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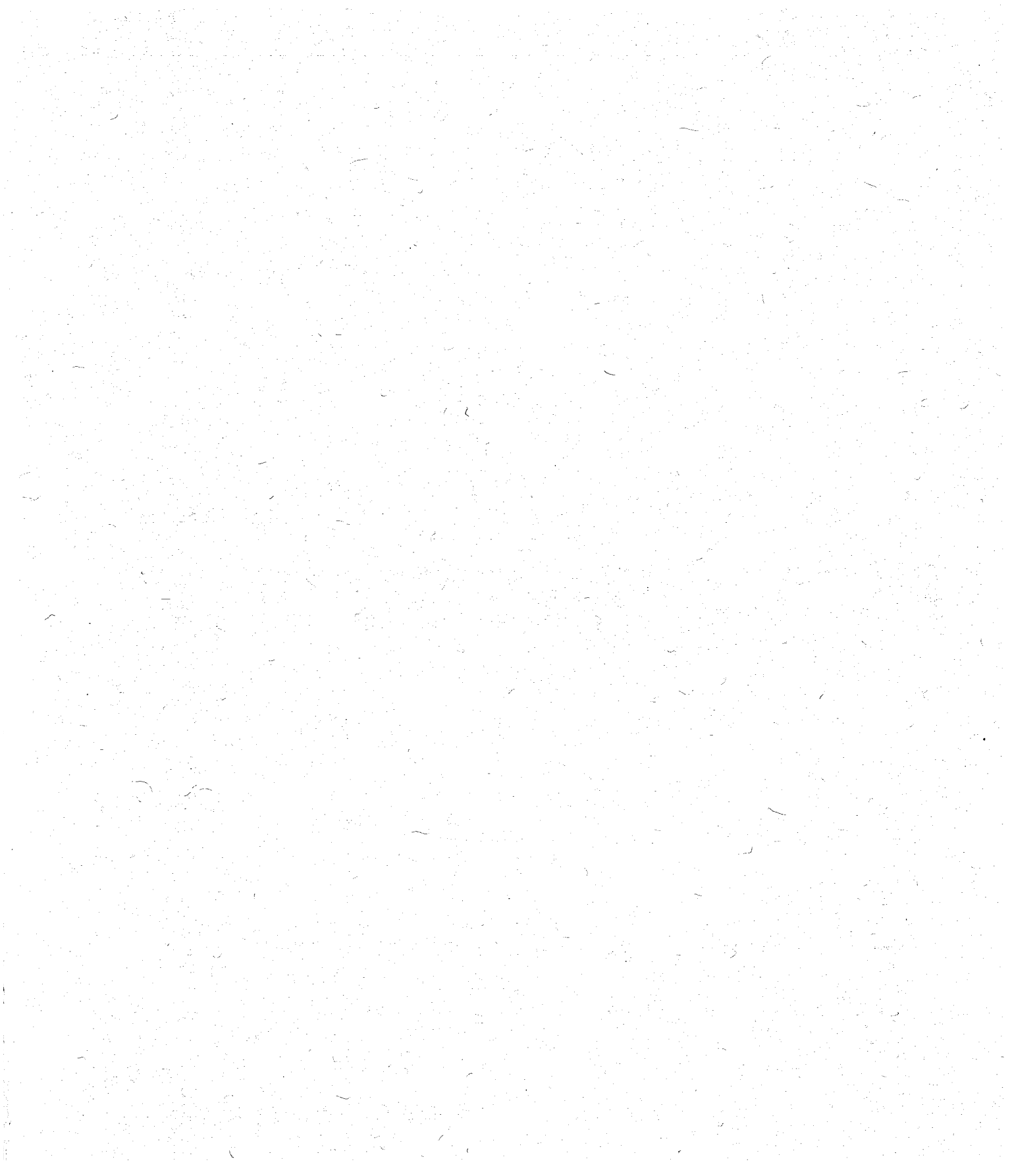
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**Suppression of Coal-Dust Explosions  
by Passive Water Barriers  
in a Single-Entry Mine**



**UNITED STATES DEPARTMENT OF THE INTERIOR**



**Report of Investigations 7815**

**Suppression of Coal-Dust Explosions  
by Passive Water Barriers  
in a Single-Entry Mine**

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**UNITED STATES DEPARTMENT OF THE INTERIOR**  
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# SUPPRESSION OF COAL-DUST EXPLOSIONS BY PASSIVE WATER BARRIERS IN A SINGLE-ENTRY MINE

by

I. Liebman<sup>1</sup> and J. K. Richmond<sup>1</sup>

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## ABSTRACT

A Bureau of Mines study is in progress to determine the effectiveness of passive water barriers in suppressing coal-dust explosions. A 2.9-ft<sup>3</sup>-capacity water-filled plastic tub was found effective in suppressing dust explosions propagating at speeds of 250 to over 1,000 ft/sec. Work directed at determining the limitations of water barriers showed that the passive water barrier technique is also feasible for the suppression of weak dust explosions propagating at speeds of 100 to 250 ft/sec. For relatively slow accelerating flames, dynamic wind forces appear to be the important quantity governing fragmentation of the plastic tub and subsequent water release and dispersion, whereas dynamic impulse appears to be the significant quantity for rapidly accelerating flames. The acoustic approximation (relation between static pressure and flame or wind speed) is shown to be valid in a long single mine entry. This relationship appears to be useful in predicting the regions within a long single entry where passive water barriers are effective in quenching a dust explosion.

## INTRODUCTION

Rock dusting has been the traditional means of controlling dust explosions in American coal mines. However, rock dusting alone is not a completely sufficient means of preventing coal-dust explosions, especially along conveyor roadways and transfer points. Barrier systems have been shown to offer additional explosion protection when used as a supplement to rock dusting; the triggered barrier is of recent innovation and still in the development stage, whereas the passive barrier--using rock dust or water--has received considerable attention.

The Bureau of Mines has in the past studied passive barrier methods of stopping coal-dust explosions; most of the work was in the use of rock-dust barriers, and only a little work was done in the use of water as the barrier medium. Both methods proved to be only moderately satisfactory. However, recent research abroad shows that the passive water barrier is an excellent means of defense. Indeed, many foreign countries are recommending their use

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<sup>1</sup>Research physicist.

in mines, and in some countries, the passive water barrier has become the principal means of protection.

The Bureau of Mines continuously conducts safety-in-mines research and as part of this effort has initiated a comprehensive study of passive water barriers to determine their usefulness in American coal mines. Of particular interest is the effectiveness of water barriers for protection along conveyor beltways. This report is the first of a progress series.

### Passive Water Barrier

The passive water barrier, as tested and used abroad, is normally made up of numerous water-filled containers mounted in the vicinity of the coal tunnel roof. During a dust explosion, the dynamic pressures induced ahead of the propagating flame tilts or ruptures the water containers, releasing and dispersing the water, which acts to suppress the approaching flame. The water containers have taken many forms and configurations: Open-top wooden or metal troughs (2, 5, 8),<sup>2</sup> rigid or foam plastic tubs (3, 6, 11, 15), or thin plastic bags (14); the water capacity of the containers varies from 0.12 to 3 ft<sup>3</sup>. In practice, a row of water containers are placed along the upper half of the mine roadway cross section supported on shelves or rigidly held in a framework; the containers occupy one-third to two-thirds of roadway width. Usually, many rows of containers, from 10 to 100 ft apart, constitute a barrier. Systems have been developed which suggest the size and number of troughs or containers to be used in a barrier (4, 7).

### Water Troughs

This report gives the results of experiments using a commercially available plastic water barrier (trough) that was found effective in controlling dust explosions traveling at flame speeds exceeding 250 ft/sec. This report also gives the results of experiments directed at determining the feasibility of passive water barriers in suppressing weak dust explosions (traveling less than 250 ft/sec). For this purpose, a metal tub instrumentated to release its water contents at a predetermined time replaced the plastic trough in the experiments.

A photograph of the plastic trough is shown in figure 1. It is made of polyvinyl chloride (PVC) and holds approximately 2.9 ft<sup>3</sup> of water. A thin plastic cover is normally used to reduce water evaporation. Other sources give a complete description of this trough (4). The metal tub, designed and constructed at the Pittsburgh Mining and Safety Research Center, has internal dimensions of 1 ft<sup>2</sup> by 2 ft long and is filled to hold approximately 1.7 ft<sup>3</sup> of water (fig. 1B). The door is closed when the tub is filled with water. During the experiment, the door is programmed to open rapidly at a preset time, and the water spills out rapidly.

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<sup>2</sup>Underlined numbers in parentheses refer to items in the list of references at the end of this report.

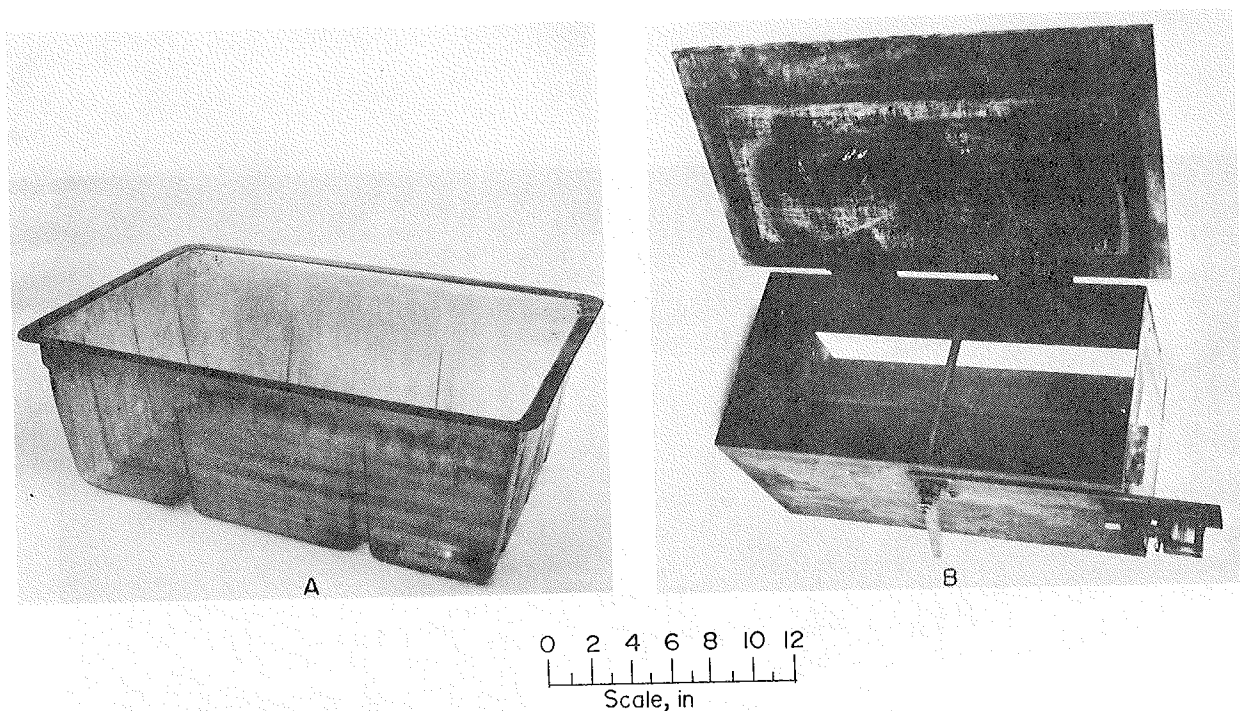


FIGURE 1. - Water tubs: *A*, PVC; *B*, metal.

Two facilities were used in the study, a metal gallery and the Bureau of Mines Experimental Mine (EM). In the 90-ft-long metal gallery, determinations were made of (1) wind velocities and dynamic pressures necessary to rupture or tilt the plastic tub and disperse its water, and (2) minimum wind velocities required to break up and disperse water during rapid spillage from the metal tub. In the Bureau's 1,300-ft-long Experimental Mine, the plastic and metal tub were used to suppress coal-dust explosions.

#### ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of G. R. Bercik, mining engineering technician and mine superintendent, Pittsburgh Mining and Safety Research Center, who was in direct control of all the dust explosion tests in the EM.

#### METAL GALLERY

Figure 2 is a photograph of the gallery, a smooth-wall cylindrical metal tunnel, 6-1/2 ft in diameter by 90 ft long, closed at one end. A single tub was mounted near the tunnel roof, 5 ft from the open end. The plastic tub was mounted by two methods--cradled or supported. In the cradled mode, the tub is rigidly held under its upper rim on all sides by a frame of 1-1/2-in<sup>2</sup> metal tubing that is suspended across the upper third of the tunnel cross section (fig. 3A). In the supported mode, the tub rests on a wood platform consisting of two 1-5/8 by 2-3/4-in wood members placed 8 in apart and suspended across the upper half of the tunnel cross section. The metal tub was bolted rigidly to the tunnel roof with the hinged door facing the open gallery end (fig. 3B).

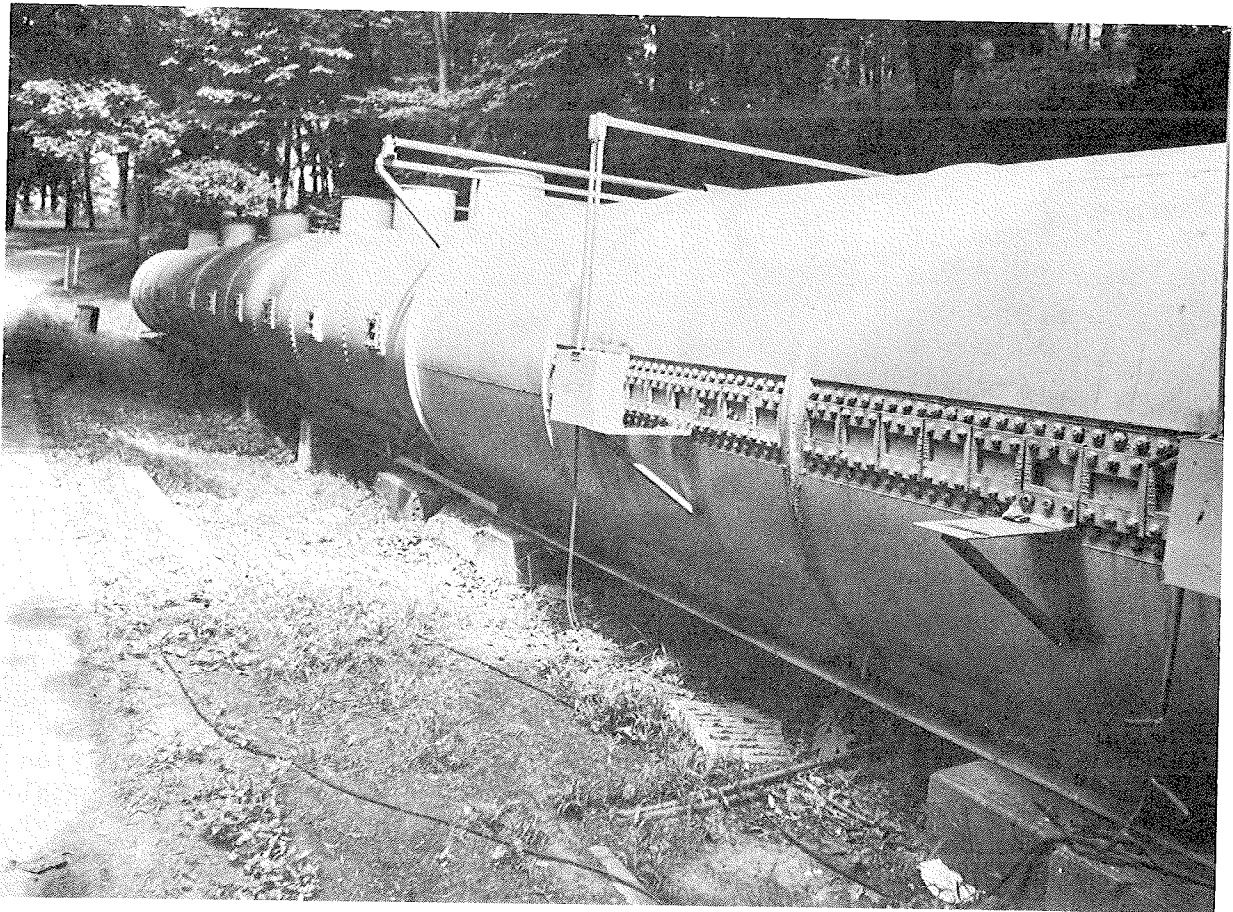


FIGURE 2. - Metal gallery.

The first 20-ft section of the closed gallery end was separated from the remaining tunnel by a removable polyethylene sheet 4 to 6 mils thick. In the experiments, this confined section was filled with a homogeneous natural gas-air mixture (6 to 9 pct natural gas). The plastic separator was removed rapidly by remote means just prior to igniting the gas at the closed gallery end by an electric spark. The ensuing flame propagated down the tunnel inducing dynamic pressures downstream that acted on the tub. Located along the gallery wall were eight ultraviolet light detectors to sense the passage of the propagating flame and three pressure transducers to determine the static pressure development. Hot wire anemometry probes were placed at a number of positions within the gallery, including a position 1 ft upstream of the water tub location to follow the gas flow developed ahead of the flame. Two high-speed cameras were used to view the water tub during the experiments. One camera placed at a window port located at the side of the gallery 10 ft from the open end, viewed the reflected image of the tub through a metal mirror mounted within the gallery. The other camera was placed about 30 ft from the open tunnel end and 20 ft from the tunnel axis.

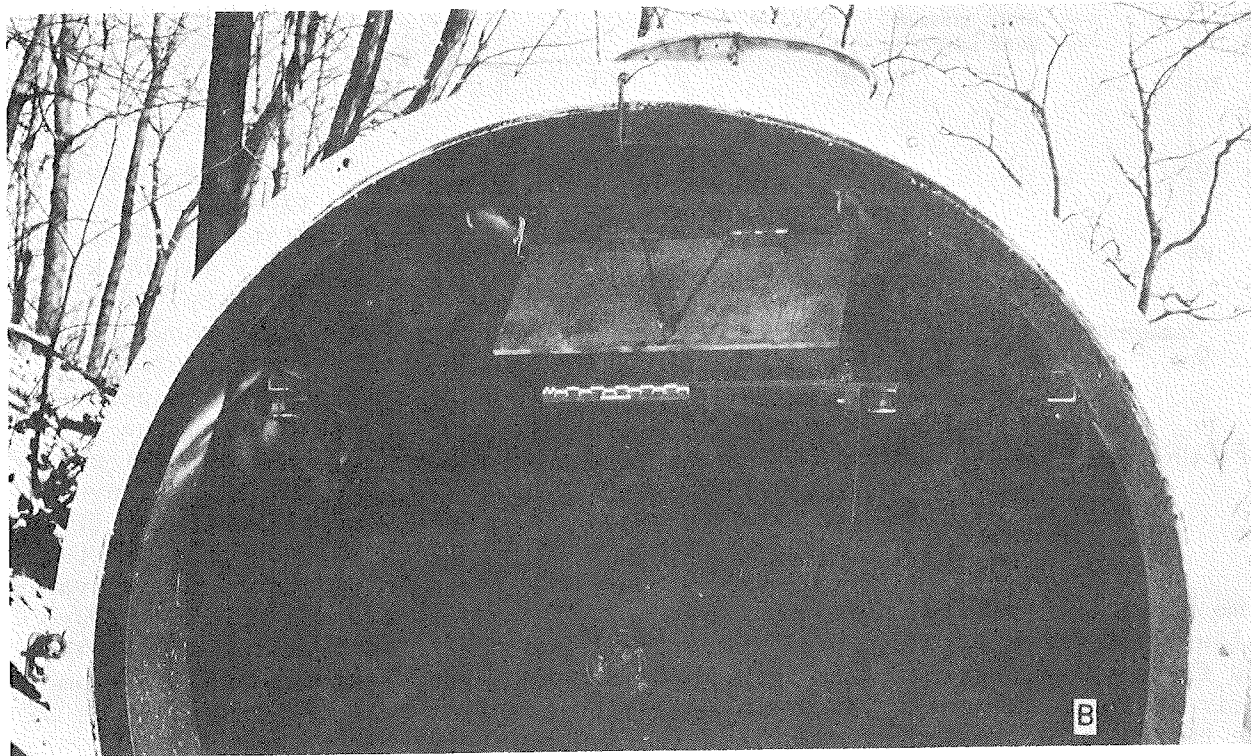


FIGURE 3. - Open-end view of metal gallery showing *A*, PVC tub mounted in cradled mode; *B*, mounted metal tub.

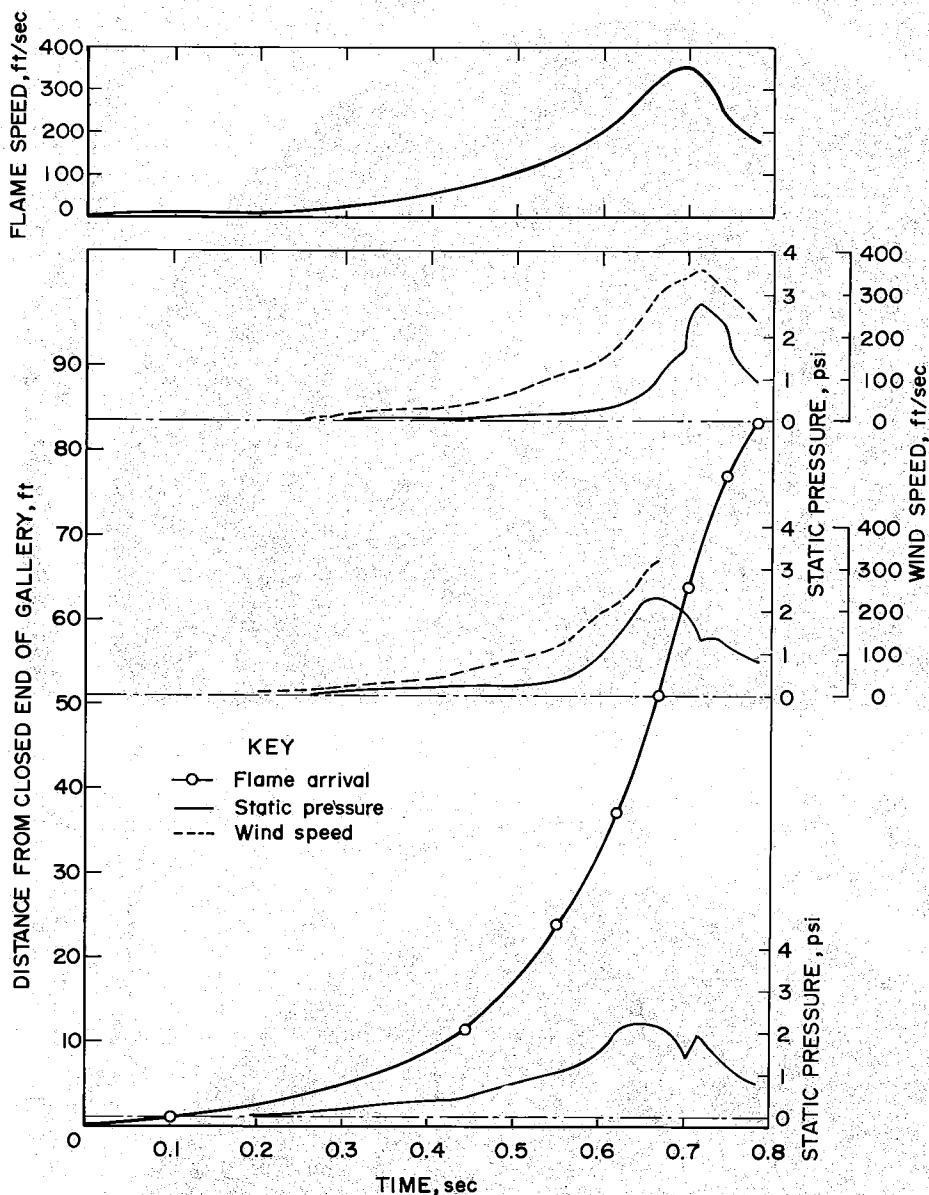


FIGURE 4. - Flame arrival time, flame speed, wind speed, and static pressure development in typical experiment in metal gallery.

### Preliminary Experiments

A number of experiments were conducted initially without the water tubs to examine the relationship between flame position and speed, induced gas flow ahead of the flame, and static pressure development. Both gas velocity and static pressure development are significant factors in the present study because tub motion and rupture, and water dispersion are dependent on the dynamic pressure,  $P_d = 1/2 \rho v^2$ , where  $\rho$ , the unburnt gas density, is proportional to the static pressure, and  $v$  is the wind velocity. Figure 4 shows the results of a typical experiment in which the initial natural gas concentration was 8.2 pct. In figure 4 are plotted the flame arrival

time along the gallery, static pressures 1, 51, and 83-1/2 ft from the closed gallery end, flame-induced wind velocity 51 and 83-1/2 ft from the closed end, and flame speed obtained from the slopes of the curve drawn through the flame arrival data. Anemometer probes sampled the gas flow near the central axis of the tunnel. The following describes the factors pertinent to the present study: The flame velocity increases during its first 50 to 60 ft of travel, and then owing to dilution of the original flammable mixture, flame speed

drops continuously in approaching the open tunnel end. In all cases, the flame propagates the full tunnel length. The gas velocity immediately ahead of the propagating flame is of the order of 1 to 50 ft/sec less than the flame velocity. This velocity difference, interpreted as the apparent burning velocity, was found to increase with flame speed. The maximum gas velocity and static pressures measured 83-1/2 ft from the closed end (1 ft upstream of tub location in subsequent experiments) corresponded closely in time with the maximum flame speeds. In additional experiments, tunnel cross-section velocity profiles and turbulent boundary layer growth were examined at a tunnel position 62 ft from the closed end. Results indicated that the unburnt gas velocity followed a typical pipe flow pattern--the velocity profile was essentially flat to within several inches of the tunnel wall during the early stage of flame propagation; the steep velocity gradient zone then progressively grew in time to a thickness of over 1 ft prior to flame passage. The turbulent boundary layer was also initially of negligible thickness and grew to a depth of over a foot immediately in front of the flame.

#### Plastic Separator

In several additional experiments, the plastic diaphragm that initially confined the 20-ft-long flammable zone was left in place to rupture during the explosions. In figure 5, the results of two experiments for removal and nonremoval of the plastic separator are compared; the initial natural gas concentration was 7.7 pct for both cases. In figure 5 are plotted the flame arrival time, flame speed, and static pressures measured 1 and 64 ft from the closed gallery end. Most significant is the large increase in flame speed and static pressure when the diaphragm is left in place to rupture. With initial natural gas concentrations as low as 6 pct and the diaphragm left to rupture, flame speeds exceeded 300 ft/sec. As shown in subsequent tub experiments, 300 ft/sec is in excess of the velocity necessary to rupture the plastic tubs. This finding is important to later runs in the EM in which the dust explosion is initiated by a similar flammable gas zone confined by a plastic separator. In this instance the diaphragm is difficult to remove prior to the explosion. Premature rupture of the plastic tubs would then be anticipated. A change in the explosion initiator source was therefore devised and is described later in this paper. It is of interest to note in figure 5 that flame speed and pressure development were approximately equivalent for both experiments during the first 20 ft of flame travel, indicating that enhancement of the combustion process occurred after the flame propagates through the separator. High-speed photographs indicated that the plastic ruptures by forming a slit opening approximately 2 ft wide that remains essentially unchanged until flame arrival. Anemometer probes showed the flow exiting the slit opening to have a low-frequency, high-intensity turbulence. Upon entering this turbulent region, the flame accelerates leading to increased flame speeds and pressures. The first pressure peak of about 0.5 psi observed in figure 5 and measured 1 ft from the gallery face occurs during the diaphragm rupturing process.

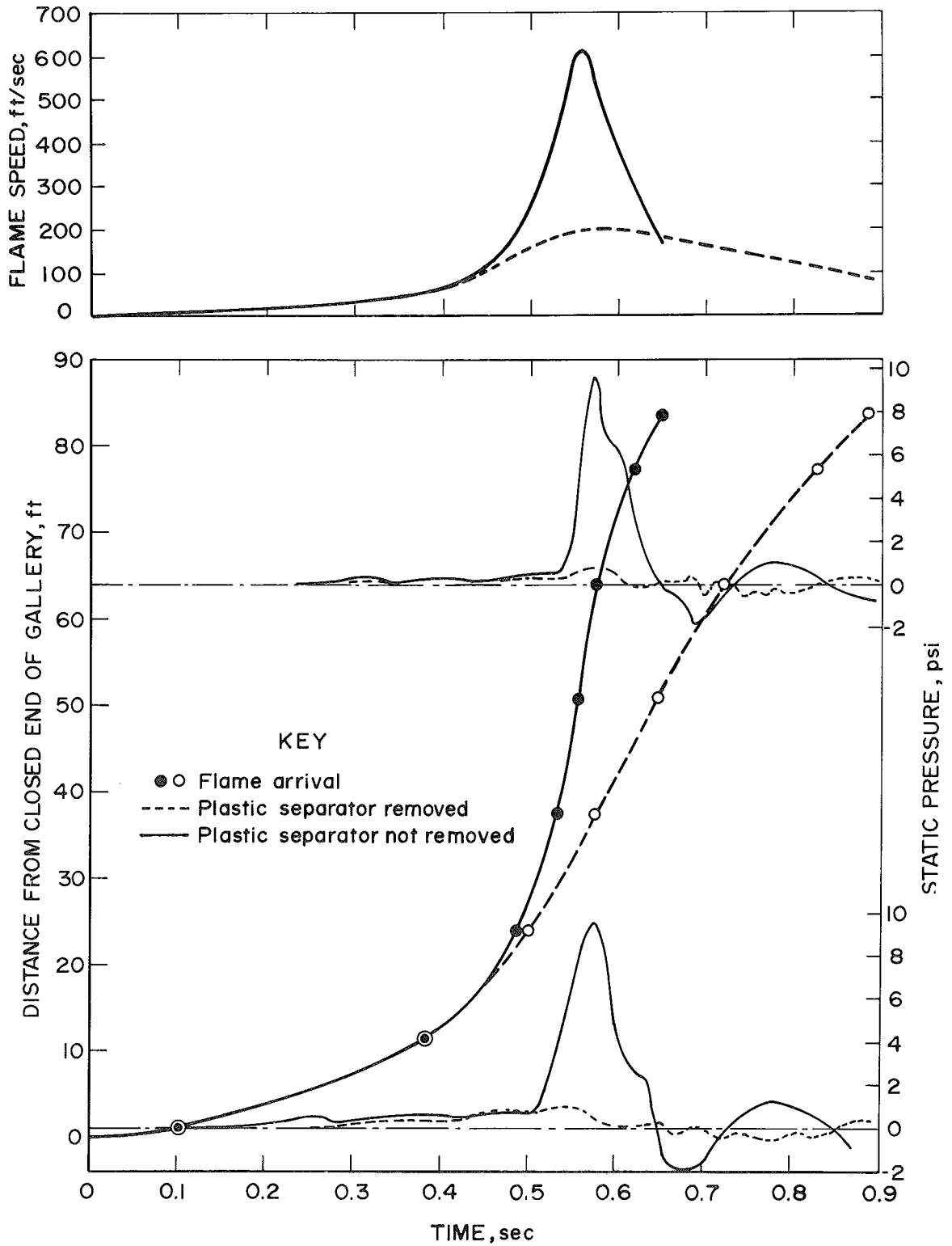


FIGURE 5. - Change in flame arrival time, flame speed, and static pressure development when plastic separator confining initial flammable zone is removed or left in place to rupture during explosion in metal gallery.

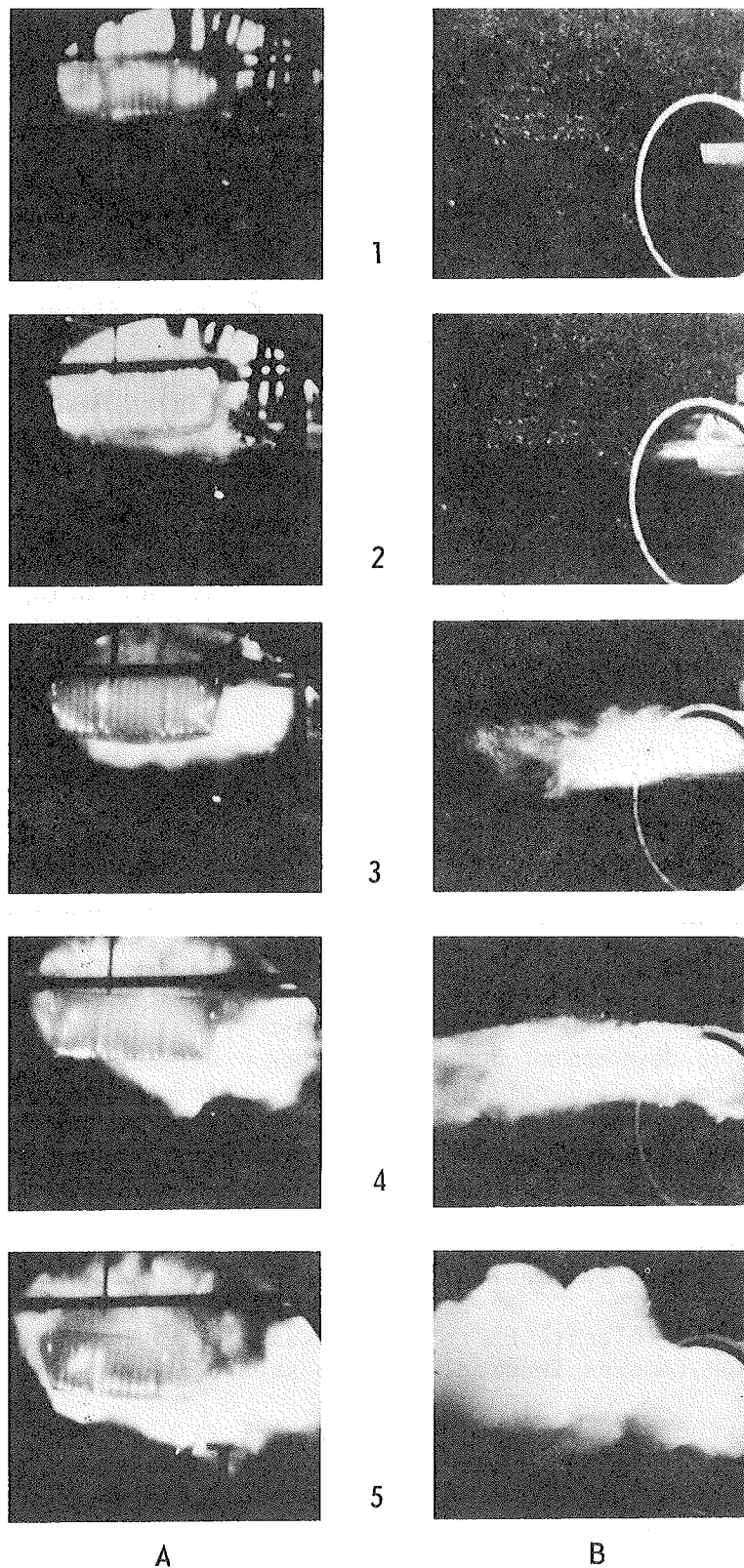


FIGURE 6. - Movie sequence showing inside A and outside B tunnel view of the PVC tub prior to and during rupture. Time between frames 24 msec. Tub lid blows off and some water dispersion begins during frame 2. Tub ruptures during frame 5.

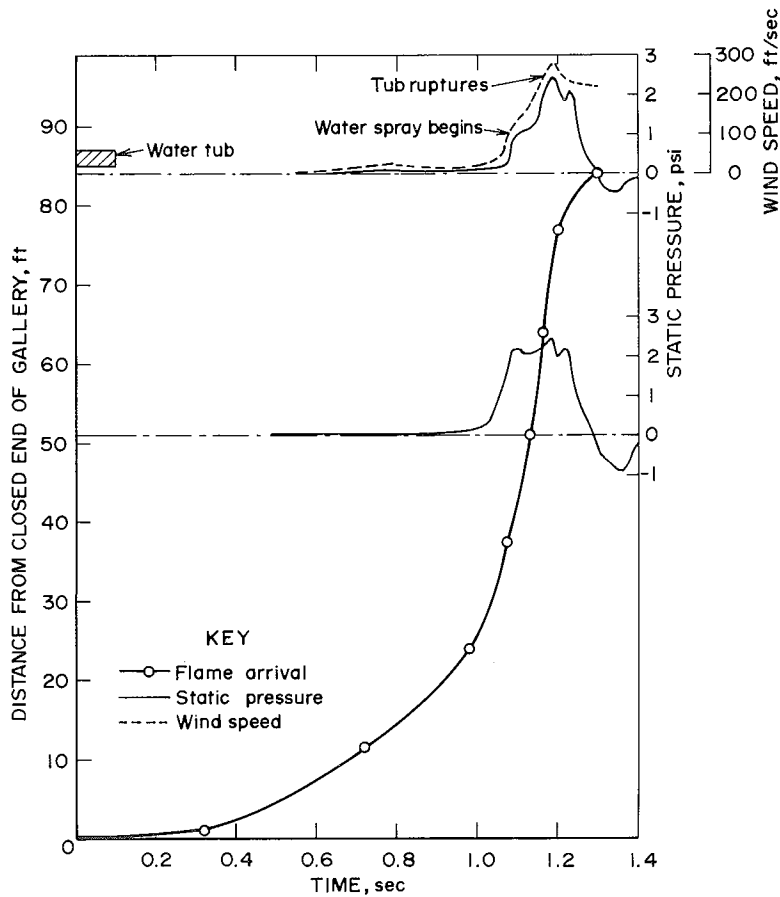


FIGURE 7. - Flame arrival time, wind speed, and static pressure development during PVC water tub experiment in metal gallery.

mode. The following comments summarize the relevant features of the experiments:

1. Maximum wind velocity less than 85 ft/sec, dynamic pressure ( $P_d$ ) less than 0.06 psi; no trough movement or water spray.
2. Maximum wind velocity 85 to 250 ft/sec,  $P_d$  0.06 to 0.60 psi; trough lid removed; trough remains in cradle; up to several gallons of water ejected.
3. Maximum wind velocity 250 to 280 ft/sec,  $P_d$  0.60 to 0.80 psi; trough ripped out of holder falling to ground up to 15 ft downstream; trough sides are cracked open; up to 50 pct of water dispersed; remaining water found in pools in vicinity of tub.
4. Maximum wind velocity over 280 ft/sec,  $P_d$  greater than 0.8 psi; tub is fractured into small pieces as it is pulled out of holder; all water is well dispersed downstream.

### Plastic Tub, Cradled

Experiments with the plastic tub mounted in the cradled mode indicate the tub rupture and effective water dispersion occur when the flame-induced wind velocity exceeds about 260 ft/sec. Figure 6 shows two movie sequences taken at the two camera locations showing the inside tunnel view (fig. 6A) and outside tunnel view (fig. 6B) of the tub prior to and during rupture. Data for the same experiment are plotted in figure 7; flame arrival, gas velocity, and static pressures were measured 1 ft upstream of the tub, and static pressure was measured 51 ft from the closed end. Also shown in figure 7 are the wind velocities when water spray and tub rupture are first observed.

Table 1 lists the conditions and results obtained for the experiments with the plastic tub in the cradled

As the wind velocities rise above 85 ft/sec, the tub lid blows off, and water is dispersed from the open tub in the form of a cloud about 1 ft high. At the tunnel exit, the cloud spreads owing to entrainment of the surrounding air. Following rupture of the tub at higher wind velocities, the size of the cloud increases drastically, having a horizontal and vertical spread of 10 to 15 ft at distances of 15 ft past the tunnel exit. At the high rupturing wind velocities, some of the water is ejected over 100 ft from the tunnel; however, most of the water is found to fall to the ground within 50 to 60 ft. At similar velocities in the confined region of a coal mine tunnel, the major portion of the water droplets would be expected to travel a good deal further. In addition, the gas flow would be highly turbulent in the mine, and the water cloud would fill the tunnel cross section rapidly. The duration of water ejection following tub rupture was estimated from the photographs to be about 0.15 to 0.1 sec during average wind velocities of 250 to 450 ft/sec, respectively. This is used in the later (EM) experiments to estimate the length of tunnel filled with water spray.

TABLE 1. - Maximum unburnt gas (wind) velocity and pressure developed in metal gallery experiments with PVC tub mounted in cradled mode

Experiment	Unburnt gas velocity, ft/sec	Dynamic pressure, psi	Static pressure, psi	Remarks
69	65	0.04	0.1	No water ejected.
70	85	.06	.2	Tub lid and a few quarts of water ejected.
47	150	.20	.3	Tub lid and a few gallons of water ejected.
50	250	.60	1.2	Tub ripped out of cradle holder, and tub sides fractured; 50 pct of water well dispersed.
48	260	.66	1.6	Similar to experiment 50.
71	280	.81	2.6	Tub ruptured into small pieces; all water well dispersed.
52	320	1.07	2.7	Similar to experiment 71.
51	340	1.21	2.8	Do.
46	370	1.45	3.0	Do.
49	380	1.50	3.4	Do.
119	560	3.90	6.5	Do.

As shown in figure 7, fragmentation of the tub took place at wind speeds of about 260 ft/sec whereas maximum wind speed was approximately 280 ft/sec. However, in the experiments in which the wind velocity and corresponding velocity gradient were higher, the required wind speed for tub rupture was also observed to increase. For example, in the last five experiments of table 1, wind speeds during the initiation of tub rupture were approximately 300 to 400 ft/sec. These increased speed requirements are a consequence of the high wind velocity gradients and imply that for rapidly accelerating flames, dynamic impulse is the governing factor for tub rupture; dynamic

impulse is defined as dynamic force  $\times$  time, where dynamic force is the dynamic pressure  $\times$  area of the tub facing the wind.

The dynamic force exerted on the tub at the minimum rupturing velocity is approximately equal to the gravitational force on the tub (180 lb). Interestingly, Rae (14) also found the minimum wind forces equal to the gravitational forces on a passive water barrier that successfully suppressed coal-dust explosions propagating in a 1,200-ft-long gallery.

#### Plastic Tub, Supported

Experiments with the plastic tub in the supported mode indicated that this method of mounting would provide less protection than the cradled method. The following comments summarize the results of these experiments:

1. Maximum wind speed less than 80 ft/sec,  $P_d$  less than 0.06 psi; no water ejection.
2. Maximum wind speed 80 to 100 ft/sec,  $P_d$  0.06 to 0.09 psi; tub lid raised; a few quarts of water ejected; no tub motion.
3. Maximum wind speed 100 to 160 ft/sec,  $P_d$  0.09 to 0.22 psi. Tub support dislodged, and tub falls striking ground 0 to 8 ft distant from tub support; tub usually undamaged or walls are splintered, presumably from the fall; a few quarts to few gallons of water dispersed, the remainder of water left in the tub or lying in pools surrounding the fallen tub.
4. Maximum wind speed 160 to 270 ft/sec, dynamic pressure 0.22 to 0.75 psi. Similar to comment 3, however, more water is dispersed, and tub strikes ground 8 to 15 ft from tub support; tub sides usually splintered.
5. Maximum wind speed 270 to 380 ft/sec, dynamic pressure 0.75 to 1.5 psi. Tub ruptured into large pieces during flight; the majority of water is dispersed within 60 ft of tunnel end.

In these experiments, the wind velocity required to loosen the tub platform and set the tub in motion was also found to increase with the velocity gradient. For example, in comment 3, initial tub drop was observed to occur when the wind speed reached 100 to 130 ft/sec, whereas in comments 4-5, tub movement began when the wind speed reached 130 to 230 ft/sec. At wind speeds less than about 270 ft/sec, the tub did not fracture into pieces, and nearly all of the water was carried along with the tub as it fell to the ground. Because of inertial forces, little water spillage occurred during twisting and turning of the tub during flight. Above wind speeds of 270 ft/sec, the tub did fragment during early flight, but it fragmented into large pieces--usually 3 to 4. Such large fragments would act to shield the water during the fall and would not allow the wind forces to operate efficiently on the water mass. In the previous cradled tub experiments, the tub was fragmented into many small pieces, presumably owing to confinement of the upper rim of the tub, and water dispersion was more effective.

From observations, it would appear that neither the cradled nor the supported tub would offer protection against slow-moving dust flames. In addition, the tubs would not be effective when mounted at distances closer than 100 ft from the ignition source unless the flame accelerated rapidly during its early stage of propagation to allow sufficient time for tub rupture and water dispersion prior to flame arrival. It is also likely that in most circumstances, the supported tub would be less efficient than the cradled tub.

#### Metal Tub

The purpose of the experiments with the metal tub was to determine the usefulness of the passive water barrier technique for the arrest of weak dust explosions. From the literature (12), it appears that the minimum propagation velocity of a self-sustaining coal-dust explosion in a mine is of the order of 100 to 150 ft/sec. Therefore, to be efficacious against weak dust explosions, passive water barriers would be required to rupture or tip and release its water at these low wind speeds. Of equal importance is the necessity that the released water be broken up and dispersed by this minimal wind force. In the present experiments, the metal tub was used to determine if low wind speeds

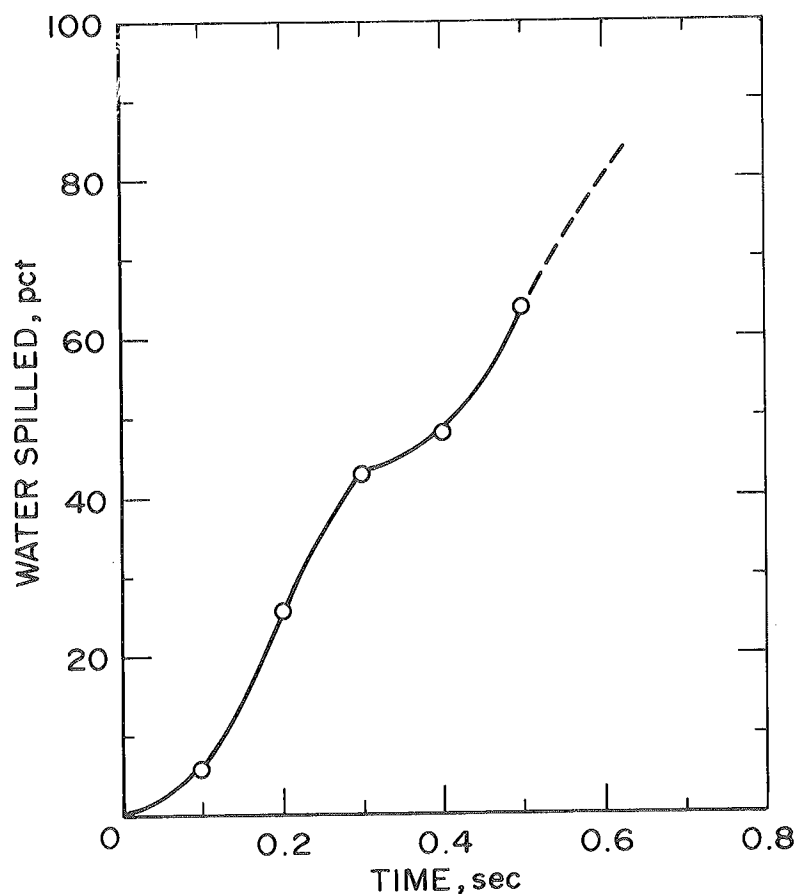


FIGURE 8. - Calculated rate of water release from 2-ft<sup>3</sup> metal tub immediately after side door is open.

are sufficient to break up and disperse water during rapid spillage; in later experiments, similar metal tubs are used in the EM for the suppression of slow-moving dust explosions. Results of these experiments would then indicate the practicality of designing a passive water barrier capable of releasing its contents at low wind speeds.

The experimental procedures were similar to those of the previous plastic tub tests; however, the metal tub was bolted rigidly to the roof near the open end of the metal gallery. The hinged tub door faced the opened tunnel end and was instrumentated to open rapidly at flame-induced wind speeds of 30 to 100 ft/sec. Figure 8 shows the calculated rate of water release immediately after the door is open. This plot is obtained from a revised version of a program published by the Los Alamos

Scientific Laboratories (1). Water release rates shown in figure 8 are based on the initial water level in the tub being 10 in. A careful examination of the photographs and corresponding wind velocity records indicates that wind speeds of the order of 70 ft/sec were necessary at the maximum water release rate (0.1 to 0.6 sec in fig. 8) for effective breakup and dispersion of the water. This maximum water release rate is equal to about 1.5 ft<sup>3</sup>/sec for each foot of tub length. This is somewhat less than the estimated average rate of 6.6 ft<sup>3</sup>/sec per foot for the plastic tub mounted in the cradled mode and being driven by average wind speeds of about 250 ft/sec (estimated from the observed 0.15 sec for duration of water spray). Effective dispersion was interpreted to occur when the flight path of the water spray leaving the tub was essentially horizontal for approximately 10 ft beyond the open tunnel end. With increased water dumping rates, higher wind speeds would be required. These experiments show that slow-moving dust flames should be readily suppressed by the passive water barrier technique. As described later in this report, dust explosions traveling at speeds in the range of 100 to 250 ft/sec were successfully quenched with similar metal tubs.

#### EXPERIMENTAL MINE FACILITY: PREPARATORY STUDIES

##### Description of Mine

The Experimental Mine facility used in the present series of tests consists of a single entry about 1,300 ft long driven into a seam of Pittsburgh coal. For the most part, the walls, roof, and floor are coated with cement to prevent interaction of the coal seam with the explosion tests. The height of the roof above the floor is approximately 6-1/2 ft, and the entry is about 9 ft wide, giving a cross-sectional area of about 58-1/2 ft<sup>2</sup>. Crosscuts, sealed with cement bulkheads, exist 50, 250, and 450 ft from the closed end. These crosscuts do not influence the explosion test results unless very strong compression waves are generated by a flame, resulting in reflected compression and expansion waves. Compression waves are also reflected from the closed end, but the open end of the mine entry is so far away that expansion waves from the latter do not influence test results.

Coal-dust explosions are usually initiated in the EM by igniting a mixture of natural gas and air confined to a region near the closed end, or face, by a plastic diaphragm. From this diaphragm, the coal dust, usually premixed with rock dust, is distributed toward the portal on the floor, on ribs along the walls, and on shelves near the roof. Pittsburgh coal dust, containing approximately 36 pct volatiles, was used in all the experiments. Two size distributions of coal dust were used--pulverized dust and mine-size dust. Pulverized dust (designated as PPC) contains particles 80 pct of which passes through a 200-mesh screen (80 pct less than 74  $\mu$ m diameter); mine-size dust (designated as MS) contains particles 100 pct of which passes through a 20-mesh screen (100 pct less than 820  $\mu$ m), and 20 pct will pass through a 200-mesh screen (20 pct less than 74  $\mu$ m). The rock dust contains particles 70 pct of which passes through 200-mesh screen (70 pct less than 74  $\mu$ m). The strength of the coal-dust explosion then becomes a function of the strength of the initiating source, the coal-dust concentration and particle size, and the concentration of rock dust.

Mine explosion measurements for the present series of experiments were confined to flame radiation histories and to static pressure histories, as observed by sensors mounted at stations along the wall of the entry. All data were recorded with light beam oscillographs on chart paper, moving at 40 in/sec, with galvanometers that have a natural frequency of 1,000 Hz and a flat (5 pct) frequency response from 0 to 600 Hz.

Two types of flame sensors were used. One is a silicon phototransistor with a maximum sensitivity in the near infrared, and a conical viewing field of about 20°. Adequate sensitivity, without voltage amplification, was obtained for all coal-dust explosions and for all but very lean gas explosions. A total of 16 of these flame sensors were available, located at 15, 25, 50, 75, and 100 ft from the face, and every 50 ft thereafter, to 650 ft from the face. The other type of flame sensor consisted of three blue-sensitive photomultiplier tubes, located 75, 150, and 250 ft from the face, each with a narrow-band interference filter centered at 4315 Å<sup>3</sup> and with slits that confined the view to about 1.5° horizontally and about 30° vertically. Adequate voltage signals were also obtained from these sensors without additional voltage amplification. Current amplification required to operate the galvanometers was obtained in all cases by the use of wide-band galvanometer driver amplifiers. The rise time of signals from the flame sensor circuits, including cables, was less than 100 μsec. It was observed that both sensors gave approximately the same arrival time for the leading edge of the flames, but the decay times were different, as noted later. Extent of flame travel could also be estimated by placing matches and bromide paper at locations near the roof.

Static pressures at the wall were measured with nine bonded strain gage pressure transducers, located at the face and at 50, 100, 200, 250, 300, 400, 500, and 600 ft from the face. These transducers each have an integral amplifier with a rated output of 5 V, and a low output impedance, providing adequate signal to drive the long cables to the recording equipment. The natural frequency of the sensing element is about 2,000 Hz, with a linearity of 0.5 pct. Frequent static pressure calibration is performed on all pressure transducers.

Event marks, such as for the rupture of a barrier and firing of the ignition circuit, were also recorded by the same oscillographs. For the present series of tests, the ignition source for the gas mixture consisted of an electric matchhead surrounded by 2 g of guncotton.

#### Development of Standard (Weak) Dust Ignition Source

The goal of this task was to devise an initiation source that would not disturb the passive barriers being tested and would have a minimum effect on explosion acceleration in the test zone but that would reliably ignite the test zone. It has been observed in the past in the EM, owing in part to

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<sup>3</sup>Recent laboratory experiments with coal-dust explosions indicate that the radiation at 4315 Å, as well as radiation in the infrared, is essentially continuum.

roughness of the walls, that flames of stoichiometric mixtures of natural gas and air will accelerate very rapidly and develop shock waves within 50 ft from the face. These shock waves often obscure pressures developed by the subsequent coal-dust explosions. Such shock waves would rupture a passive barrier considerably in advance of a slowly moving dust flame.

Because of experience with explosion-ruptured diaphragms in the 6-1/2-foot metal gallery (with smooth walls), the diaphragm effect was investigated in the EM. A series of tests were conducted with 20-foot zones of mixtures (about 1,170 ft<sup>3</sup>) of 9.5 pct, 8.0 pct, and 7.0 pct, of natural gas and air. For the test series, the diaphragm was either broken conventionally or removed completely from 0 to 30 sec before ignition. For the 7.0 pct mixtures, guncotton had to be used to obtain reliable ignition, but single sparks were used in the other cases. For the 9.5 pct and 8.0 pct mixtures, the maximum explosion pressures developed were about the same whether the diaphragm was removed immediately before ignition or not. From this it was concluded that wall roughness in the EM is more important in accelerating flame than is an aperture effect due to a partially broken diaphragm. When the diaphragm was removed 30 sec before ignition of a 7.0 pct mixture, the mixture either did not ignite at all (apparently due to diffusion of air into the zone), or it burned very weakly, developing no measurable pressure. So a final, reproducible, weak ignition source was devised. The weak ignition source consisted of a 10-ft zone of 7.0 pct natural gas (containing about 41 std ft<sup>3</sup> of natural gas) and developed a maximum overpressure of about 2 psi. In this case, the flame extent was between 25 and 50 ft, developing a maximum flame speed of about 150 ft/sec. As with all gas zones, the natural gas and air were mixed with a circulating pump until an on-line infrared gas analyzer indicated the composition was constant.

To insure reliable ignition of the test coal dust raised by the gas explosion, an additional "booster zone" of pulverized dust was placed between the ignition zone of 7.0 pct natural gas-air mixture and the test dust zone. This "booster zone" was 10 ft in length, consisting of 10 lb of pulverized coal. Of the 10 lb of coal, 5 lb was placed uniformly on the floor and ribs, and 2-1/2 lb each was placed on two shelves near the roof at 14 ft and 18 ft from the face. With the "booster zone" added to the standard ignition source, the flame now traveled past 50 ft, but there was no further increase in maximum pressure. This standard composite ignition source was used for all subsequent tests described in this report and will be referred to as the standard ignition source.

#### Development of Standard Dust Explosions

For the purpose of evaluating the passive water barriers, three ranges of dust explosion intensities (based on flame speed at the barrier location) were considered desirable. These ranges were based on a goal of nearly constant flame speed, approaching a barrier, and the assumption that the flame speed is very nearly equal to the air speed at the leading edge of the flame (small burning velocity relative to the approaching unburned mixture). The three ranges are as follows: Weak (less than 225 ft/sec--not expected to break the PVC barriers), moderate (between 225 and 500 ft/sec--expected to break the

PVC barriers and result in flame quenching every time), and strong (greater than 500 ft/sec--expected to break the PVC barriers every time but not necessarily result in flame quenching every time).

The intensity of the dust explosions was varied by changing the length of the dust zone (from 150 ft to 350 ft), varying the concentration of rock dust (from 40 pct to 65 pct), varying the coal dust particle size (pulverized coal dust or mine-size dust), or varying the runup distance to the barrier (located at either 200 ft or 300 ft from the face).

For the test dust zones, beginning at 20 ft from the mine face, the coal dust was distributed at the rate of 1 lb per linear foot of entry, in addition to the rock dust. If all the coal dust so distributed were thrown into suspension within the test zone, the concentration in air would be about 300 mg/liter, or about 0.3 oz per cubic foot of mine entry. The coal dust and rock dust for each test were well mixed, and one-third was broadcast uniformly on the floor, one-third was spread on ribs attached to the walls, and one-third was placed on shelves placed near the roof at 10-ft intervals. The coal from which the dust was made was mined from another part of the same coal seam.

#### Flame and Pressure Development

According to the way the PVC passive water barriers were designed to rupture in the path of an explosion, the relevant physical property of the flow is the critical dynamic pressure on the upstream faces of these barriers. Since it was not yet possible to measure the dynamic pressure or air velocity in the mine, flame speed and static pressure distribution in time and space were considered as possible useful alternatives. For a single dust explosion gallery, Rae (13) has shown that for low-speed flow, the flame speed was very nearly equal to the wind speed, at least up to about 60 m/sec, and was proportional to the static pressure at the wall (in the absence of reflections) by an acoustic approximation, as follows:

$$\Delta p = \rho_0 c_0 v, \quad (1)$$

where  $\Delta p$  = increase in static pressure at flame arrival,

$\rho_0$  = density of unburnt gas (assumed constant in this case),

$c_0$  = velocity of sound in unburnt gas,

and  $v$  = particle velocity, or wind speed.

If the wind speed is known, the dynamic pressure,  $1/2 \rho v^2$  can be estimated. So a study was made to test the validity of this approximation and to determine if there was a relation between static pressure and flame velocity of gas and dust explosions, over a wide range, in the EM.

Static pressures can be measured fairly accurately at several discrete stations, and transmitted and reflected sound and pressure waves can be interpreted by means of wave diagrams. But flame arrival times (from which flame speeds can be estimated) are much more ill-defined, especially with dust explosions, in which a definite flame front almost never exists. Nevertheless, a useful definition of flame arrival was found to be the first appearance of a signal from a flame sensor (called the leading edge of the flame), especially if followed in consistent manner by an increase of radiation to about 50 pct of the maximum (called the arrival of substantial flame). Additional information is also available, including the maximum irradiation received and the duration of the radiation at different stations and at different wavelengths. Flame speeds are then estimated by graphically taking slopes along a smoothed curve of arrival time of leading edge versus distance. If the flame has moderate acceleration and undergoes no reversals, it is felt that flame speeds taken in this manner are accurate within  $\pm 10$  pct. It was found that the flame speeds are roughly proportional to the static pressure rise at the flame front itself, in accordance with equation 1, up to about 300 ft/sec, but that the static pressure rise increases more rapidly than flame speeds at higher values of the flame speeds. This trend is the same for gas explosions as well as dust explosions but will require more research for confirmation because more factors, especially flame acceleration,<sup>4</sup> are involved.

Flame arrival time is plotted on the wave diagram (previously mentioned), which includes pressure histories as well as wave arrival times. An example of such a plot is shown in figure 9 (EM test 3433, without a barrier), which shows compression waves being driven in both directions by an accelerating flame as well as being reflected from the face and from a crosscut. A "piston" diagram of the same data is shown in figure 10 indicating how the flame acts as a piston to drive flow ahead of it. The maximum static pressure within the flow, as well as the maximum velocity of gas, occurs near the flame "front" in agreement with the theory of one-dimensional combustion dynamics such as described by Jones (9). The flow field ahead of the flame is important in understanding the performance of passive barriers, which must operate at the proper time to extinguish the flame.

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<sup>4</sup>More recent measurements with dynamic pressure probes have verified the validity of equation 1 up to 300 ft/sec as well as the approximate equivalence of flame speeds in this range.

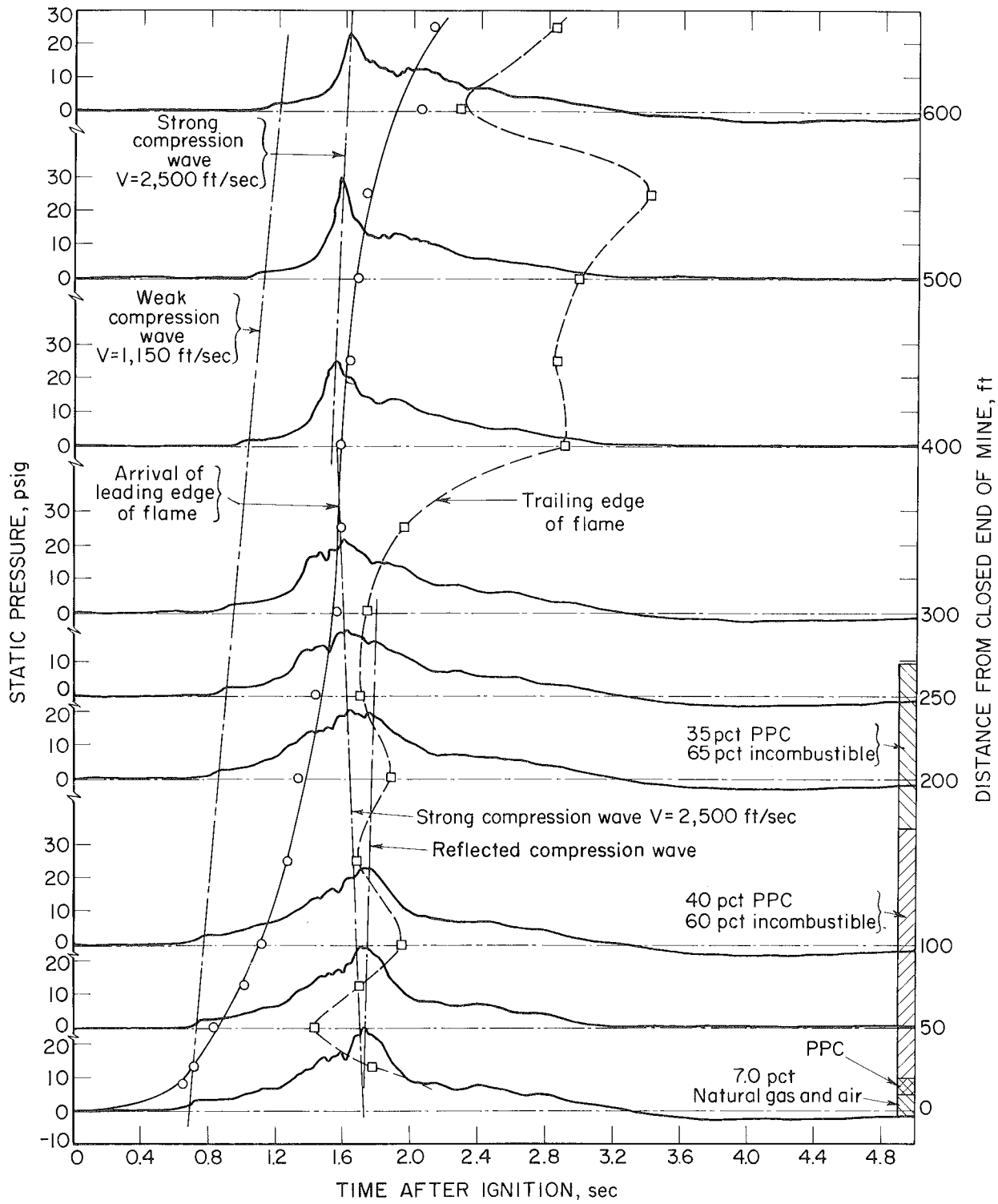


FIGURE 9. - Wave diagram of coal-dust explosion, EM test 3433.

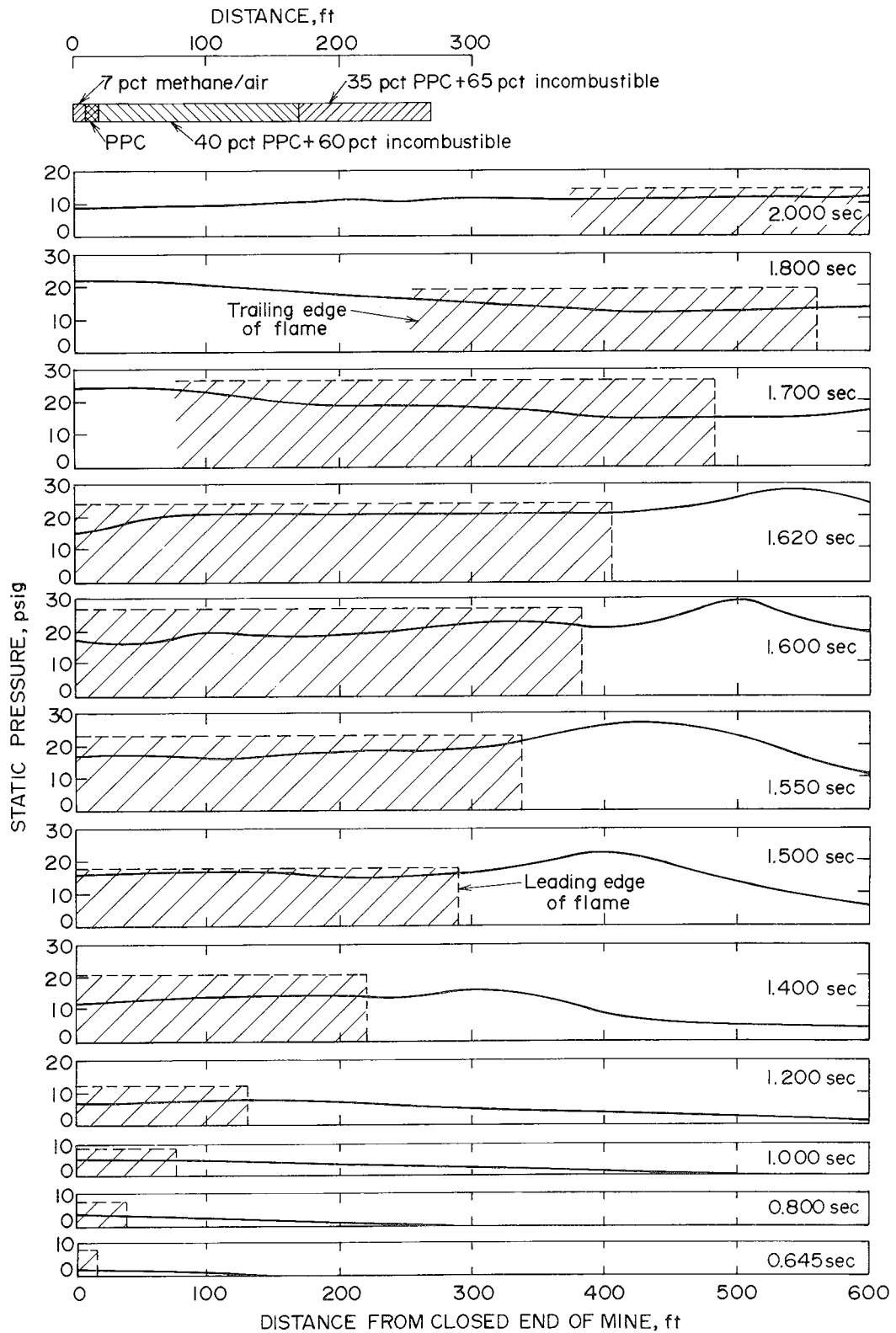


FIGURE 10. - Instantaneous pressure profiles (piston diagram), EM test 3433.

EXPERIMENTAL MINE FACILITY:  
WATER BARRIER STUDY

Summary of Experiments,  
PVC Water Tub



FIGURE 11. - Two PVC water tubs mounted near mine roof.

By experiments in the metal gallery, as well as in Germany, where the plastic barriers were designed, it was determined that the barriers were most effective if placed at least 200 ft from the ignition source. In this way, sufficient runup distance could be obtained to produce a dynamic pressure of the air on the leading face sufficient to rupture the barriers and also obtain sufficient air velocity to disperse the water effectively. Because

it was also found from work in the metal gallery that most effective dispersion could be obtained by cradling the plastic barriers in a metal frame, such frames were mounted in the EM near the roof at 200 ft and 300 ft from the face. Either one or two tubs were used in the experiments. Figure 11 shows two tubs mounted at the 200-ft station. When one tub was used, it was mounted either in the center of the tunnel or near the rib. In the two-tub arrangement, one tub was mounted near a rib, and the other tub was mounted in the center.

In order to mark the time of rupture of the plastic barriers during a test, break wires were attached to the barriers in such a way that, when the barrier ruptured, a circuit was interrupted and an event mark occurred on the oscillograph record. This event mark showed that the barrier break occurred always when the flame front was about 100 to 150 ft away, which allowed at least 0.2 sec for the water to be dispersed in advance of the flame. The dust explosion was quenched in all cases where rupture occurred, as shown later. After the test, water was found on the floor of the mine, and sometimes on the roof, as far as 100 ft towards the open end. It was felt that the water had to be in the air rather than on the floor to be effective in quenching an explosion. By the time the barriers were broken, nearly all of the dust would have been blown off the walls and roof, and most would have been lifted off the floor.

The results of the PVC water barrier tests, including some control tests without barriers, are summarized in table 2. In an effort to obtain constant flame speeds and constant pressures approaching the barriers, the rock dusting was graded to try to reduce the continuous flame acceleration or deceleration usually obtained with uniform loading. With a very few exceptions, the aforementioned goal was not obtained.

TABLE 2. - Summary of explosion suppression tests in EM

Test	Length of test zone, ft	Size of dust <sup>1</sup>	Pct incom-bustible/rock dusting length, ft <sup>2</sup>	Maximum flame speed approaching barrier station, ft/sec	Maximum flame static pressure approaching barrier station, psig	Number of barriers	Location of barriers, ft from face	Barrier break	Comments
3418	150	PPC	65/150	500	8.5	1	200	Yes	Flame quenched at 250 ft.
3419	-	-	-	~100	2.0	1	200	No	Control test with gas only.
3420	-	-	-	~100	2.0	1	200	No	Control test with gas and 10 lb PPC
3421	200	MS	65/200	150	3.0	1	200	No	Flame to 50 ft.
3422	200	MS	45/200	200	3.5	1	200	No	Flame to 250 ft.
3423	200	MS	40/200	225	4.3	1	200	Yes	Flame quenched at 250 ft.
3424	300	MS	40/300	150 (100 ft)	3.3 (100 ft)	0	-	-	Test zone extended 100 ft. Flame to 250 ft.
3425	300	MS	40/120 30/120 40/60	600 (600 ft)	16 (600 ft)	0	-	-	Control test. Flame past 650 ft.
3426	300	MS	40/120 30/120 40/60	150	2.5	2	200	No	Flame to 150 ft.
3427	300	MS	40/120 30/120 40/60	165	3.5	2	200	No	Same loading as 3426. Flame to 500 ft.
3428	300	MS	40/120 30/120 40/60	140	2.5	2	200	No	Flame to 650 ft. PPC booster zone = 15 ft.
3429	300	MS	35/120 40/180	200	3.9	2	200	No	Flame to 650 ft.
3430	300	MS	35/120 40/180	250	5.0	2	200	Yes	Flame quenched at 250 ft.
3431	300	MS	30/120 40/180	300 (600 ft)	4.5	0	-	-	Control test. Flame to 650 ft.
3432	300	MS	30/120 40/180	275	5.5	1	200	Yes	Flame quenched at barrier.
3433	250	PPC	60/150 65/100	>1,200 (500 ft)	30	0	-	-	Control test. PPC booster zone = 10 ft.
3434	250	Hybrid	60/150 65/100	225	4.0	2	200	No	Flame to 650 ft.
3435	250	Hybrid	60/150 65/100	275	3.8	2	200	No	Flame to 650 ft.
3436	250	Hybrid	50/50 60/100 65/100	260	6.5	2	200	Yes	Flame quenched at barrier.

See footnotes at end of table.

TABLE 2. - Summary of explosion suppression tests in EM--Continued

Test	Length of test zone, ft	Size of dust <sup>1</sup>	Pct incom-bustible/rock dusting length, ft <sup>2</sup>	Maximum flame speed approaching barrier station, ft/sec	Maximum flame static pressure approaching barrier station, psig	Number of barriers	Location of barriers, ft from face	Barrier break	Comments
3437	250	PPC	60/150	>500	12.5	2	200	Yes	Flame quenched at barrier.
3438	250	PPC	65/100 50/50 60/100 65/100	320	No data	2	200	Yes	Flame quenched at barrier.
3439	250	PPC	45/100 60/50 65/100	400	16	2	200	Yes	Flame quenched at barrier.
3440	350	PPC	50/100	>700	25	2	300	Yes	Flame quenched at 250 ft.
3441	350	PPC	60/250 50/100 60/250	>600	24	1	300	Yes	Flame quenched at barrier.
3458	350	PPC	45/100 50/250	1,000	27	1	300	Yes	<sup>3</sup> Flame quenched at 400 ft.
3459	350	PPC	45/100 50/250	1,154	34?	1	300	Yes	<sup>3</sup> Flame quenched at 400 ft.
3460	250	PPC	45/100 50/150	700	14	1	200	Yes	Flame quenched at barrier.
3461	150	PPC	60/150	286	7.5	<sup>4</sup> 2	110	-	Barrier door did not open. Flame to 550 ft.
3462	150	PPC	65/150	241	5.3	<sup>4</sup> 2	110	-	Barrier door opened late. Flame to 450 ft.
3463	150	PPC	65/150	216	6.0	<sup>4</sup> 2	110	-	Flame quenched at barrier.
3464	150	PPC	75/150	173	<1.0	<sup>4</sup> 2	110	-	Flame to 50 ft only.
3465	150	PPC	70/150	118	4.5	<sup>4</sup> 2	110	-	Flame quenched at barrier.

<sup>1</sup>Size of dust:

MS = Mine-size dust, 100 pct through 20 mesh (100 pct <840  $\mu$ m).

PPC = Pittsburgh pulverized coal dust, 80 pct through 200 mesh (80 pct <74  $\mu$ m).

Hybrid = PPC contaminated with unknown amount of MS.

<sup>2</sup>Volatile content of coal  $\approx$  36 pct. Ash content of coal  $\approx$  8 pct. Size of rock dust: 70 pct through 200 mesh (70 pct <74  $\mu$ m).

<sup>3</sup>Flame is considered to be quenched at 400 ft. Explanation is given in text.

<sup>4</sup>Steel containers with 1.7 ft<sup>3</sup> of water each. Door outby opens. See text.

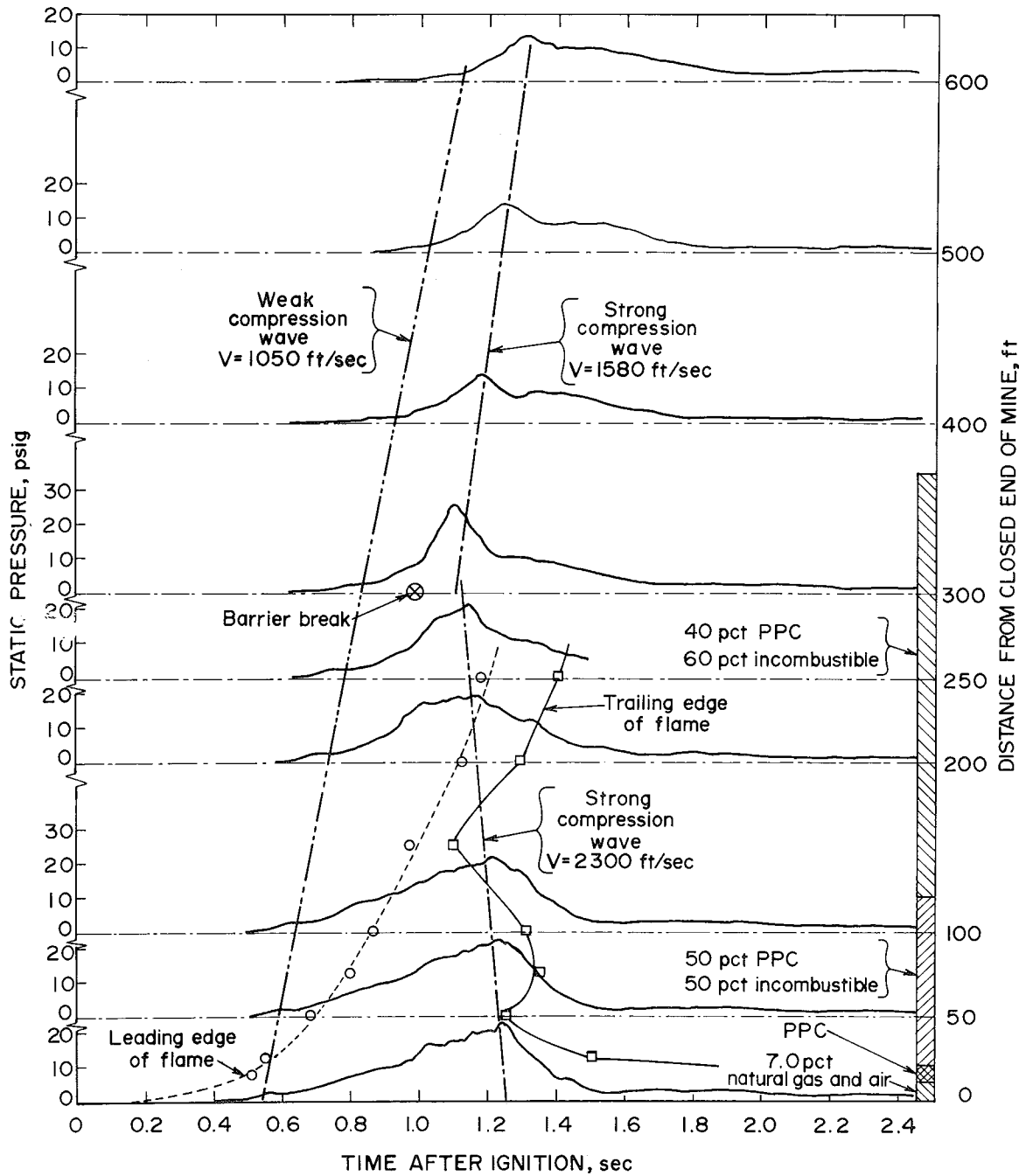


FIGURE 12. - Wave diagram of coal-dust explosion with suppression by two PVC water tubs placed 300 ft from closed end of mine, EM test 3440.

Early tests verified that the standard weak ignition source did not rupture the water barriers and also that the pressure developed (about 2 psig) was less than that developed by any self-propagating dust explosion which the former ignited.

Mine-size coal dust contributed all the data for weak explosions; as a matter of fact, it was difficult to produce sufficient flame speed and pressure 200 ft from the face to rupture the barriers with this dust when rock-dust contents were greater than 30 pct. In every case in which the barrier was located 200 ft from the face and barrier rupture occurred, the flame disappeared within 50 ft or less after the barrier, with consequent rapid decrease in static pressure at the barrier station. The minimum flame speed that produced barrier rupture was about 250 ft/sec, and the minimum static pressure associated with this rupture was about 4 psig. In cases in which no barrier rupture occurred and in control tests without a barrier present, the flame continued to accelerate slowly past the end of the dust zone.

In order to obtain flame speeds 300 ft/sec or greater 200 ft from the face, pulverized coal dust was used with rock-dust concentrations of 50 pct or less. In order to produce flame speeds in excess of 600 ft/sec approaching the barriers, the barriers were moved to 300 ft from the face. In these cases, static pressures in excess of 20 psig were produced. Flame extinguishment, in these tests, occurred near the barrier site when the maximum flame speeds were below 1,000 ft/sec (tests 3440, 3441). Whereas, when the flame speed exceeded 1,000 ft/sec (tests 3458, 3459), the flame was not quenched until it had propagated 100 ft beyond the barrier site. However, experience from previous tests indicate that such flames would be expected to propagate beyond the final test station located at 650 ft from the face when a barrier is not used. Therefore, the barriers in the latter two tests are also considered to be successful in quenching the explosion. Since only one tub was used in the latter experiments, it is believed that the use of two tubs would have resulted in a decrease in the flame quenching distance beyond the barrier. In all other tests one barrier seemed to be as effective as two, and the location of the tubs in the tunnel cross section appeared to have little influence on the effectiveness.

In many cases of strong explosions in which barrier rupture occurred, no signal was observed from the flame sensor immediately upstream of the barrier location, but indications of heating were obtained from matches and bromide papers placed 40 ft toward the open end from these locations. In these same cases, the flame static pressure began to decrease rapidly as the flame approached 50 to 100 ft in by the barrier. A wave diagram illustrating a flame extinguishment and its effect on flame and pressure development is shown in figure 12 (EM test 3440). Flame speeds and flame-induced pressures are shown in figures 13-14.

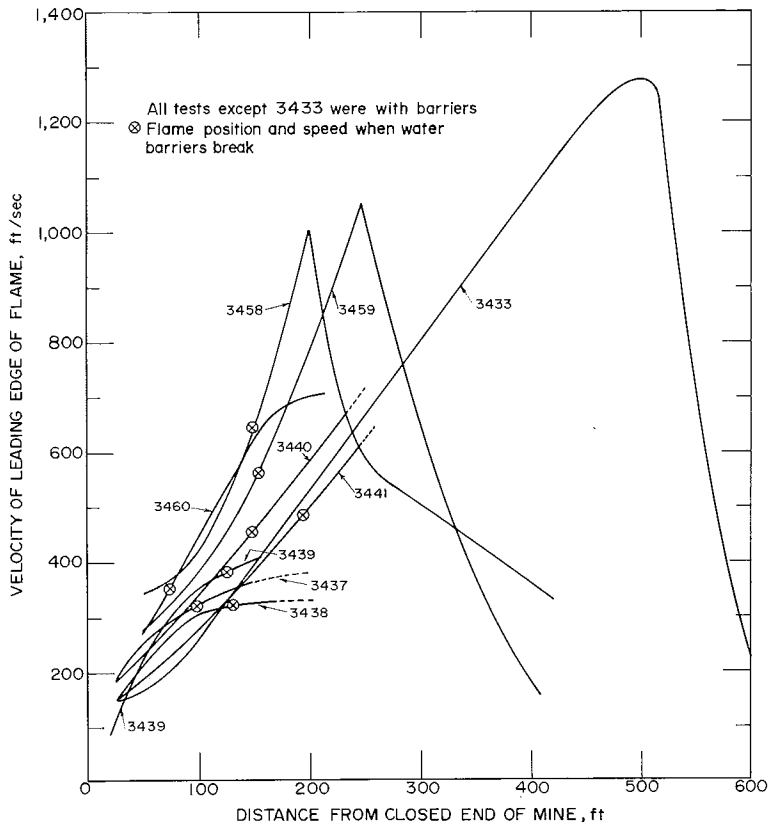


FIGURE 13. - Flame speed versus distance in EM tests.

at the end of table 2. Results of the experiments are plotted in figure 16; figure 16A shows the flame arrival time and the time the tub door first opened; figure 16B, flame speed; and figure 16C, wind velocity at the tub site calculated from the static pressure data in accordance with equation 1. In test 3461, the tub door did not open owing to a malfunction in the electrical circuitry, and the flame propagated to 550 ft. In test 3462, the flame was not suppressed because the time of the door opening--0.82 sec following ignition--allowed an interval of only 0.1 sec for water spillage prior to flame arrival. From figure 8, we see that only a few percent of the available water supply would be released in this short time. Explosion suppression by the barrier was obtained in tests 3463 and 3465 in which the tub door opened about 0.5 sec following ignition allowing approximately 0.4 sec for water release before the flame arrived, which corresponds to a discharge of about 50 pct of the water supply.

#### Discussion of Results, PVC Water Tub

An important relationship obtained in the current research in the EM is the approximate linear relationship between flame speed and static pressure rise at the flame, as expressed by the acoustic approximation, equation 1. A plot of flame speed versus static pressure rise measured at the flame front is

#### Summary of Experiments, Metal Water Tub

Two water-filled metal tubs, duplications of the tub shown in figure 3B were mounted near the mine roof (fig. 15) 105 ft from the face. Mounting the tubs close to the ignition source made it more convenient to determine the effectiveness of the barriers in suppression of weak explosions because a runup distance is normally required for a dust explosion to attain high propagation rates. The tub doors opened outby and were programed to open about 0.5 to 0.8 sec following ignition. An event signal was transmitted to the oscillograph recorder through actuation of a switch during opening of the tub doors.

The conditions and comments of five tests with the metal tubs are summarized

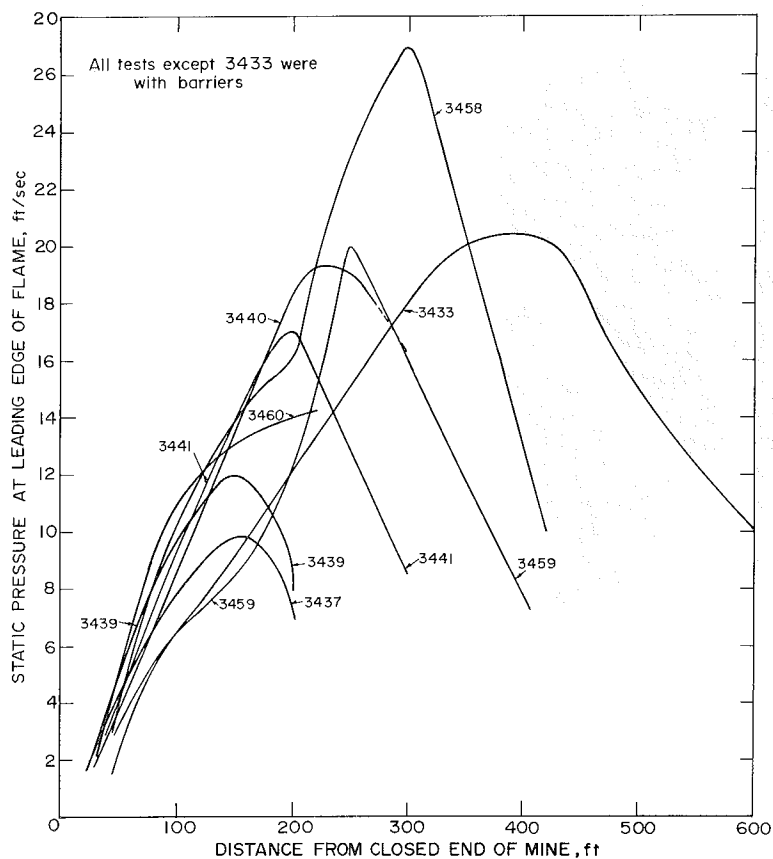


FIGURE 14. - Static pressure at flame front versus distance in EM tests.

shown in figure 17 and shows that the acoustic approximation holds reliably at flame speeds up to 300 ft/sec for both gas and dust explosions with weak ignition sources. Such information is useful in predicting the rupture of the kind of barriers tested in this series for long tunnels with no crosscuts. Implicitly, the approximate equality of flame speed and air speed is verified, and the dynamic pressure developed in the weak explosions can be estimated. At higher flame speeds and pressures, the relation is not clear but remains the subject of further research as velocity probes come into use. At flame speeds greater than 400 ft/sec, higher static pressures are also observed, but it is not clear that the particle velocity will increase in a linear fashion. Dynamic pressure is the important

quantity that governs barrier rupture because in several cases, the flame passed by a barrier without rupturing it and developed higher speeds and static pressures later with still no effect on the barrier. The minimum dynamic pressure for barrier rupture in the present series of tests is about 0.6 psi compared with about 0.7 psi found in the metal gallery. One would expect the mean air speed to drop rapidly to zero behind the leading edge of the flame.

Making use of the acoustic approximation and wave diagrams, one can, in many situations, predict the regions of the EM where the PVC barrier would be effective in quenching explosions. For example, using a static pressure requirement of about 4 to 6 psi, data of flame arrival time and associated static pressures in figure 12 (test 3440) implies that the barrier would also quench the explosion when placed as close as 100 ft from the mine face, whereas the data of figure 9 (test 3433) indicates that the barrier would be effective when placed within the region of 150 to beyond 600 ft from the mine face. However, such predictions must be made judiciously in the case of rapidly accelerating flames; for example, in test 3458 and 3459, flame acceleration and static pressure rise were extremely fast, and pressures as high as 14 psi were registered at the barrier site during initiation of the tub

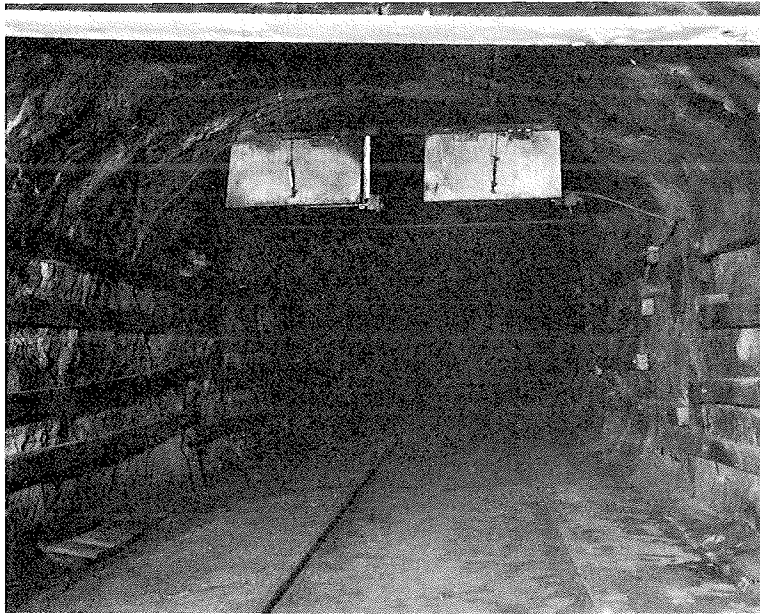


FIGURE 15. - Two water-filled metal tubs mounted near mine roof.

portional to about  $v^{0.8}$ . An analogous situation will exist in a coal mine, especially in the vicinity of crosscuts; in this case, a more comprehensive treatment than the acoustic approximation will be necessary to determine the relationship between static pressure and wind speed.

Based on the previous estimate of 0.10 to 0.15 sec for the duration of water ejection following PVC tub rupture, the length of mine tunnel filled with water spray would be on the order of 40 ft. When one tub is used, this would yield an average concentration of 1.2 oz of water per cubic foot of tunnel, assuming the total tunnel cross section is filled with water spray. This can be compared with 1.3 oz/ft<sup>3</sup> calculated by F. W. Mayer (10) to be the minimum quantity of water necessary to quench a coal-dust explosion propagating through a stoichiometric mixture (0.12 oz coal dust per cubic foot of air). On this basis, our water requirements would be considerably smaller because of the rock dust and excess coal dust in the mixture.

The recommended quantity of water to be used in conjunction with the PVC tubs is 36 lb per square foot of tunnel cross section (7). This is much greater than the 3 lb/ft<sup>2</sup> found necessary in tests with one tub. However, the recommended water quantity is purposely greater than the minimum requirements in order to offer added protection. In addition, the recommendation was established from explosion suppression tests where little or no rock dusting was used.

Other indications of dust flame structure and its noneffect on the barriers is the great depth of slow combustion and/or hot particles behind the leading edge of the flame, as indicated by the flame sensors. Particularly, in the cases where mine-size dust was used, this hot zone might extend 400 ft

rupture. This confirms the previous findings in the metal tunnel study that dynamic impulse also is important in governing barrier rupture. Additional study is needed in this area in order to use the impulse concept properly.

In the metal gallery experiments, the static pressure-wind speed data did not fit the acoustic approximation owing to the shortness of the tunnel, allowing multiple interactions between the pressures developed ahead of the flame and rarefactions from the open tunnel end. In these experiments the static pressure was found to be pro-

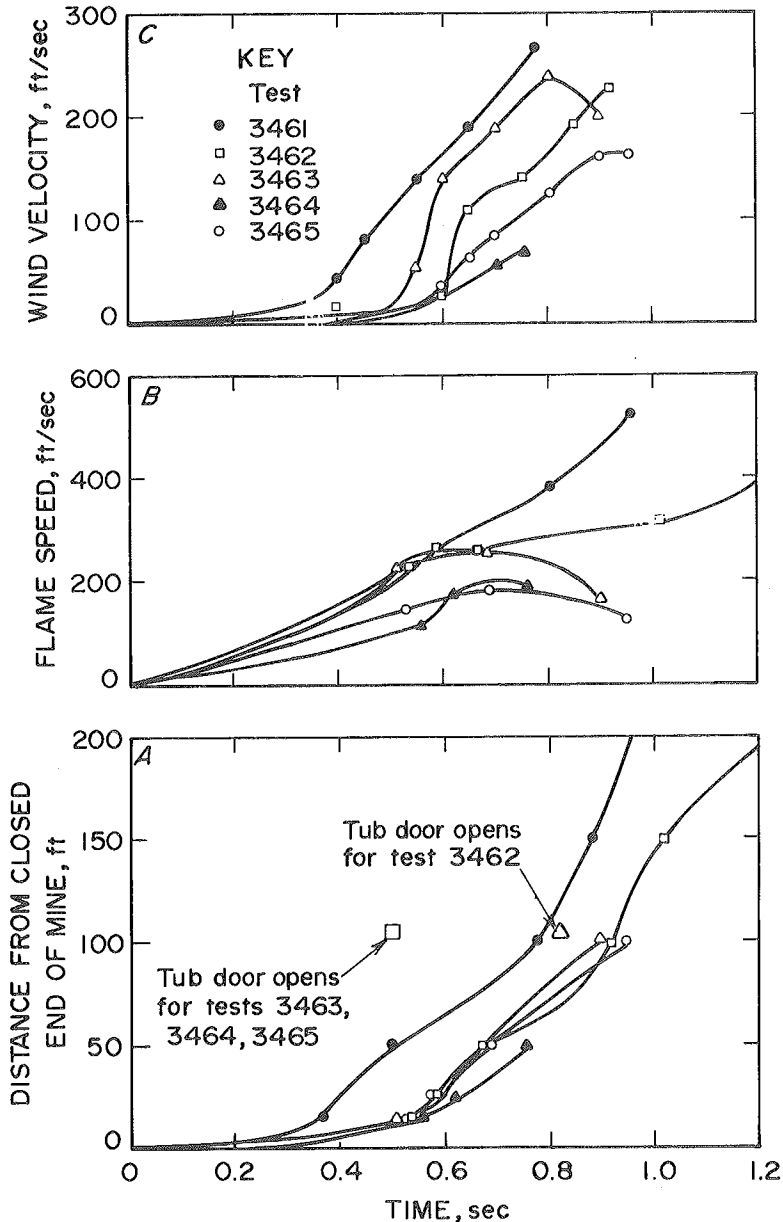


FIGURE 16. - Results of metal water tub tests in EM:  
 A, Flame arrival time; B, flame speed;  
 C, calculated wind velocity at tub site.

behind the leading edge with still no effect on the barrier except for scorching. Further evidence of slow combustion and negligible mean air velocity is the very slow decrease in static pressure behind the leading edge of the dust explosions, in contrast with a very rapid decrease in pressure behind the leading edge of gas explosions or quenched dust explosions. Intermediate rates of static pressure drop occurs with pulverized dust, apparently as a result of rapid completion of combustion, followed by fairly rapid radiative cooling to the walls. Short pressure pulses are usually followed by an expansion wave from the open end after flame extinguishment.

An unexpected gas dynamic process occurred during most of the quenching tests, as illustrated in figure 12, in which two barriers, located at 300 ft from the face, began releasing their water when the leading edge of the flame reached the 150-ft station. Although the static pressure at the leading edge of the flame and the flame speed itself soon began to decrease, when the leading edge of the flame arrived at 250 ft, the flame pressure had already

dropped about 6 psi from its maximum value, and no flame arrival indication ever appeared from the flame sensor at the 300-ft station. There was no indication that water could have obscured the latter sensor. Matches in the roof at 350 ft indicated some flame (or hot products) but provided no information about the time of arrival. The peak pressure dropped by 50 pct between the 300-ft and 400-ft stations but dropped very slowly thereafter. The aforementioned pressure data is consistent with the hypothesis that the sudden

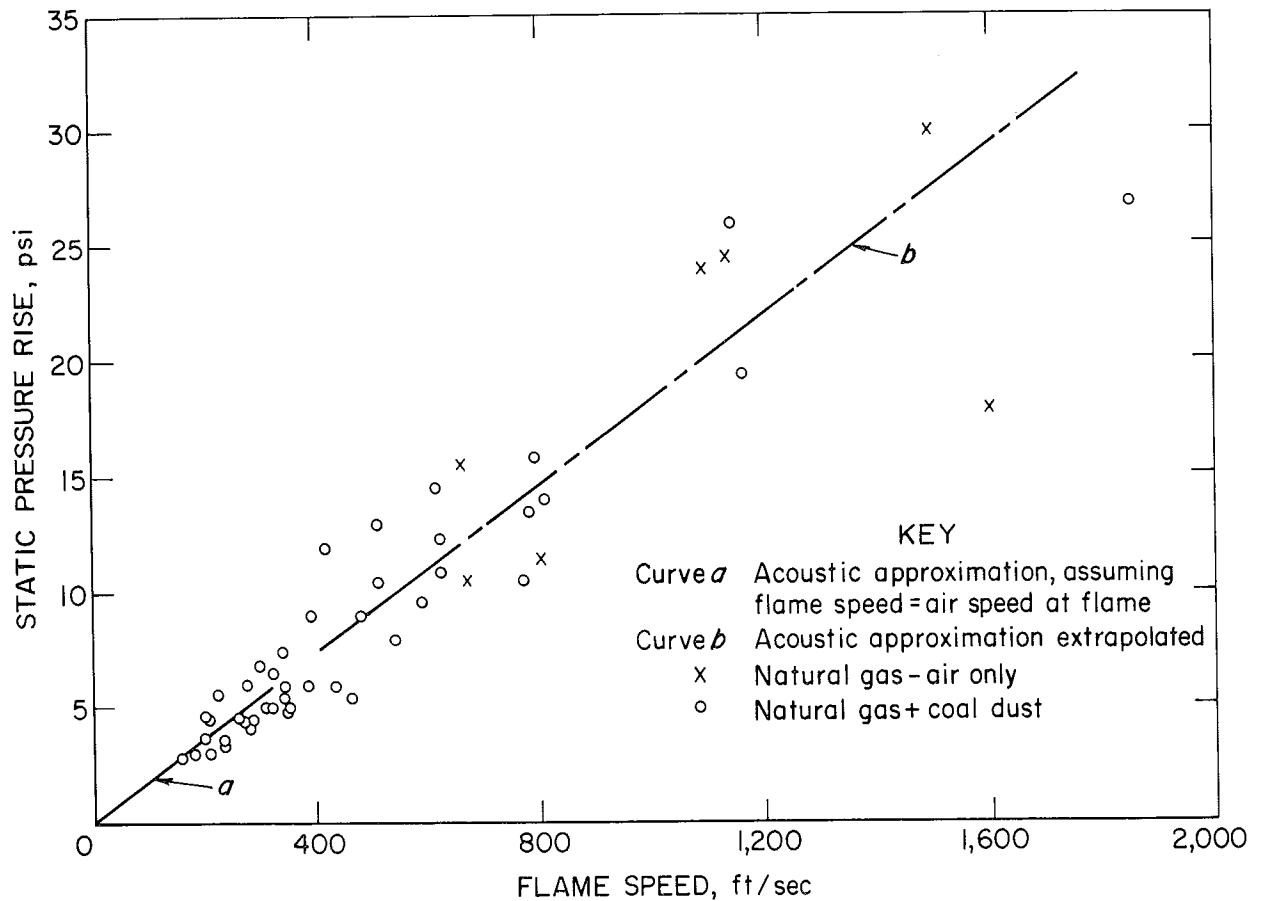


FIGURE 17. - Static pressure at flame front versus flame speed in EM tests.

ejection of 5.8 ft<sup>3</sup> of water into the air flow reduced the momentum and velocity of the latter by about 50 pct, and could have reduced the flame speed by even more. In fact, the flame sensors indicated the leading edge of the active part of the flame might never have arrived at 300 ft. Control tests with no water ejection indicate no effect due to the presence of the container itself. Further research with velocity probes are needed to verify these tentative conclusions.

The velocity of compression waves radiating from the zone of interaction indicate 1,500 ft/sec in the unburned gas outby, consistent with a velocity of sound given by adiabatic compression in the latter region. The compression wave traveling back towards the face traveled at about 2,000 ft/sec, consistent with a mean velocity of sound corresponding to 940° K in the hot gas. The latter value is typical for compression waves traveling in the hot products, where the former could be observed.

### Discussion of Results, Metal Water Tub

Results of the tests with the metal tubs show that the passive water barrier technique is feasible for the suppression of weak dust explosions. In the successful explosion-quenching tests 3463 and 3465, the flame speed is observed to decrease in the vicinity of the water barrier (fig. 16). This flame behavior is analogous to the previously described tests with the PVC barriers in which it was hypothesized that the rapid injection of water spray into the airstream serves to reduce the speed of the approaching flame. In test 3464, the flame did not go beyond the 50-ft station and is considered to be prematurely quenched for similar hypothetical reasoning given previously, since in tests presently in progress (not reported here) with similar coal-rock dust mixtures and without a water barrier, the flame propagates for about 150 ft before being self-quenched.

The present problem is the development of a fragile tub or novel method whereby tub fragmentation and/or water spillage is readily affected by a small wind force. Such a tub could be positioned close to the ignition source to limit the extent of the explosion. This minimum distance, however, is restricted by the time interval the required wind forces are available. For example, when the tub is 100 ft from the ignition source, effectual wind velocities--considered to be over 70 ft/sec from the metal gallery study--will be present for about 0.3 sec (test 3463 of fig. 16); whereas reducing the tub distance to 50 ft would allow only 0.1 sec.

### FUTURE WORK

The 90-ft-long metal gallery will be used to study other water barriers and additional modes of barrier mounting. From this study, barriers chosen to be most effective will be tested in the single entry of the EM to determine their limitations in the suppression of coal-dust explosions. Work will also be directed at developing a passive water barrier useful in suppressing a weak dust explosion during its early stages of propagation. In this work, static pressure forces instead of dynamic wind forces will be utilized to rupture or open the tub. Based on the knowledge gained in these investigations, a comprehensive study will be made in a double-entry mine of the EM using selected and developed passive water barriers in a variety of locations in the mine for weak, medium, and strong dust explosions.

### SUMMARY

Results of this and other studies indicate that a plastic water barrier (water-filled PVC tub) is an effective device for the control of dust explosions in coal mines. With the tub fixed near the mine roof in a cradled mode--tub held rigidly on all sides--moderate to strong explosions were successfully suppressed. Minimum flame-induced wind speeds of about 250 ft/sec or corresponding dynamic wind pressures of approximately 0.6 psi were necessary to rupture or fragment the tub in order to affect water release and dispersion. Dynamic pressure was observed to be the important quantity governing rupture of the barrier for relatively slow accelerating flames, whereas dynamic impulse appeared to play the significant role for rapidly

accelerating flames. As little as one tub (containing approximately 180 lb of water) mounted 200 or 300 ft from the explosion initiation was found to be sufficient in quenching dust explosions propagating at flame speeds of 250 to over 1,000 ft/sec.

An acoustic approximation--relation between static pressure and wind speed--is shown to be valid in a long single entry. This relationship appears to be useful in predicting the regions within a long single entry where passive water barriers might be effective in quenching a dust explosion.

Work was directed at characterizing the necessary conditions for a passive water barrier to control weak dust explosions (flame speeds less than 250 ft/sec). Results indicated that the passive water barrier technique is feasible for the suppression of dust explosions propagating in the range of 100 to 250 ft/sec.

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<sup>5</sup>Titles enclosed in parentheses are translations from the language in which the item was published.

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