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ABSTRACT

Under an Electric Power Research Institute (EPRI) program, bench and large pilot scale laboratory tests were conducted to investigate the mechanisms of coal pulverizer fires and explosions. Bench scale laboratory tests were used to determine the effectiveness of gaseous, liquid and solid fire extinguishing agents. Liquid/solid agents extinguished the fires faster than the gaseous agents although flow mode application of some gaseous agents approached liquid/solid agent performance. Steam results showed an increased fire life with a range of application amounts. Full scale laboratory test rigs were used to create and monitor coal system explosions on demand. The tests were designed to answer fundamental questions about explosion origin and growth. Fast acting flame probes and pressure transducers provided detailed flame and pressure histories throughout the apparatus. Ignition events within the coal pipe created only weak pressure rises while ignition events within the mill volume created explosions exceeding 1000 psig. Explosion strength was shown to depend on dust concentration, ratio of mill volume to coal pipe area, as well as coal type.

ACKNOWLEDGEMENT

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INTRODUCTION

Recent EPRI sponsored research[1] shows that U.S. pulverized coal fired utility plants experience a wide range of fire and explosion frequencies. Plants range from fire and explosion free operation to many fires and/or explosions per year per unit. The historical data show that the industry's frequency of fires and explosions is increasing. Along with these occurrences there is increased industry interest in fire detection and control, and explosion prevention and suppression.

Historical fire data can not give any information about the effectiveness of fire extinguishing agents. Because of event variability and limited fire detection systems at operating plants, the evaluation of an extinguishing agent is essentially subjective. To alleviate these problems laboratory experiments were conducted at Fenwal, Inc. (Fenwal) in Ashland, Massachusetts. The controlled conditions of the experiments provide the first indications of effectiveness for various extinguishing agents. However, field testing and observation must be the ultimate testbed for acceptance. The laboratory experiments provide initial screening. They point out the most promising candidates, amounts and techniques.

Many theories and opinions exist to explain explosion origins. However, the fundamental questions of where and how an explosion is triggered are unanswered. In order to obtain an understanding of explosion origin and growth, full scale coal pipe and simulated mill tests were conducted at the Central Electricity Generating Board's (CEGB) Explosion Test Facility in Foulness, England[2]. 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 permited detailed measurements to be made for understanding growth mechanisms of pulverized coal system explosions.

PULVERIZER FIRE EXTINGUISHING TESTS

The utility industry uses a fairly wide variety of fire extinguishing agents. Most of these agents were tested in experiments at Fenwal: water, steam, CO_2, N_2, foam, lime, Halon 1301, Hymix (50% mixture by weight of Halon 1301 and monobasic ammonium phosphate), laboratory flue gas (15% moisture, 15% CO_2, 4% O_2, 66% N_2), and wetted water (water plus 1% wetting agent to reduce surface tension).

The experiments involved simulated deep seated pulverizer fires. The tests were conducted in a 12 cubic foot drum simulating a coal mill as shown in Figure 1. The drum end had either a 1-inch or 3-inch hole to control air leakage. The 1-inch hole simulated new, tight-fitting dampers with a leakage flow of 10% of full mill air flow rate. The 3-inch hole simulated aged dampers with a leakage flow of 30% of full mill air flow rate. Two thermocouples were mounted in the pulverizer, one in the center of the fire, the other three inches from the top of the mill, directly above the fire location. The temperature readings were used to determine if the fires were comparably active and when agent should be released. A fire was considered extinguished when the temperature at the upper thermocouple dropped to 125°F.

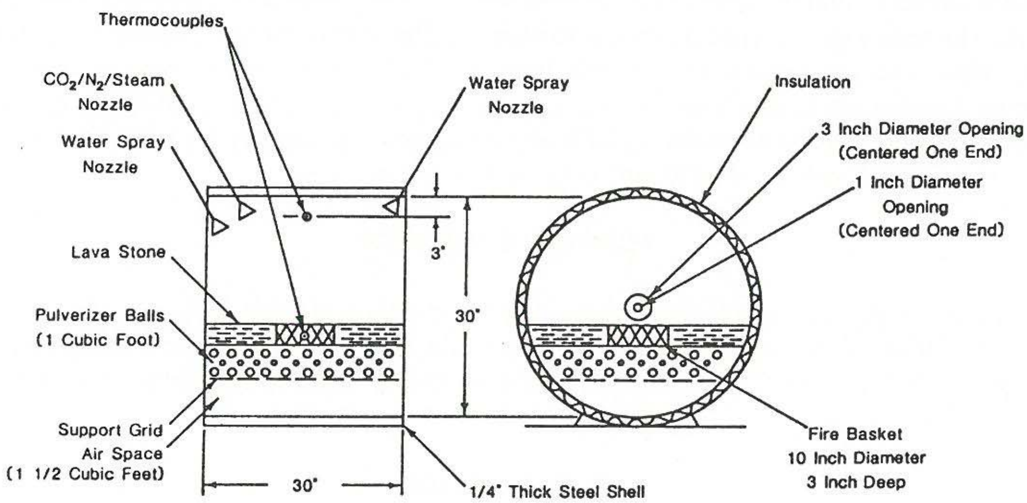

Figure 1 The Fenwal Simulated Mill for Testing Fire Extinguishing Agents

In each test, a similar subbituminous coal mass was placed in a metal basket 10 inches in diameter by 3 inches deep, ignited, and allowed to come to full burn before being inserted in the simulated pulverizer. Various types and amounts of extinguishing agents were applied to the fire through nozzles mounted at the top of the pulverizer. Two modes of agent application were used: dump and flow. In dump mode, a fixed volume of agent was released almost instantaneously. In flow mode, the agent was released at a fixed flow rate over a long period of time. All agents were tested with the 1-inch diameter damper air flow. The most effective agents were tested with the 3-inch diameter damper airflow.

Tables I, II and III present the fire extinguishing test results. The measure of agent effectiveness is the percent decrease in free burning time, computed as the difference between untreated and treated burn times divided by the untreated burn time. These results are plotted in Figures 2, 3 and 4. Three separate figures are needed as a direct result of the differences between liquid/solid and gaseous agents. The large difference in scale of mass applied during a test requires separating the liquid/solid agents from the gaseous agents. Gaseous agents work on a volume basis by displacing oxygen needed for combustion. Liquid/solid agents work on a surface coating basis by forming combustion blockage layers on the coal. These factors point to a weight basis for comparing liquid/solid agents and an equivalent mill volume basis for comparing gaseous agents. Liquid/solid agents would be applied most often in a burst or dump mode. Gaseous agents may be applied in either a dump mode or a flow mode requiring an effectiveness picture for both techniques. The fire extinguishing test results may be summarized as:

1. High air flow rates through a mill during a fire extinguishing process degraded the performance of all extinguishing agents, the higher the air flow rate the poorer the agent performance.
2. Liquid/solid agents work better than gaseous agents on fires in a mill with its contents at rest. Motion of the mill contents during fire treatment will require larger application amounts.
3. Foam and lime showed an "optimal amount" phenomenon for applications in a mill with non-moving contents. If less than the optimal amount was used, the burning time could be reduced by a larger application amount. If more than the optimal amount was used, the burning time did not fall below that of the optimal amount. The optimal amount phenomenon may not hold in a mill with moving contents due to motion induced dispersion of the agent.
4. Water and Hymix showed an enhancement effect for applications in a mill with non-moving contents. As more agent was applied the effectiveness increased faster than the increase in agent amount. This effect may not apply to a mill with moving contents.
5. Water treated with the wetting agent was less effective than plain water. Different concentrations of the same wetting agent or different wetting agents will give different results. Based on the limited tests above it is not possible to say that wetting agents for water are always detrimental to fire extinguishing effectiveness.
6. At 100% mill volume amounts, nitrogen was ineffective as a fire extinguishing agent.
7. Steam, CO_2, and flue gas were essentially equivalent in performance in dump mode and were better than nitrogen. However, they do not approach the performance of the liquid/solid agents.
8. Large amounts of steam showed a fire enhancing effect, causing the fire to burn longer than when smaller amounts of steam were used.
9. Halon 1301 begins to approach the performance of liquid/solid agents. The upswing in the curve means that as long as the mill can be made fairly airtight at the time of discharge, a critical minimum amount of Halon 1301 will produce essentially maximum fire extinguishing effectiveness. In these tests, the critical amount of Halon 1301 after release was equal to approximately ⅓ the mill volume. However, even with a realistically airtight mill, Halon 1301 does not produce the almost instantaneous fire quenching shown in its traditional applications.
10. Dump mode application of any gaseous agent (including Halon 1301) into an operating mill would be ineffective due to the rate of air movement through the mill.

11. Flow mode application of gaseous agents was more effective than dump mode and should be preferred. In flow mode gaseous agent performance approached that of liquid/solid agents due to the larger application amounts possible.

12. The testing does not show how much, how fast or how long to flow the gaseous agents for an arbitrarily chosen fire occurrence. There were indications that if a fixed mass of gaseous agent is to be applied, slower discharge rates and longer discharge times produce better performance.

13. In flow mode nitrogen and flue gas performed similarly and better than carbon dioxide.

Agent	Application Quantity/Duration (lbs)	(sec)	Max Temp at Upper Thermocouple (°F)	Time to 125°F at Upper Thermocouple (min)	% Decrease in Free-burning Time
			1-inch Diameter Opening		
None	—	—	515	114	—
Hymix	1.2	—	365	41	64.0
	.6	—	335	84	26.3
Foam	8.0	—	420	48	57.9
	4.0	—	855	40	64.9
Lime	2.8	—	705	69	39.5
	1.4	—	500	60	47.4
	.7	—	785	60	47.4
Water	7.0	60	415	22	80.7
	2.1	13	565	90	21.0
Wetted	11.4	60	718	40	64.9
Water	5.2	30	615	75	34.2
			3-inch Diameter Opening		
None	—	—	520	270	—
Hymix	1.2	—	905	60	77.8
Foam	8.0	—	1210	216	20.0
Water	8.4	60	1105	93	65.6

Table I Fire Extinguishing Test Results for Liquid/Solid Agents in Dump Mode

1-Inch Diameter Opening

Agent	Quantity (lbs)	Quantity (Equivalent) (Mill) (Volume %)	Max Temp at Upper Thermocouple (F)	Time to 125°F at Upper Thermocouple (min)	% Decrease in Free-burning Time
None	—	—	515	114	—
Halon 1301	2.3	50	385	64	43.9
	1.7	37	535	63	44.7
	.6	13	315	78	31.6
Flue Gas	.8	80	620	66	42.1
	.4	40	795	90	21.0
Steam	1.7	100	940	84	26.3
	.9	50	885	77	32.5
N_2	.9	100	570	104	8.8
	.5	50	630	108	5.3
CO_2	1.4	100	535	69	39.5
	.7	50	630	87	23.7

Table II Fire Extinguishing Test Results for Gaseous Agents in Dump Mode

1 - Inch Diameter Opening

Agent	Quantity (lbs)	Quantity (Equiv) (Mill) (Volume %)	Flow Rate (ft^3/ (min)	Discharge Duration (min)	Max Temp at Upper Thermo-couple (°F)	Time to 125°F at Upper Thmcpl (min)	Percent Decrease in Free-burning Time
None	—	—	—	—	515	114	—
Flue Gas	1.8	180	1.0	30	570	33	71.0
	1.0	100	.6	30	900	55	51.8
N_2	2.2	244	1.0	30	420	23	79.8
	1.7	189	.5	45	485	41	64.0
CO_2	5.2	371	1.0	45	590	38	66.7
	3.2	229	.5	55	325	50	56.1

Table III Fire Extinguishing Test Results for Gaseous Agents in Flow Mode

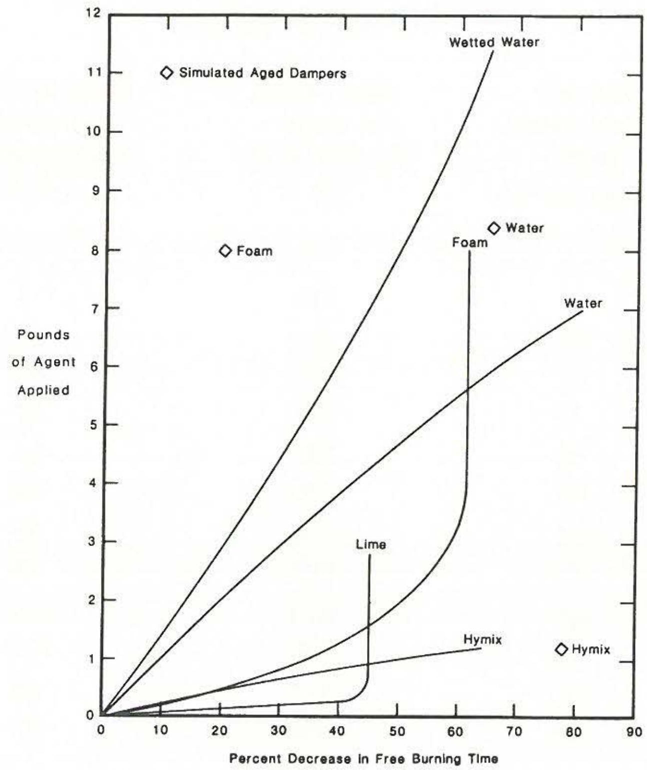

Figure 2 Approximate Effectiveness of Liquid and Solid Fire Extinguishing Agents Used in Dump Mode Application on a Test Fire in a Simulated Mill

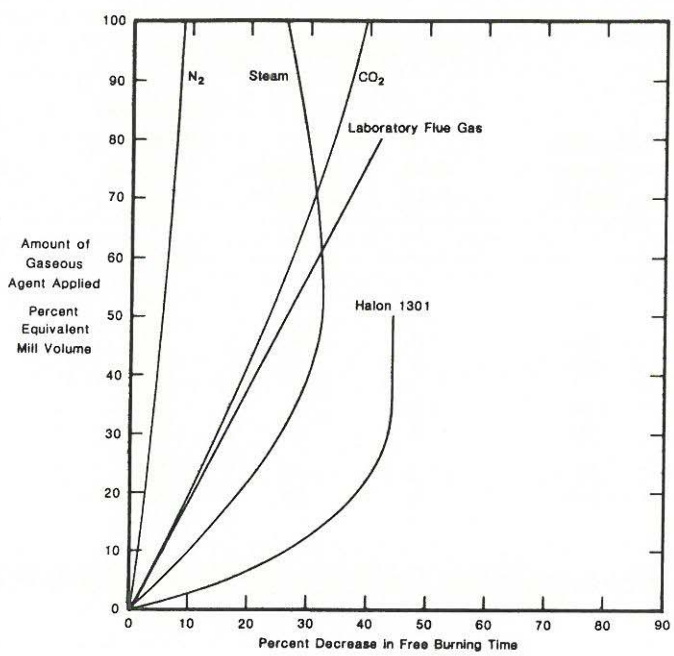

Figure 3 Approximate Effectiveness of Gaseous Fire Extinguishing Agents Used in Dump Mode Application on a Test Fire in a Simulated Mill

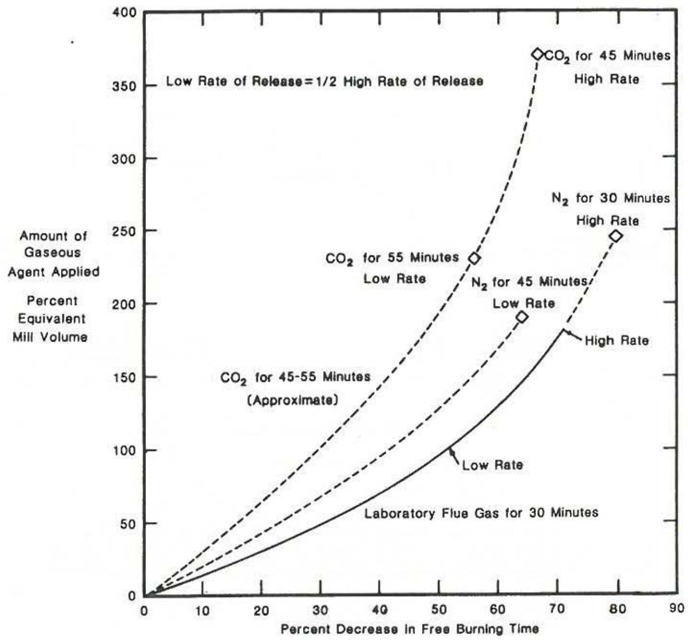

Figure 4 Approximate Effectiveness of Gaseous Fire Extinguishing Agents Used in Flow Mode Application on a Test Fire in a Simulated Mill

The specific numerical results of this testing are related to the size of the fire and pulverizer used in the experiments. These two variables affect the performance of the agents involved and further testing should be carried out to determine the overall effectiveness in a wider range of conditions.

PULVERIZER EXPLOSION STEAM INERTING TESTS

There is increased interest among utilities in the use of inerting agents, and a variety of agents are in use today. 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.

Fenwal conducted a series of experiments on steam inerting. The goal was to determine the minimum quantity of steam needed to prevent an explosion in a mill isolated from coal pipes and air ducts and filled with a reactive coal dust cloud. The tests were conducted in a 67 cubic vessel shown in Figure 5. Oklahoma bituminous coal ground to 72% -200 mesh was injected into the vessel to form a uniform cloud of 0.40 oz/ft3 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.

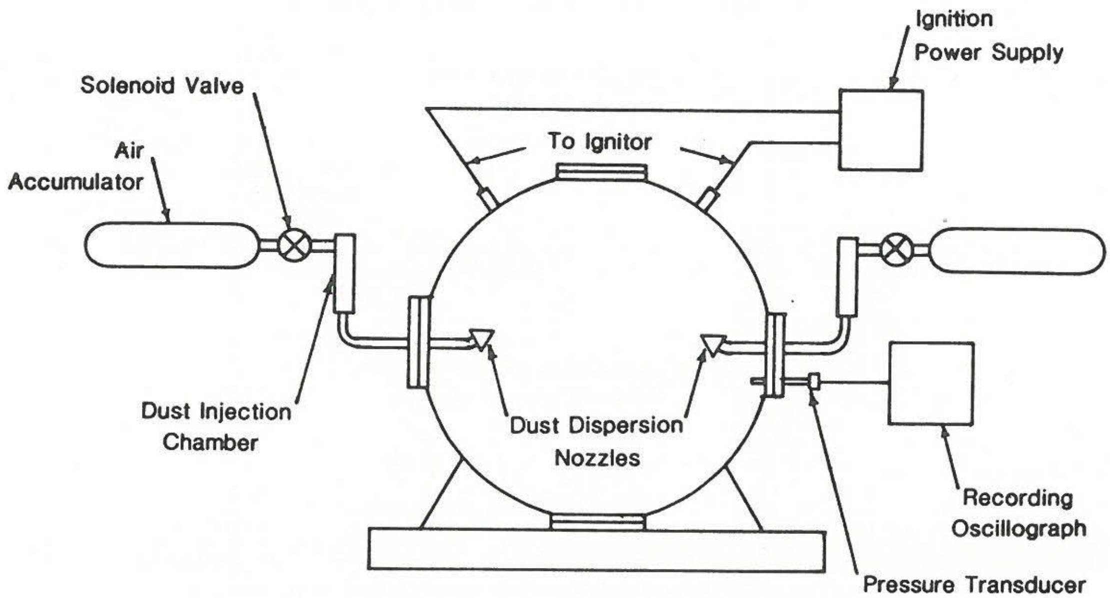

Figure 5 The Fenwal 67 Cubic Foot Vessel Used in Explosion Testing

The results of these tests are given in Table IV. Repeated tests at 18% steam by volume failed to produce an explosion, 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 mill. 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 the 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)	Explosion	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% -50, 72% -200, 0.40 oz/ft^3

Table IV Steam Inerting Test Results

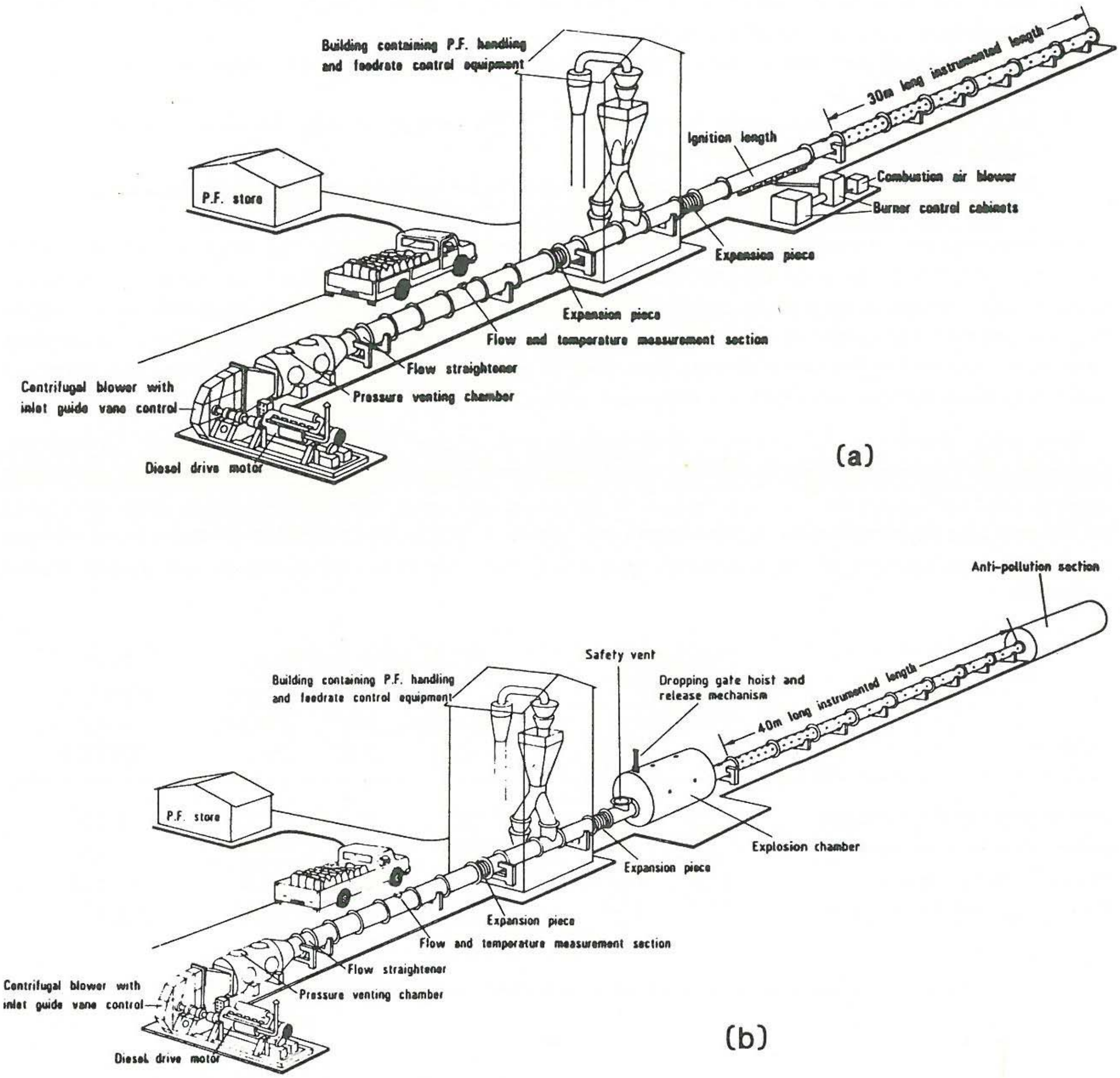

Figure 6 The CEGB Explosion Test Facility

PULVERIZED COAL SYSTEM EXPLOSION TESTING

The CEGB Full-Scale Explosion Test Facility

Figure 6 is a schematic of the CEGB explosion test facility built to focus on the origin and propagation of explosions in coal pipes. This facility contains many features important for fundamental and applied research on coal system explosions:

1. A 24-inch diameter pipe, which is a typical average coal pipe size for the utility industry. The full scale pipe eliminates uncertainties about effects of scale on ignition and flame propagation.
2. Control of dust concentration and transport velocity in the pipe over a wide range.

3. Large and small trigger ignition sources such as slow chemical ignitors, violent injections of burning masses, and reproducible pipeline fires.
4. A range of mill volumes upstream of the instrumented section with wide range of ignition trigger locations possible.
5. High speed pressure and flame front detection instrumentation at close intervals along the test section to provide detailed event histories.
6. Room for longer and more complicated pipe geometries including bends and obstructions.

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 mill volume-coal pipe geometry with the ignition source within the mill 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 mill volumes were used as shown in Figure 6b.

Four coals covering a wide range of characteristics were selected for testing: Pennsylvania bituminous, Oklahoma bituminous, Wyoming subbituminous, and North Dakota lignite. Table V gives the proximate analyses. Table VI gives the size distributions of the pulverized coals. The slightly coarser grind designated M 190 was considered typical of vertical spindle mill product. The very coarse grind designated CM 100 was considered representative of the size distribution within the body of a vertical spindle mill during normal operation.

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 V Coal Characteristics for Coals Used in the CEGB Explosion Tests

Coal	Grind	Mass Percent 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 VI Size Distributions of Coals Used in the CEGB Explosion Tests

Figure 7 is a schematic of the "T-injector" from which bursts a violently burning mass of gas. The T-injector simulates a sudden eruption of a coal pipe fire when used in the arrangement shown in Figure 6a. Table VII gives the test results while Figure 8 plots the maximum pressure recorded at a transducer versus the location of the transducer. Figure 8 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 small but short lived fire events originating in the coal pipe should not trigger an explosion in that coal pipe.

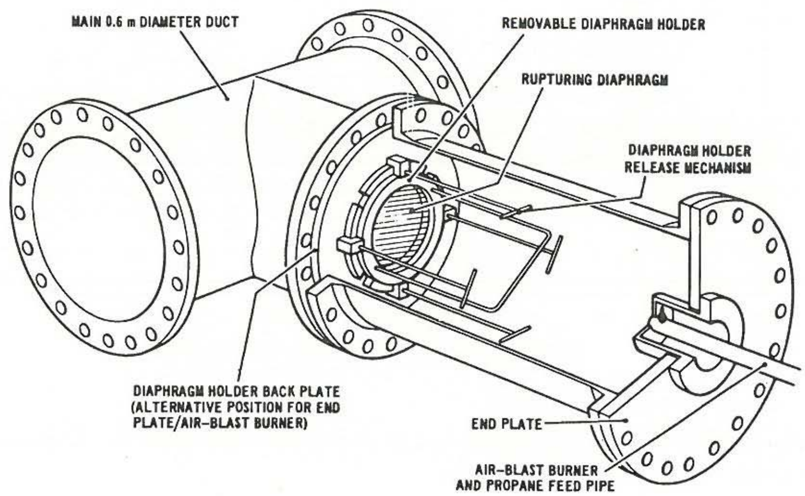

Figure 7 The CEGB "T-Injector" Injected Flame Ignition Source

Coal Dust Concentration (oz/ft^3)	Maximum Pressure (psig)*	Maximum Pressure (psig)**	Maximum Flame Velocity (ft/sec)
None	13.1	6.8	None
0.31	17.5	8.0	295
None	9.1	6.5	None
0.16	13.6	4.8	230
None	19.6	8.6	None
0.49	14.5	7.1	328
0.07	20.6	9.7	No Ignition
0.67	11.3	7.7	164

* Pressure measured at wall opposite T-injector
** Peak of pressures measured at positions downstream of T-injector
All tests used Wyoming Subbituminous of grade CM 100
All tests had air velocity of 3935 ft/min in coal pipe

Table VII Summary of CEGB Pipeline Fire Tests Using the T-injector Source

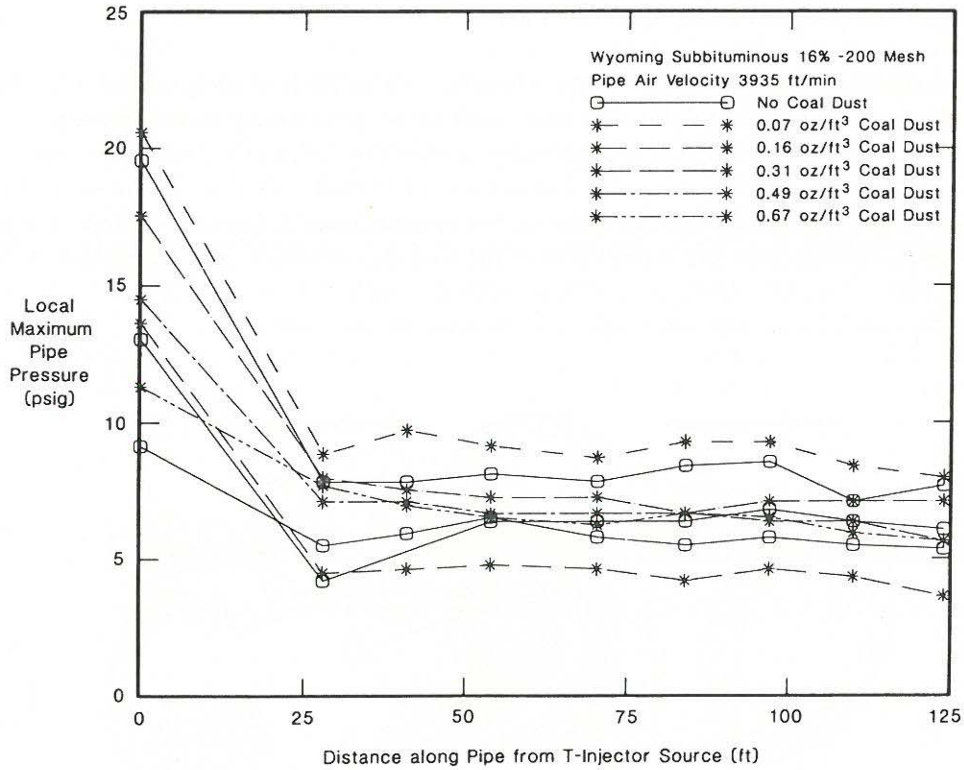

Figure 8 Local Maximum Pipe Pressure versus Position Along the Coal Pipe for Explosion Testing Using the T-Injector Source in the Coal Pipe

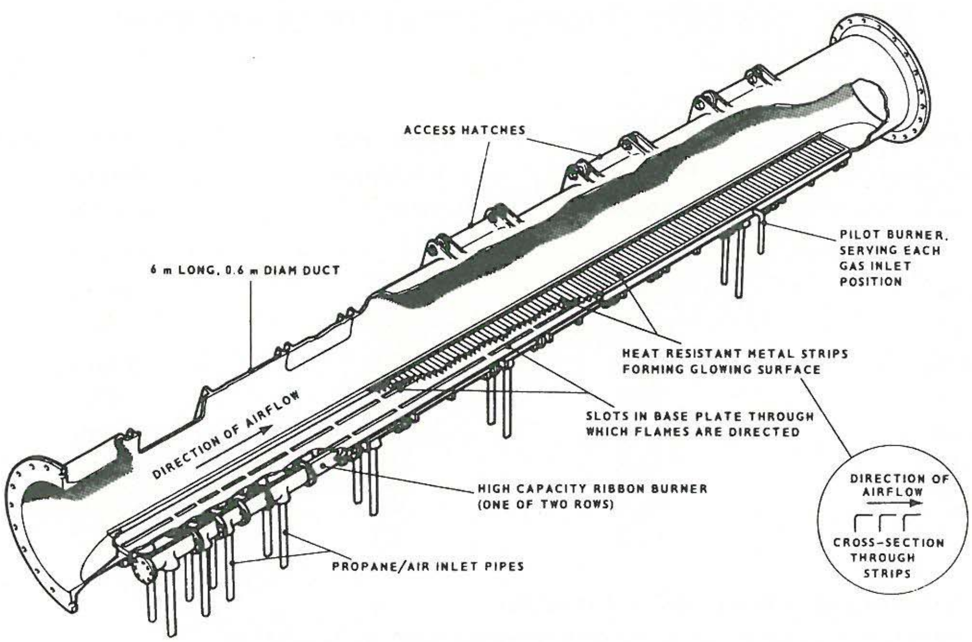

Figure 9 The CEGB "Burning Bed" Coal Pipe Burning Coal Bed Ignition Source

Figure 9 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 from only the pilot to a maximum of 8.37 feet. The firing rate produced a heat flux of 0.115 MBtu/hr/ft^2 from a stainless steel grate which shielded the flames from the dust flow. The firing rate was sufficient to keep the grate incandescent with a surface temperature between 1300°F and 1650°F. This condition corresponds roughly to a bed of coke burning at 1830°F.

Table VIII summarizes the results of the large pipeline fire tests. Coal type and grind determined the minimum length of burning bed necessary to obtain any sustained ignition of the dust stream. Longer bed lengths lengthened the extent of the flame zone producing a longer transit time past a flame detector. For all bed lengths the flame zones always first appeared well downstream of the burning bed ignitor. In about one third of the tests the flame front died before reaching the end of the test section. Maximum flame velocities in the range from 300 ft/sec to 1300 ft/sec were higher than the air velocity but below the speed of sound of the pressure waves. Therefore, the flame zone spread back upstream toward the burning bed but died before reaching it. The peak pressure almost always occurred at the upstream end of the instrumented section in the region where the dust flow first ignited. As the pressure wave and flame moved downstream the pressure dropped.

Coal Type	Coal Grind	Mixture Velocity (ft/min)	Coal Dust Concen. (oz/ft^3)	Bed Length (ft)	Maximum Pressure (psig)	Maximum Flame Velocity (ft/sec)
PA Bituminous	SF 250	1969	0.46	8.4	2.32	231
PA Bituminous	SF 250	2953	0.32	8.9	3.92	623
OK Bituminous	SF 250	984	0.37	1.5	.15	82
OK Bituminous	SF 250	2953	0.34	3.0	4.50	459
OK Bituminous	SF 250	5906	0.30	3.0	9.14	689
OK Bituminous	SF 250	5906	0.32	3.0	8.85	—
OK Bituminous	SF 250	5906	0.32	3.0	3.19	509
OK Bituminous	SF 250	5906	0.33	3.0	19.58	463
OK Bituminous	SF 250	5906	0.35	3.0	3.19	374
ND Lignite	SF 250	2953	0.31	5.9	2.18	558
ND Lignite	SF 250	5906	0.33	5.9	15.66	515
WY Subbituminous	M 190	2953	0.33	5.9	1.45	492
WY Subbituminous	M 190	4921	0.17	5.9	13.34	1,312
WY Subbituminous	M 190	5906	0.31	5.9	6.38	919
WY Subbituminous	SF 250	984	0.39	O-Pilot	.44	443
WY Subbituminous	SF 250	1969	0.40	3.0	4.79	820
WY Subbituminous	SF 250	2953	0.31	3.0	7.54	787
WY Subbituminous	SF 250	5906	0.26	5.9	15.95	656
WY Subbituminous	SF 250	5906	0.30	5.9	16.10	1,312

Table VIII Summary of CEGB Pipeline Fire Tests Using the Burning Bed Source

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

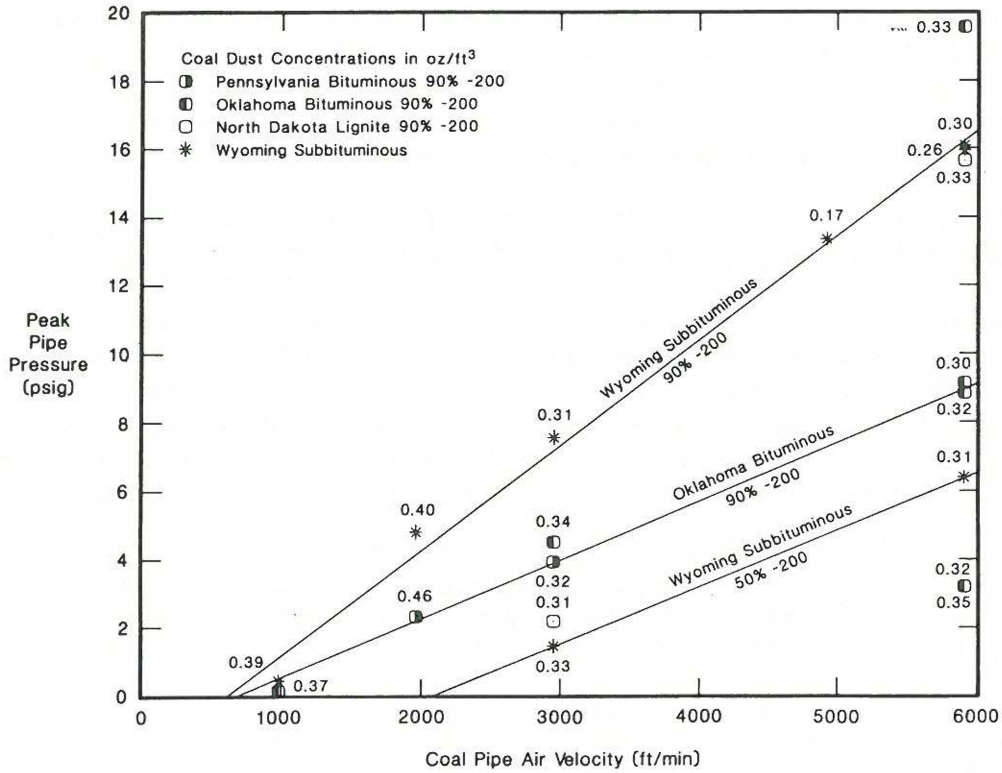

Figure 10 Peak Pipe Pressure versus Coal Pipe Air Velocity for Explosion Testing Using the Burning Bed Ignition Source

Explosion Testing Using Mill Fire Ignition Sources

The last series of CEGB experiments added the remaining major coal system component, the volume representative of a full sized mill as shown in Figure 6b. 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 mill rather than a specific type. The ignition source was moved back upstream into the mill volume. Two types of ignition sources were used in various locations relative to the mill-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 mill 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.

Table XI is a summary of the testing with the mill/pipeline combined geometry. Figures 11, 12 and 13 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 mill (up to 107 psig), and flame speed in the pipe (up to 9350 ft/sec). These results are impressive because energy sources as small as a teaspoonful of burning coal triggered the explosions while large pipeline fires set off only small puffs. 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. mill, 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 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 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. When the explosion pressure wave or shock front hits an obstruction or termination condition in the pipe, a large reflected pressure wave radiates upstream toward the vessel with the triggering fire. This return wave can pressurize the vessel to over 100 psig.

3. Fine grinds of coal with dust concentrations near 0.3 oz/ft3 produce the largest explosion pressures and flame speeds. Higher and lower dust concentrations produce weaker explosions.

4. A reduction in the ratio of vessel volume to coal pipe area reduces the peak values of pressure and flame speed in an explosion. 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%.

Coal Type	Coal Concen. (oz/ft^3)	Vessel Volume (ft^3)	Pipe Max P (psig)	Vessel Max P (psig)	Maximum Flame Speed (ft/sec)
Pennsylvania Bituminous	0.25	742 a	107.	58.	4265 *
Oklahoma Bituminous	0.27	742 a	399.	84.	5220 *
N. Dakota Lignite	0.28	742 a	186.	77.	3575 *
Wyoming Subbituminous	0.27	742 a	1182.	94.	9350 *
Wyoming Subbituminous	0.22	742 a	377.	78.	4100 *
Wyoming Subbituminous	0.11	742 b	107.	48.	2625 **
Wyoming Subbituminous	0.31	742 b	325.	107.	4430 **
Wyoming Subbituminous	0.51	742 b	100.	75.	2560 **
Wyoming Subbituminous	0.13	530 b	14.5	18.9	1475 **
Wyoming Subbituminous	0.29	530 b	174.	55.	3840 **
Wyoming Subbituminous	0.31	530 b	142.	54.	3935 **
Wyoming Subbituminous	0.65	530 b	14.5	20.3	938 **

All tests run with fine grind (90% -200 mesh)
a T-Injector Source
b Chemical Ignitor Source
* Initial pipe air velocity 5905 ft/min
** Initial pipe air velocity 3935 ft/min

Table IX Summary of CEGB Mill/Pipeline Combined Geometry Explosion Tests

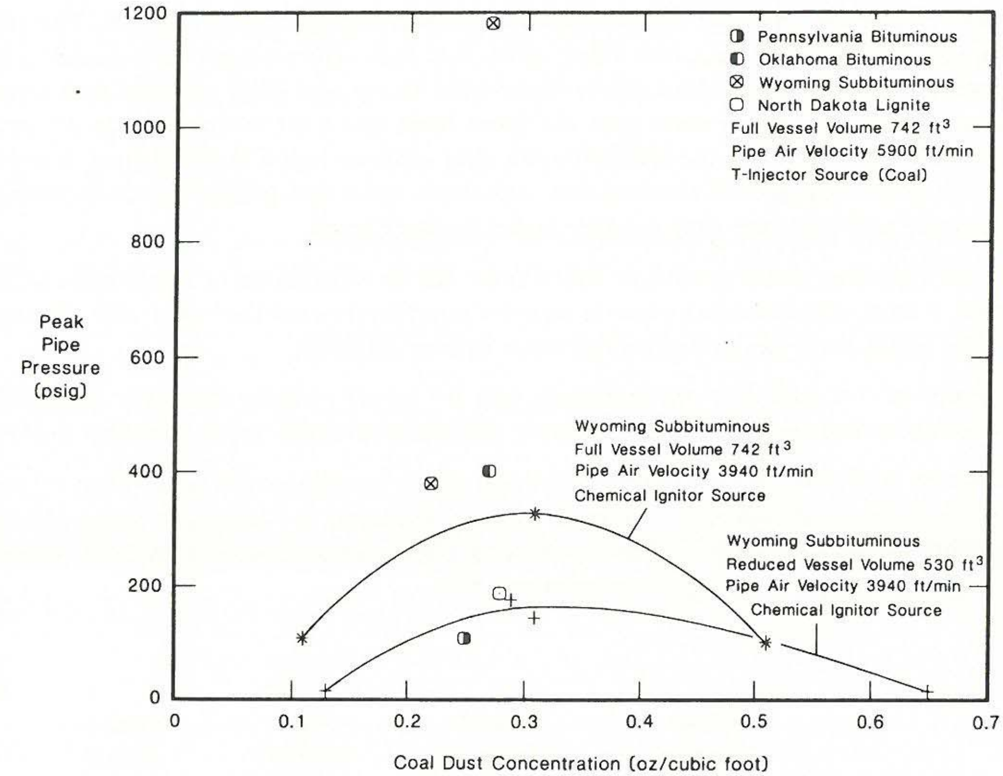

Figure 11 *Maximum Pipe Pressures versus Coal Dust Concentration for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition*

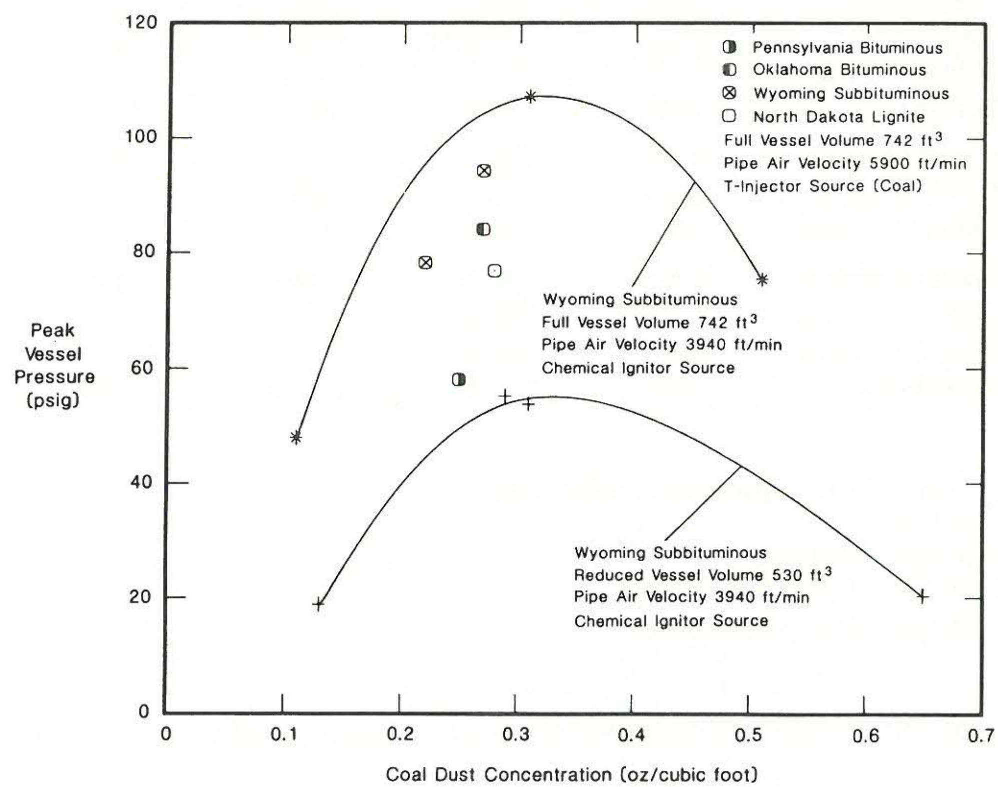

Figure 12 *Maximum Vessel Pressures versus Coal Dust Concentration for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition*

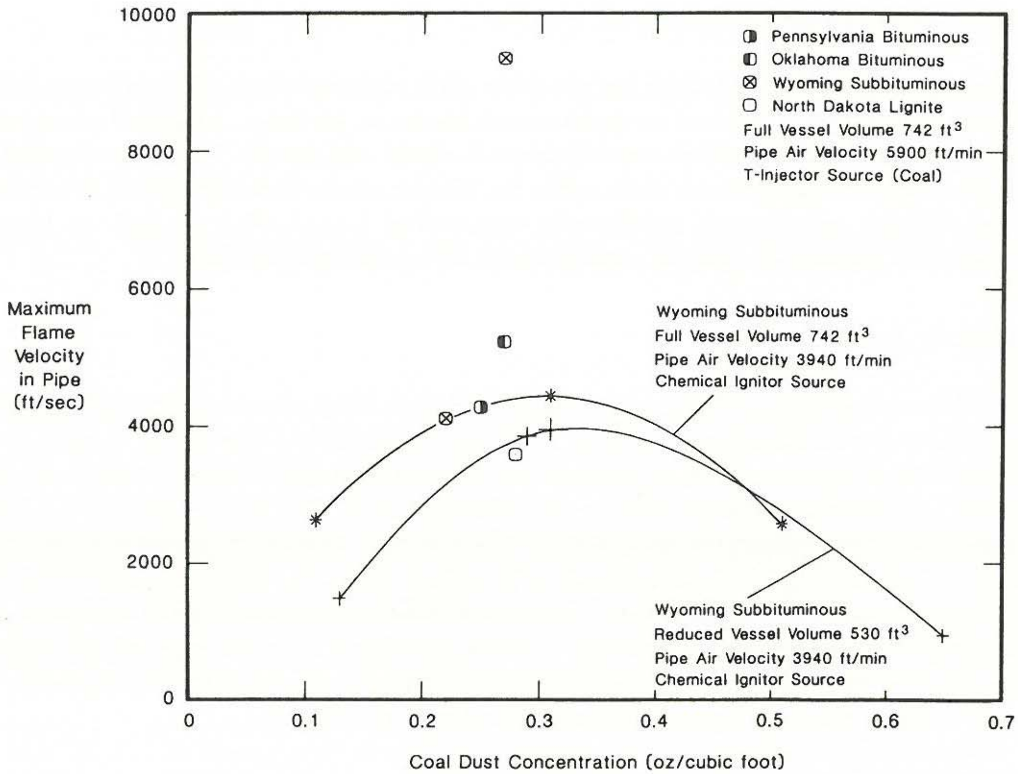

Figure 13 Maximum Flame Speed versus Coal Dust Concentration for Explosion Testing Using the Combined Vessel/Pipe Geometry and Vessel Ignition

CONCLUSIONS

The conclusions stated in this report are derived from laboratory testing, are general in nature, and are not directed at any specific plant or utility. Because of the complicated relationship of variables governing the creation of fires and explosions, the initiation of system modifications without a thorough analysis may produce results directly contrary to those desired.

Fire Extinguishing Agents

The most effective extinguishing agent under laboratory conditions was water. Water is inexpensive but deluging or flooding must be used to guarantee successful extinguishing. All the gaseous materials were relatively ineffective. The use of steam as an extinguishing agent created a potentially hazardous situation by extending fire life and possibly creating reactive species through gasification reactions. Other extinguishing agents showed promise of alleviating the disadvantages of water. However, further large scale testing is required prior to recommendations for actual plant installation.

The Effect of Equipment Size Factors on Explosions

A major conclusion of the experiments is that the size relationship of mills, classifiers, crushers and fans to coal pipes is crucial in explosion origin and growth. The relative sizes determine whether or not an explosion can occur as well as the magnitude of the resultant forces. Explosion evolution requires a change in volume and must originate in a mill system component other than a coal pipe. While a fire is located in a coal pipe, it can not trigger an explosion. However, if the fire moves and enters a piece of equipment of different size and venting characteristics, then the probability of an explosion becomes great. The relocation of a fire to other components of a mill system such as the classifier, crusher, fan or mill creates explosive conditions.

The Effect of Fuel/Air Ratios on Explosions

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 mill system components. In addition, testing indicates that the more powerful the ignition source the richer the mixture can be and still support an explosion. Not detecting a fire until it is out of control increases the range of fuel/air ratios that can explode. Detection and control of small fires reduces the risks of explosions for all operating conditions.

Explosion Inerting Agents

Complete, continuous inerting with a dynamic pulverizer system is not practical. Although inertant reduces the oxygen available for an explosive reaction, it is difficult to determine whether the inertant is effective. In many instances the oxygen content is in the explosive range when coupled with other reactive gases. Some inertants inhibit fire detection although they do not extinguish fires. The steam inerting tests showed that under controlled laboratory conditions, no guaranteed safe level of steam inerting could be determined. Explosions occurred in an atmosphere with as much as 16 percent steam by volume. It is doubtful that steam inerting can be proven safe under all conditions. If it is determined that an inerting system is necessary, additional instrumentation and controls are required. Extensive training is required 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.

Explosion Containment

The forces developed in the full scale tests prove that it is not practical to reinforce the mill system components. Although developed under controlled conditions, the 1200 psig explosion pressures confirm the forces seen in power plants. In addition, there is no evidence to suggest that these are the maximum forces that could be obtained. Explosions can not be contained by sheer structural strength. Research must develop other methods for control and prevention.

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2. Gardner, B.R., Winter, R.J., More, M.J., Broske, D.R., Carini, R.C., "Some Explosion Tests on Typical American Coals" Nov. 1985.