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SUMMARY

A series of tests is described using pulverized US coals in the Central Electricity Generating Board (CEGB) explosion test facility. The tests were carried out by the CEGB for Riley Stoker Corporation (Riley) as part of an Electric Power Research Institute (EPRI) Contract. Results show the effect on explosibility of dust particle size and coal type. Ignitions in straight pipes are found to produce relatively low pressures, but the combination of pipe and a large explosion chamber could generate incident pressure pulses in excess of 300 psig and, in some cases, detonation waves in the pipe.

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INTRODUCTION

As part of a program of research into the underlying causes of past explosions in coal pulverizer systems, the CEGB Technology Planning and Research Division (TPRD) has constructed a full-scale explosion test facility. Discussions with EPRI and Riley have led to a contract being placed with TPRD for the testing of a series of US coals in the facility. This paper describes the experimental apparatus, the test procedures and the results obtained.

THE TEST PROGRAM

The program fell into three distinct series:

Series A

To determine the explosibility of Western sub-bituminous coal of size grade typical of that in the body of a vertical spindle pulverizer.

Series B

For four typical US coals of fine size grade, to determine the maximum pressures and flame speeds generated by a deflagration ignited by a (simulated) pipeline fire source.

Series C

For a fine-grade Western sub-bituminous coal, to determine the maximum pressures and flame speeds produced when the explosion is initiated in a large vessel (simulating a pulverizer body) and propagates into the straight pipe.

THE EXPLOSION TEST FACILITY

Because the effects of scale on ignition and flame propagation were not known, the decision was taken to employ a full-size test duct and to reproduce flowing suspensions of coal dust, representative of a large power station pulverizer plant. To save costs however, the transporting air was not heated; laboratory tests suggest this limitation does not detract significantly from the applicability of the results obtained.

For safety purposes the rig was located at the secure, remote site of the UK Atomic Weapons Research Establishment (AWRE) at Foulness and constructed and operated to CEGB requirements by AWRE staff.

To minimize the number of interacting parameters, the rig was initially constructed in the form of a simple straight pipe of approximately a 24 inch diameter, as shown in Figure 1. This configuration was used for Series A and B.

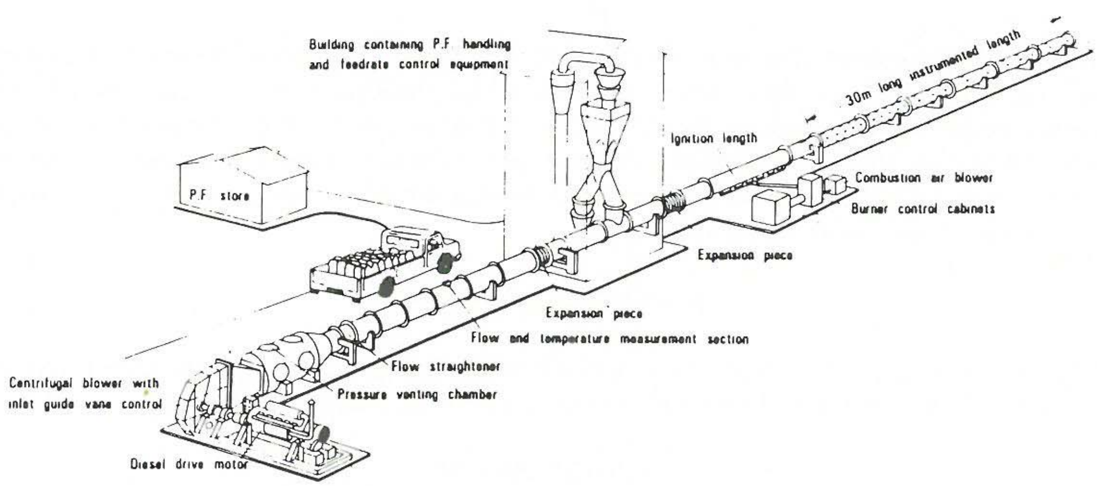

Figure 1 Arrangement of Test Facility for Series A and B

A controllable air flow was provided by a diesel-driven blower and flow-rate measured by calibrated venturi nozzle. Pulverized fuel (PF) is injected into the flow from a screw-feeder system, the mass throughput being measured by the loss-in-weight of the supply hopper. The overall length of the pipeline was approximately 260 ft., of which some 120 ft. was downstream of the PF feeder. This test length contained a 20 ft. ignition section followed by some 100 ft. of instrumented pipe.

Instrumentation consisted of pressure transducers and flame detectors at 39 and 78 inch intervals and access for traversing probes was provided.

Two types of ignition source were used:

- A simulated burning coal bed - in which a ten inch wide grating in the floor of the pipe was heated to incandenscence from below by ribbon burners supplied with a propane/air mixture. Various bed lengths could be selected from six in. to 16 ft., the combustion products passing through the grating into the pipe flow. Burner setting was adjusted to give grating temperatures of between 1300 and 1650°F, the heat flux intensity from the bed being approximately 34 kW/ft^2 which according to the literature corresponds to that of a burning bed of coke at 1800°F.
- An injected flame - an explosion in a 16 ft^3 side chamber was initiated by an electrically fired ignitor in a mixture of propane/air or PF/air, the expanding mixture bursting a light diaphragm and entering the test pipe as a jet of flame.

To investigate the effects of a pulverizer body and outlet pipe combination, a large chamber was inserted into the test duct for Series C, as shown in Figure 2.

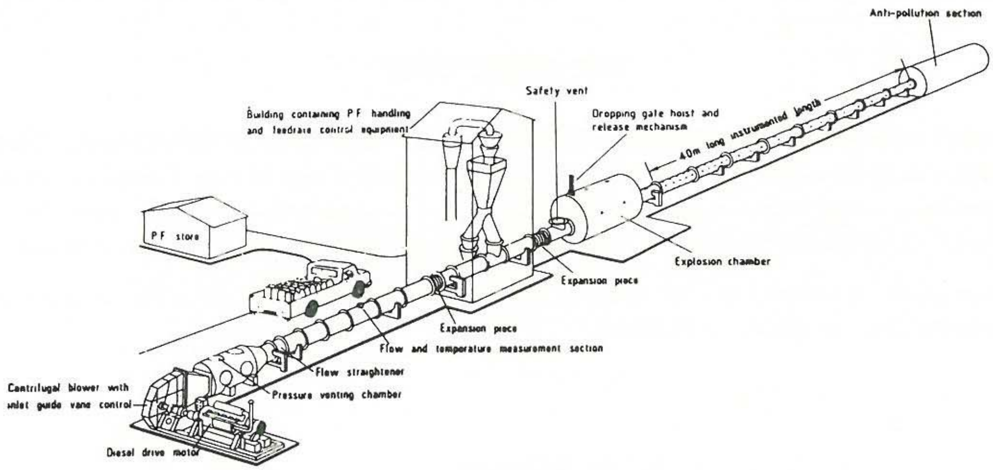

Figure 2 Arrangement of Test Facility for Series C

The chamber volume was approximately 720 ft^3 and the internal geometry of the vessel is shown in Figure 3. An adjustable deflector vane disperses the incoming PF in the chamber and various ports are available for pressure transducers, flame detectors and mixture sampling probes. To protect the upstream components of the rig a gate valve is actuated in the ignition sequence to close before a flame can propagate into the inlet pipe.

Two ignition methods were employed:

- An injected source - from a side limb where a 0.25 lb charge of PF was dispersed in air and ignited by chemical ignitor before injecting through a bursting diaphragm into the interior or the chamber.
- Chemical ignitors - two 5 kJ ignitors being activated electrically, their relatively slow energy release-rate being particularly effective for igniting coal dust suspensions. The ignitors were supplied by Sobbe Friedric MbH, W. Germany.

With the large vessel in place the instrumented test pipe downstream of the vessel outlet was some 130 ft. long.

At the outlet end of the test pipe it was necessary to install a pollution control system of water sprays contained in a six ft. diameter open ended duct.

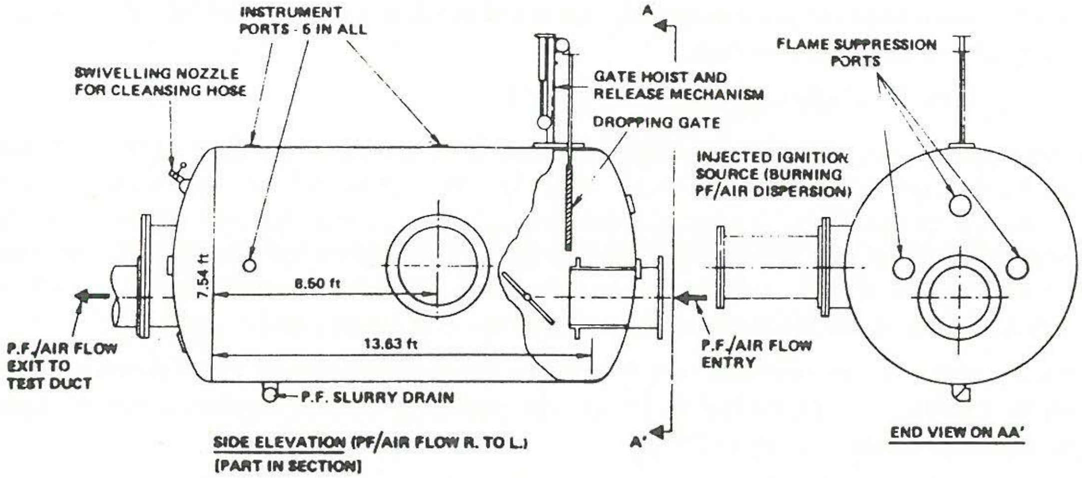

Figure 3 Details of the Explosion Chamber for Series C

THE COALS USED

The four coals to be tested were selected by EPRI to cover a wide range of characteristics. Samples were supplied by Riley shipped to the UK and ground by the Standard Pulverized Fuel Company, Yorkshire. The PF was hermetically sealed in heavy duty polythene bags for transport and storage at Foulness. Systematic analysis showed no significant changes in construction between stored and freshly ground coal dust.

Proximate analyses of samples of each coal are tabulated in Table I. In all cases the moisture content was significantly lower than originally anticipated.

Coal	Description	Moisture Content (Raw) %	Moisture Content (PF) %	Dry Basis (PF) Volatiles %	Ash %	Fixed Carbon %	Calorific Value kJ/Kg
1	Eastern Bituminous	4.3	1.5	18.2	18.8	63.0	28020
2	Midwestern Bituminous	3.8	1.5	38.6	12.1	49.3	30620
3	N. Dakota Lignite	32.8	13.1	41.5	10.5	48.0	24400
4	Western Sub-bituminous	27.9	17.3	41.3	7.1	51.6	28030

Table I Proximate Analyses of Milled Coals (Grade SF 250) Showing Change in Moisture Content During Milling

Sieve analyses of the dust were also carried out, the results being shown in Table II. The finest grade SF 250 is slightly finer that the produce from a tube-ball mill; the coarser grade M 190 is more typical of the output of some vertical spindle pulverizers. The very coarse CM 100 grade is thought to be representative of the material in the body of a vertical spindle mill.

		Mass % Greater Than				
Coal	Grade	1000 μm	500 μm	250 μm	100 μm	71 μm
1	SF 250	0	0	0	1.4	11.9
2	SF 250	0	0	0	2.6	11.1
3	SF 250	0	0	0	1.1	10.3
4	SF 250	0	0	0	2.9	14.2
4	SF 190	0	0.20	3.8	30.9	47.6
4	SF 100	0.1	14.3	44.5	75.5	84.1

Table II Size Distributions of Tested Coals Determined by Sieve Analysis

TEST RESULTS · SERIES A

In this series, suspensions of the coarse grade, CM 100, of the coal No. 4 (Western sub-bituminous), at a flow velocity of 65 ft/sec., were ignited by an injected propane/air flame from a side chamber. A range of dust concentrations were tested from 0.07 to 0.67 oz/ft^3.

A typical result is shown in Figure 4 as a set of pressure/time traces of the several transducers mounted along the test duct. The traces are positioned against a vertical axis representing the distance downstream from a reference point on the test-pipe. The position of the injected source is also shown.

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At each transducer station, flame detectors also recorded the leading edge of the burning coal/air mixture and, in some cases also showed the back of the flame. The loci of the flame leading and trailing edges are also shown in Figure 4.

The pressure recordings show a sharp pressure wave passing rapidly through the pipe, originating from the firing of the injected source. The slope of the line joining the pressure peaks provides the propagation velocity which, for this finite amplitude pulse, was 1450 ft/sec. Flame speed can be seen to be much slower, the mean slope of the leading edge locus taken over the pipe length giving a mean velocity of approximately 100 ft/sec.

Evidently the ignition sources has started a small PF fire which is carried down the pipe by the air flow. In all cases this burning PF produced no significant pressure pulses, the only pulses detected being from the ignition source. It was concluded that over a concentration range of approximately 0.07 to 0.67 oz/ft^3 this coarse grade of coal No. 4 will sustain a fire but is not explosive, when ignited by the injected flame. Whilst not a hazard in itself, this conveyed fire could conceivably from an ignition source further downstream if it encounters an explosive mixture.

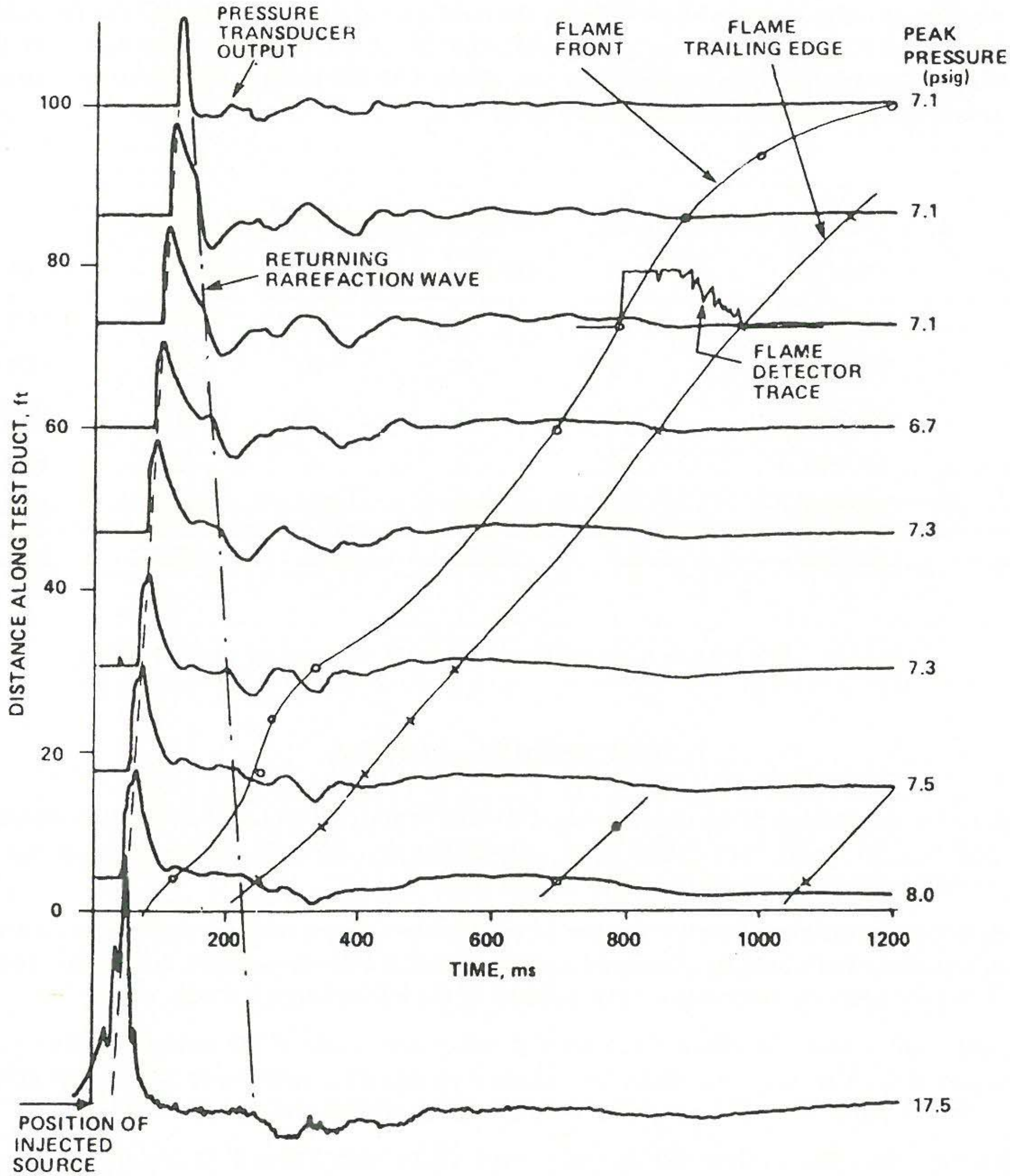

Figure 4 Example Test Result: Series. Western Sub-bituminous coal 4, Grade CM 100, Concentration 0.31 oz/ft^3, Mixture Velocity 65 ft/s Injected Flame Ignition Source.

TEST RESULTS - SERIES B

A wide range of tests were conducted with the four coal types to determine the largest pressures arising from explosions initiated by the simulated burning bed ignition source. Flow velocity of the suspension was varied from 16 to 98 ft/sec. and concentration from 0.17 to 0.46 oz/ft^3. Most tests used the fine grade of SF 250, but some tests of coal 4 at the M 190 grade were also included.

Some typical pressure and flame front traces are shown in Figure 5 and 6 for coals 4 and 1 respectively. Pressures developed by the explosion mixture can now be seen multiplicity of pressure waves traversing the length of the pipe.

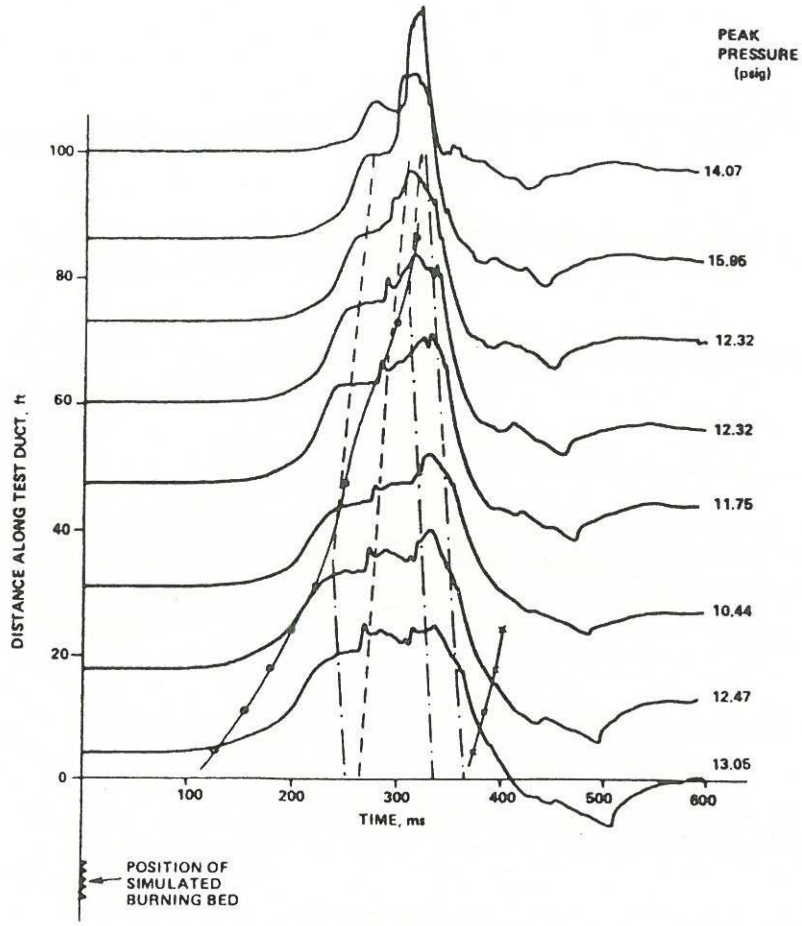

Figure 5 Tests Results for Coal No. 4, Series B, Western Sub-Bituminous Coal, Grade SF 250, Concentration 0.26 oz/ft^3, Mixture Velocity 100 ft/s, Simulated Burning Bed Ignition, Length 6 ft.

Considering firstly the example in Figure 5, following the establishment of the required flow and concentration in the test pipe, the simulated burning bed is increased in temperature until ignition occurs, or until the limiting temperature of the ignition source is reached. As can be seen in Figure 5, ignition of the mixture occurred and a relatively prolonged pressurization is produced. As the deflagration propagates down the flame front accelerates to some 650 ft/sec. At the pipe outlet the flame and pressure wave fronts are almost coincident and a noticeable steepening of the pressure wave is evident. The actual amplitude of the pressure wave remains modest at around 14.5 psig.

Coal 1 shows the lowest explosion pressures, as shown in Figure 6 only reaching 3.9 psig with with evidence from the traces that the flame may be extinguishing towards the end of the pipe. Interestingly, the explosion appears to originate well downstream of the ignition source and flames then propagate in both directions.

Summarizing the results the various tests:

- In all cases the maximum pressures generated were modest, the highest value recorded being 19.6 psig (for coal 2; SF 250; concentration 0.33 oz/ft^3: mixture velocity 98 ft/sec; ignition source active length 5.9 ft).
- In general, coal 4 gave the highest pressures and flame accelerations closely followed by coals 3 and 2, with coal 1 being distinctly less explosive.

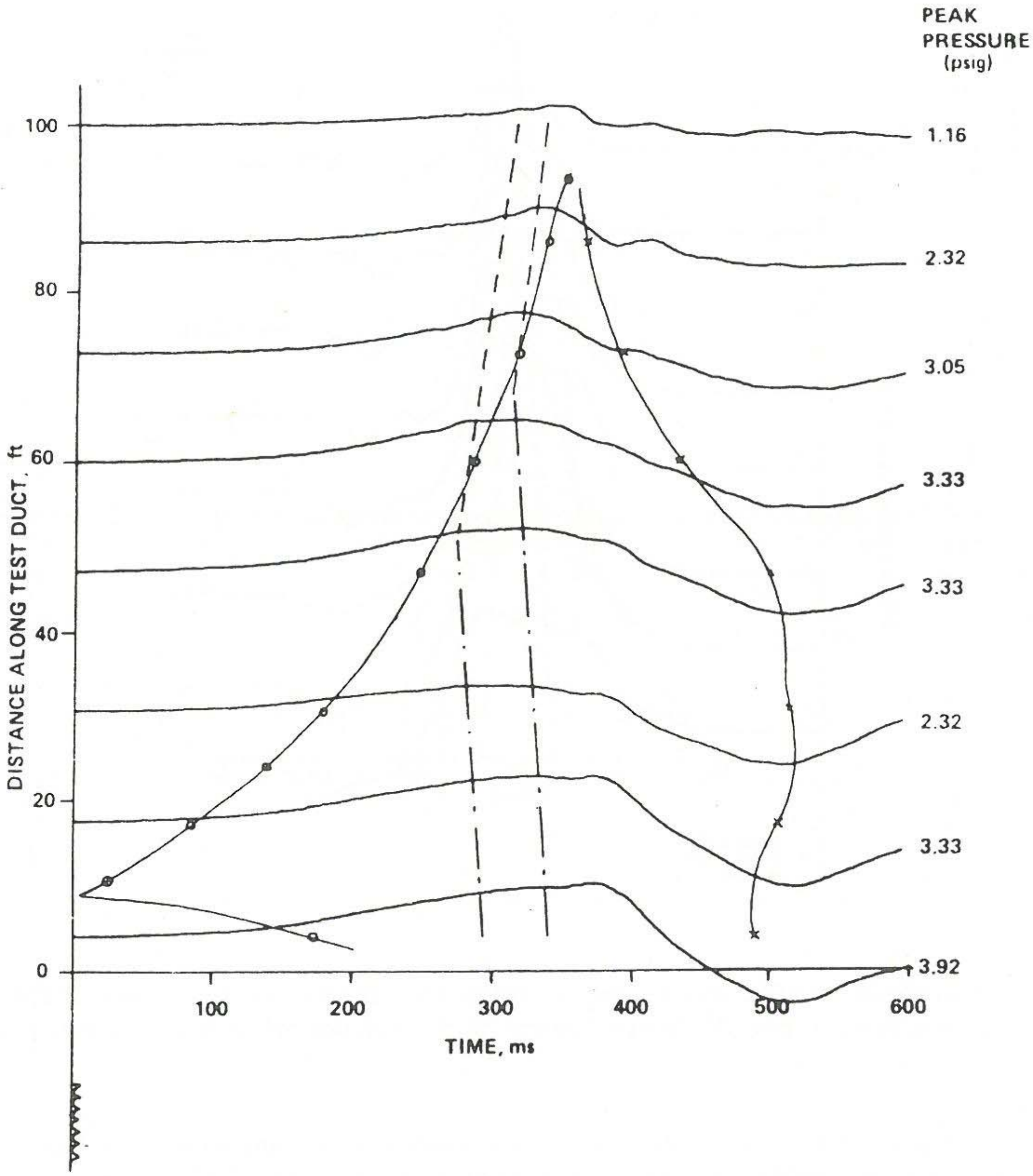

Figure 6 Test Result for Coal No. 1, Series B, Eastern Bituminous Coal, Grade SF 250, Concentration 0.32 oz/ft^3, Mixture Velocity 50 ft/s Simulated Burning Bed Ignition, Length 9 ft.

- For coal 4, the M 190 grade gave only a slightly lower pressures and flame speeds than the SF 250 grade.
- Pressure peaks and flame speeds decreased noticeably at decreased mixture flow velocity.
- The optimum PF/air concentration giving the highest pressure for all coals appeared to be around 0.26 - 0.33 oz/ft^3.

The test series has therefore shown that flowing suspensions in the test pipe can be ignited by the simulated burning bed source, but that explosion pressures generated in the 120 ft of straight pipe did not exceed 20 psig.

TEST RESULTS - SERIES C

The addition of the large chamber to represent the volume of the pulverizer was found to have a dramatic effect on the explosion process. The events following ignition of the chamber contents are well illustrated in Figure 7, showing the pressure and flame traces for the test pipe and the pressure generated in the large chamber for a particular test on coal 2.

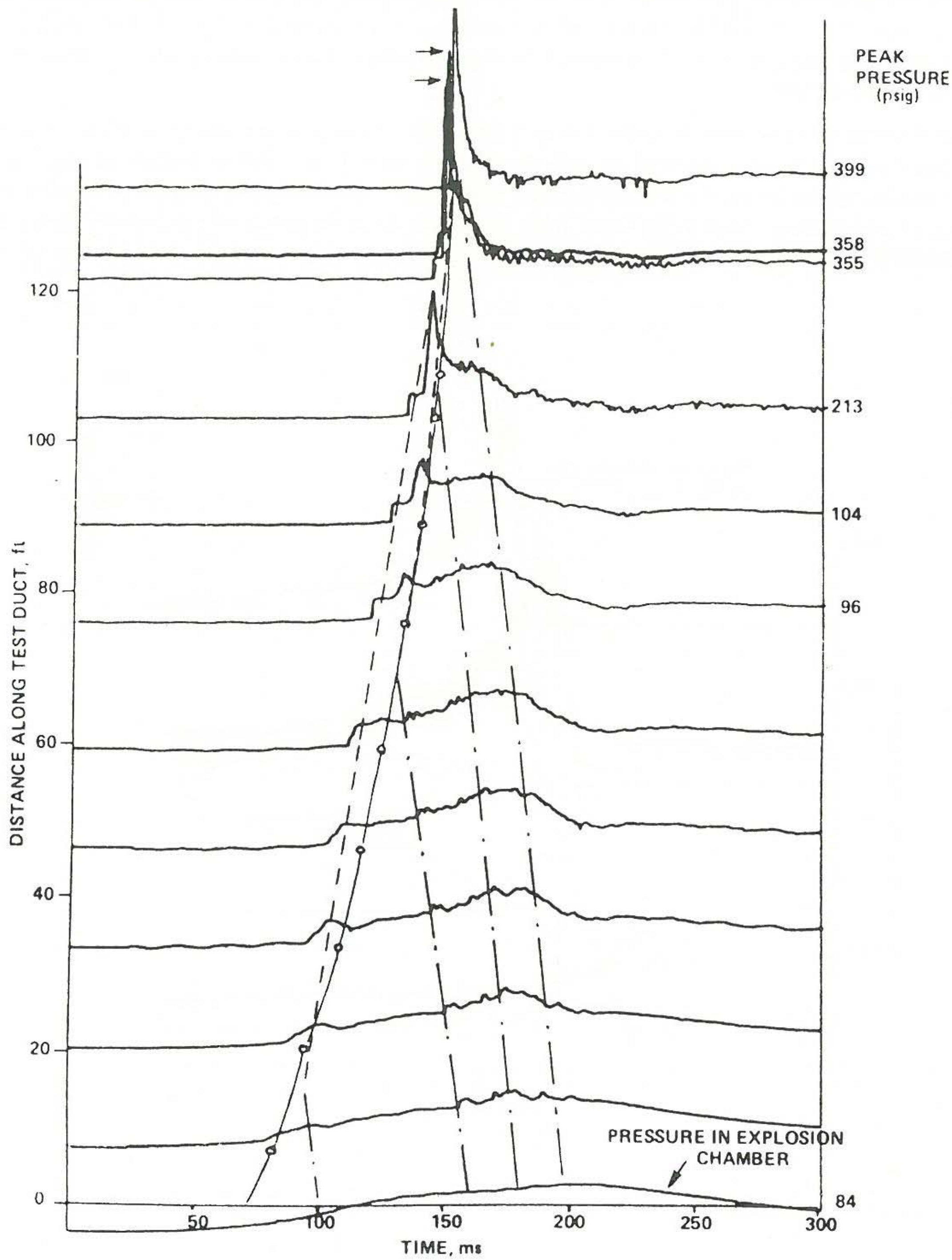

Figure 7 Example Test Result: Series C, Mid-Western Bituminous Coal 2, Grade SF 250, Concentration 0.27 oz/ft³, Pipe Velocity 100 ft/s, Injected Source in Explosion Chamber.

For this test the mixture concentration and flow velocity was first established through the chamber and test pipe. Burning PF is then injected from a side chamber into the centre of the main vessel. As the flame spreads through the large chamber, the inlet gate valve is closed to protect the upstream components. The complete sequence from side limb ignition to gate closure may take some 130 ms.

The combustion of the mixture in the large vessel raises the pressure relative slowly as shown in Figure 7 - bottom pressure trace - the maximum of 84 psig being reached some 200 ms after ignition. The chamber contents vent into the outlet pipe until, at 70 ms after ignition, the flame front reaches the outlet and jets into the testpipe. From this highly energetic start, the deflagration accelerates rapidly down the pipe, small pressure waves reinforcing in front of the flame to form a steep fronted wave with a peak amplitude of around 400 psig at the pipe outlet.

Expanded traces of these measurements towards the outlet of the pipe are shown in Figure 8 and it can be seen that the flame front is catching up with the pressure wave front. This is thought to result from the adiabatic heating of the air by the leading pressure wave, flame speed increasing in the preheated mixture. The increased rate of heat-release at the flame front in turn results in the production of further pressure waves which reinforce and steepen the leading wave.

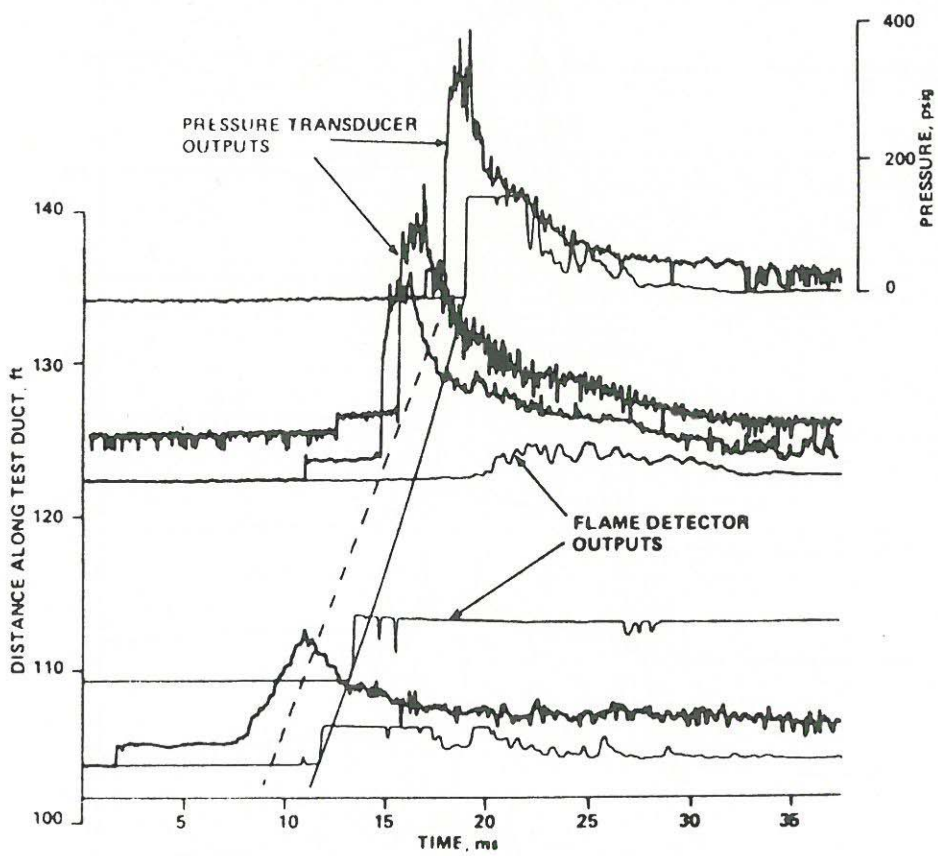

Figure 8 Expanded Pressure and Flame Traces of Series C Test Shown in Figure 7.

This positive feed-back mechanism is seen even more dramatically in the latter traces for the similar test of the more explosive coal 4, Figure 9. In this case the flame front actually catches the pressure wave, the combined wave reaching a recorded peak pressure of 1180 psi and a propagation velocity of 9350 ft/sec. This may be the clearest evidence to date that, under the appropriate conditions, detonation waves can occur in coal dust suspensions.

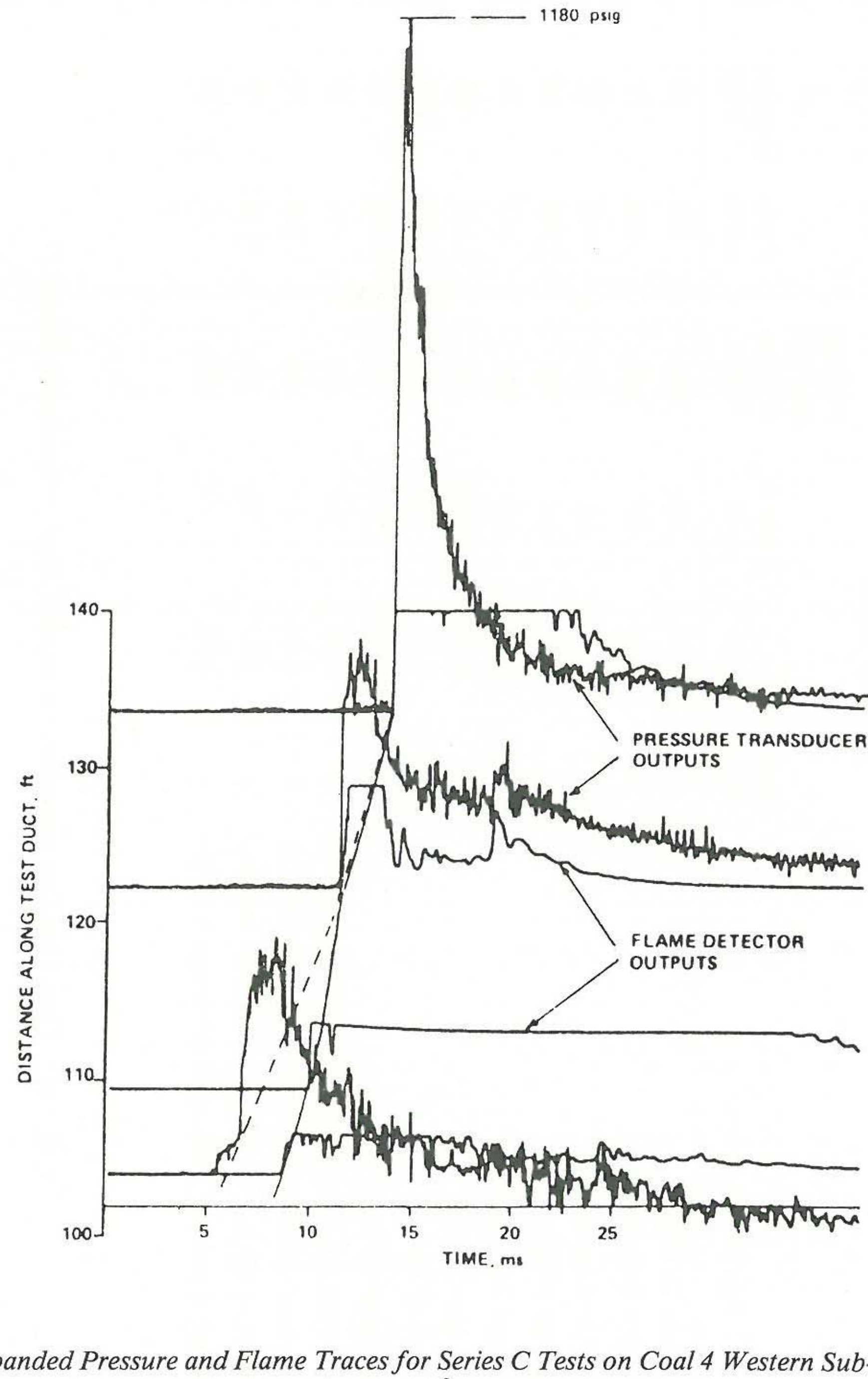

Figure 9 Expanded Pressure and Flame Traces for Series C Tests on Coal 4 Western Sub-Bituminous Coal, Grade SF 250, Concentration 0.27 oz/ft^3 Pipe Velocity 100 ft/s, Injected Source in Explosion Chamber.

Test Ref. No.	Test Arrangement	Coal Type	Concentration oz/ft^3	Concentration lb air/lb coal	Mixture Velocity In Pipe ft/sec	Max Pressure In Pipe psig	Max Pressure In Chamber psig	Max Flame Velocity In Pipe ft/sec
1	Injected Source	1	0.25	4.8	100	107	58	4270
2	Injected Source	3	0.28	4.3	100	186	77	3580
3	Injected Source	2	0.27	4.4	100	399	84	5220
4	Injected Source	4	0.27	4.4	100	1182	94	9350
5	Injected Source	4	0.22	5.5	100	377	78	4100
6	Chemical Ignitor	4	0.11	10.9	65	107	49	2620
7	Chemical Ignitor	4	0.31	3.9	65	325	107	4430
8	Chemical Ignitor	4	0.51	2.3	65	100	75	2560
9	Chemical Ignitor, Reduced Chamber Volume	4	0.13	9.2	65	15	19	1480
10	Chemical Ignitor, Reduced Chamber Volume	4	0.29	4.1	65	174	55	3840
11	Chemical Ignitor, Reduced Chamber Volume	4	0.31	3.9	65	142	54	3940
12	Chemical Ignitor, Reduced Chamber Volume	4	0.65	1.8	65	15	20	940

Table III Tests Using the Chamber and Straight Pipe Arrangement (Figure 2)

The range of tests carried out using the large chamber and pipe combination are listed in Table III. The above test on coal 4 clearly generated the highest pressure, the other parameters studied leading to reduced pressurizations, but the majority still being significantly higher than those generated by pipeline ignition in Series B. Summarizing the main results:

- Coal type: the highest pressures were generated using coal 4, then in descending order of explosion pressure by coals 2, 3 and 1.
- Mixture concentration: the highest pressures were developed with mixtures of approximately 0.3 oz/ft^3 PF/air concentration.
- Chamber volume: in a limited number of tests using coal 4 a reduction in chamber volume of 28% (by in filling with balk of timber) produced a significant reduction in the maximum pressure by altering the venting ratio of vessel volume to pipe outlet area. The generation of high pressures also showed a greater dependence on optimum mixture concentration.
- Ignition source: the direct use of chemical ignitors to ignite the contents of the large chamber produced reduced maximum pressures as can be seen in Table III. The localized heating of these devices is thought to be less effective in producing rapid combustion and pressure rise in the chamber than the highly turbulent dispersion of burning PF from the injected ignition source, which in turn produces greater displacement velocities and turbulence levels ahead of the flame in the downstream test duct.

CONCLUSIONS

The test results have provided a valuable insight into the ignition and development of explosions in coal dust and air mixtures. The most important result is the demonstration that large pressures can occur when an explosible mixture is ignited in a large vessel connected to a pipeline. Depending upon the ratio of vessel volume to pipe outlet area, it has been shown that under certain conditions very large amplitude pressure waves and even detonations can be produced.

Throughout the tests the mid-western bituminous and the western subbituminous coals were generally found to produce the highest pressures; the eastern bituminous coal was least explosive.

Dust particle size was found to have a strong influence on explosibility. At the coarsest grade tested (55.5% $< 250\ \mu m$, 24.5% $< 100\ \mu m$ even the western sub-bituminous coal was difficult to ignite and, at the optimum concentration, the mixture burned slowly with negligible explosion pressure production.

Ignition of a flowing mixture by a simulated fire in a straight pipe was found to occur over a wide range of concentrations for all fine grade dusts tested. However, in all cases the explosion pressures produced were less than 20 psig.

The implications of these results for power station plant has not been addressed here and is beyond the scope of this study. It is important to acknowledge, however, that whilst the test have shown the factorsleading to large explosion pressures, power station plant design and operating procedures can be selected to ensure that the probability of occurrence of such explosive conditions is minimal. This is evidenced in the CEGB by an absence of damaging explosions in pulverizer plant since 1979. The experimental data should be useful however in checking the margins of safety in plant.