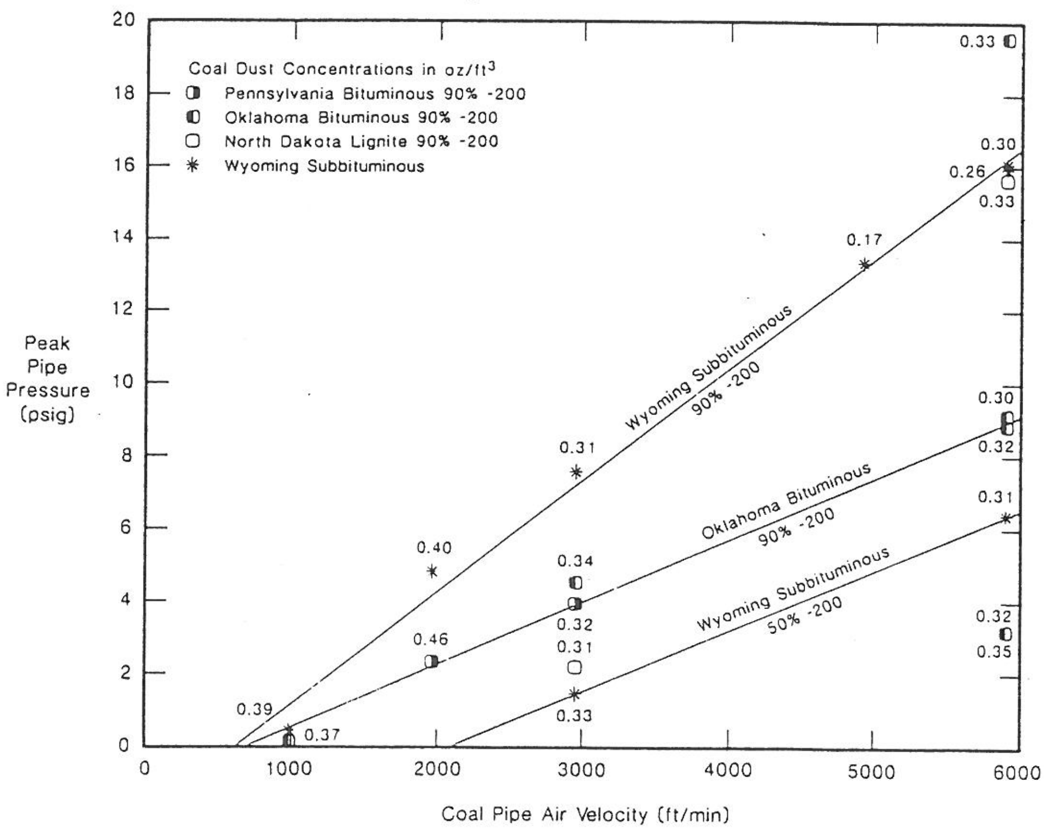


Figure 8 Peak Pipe Pressure Versus Coal Pipe Air Velocity for Explosion Testing Using the Burning Bed Ignition Source

EXPLOSION TESTING USING PULVERIZER FIRE IGNITION SOURCES

The last series of CEGB experiments added the remaining major coal system component, the volume representative of a full sized pulverizer as shown in Figure 4b. The vessel volume of 742 cubic feet in full form and 530 cubic feet 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 0.2 pounds of finely ground coal dispersed in the injector and triggered with a 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 Btu chemical ignitors, the energy equivalent of approximately 0.02 oz. of coal, gave a reproducible source of modest energy release rate.

Figures 9, 10 and 11 plot the maximum pipe pressure, maximum vessel pressure, and maximum flame velocity respectively as functions of coal concentration. Prominent are the high values for peak pressure in the pipe (up to 1180 psig), peak pressure in the pulverizer (up to 107 psig), and flame speed in the pipe (up to 9350 ft/sec). These results are impressive because energy sources are small as a teaspoonful of burning coal triggered detonation while large the pipeline fires produced low level pressure events. The vessel/pipe explosion tests may be summarized 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 source. A fire of even modest size and intensity enters a dust laden vessel and ignites the contents. The vessel pressure and flame fronts vent into a dust laden coal pipe. The pressure wave turbulence appears to enhance the burning and speed of the flame front in the pipe. Pipe pressure rises to several hundred psig as the pressure wave pulls the flame front into itself downstream in the pipe. If the flame front catches up with the pressure wave, they coalesce into a burning shock front (i.e., detonation) with almost instantaneous rates of pressure rise, supersonic speed and pressure levels exceeding 1000 psig. Longer coal pipe runs may produce higher pressure levels.
2. The expansion of the burning flame front/pressure wave system moving downstream generates a pressure front moving upstream toward the vessel. This rising pressure is terminated by an expansion wave created by the coalescence into the shock front. This return wave can pressurized the vessel to over 100 psig.
3. Fine grinds of coal with dust concentrations near 0.3 oz/ft3 produce the largest pressures and flame speeds. Higher and lower dust concentrations produce weaker events, 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 explosion. A 28% reduction in vessel volume reduced peak explosion pressures 50%.

LABORATORY STEAM INERTING TESTS

Fenwal conducted a series of experiments on steam inerting. The goal was to determine the minimum quantity of steam need to prevent an event 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 67 cubic foot vessel to form a uniform cloud of 0.40 oz/ft^3 coal concentration in the 250°F vessel air. Specific amounts of steam were bled into the vessel. A nitrocellulose ignitor was triggered 0.3 seconds after the steam was introduced into the vessel.

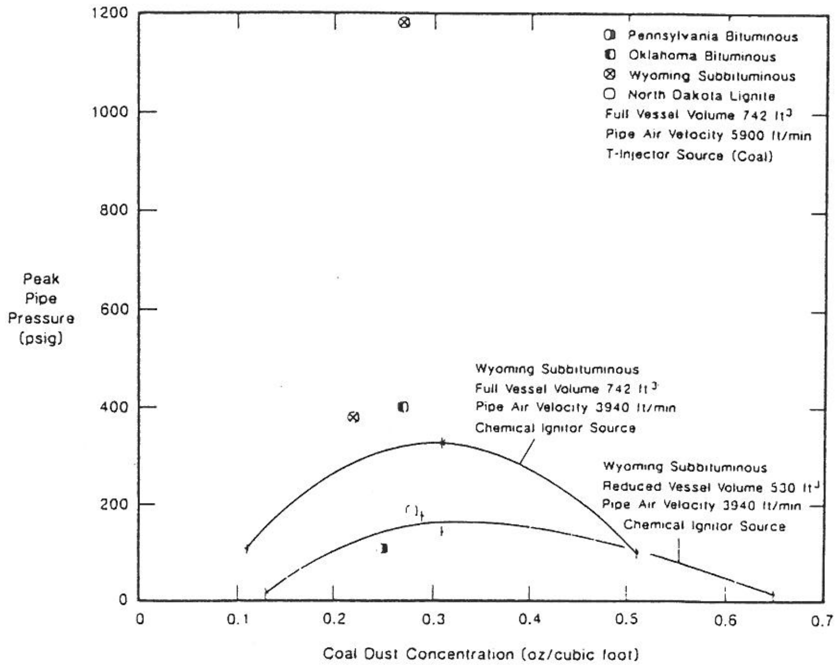


Figure 9 Maximum Pipe Pressures Versus Coal Dust Concentrations for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition

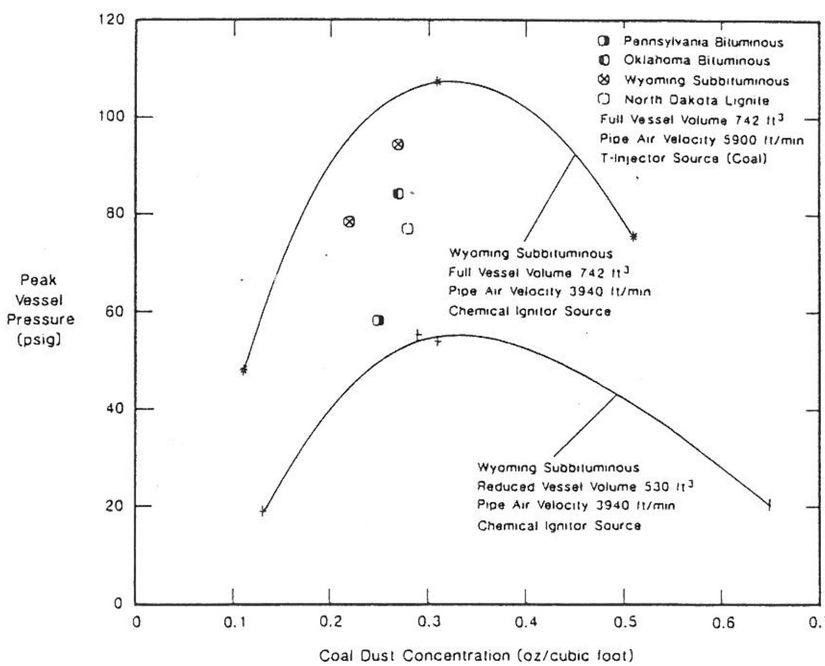


Figure 10 Maximum Vessel Pressures Versus Coal Dust Concentrations for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition

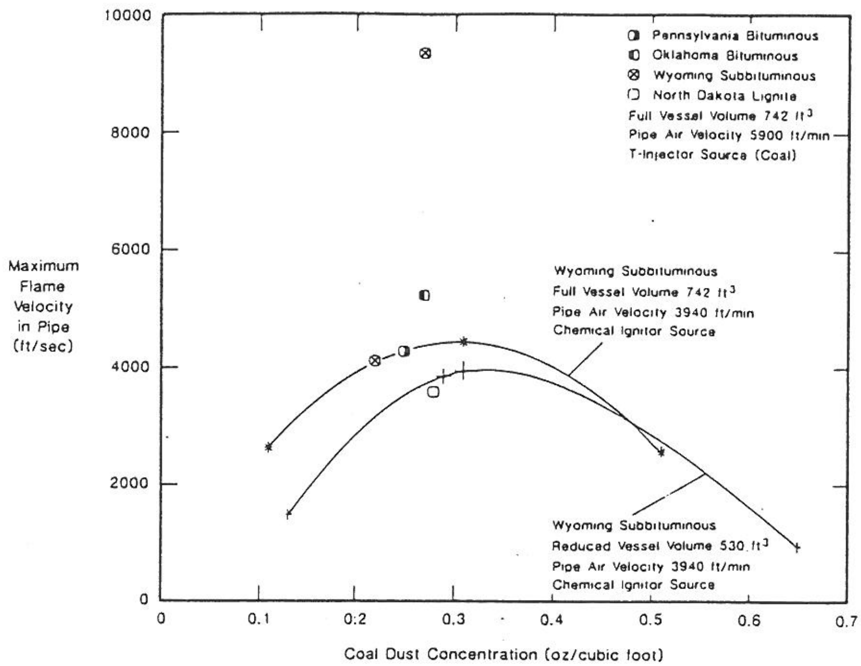


Figure 11 Maximum Flame Speed Versus Coal Dust Concentration for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition

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-detonation environment in the simulated isolated pulverizer. However, under-inerting with steam appears to lead to a more explosive condition in the mill. One hypothesis is that small amounts of steam participate in gasification reactions with coal to produce highly combustible and explosive gaseous species. The 18% minimum value shown above is related specifically to this experiment. Further testing is necessary to determine whether or not this is practical for field application.

Percent Steam by Volume	Steam Pressure (mm Hg)	Explosive Event	Maximum Pressure (psig)
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, 98% -5, 72% -20, 0.40 oz/ft^3

Table IV Steam Inerting Test Results

CONCLUSIONS

The conclusions stated in this report are derived from statistical analysis of the survey process and laboratory testing. The survey results indicate that there is no single condition or combination of conditions that is always present in explosion situations. The laboratory testing 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 and the conclusions 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 explosions were caused by fires. Second, all explosions were reported to occur during start-up, shut down, feed interruption or other transient conditions.

Coal Type

The type of coal is a major factor in explosion frequencies. Units using subbituminous coals show twice the frequency of explosions as units with bituminous coals. Firing a subbituminous coal does not indicate a hazardous situation by itself. There are many utilities operating with subbituminous coals that are reporting explosion frequencies below the norm. However, when joined with the other characteristics, subbituminous coals appear to exaggerate any sensitive condition. The survey sampling with lignite is too small to allow any evaluation. The blending of coals, though it can not be used statistically, does indicate possible operational problems. Blends that are not homogeneous force pulverizer operation to react to changes in fuel characteristics. Follow-up interviews revealed that units that have converted to washed coal, for economic or environmental reasons, have had a marked decrease in explosions as a side benefit.

Fuel changes should not be made until after a complete analysis of the fuel has been made to determine the coal's reactivity. Because the characteristics of the coal show one of the strongest influences on explosion frequency, any changes in coal supply would have an effect on a plant's frequency of explosions.

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, the plants may 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 increased. The relocation of a fire to other components of a pulverizer system such as the classifier, crusher, fan or pulverizer can create a detonation.

Pulverizer Age

The more experienced plants have lower explosion frequencies. However, complicating this statement are the facts 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. There is a correlation of lowered explosion frequencies with improvements in maintenance and operating procedures. Interviewers reported that plants that have instituted improved maintenance or operating procedures have lowered their frequencies of explosive events. Also, equipment manufacturers periodically modify their recommended maintenance procedures and replacement parts. It is important that plants with concerns review their maintenance and operating procedures and periodically contact the equipment manufacturers.

Pulverizer Type and Operation Mode

The survey results show vertical spindle pulverizers have experienced twice the explosion frequency of ball pulverizers and three 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. Many vertical spindle pulverizers are in suction operation and grind subbituminous coals. The interrelationship of various factors make it impossible to determine how sensitive pulverizers are to coal types.

Inerting Systems

The survey responses showed that less than one-fifth of all units use inerting systems. Comparing all other units to the units with inertants, plants without inerting systems have lower explosion frequencies. In every case the frequency of explosions is higher with subbituminous coals. The information on inertants is not conclusive, but does reveal concerns that require further investigation. If it is determined that an inerting system is necessary, additional instrumentation and controls are required. Extensive training is important to assure full understanding of the system by operational and maintenance personnel. Inerting is no guarantee of elimination of explosions, but with extreme care, the frequency of explosions may be reduced.

In summary, the experiments confirm that explosions can not occur while equipment is 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.

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