

DUST DEFLAGRATION EXTINCTION

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Two basic phenomenological models for deflagration propagation in dust clouds are discussed as the basis for interpreting explosion suppression results. The first model is based on oxygen diffusion to fuel dust particle as the controlling step in explosion propagation through a dust cloud. The second model assumes explosion propagation is controlled through fuel particle volatilization followed by combustion in the gas phase. With this scientific framework as the basis, the inhibition aspects of explosion suppression are discussed to provide guidelines for industrial dust explosion mitigation. As part of the analysis, experimental results are presented for organic, inorganic and hybrid high K_{max} dust explosions and dust explosion suppression. Inorganic dusts fuels included aluminum, and silicon. Organic fuels in the experiments were Pittsburgh coal, cornstarch, polyethylene, anthraquinone, calcium stearate, cadmium stearate, and cornstarch w/propane. Extinguishing agents used in the experiments were sodium bicarbonate, potassium bicarbonate, mono-ammonium phosphate and calcium carbonate.

Key Words: Dust Deflagrations, Extinction, Explosion Suppression

INTRODUCTION

Dust cloud explosions are a well known hazard that are present in the chemical, mining and agricultural industries. In order to provide a safe manufacturing and processing environment, a clear scientific understanding of the explosibility behavior of dust clouds is necessary. Equally important is an understanding of the extinction or suppression behavior of dust cloud deflagrations. Dust explosion suppressants have been used for many years and are equivalent to gaseous inertants like helium, nitrogen or carbon dioxide. The quantity of suppressant needed to reach the explosibility limit has been described in several ways: percentage of inert dust in the total dust cloud mixture, percentage of incombustible material in the total dust cloud and ratio of inert dust to the fuel dust. However, all three methods are incomplete in describing the flammability behavior of a fuel/inert dust mixture. In this paper, we describe a minimum inerting concentration below which explosions are possible and above which explosions are not possible. Minimum inerting concentration is more useful when applying suppression to a variety of industrial scale volumes. In addition, it also allows us to understand dust explosibility behavior in the same terms as gas flammability behavior especially as described in flammability curves.

In this paper, dust cloud explosion propagation models are discussed in order to understand deflagration extinction. Extinction of dust cloud deflagrations was measured in a 1 m³ chamber using pre-inerting and active suppression. Fuels evaluated were Pittsburgh coal, cornstarch, polyethylene, anthraquinone, silicon, calcium stearate, cadmium stearate, propane w/cornstarch and aluminum. Extinguishing agents used were sodium bicarbonate, potassium bicarbonate, mono-ammonium phosphate and rock dust (calcium carbonate).

BACKGROUND

Evaluating and understanding self-sustaining flame propagation through dust clouds must begin with an understanding of the ignition mechanisms of dust particles. The first step in igniting a dust particle located in front of a propagating flame is heating the dust particle. The

particle will absorb energy from the flame through radiative heat transfer and convective heat transfer. In the classical view, the next step is volatilization from the solid fuel particle and mixing of gaseous fuel with the gaseous oxidizer (oxygen). The final step is the combustion reaction in the vapor space away from the solid particle. This 3-step process (heating, volatilization and vapor phase reaction) is identified as the homogeneous model. It is homogeneous because the fuel and oxidizer are the same physical state at the reaction point. An alternative model is the heterogeneous model. In this model, the gaseous oxidizer diffuses to the particle surface and the combustion reaction occurs at the particle surface. It is heterogeneous because the fuel and oxidizer are different physical states at the reaction point.

In Essenhigh's review of ignition of coal particles⁴, the prevalence of homogeneous vs. heterogeneous dust particle ignition was described to be dependent upon particle diameter and heating rate. In summary, at low particle diameters heterogeneous ignition is prevalent at most heating rates. As particle diameters get larger, both, heterogeneous and homogeneous ignitions are possible with homogeneous ignition becoming more dominant.

A survey of the literature presented by Eckhoff³ indicates that metal dusts may also undergo both heterogeneous and homogeneous ignition. However, most of the experimental studies provide evidence of heterogeneous ignition and only limited evidence of homogeneous ignition is available. In addition, Eckhoff³ noted that radiative heat transfer was of greater importance in metal dust ignition than in coal dust ignition. Radiative heat transfer is proportional to the fourth power of temperature and metal dust flame temperatures are typically much higher than coal dust flame temperatures. This importance of radiative heat transfer in metal dust ignition is supported by the experimental work of Leuschke⁸. Leuschke⁸ generated two dust clouds on either side of a double glass window, ignited one side with a flame and observed whether the other side underwent ignition.

Extinction of dust cloud deflagrations by the use of inert dusts is a common practice in industrial explosion suppression. For example, in the mining industry rock dust is used to prevent flame propagation within mine galleries. Another example is the use of explosion suppression to mitigate explosions in dust collectors and spray dryers in the process industries. In process equipment, sodium bicarbonate is discharged into the hazard volume upon detection of an incipient deflagration. In both of these cases, the purpose of the inert material is to prevent a self-sustained flame from propagating through the entire hazard volume.

Suppressant agents (inert dusts and gases, water, and halocarbons) can prevent explosions by absorbing energy produced by the combustion reaction ("physical" mechanism) and/or by "chemically" participating in the combustion reaction. One example of a suppressant agent that chemically participates in the combustion reaction is Halon 1301. Chemical suppression occurs by the termination of chain branching reactions in the combustion process. An example of a suppressant agent that is primarily a physical agent is rock dust. Suppressant agents such as sodium bicarbonate and mono-ammonium phosphate are thought to provide extinction of the flame by both physical and chemical mechanisms.

Physical suppressant agents prevent explosion propagation by absorption of the thermal and radiant energy produced by the combustion reaction. This absorption competes with the heating of the unburned fuel particles. As the amount of suppressant (inert) particles increase,

they absorb enough of the available energy such that the fuel particles cannot combust and flame propagation is prevented.

A. Hamins⁵ quantified the physical vs. chemical effects of extinction agents using a critical flame temperature criterion. Using a heptane flame as the combustion source, Hamins⁵ looked at various extinction agents (N₂, CF₃Br and NaHCO₃). Hamins⁵ calculated the flame temperature for a mixture that included an amount of extinction agent equal to that measured in cup burner extinction experiments. Comparing the calculated flame temperatures with the assumption that N₂ was 100% physical, Hamins⁵ estimated the % physical vs. % chemical. CF₃Br was estimated to be 12% physical and 88% chemical, while, NaHCO₃ was estimated to be 47% physical.

One can assume radiant energy absorption is negligible and focus on thermal absorption as the primary physical mechanism in suppression. This assumption has not been validated by analysis or experimentation and is primarily made for the convenience of describing the physical model. With thermal energy absorption as the predominant mechanism, suppression can be described as having two methods of heat absorption: thermal heating and decomposition. Increasing the amount of suppressant in the dust cloud increases the total heat capacity of the system and the total amount of heat needed to reach the reaction temperature. Endothermic decomposition of the suppressant material may absorb thermal energy. If decomposition occurs, it is likely to alter the gas phase composition and provide gas phase inerting. On the basis of a homogenous dust particle deflagration model, with the assumption that the inert particles completely decompose in the flame front, a thermal energy balance for this process is given in equation I.

$$y_s H_d + [y_s C_{p,s} + (y_f - x_v) C_{p,f}] \Delta T + (\rho C_{p,fp}) \Delta T = H_v x_v \quad (I)$$

This model is more fully described in the paper by Richmond, Liebman and Miller⁹. Extinction of the flame was assumed to occur at a hydrocarbon air limit temperature for the flame (1500 K). Richmond showed that by plotting fuel dust concentration on the Y-axis and suppressant dust concentration on the X-axis, an explosibility extinction curve is produced that is similar to a gaseous flammability curve. The combinations of fuel and suppressant concentrations within the curve are explosible and the combinations outside are non-explosible. The authors of this paper further propose that a minimum inerting concentration (MIC) can be defined at the nose of the curve. The suppressant (inert material) concentration at the nose represents an explosible limit. Suppressant concentrations above the limit will not support combustion. Suppressant concentrations below the nose may support combustion. The minimum inerting concentration becomes extremely important in the practical application of explosion suppression. In industrial explosions, the fuel concentration and the volume are typically not in design control. However, suppressant concentration is a controllable parameter. By knowing the minimum inerting concentration, suppressant concentration above the MIC can be used for the safe design of explosion suppression.

The thermal balance above takes into account the transfer of heat from the combustion reaction to the unburned material ahead of the flame. However, another important consideration is the rate at which the transfer occurs. Focusing on the thermal energy absorption portion of the energy transfer, the unburned material ahead of the flame will absorb heat and then potentially decompose. The rates for these two steps are described

below. Thermal energy absorbed by the particles (either fuel or inert) is described by equation II.

$$hA(T_f - T_p) = V\rho C_{p,f} (dT_p / dt) \quad (\text{II})$$

Thermal energy transfer rate due to decomposition of particles is described by eq. III.

$$hA(T_f - T_d) = \rho H_d A (dr / dt) \quad (\text{III})$$

Assuming that radiative heat transfer and convective heat transfer are equally important, the appropriate energy transfer equation is given in equation IV. Including the radiative heat transfer term in the transfer equation allows analysis of the potential importance of flame temperature in the flame propagation or flame extinction process for all dusts but particularly of metal dusts which typically have higher flame temperatures.

$$A_f (\epsilon_f \sigma T_f^4 - \alpha_{fp} \sigma T_p^4) + hA(T_f - T_p) = V\rho C_p (dT / dt) \quad (\text{IV})$$

Assuming both the inert particle and the combustible particle follow a homogeneous pathway, the next step after heating would be decomposition of the inert particles and volatilization of the fuel particle. The final step would be either continued flame propagation or extinction of the combustion reaction via physical and/or chemical mechanisms. It may be possible that either the fuel particle or the inert particle will more rapidly reach its decomposition or volatilization temperature. In the case of the fuel particle volatilizing faster than the inert particle, flame propagation is likely to continue. If the inert particle decomposes faster than the fuel particle, then extinction of the flame is likely. In effect, the relative ability of the materials to absorb energy will be important in the extinction process.

EXPERIMENTAL

To obtain dust cloud explosibility limits data, a 1 m³ spherical chamber was chosen instead of a 20 liter chamber. The standard ignition source of 10,000 J generates a pressure of 1.2 bar in the 20 liter chamber without an explosible mixture. The same ignition source in a 1 m³ chamber would provide sufficient energy to initiate the explosion without overdriving or underdriving the explosion. The pressure generated in a 1 m³ chamber is 0.02 bar.

The Fike 1 m³ vessel is a spherical explosion chamber designed to gather explosion severity and explosion protection testing data. A schematic of the apparatus as used in the test program is shown in Figure 1. The vessel has a design pressure of 20.5 barg and is capable of containing most explosions. It consists of two 122 cm i.d., 0.9525 cm thick carbon steel hemispherical sections that can be separated to allow access to the interior.

Two types of experiments, Inerting and Suppression, were conducted. In the inerting experiments, fuel was pre-mixed with suppressant dust and then discharged into the 1 m³ chamber. The resulting dust cloud was ignited and deflagration progress was observed. The experimental setup for the inerting experiments is shown in Figure 1. In the suppression experiments, fuel dust is discharged into the 1 m³ chamber and ignited. The resulting deflagration activates the suppression system and the suppressant dust is discharged into the propagating deflagration. The experimental setup is shown in Figure 2.

Figure 1: 1 m³ Chamber setup for Deflagration Inerting.

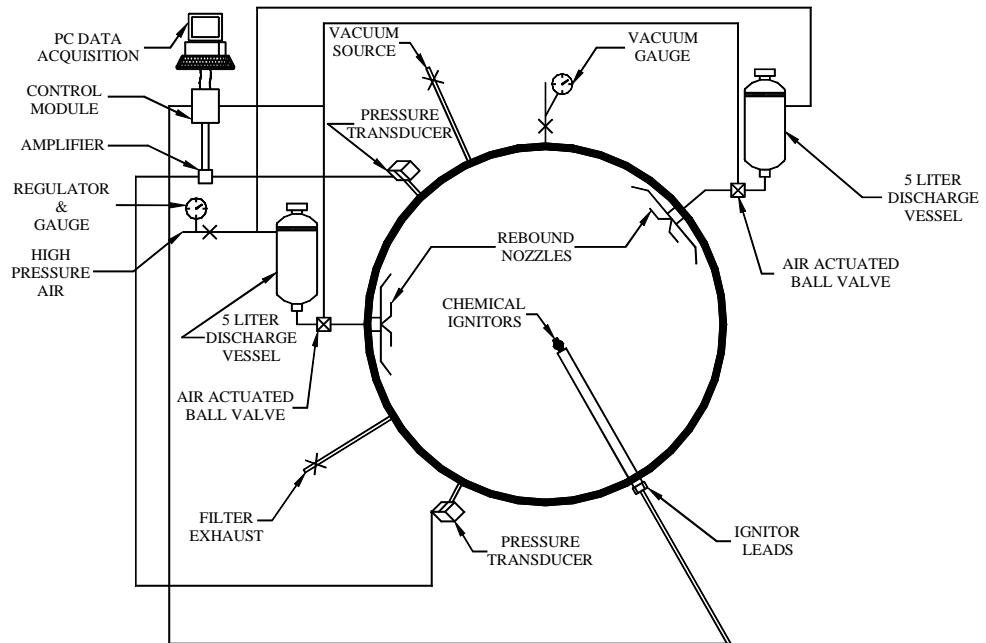
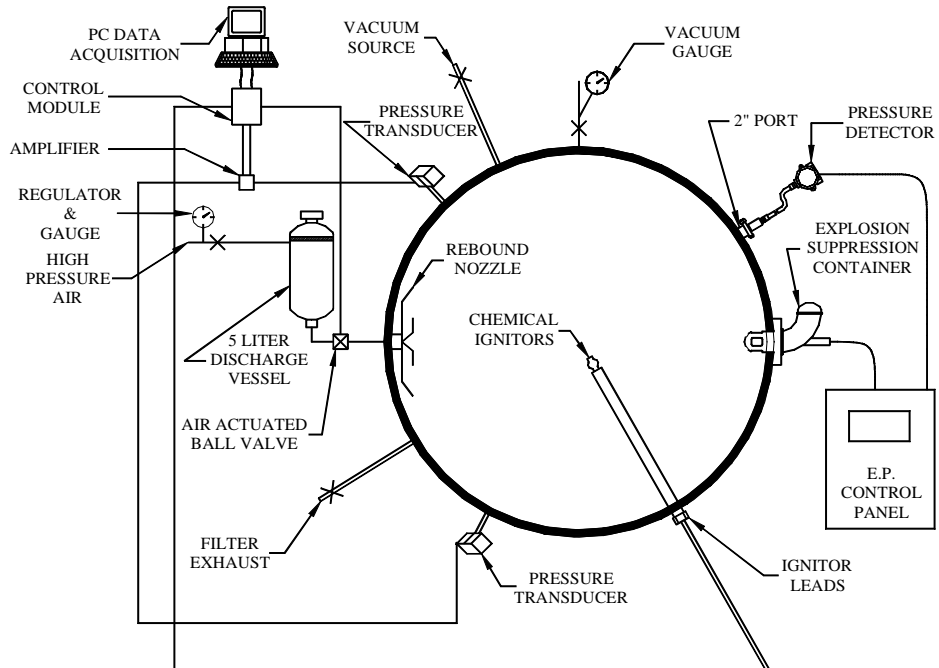


Figure 2: 1 m³ Chamber setup for Deflagration Suppression.



For the inerting experiments, two dust injection systems, each consisting of a 5 liter discharge cylinder, a ball valve and a rebound nozzle were used. In order to create the desired dust cloud in the 1m³ chamber, a weighed amount of pre-mixed suppressant and fuel dust were placed in each 5 liter cylinder. The discharge cylinders are pressurized with dry air and pneumatic actuators simultaneously open the ball valves between the cylinder and the rebound nozzle. To conduct the experiment at atmospheric pressure, the vessel is partially evacuated prior to dust injection. The discharge vessels are pressured to 20 barg and 0.100 bar is evacuated from the 1m³ vessel.

Two variable reluctance transducers were used to monitor the pressure inside the 1m³ chamber during the experiment. The dust clouds were ignited with two chemical igniters. The chemical igniters are manufactured by Sobbe and contain 40% zirconium, 30% barium nitrate and 30% barium peroxide. Each igniter has 1.2 grams of this pyrotechnic mixture and releases about 5000 joules of energy in about 10 milliseconds.

To obtain a flammability curve for a particular mixture, the fuel dust concentration and the inertant dust concentration were varied. All experiments were conducted at atmospheric pressure in air. The maximum pressure generated during each experiment was used to evaluate whether an explosion had occurred or not. At a specific fuel dust concentration, the inertant dust concentration would be varied until the boundary between explosible and non-explosible was found. Typically, there was a dramatic decrease in maximum pressure as this limit was reached i.e. from greater than 6 barg to less than 1 barg. At each fuel dust concentration, two inertant dust concentrations adjacent to each other were identified, one of which was explosible and the other being non-explosible. The average value between these two points was plotted as shown in Figures 3, 4, 5, 6 and 7. The average value represents the explosibility limit.

For the suppression experiments, an active explosion suppression system consisting of a pressure detector, a control panel and a suppressant discharge container were used. The explosion pressure detector was an electronic strain gauge threshold detector capable of responding to incipient deflagrations (i.e. response time of 1 ms or less). Upon detection, the control panel initiates a gas cartridge actuated rupture disc valve on the suppressant discharge container. In most of the experiments, a 2.5 liter discharge container with 5 lbs. of sodium bicarbonate was used. The 2.5 liter discharge container was pressurized with dry N₂ to 900 psig. Once the rupture disc valve has opened, the N₂ and NaHCO₃ are rapidly discharged into the chamber. In some of the experiments, two 2.5 liter containers were used to increase the quantity of NaHCO₃ discharged into the chamber. Five liter discharge containers with 10 lbs. of NaHCO₃ were also used in some experiments. The maximum pressure reached after ignition of the fuel dust and discharge of suppressant agent into the enclosure was recorded for each experiment. The average value from the experiments is reported as the total suppressed pressure (TSP).

INERTING RESULTS

Experiments were conducted with Pittsburgh coal, cornstarch, polyethylene, anthraquinone and aluminum. The inertant dusts used with Pittsburgh coal and cornstarch were sodium bicarbonate (SBC), mono-ammonium phosphate (MAP) and rock dust (RD). Sodium bicarbonate and mono-ammonium phosphate were used with anthraquinone and aluminum. Polyethylene experiments were conducted with SBC. The Pittsburgh coal experiments (see Figure 3) clearly demonstrate the minimum inerting concentration (MIC) concept. From Figure 3, the MIC for MAP is approximately 125 g/m^3 . This implies that if concentrations of MAP above 125 g/m^3 were present then dust cloud explosions are not possible at any fuel dust concentrations. Similarly, the MIC for SBC and RD are 550 g/m^3 and 1125 g/m^3 respectively. The MIC results from all of the experiments are summarized in Table 1 below.

Table 1: Minimum Inerting Concentrations (g/m^3)

	SBC	MAP	RD
Pittsburgh coal	550	125	1125
Cornstarch	625	875	>2750
Polyethylene	1000	NA	NA
Anthraquinone	1750	>1500	NA
Aluminum	>2750	>2750	NA

NA – not available

As the flame front is propagating into the unburned material, it encounters both fuel and inert particles. The critical characteristics of the unburned material are the specific heat, heat of decomposition, decomposition temperature, thermal conductivity, particle radius and surface area of the particle. These characteristics are important for the fuel particle and the inert particle because it is the relative capability to absorb thermal energy that determines whether the explosion will propagate. The critical characteristics of the flame front are the heat of combustion and the flame temperature. Fuels with high flame temperatures and heats of combustion will be relatively harder to suppress. As an example, the above table of MIC's shows that aluminum has the highest MIC and is the hardest to suppress. Aluminum also has the highest flame temperature of all the fuels tested. Pittsburgh coal, on the other hand, would have a relatively lower heat of combustion and flame temperature. At high concentrations of Pittsburgh coal (and cornstarch to some extent), this lesser amount of energy is now distributed across additional fuel and suppressant. As a consequence, less suppressant is required to inert the deflagration and the curve turns back (see figures 3 and 4).

In comparing different suppressants to each other, the following factors will make for a more effective suppressant,

- Higher specific heat
- Lower decomposition temperature

Figure 3: Pittsburgh Coal Deflagration Inerting in a 1 m³ Chamber.

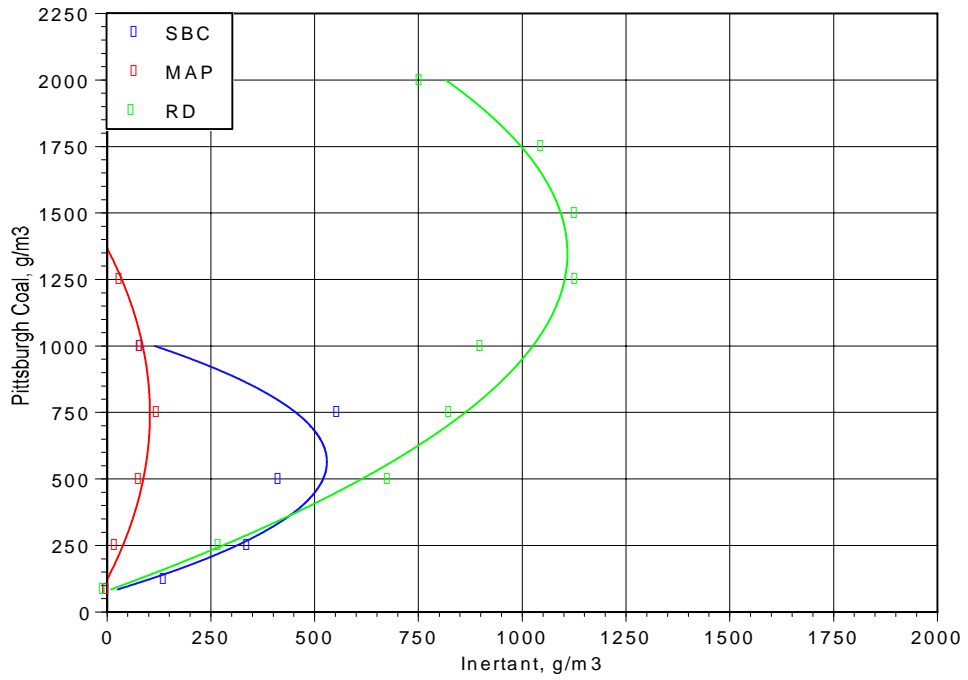


Figure 4: Cornstarch Deflagration Inerting in a 1 m³ Chamber.

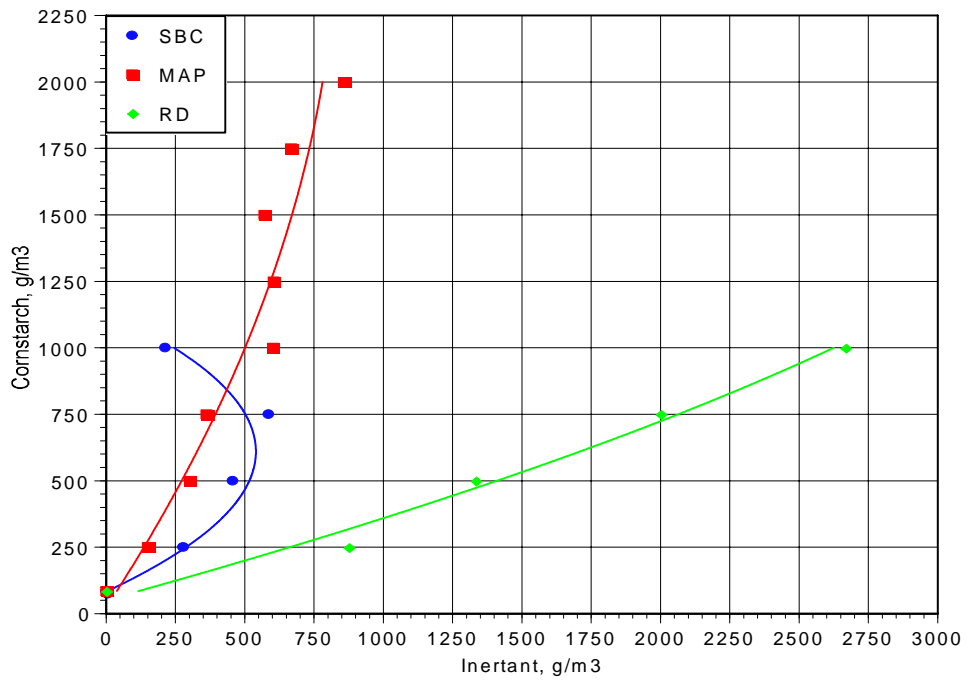


Figure 5: Anthraquinone Deflagration Inerting in a 1 m³ Chamber.

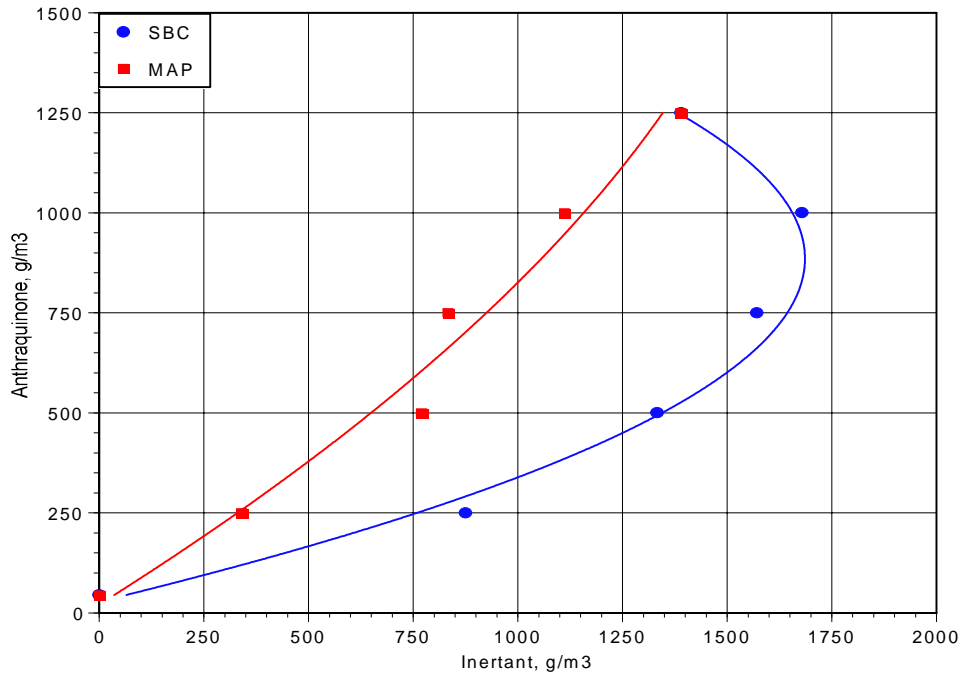


Figure 6: Polyethylene Deflagration Inerting in a 1 m³ Chamber.

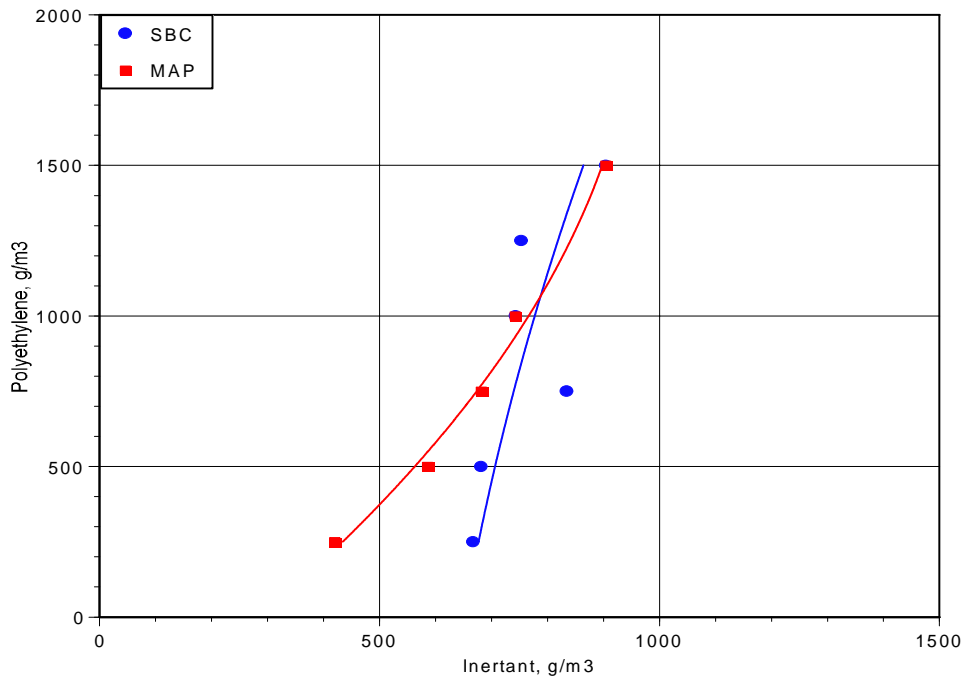
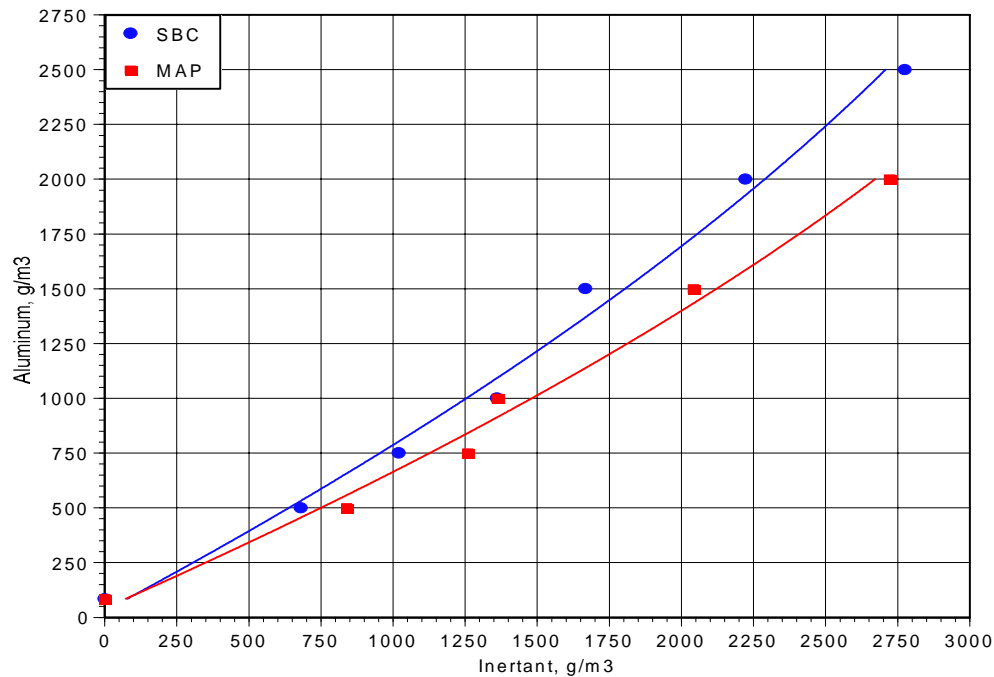


Figure 7: Aluminum Deflagration Inerting in a 1 m³ Chamber.

- Higher heat of decomposition
- Higher thermal conductivity
- Smaller particle radius
- Larger surface area

For example, rock dust is clearly a poorer suppressant than either SBC or MAP. This is most likely due to the inability of rock dust to decompose in the propagating flame front. Rock dust has a decomposition temperature of approximately 1100 K, whereas SBC and MAP have decomposition temperatures around 500 K.

The relative effectiveness of SBC and MAP are harder to generalize. Looking only at the Pittsburgh coal data (figure 3), it would appear that MAP is significantly better than SBC. However, cornstarch data (figure 4) implies that SBC is slightly better than MAP. Anthraquinone and aluminum data in figures 5 and 6 do not provide any clear evidence that one is better than the other. The minimum inerting concentrations for SBC and MAP vary consistently with the fuel. For both SBC and MAP, the lowest MIC is with Pittsburgh coal and the highest MIC is with aluminum.

SUPPRESSION RESULTS

Table 2 summarizes the results from all of the explosion suppression experiments. The fuel used and the optimal concentration of fuel are given in the first two columns. The maximum explosion pressure and the maximum rate of pressure rise (K_{st}) are given in the third and fourth columns. The detector set pressure used in the experiments is given in the fifth column. The extinction (suppression) agent used, the number of discharge containers and the volume of the containers are shown in columns 6, 7, and 8 respectively. SBC indicates sodium bicarbonate and PK indicates potassium bicarbonate. At each set of conditions, multiple experiments were conducted. The maximum pressure after initiation of the explosion and automatic activation of the suppression system was obtained for each experiment. The average of the maximum pressures from the experiments at each set of conditions is reported in the last column in Table 2. This column is designated as TSP Avg. TSP indicates total suppressed pressure.

The rationale for using the term total suppressed pressure (TSP) is that it allows an analysis of the components that make up the total pressure observed during the experiments and it allows prediction of the total pressure for real world applications. The components that make up the total suppressed pressure in any enclosure are:

1. Set pressure of the detector
2. Combustion pressure associated with flame growth
3. Pressure due to injection of N_2 from the discharge container

An example of pressure due to N_2 injection is that discharging one 2.5 liter container into an empty $1m^3$ enclosure will generate a pressure of 1.4 psig. After ignition, the combustion (or deflagration flame) is allowed to grow and generate pressure inside the $1m^3$ enclosure. Part of this combustion generated pressure is represented by the threshold setting of the pressure detector. After the set pressure has been reached, the flame continues to grow until it has been extinguished. The deflagration flame will stop propagating at the point when the extinguishing agent has been discharged and the flame has been completely surrounded. The flame must be surrounded by a concentration of extinguishing agent greater than the minimum inerting concentration. At this point, the maximum pressure will occur in the enclosure. After this maximum, the pressure will decrease due to cooling of the hot gases. The TSP in table 2 is the maximum pressure observed and not the final pressure observed. The final pressure is generally lower than the TSP.

The results show that deflagrations can be extinguished with active systems. More specifically, dust deflagrations with organic fuels, inorganic fuels and hybrid fuels can be extinguished. Generally, maximum explosion pressures can be decreased to less than 5% (i.e. TSP can equal 5% of P_{ex}). For the Aluminum dust used in these experiments, TSP was on the order of 10% to 20% of P_{ex} .

Table 2: Suppression of Dust Cloud Deflagrations in a 1 m³ Chamber.

Fuel	Conc. (g/m ³)	P _{ex} (psig)	K _{st} (Bar.m/s)	Set Press. (psig)	Extinction Agent	HRD #	HRD Size (Liters)	TSP Avg. (psig)
HYDROCARBON DATA								
Cornstarch	750	122	220	0.5	SBC	1	2.5	3.0
				1.5	SBC	1	2.5	3.6
				3	SBC	1	2.5	5.2
				7.5	SBC	1	2.5	17.0
Cadmium Stearate	250	110	343	0.8	SBC	1	2.5	4.5
				1.5	SBC	1	2.5	12.7
				1.5	SBC	2	2.5	6.7
Calcium Stearate	188	107	453	0.5	SBC	1	2.5	3.1
				1.5	SBC	1	2.5	4.6
				3	SBC	1	2.5	15.0
HYBRID DATA								
3.3% Propane 100 g/m ³ cornstarch		119	420	0.5	SBC	1	2.5	2.9
				1.5	SBC	1	2.5	8.5
				3	SBC	1	2.5	>25
4% Propane 100 g/m ³ cornstarch		119	504	0.5	SBC	1	2.5	3.4
				1	SBC	1	2.5	5.0
				1.5	SBC	1	2.5	15.1
				0.5	SBC	2	2.5	4.3
				1	SBC	2	2.5	6.2
				1.5	SBC	2	2.5	8.7
Metals								
Silicon	1000	120	120	0.5	SBC	1	2.5	4.8
				0.5	PK	1	2.5	4.0
				0.5	PK	1	5	4.4
Aluminum	1750	125	300	0.5	SBC	1	5	30.2
				0.5	SBC	2	5	12.2
				0.5	PK	1	5	13.9
				0.5	PK	2	5	13.1
				1.5	PK	1	5	22.9

Figure 8: Effect of set pressure on maximum suppressed pressure (1, 2.5liter discharge container with SBC)

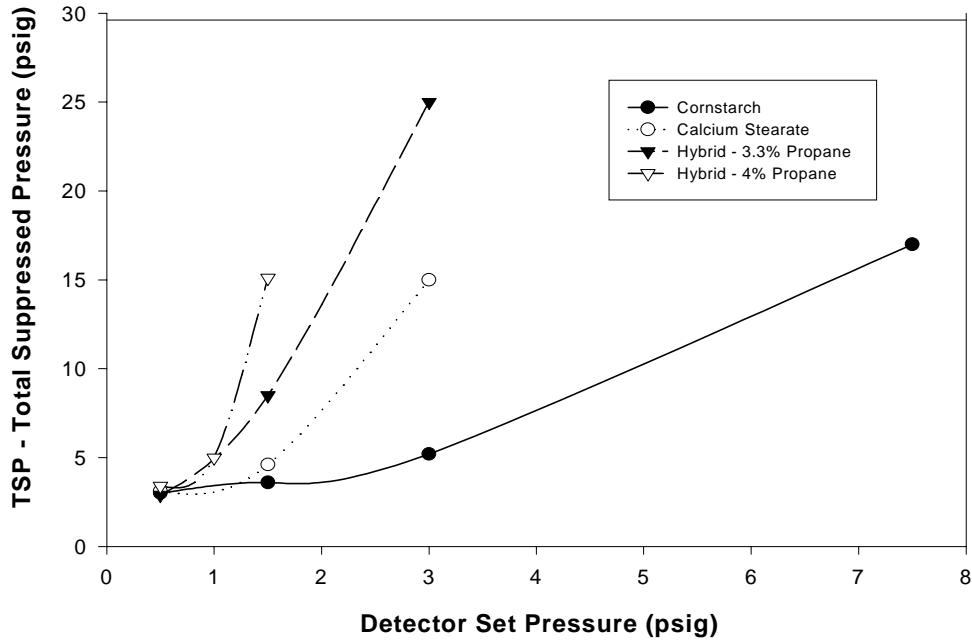
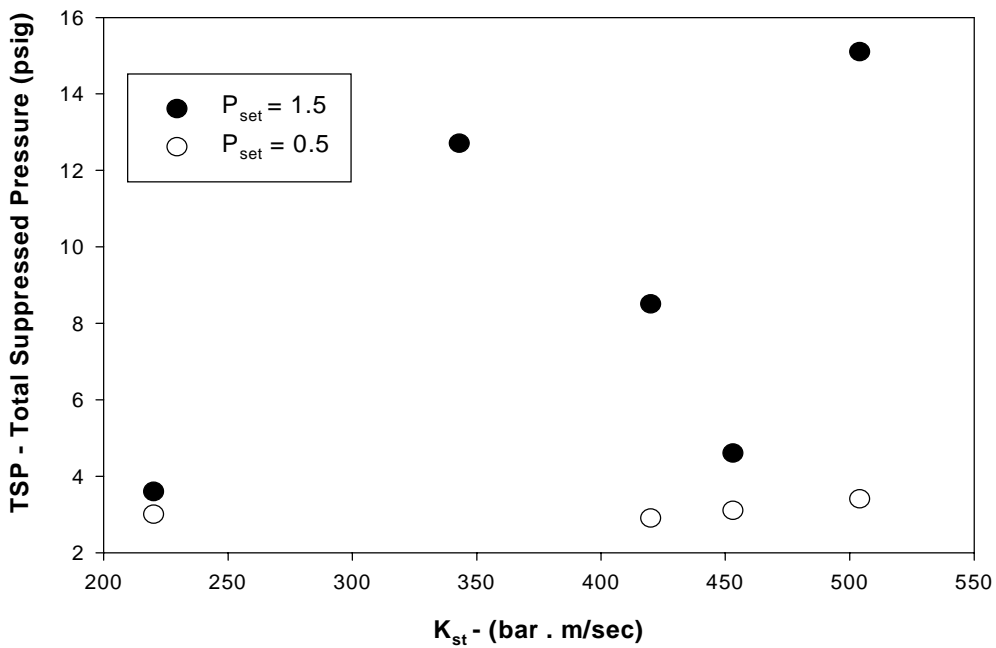


Figure 9: Effect of Kst on total suppressed pressure (1, 2.5 liter discharge container with SBC)



There was a clear trend between the set pressure of the detector and the TSP achieved (see figure 8). As expected, increasing the set pressure increases the TSP. For cornstarch, increasing the set pressure from 0.5 psig to 3 psig results in a change of TSP from 3.0 psig to 5.2 psig. For calcium Stearate, a similar increase in set pressure results in a change of TSP from 3.1 psig to 15 psig. For the 3.3% Propane hybrid case, the TSP changes from 2.9 psig to a TSP of greater than 25 psig.

A definitive trend between maximum rate of rise (K_{st}) and TSP was not observed. At a P_{set} of 0.5 psig, TSP was approximately 3.0 psig for the hydrocarbon ($K_{st} = 220$) and hybrid ($K_{st} = 504$) experiments. For the metal dust experiments at a P_{set} of 0.5 psig, TSP was considerably higher than the hydrocarbon and hybrid data. At a P_{set} of 1.5 psig, there was significant scatter in the TSP's observed (see figure 11). It should be noted that high K_{st} dust deflagrations have an inherently higher scatter than low K_{st} deflagrations.

In most of the experiments, sodium bicarbonate was the extinguishing agent used. With respect to the extinguishing agent, the experimental variables under control include total mass, mass flux and fuel/agent compatibility. These variables were not a focus of this study. However, the results do provide experimental evidence of the effect of these variables on TSP. The effect of mass and mass flux can be observed in the cadmium stearate, silicon and aluminum results. Increasing the mass and mass flux of SBC in the Cadmium Stearate experiments resulted in a decrease of the TSP from 12.7 psig to 6.7 psig. Increasing the mass of Potassium Bicarbonate (PK) in the silicon experiments had a negligible effect of 0.4 psig on the TSP. Increasing the mass and mass flux of SBC in the Aluminum experiments decreased the TSP from 30.2 psig to 12.2 psig. Increasing the mass and mass flux of PK in the Aluminum experiments had a negligible effect on the TSP. In the Aluminum experiments, PK was a better, more compatible, extinguishing agent than SBC.

CONCLUSIONS

The inerting results show that a flammability curve can be created for fuel/inert dust mixtures. This flammability curve for dusts has the same characteristics as a flammability curve for gas mixtures. A lower flammable limit, an upper flammable limit and a minimum inerting concentration can describe the flammability behavior of dusts.

The suppression results show that high K_{st} deflagrations and metal dust deflagrations can be extinguished and the maximum explosion pressure can be reduced to an acceptable level. The effectiveness of the extinguishing agent used is dependent upon the compatibility of the fuel dust with the inert dust. It is believed that specific heat, thermal conductivity, absorptivity, particle geometry and particle decomposition play a critical role in the effectiveness of suppressants. These factors along with flame temperature and heat of combustion may explain the variation in explosion severity and extinguishment effectiveness.

NOMENCLATURE AND CONVERSIONS

y_s - Suppressant concentration (inert dust)

H_d - Heat of decomposition

$C_{p,s}$ - Specific heat of suppressant

y_f - Fuel dust concentration

x_v - Volatilized fuel concentration

$C_{p,f}$ - Specific heat of the fuel

ΔT - Temperature change from ambient to flame

ρ - density of flame products

$C_{p,fp}$ - Specific heat of flame products

H_v - Heat of combustion of volatilized fuel

h - Heat transfer coefficient, $h = \lambda Nu / 2r$

Nu - Nusselt number

r - Mean particle radius

A - Particle surface area

T_f - Flame temperature

T_p - Particle temperature

V - Particle volume

ρ - Particle density

T_d - Decomposition temperature

A_f - Surface area of the flame

ϵ_f - Emissivity of the flame

σ - Stefan - Boltzman constant

T_f - Flame temperature

α_{fp} - Absorptivity of the particle

T_p - Particle temperature

14.504 psig = 100 kPa

1 bar = 100kPa

1 lb = 453.6 grams

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