Explosion Protection with Metal Dust Fuels

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Abstract

Industrial explosions have been a risk for as long as man has been processing, storing and transporting materials. Managing the explosion risk involves characterization of the hazard followed by implementation of explosion prevention and protection techniques. Many of the reported explosions have involved dusts that are organic or carbonaceous in nature (fuels, polymers, pharmaceuticals). Nevertheless, metals dust explosions do occur and can be destructive.

Metal dust explosions have unique deflagration characteristics in comparison to organic fuels and that can make them more difficult to control. The flame temperature of some metals dusts can exceed 3500 °C, more than a 1000 °C higher than an organic flame. This can result in high explosion pressures, P_{max}. Also, the pressure rate of rise, K_{max}, as well as the flame speed, can greatly exceed that found with organic fuels. All of these contribute to making explosion protection more difficult.

The success of explosion protection lies in the speed of the system as well as the effectiveness of the system. The detection and activation processes as well as the mechanical response of the components determine the overall speed. The effectiveness for example with suppression lies in the ability of the suppressant agent to stop the flame propagation.

The application of the explosion protection techniques, suppression, venting and isolation to metal dust explosions is reviewed and limits associated with each technique will be presented. Experimental results will show that metal dust explosions can be controlled when the explosion protection techniques are properly applied.

Introduction

Industrial explosions have been a risk for as long as man has been processing, storing and transporting materials. Managing that risk involves first characterization of the explosion hazard followed by the design of prevention and protection techniques. Characterization quantifies the hazards through standard and non-standard tests. Once characterized, the hazard can be managed through clear determination of the prevention and protection objectives followed by selection and implementation of the appropriate technology.

Protection techniques include containment, isolation, suppression, and venting either separately or in combination.
Most of the reported industrial explosions have involved dusts that are organic (carbon) in nature. This is to be expected since most of the materials in commerce are organic (fuel, agricultural, pharmaceuticals). Never-the-less metal dust explosions do occur in industrial processes and can be quite violent. An explosion at a silicon powder production plant in Bremenger, Norway (1) in 1972 totally destroyed the milling/grinding section. The explosion is believed to have started from an oxy/acetylene torch having cut into an active dust conveyance line. A fine layer of dust on the inside of the piping may have been the point of ignition. This primary explosion may have raised dust deposits throughout the plant allowing the propagation that devastated the entire building.

In the following year, an explosion occurred in Gullaug, Norway in (1), in the mixing section at a slurry explosive factory. The explosion completely destroyed the premix building and resulted in five fatalities. It appears to have started in central screw of the batch mixer lined with rubber to avoid mechanical sparks. A nitrogen inerting system was in place but may have understated the oxygen concentration in the mixing tube. The aluminum was in a flake form with a thickness of 0.1microns and a minimum ignition energy of ~1 mJ. The ignition is believed to have been due to a propagating brush discharge.

Very recently, a report was made of the aluminum dust explosions in the Verbano Cusio Ossola district of northern Italy. The area has a number of industries that have polishing and buffing operations involving aluminum and aluminum alloy products (coffee pots, pans, etc.). Airborne particles collected at a finishing stations were of two shapes and sizes; belt shaped, less than 200 microns, and isometric, less than 5 microns. No less than 6 explosions were reported since 1995, resulting in 2 fatalities and 16 injuries. Three of the explosions involved some form of dust collection equipment.

Metal Dust Explosions

Metal dusts are similar to carbon dusts in that they undergo oxidation (combustion) reactions with oxygen and the combustion can propagate through a dust cloud. They differ in the nature of the products formed; metal dusts form metal oxide dusts while carbon fuels form carbon dioxide and water. Most carbon fuels propagate by a heterogeneous mechanism. Upon heating, the materials generate various hydrocarbon volatiles, which then undergo gas phase combustion. In other words, the pyrolysis or decomposition temperature is lower than the flame temperature. Metal dusts are capable of propagating by this pre-volatilization process as well as by a surface reaction process. Of importance is the volatility of the metal at the flame temperature and how particle size and shape affects this.

Particle size and shape have a strong effect on the hazard of processing metal dusts. Very small particles of aluminum and magnesium can have exceptionally low ignition energies. The large summary of test data by BIA (3) reports minimum ignition energies from < 1 mJ to over 1000 mJ with a strong dependency on median particle size. Ignition energies less than 1 mJ were associated with particles size less than or equal to 10 microns while energies greater than 50 mJ were found with particles 50 microns and larger. Britton (4) notes that "the ignition energy of finely divided metals is unusually low when freshly milled, although it is difficult to conduct tests using typical MIE equipment, since dust surfaces rapidly oxidize on exposure to air." While coarse particle, i.e., 100 micron, only represent a moderate hazard, a small fraction of fines can magnify the explosion hazard. A few per cent by mass can be sufficient to change the danger. Particle shape appears to be also important in determining the severity of the explosion. In a study (5) sponsored by the British Material Handling Board (BMH), aluminum powder was able to generate K_{max} value between 300 and 400 at optimum concentration. When in the flake form, the K_{max} was 600 and a value as high as 1400 was reported.

Metal dusts are also unique in their thermodynamic properties when compared to carbon fuels. They exhibit more variability and extremes as illustrated in Table 1 and Figure 1 for a select group of metals.

Table 1. Physical Properties of Selected Metal Dusts. (3, 6)

Metal	ΔH_c kJ/mole	Flame Temp °K	Explosibility Parameters		Volatile at Flame Temp ?
			$P_{max,}$ bara range	K_{max} bar.m/s range	
Al	1100	3550	Up to 13.0	Up to ~800	Yes
Ti	--	3450	5.7	~35	No
Ta	--	3290	~4	~7	No
Mg	1240	3100	Up to 17.5	Up to 500	Yes
Si	830	2870	9.5 – 10.8	100 - 168	Yes
B	--	2850	7.0	~35	Yes
Cr	750	2840	~3	~3	--
W	--	2670	~3.3	~5	No
Carbon	~400	2320	~5.0 – 9.0	~50 - 350	Yes
Fe	530	2250	4.5	~29	No
Ni	--	2240	1.0	~0	---
Zn	700	1860	4.4	~17	Yes
Pb	--	1660	1.1	~0	--
Cu	300	1510	1.0	~0	--

Aluminum for example has a heat of combustion of 1100 kJ/mole compared to 400 kJ/mole for coal. Flame temperatures follow the same trend; 3550 °K vs. 2320°K. The effect of these differences is seen in the deflagration parameters, K_{max} and P_{max}. The thermodynamic data listed in Table 1 are specific for the tested material and represent the range that can be found. The dusts with the highest P_{max} and K_{max} parameters (B, Mg, Al, Si) also had the highest adiabatic flame temperatures. On the other hand, some dusts had high flame temperatures but intermediate expobility parameters (Ti,) or low parameters (Cr, Ta).

The extreme values for K_{max} and P_{max} for metals such as Al and Mg create explosion protection problems. This starts with the explosion detection process, which is almost always based on pressure. A deflagration that is characterized by a very high K_{max} (>300) also shows this same fast rate of pressure rise at the initiation of the reaction. That is, the time required for the pressure to rise to the detector set point (e.g., 0.5 psi/35 millibar) may be as little at 5-10 ms for aluminum compared to 25 ms for coal. The time to reach maximum pressure is likewise much shorter. This reduces the time available for the explosion protection hardware to act; detect the pressure, process the signal and initiate the suppression or isolation process. The consequence could be an incompletely suppressed explosion or failure to block flame propagation.

Extreme P_{max} values (or flame temperatures) also cause protection problems. Suppression with materials such as sodium bicarbonate is believed to be largely a result of heat abstraction. The extremely hot metal dust flames require "better" suppression; either from a material with a higher heat capacity or from a higher rate of heat absorption. The latter may be achieved by using more suppressant material.

Isolation, whether mechanical or chemical, is also made more difficult by extremes in P_{max} or K_{max}. Materials with high K_{max} are going to have higher flame speeds and are more likely to transition to detonation with pressures exceeding 30 bar. The higher flame speeds again require that the protection system be "faster", in order to introduce chemical suppressant before the flame arrives or to close the gate before the flame arrives. The higher flame temperature again will require better suppression when chemical isolation is used.

Dust Explosion Management

The management of dust explosions can involve preventive and protective measures. Grinding in one process that is responsible for the generation of metal dust capable of being suspended in the air. The use of wet grinding or the collection of the grinding dust by a wet medium can mitigate the hazard. In the manufacturing of powders such as aluminum or magnesium, inerting to reduce the oxygen concentration is an effective practice. Nitrogen can be used for aluminum although helium or argon is required for magnesium. Other prevention practices such as housekeeping, grounding/bonding, hot work permits, etc. should be routinely practiced.

Protection techniques are applied in addition to preventive measures.

Containment. Containment requires that the vessel be constructed with a strength that matches the hazard. This can be as high as 12 - 18 bar for explosions at atmospheric pressure and higher is elevated pressures are possible during material processing. Connected vessel and ducts must also be able to sustain these pressures.

Suppression. Suppression is the process of controlling 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. 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. . Suppressant agents such as sodium bicarbonate and mono-ammonium phosphate are thought to provide extinction of the flame by both physical and chemical mechanisms.

In suppression experiments, fuel dust is discharged into a test vessel, e.g., $1m^3$ 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.

In order to create the desired dust cloud in the $1m^3$ chamber, a weighed amount of fuel dust was placed in a 5 liter cylinder. The discharge cylinder is pressurized with dry air and a pneumatic actuator opens the ball valves between the cylinder and the rebound nozzle releasing the dust cloud. The dust clouds were ignited with two chemical igniters. Two variable reluctance transducers were used to monitor the pressure inside the $1m^3$ chamber during the experiment.

An active explosion suppression system consists of a pressure detector, a control panel and a suppressant discharge container. The explosion pressure detector (electronic strain gauge) is capable of responding to incipient deflagrations with a response time of l ms or less. Upon detection, the control panel initiates a gas cartridge actuated rupture disc valve on the suppressant discharge container. The discharge container was pressurized with dry N_2 to 900 psig. Once the rupture disc valve has opened, the N_2 and $NaHCO_3$ are rapidly discharged into the chamber. In some of the experiments, two 2.5 liter containers or one 5 liter container was used to increase the quantity of $NaHCO_3$ discharged into the chamber. The maximum pressure reached after ignition of the fuel dust and discharge of suppressant agent into the enclosure is reported as the total suppressed pressure (TSP). 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

The results show that 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}).

The suppression of metal dust explosions has generally been felt to be difficult if not impossible. A report from the British Material Handling (BMH) Board (5) stated that "metal dusts explosion hazards have always been considered to be beyond the capability of explosion protection technology..." Very few examples of attempts to suppress metal dust explosions exist. Bartknecht (7) reported on the suppression of K_{max} 300+ aluminum dust in a 1 m^3 vessel with sodium bicarbonate. At low aluminum concentration, suppression was effective. However at concentrations above 500 g/m^3 where the K_{max} exceeded 300, suppression was not successful (P_{red} was 90% of P_{max}). The failure was attributed to the low suppressant discharge velocity of 10 m/s. BMH also investigated metal dust protection in 1988 (5). Using aluminum flake (K_{max} = 300 bar.m/s) in a 6.8 m^3 vessel with a detection pressure of 0.75 psi (50 mbar), various suppressant agents were screened. The agents Dessicarb (sodium bicarbonate) and rock dust (calcium carbonate) showed some promise (P_{red} less than 3 barg) which china clay, talc, silicon oil, MET-L-X, and Furex 770 were unsuccessful. A reduced pressure of 26.5 psig (1.8 barg) was achieved at a suppressant concentration of 28 lbs/m^3 of Dessicarb. Less suppressant (14 lbs/m^3) resulted in 41.2 psig (2.8 barg) reduced pressure.

In a continuation of this effort, suppression assisted by venting was tested. Using an 18.5 m^3 vessel, Dessicarb at 12.5 lbs/m3, a 0.95 m^2 vent (Pstat = 0.2 bar), P_{set} of 0.6 psi and an aluminum deflagration of K_{max} 350, the reduced pressure was ~1.3 barg, a small improvement. At K_{max} = 600, however, the P_{red} was 3.8 bar.

More recent testing was reported by Fike Corporation (8). Testing was performed in a 1 m^3 vessel using high rate discharge containers and electronic pressure detection. These containers open in <1 ms and discharge suppressant at 100 m/s (330 ft/s) in the first 2 meters (see Figure 3). The electronic pressure detector responded in ~1 ms which represents a significant improvement in response time. Silicon and aluminum dusts were tested and the results are shown in Table 2 below.

Table 2. Suppression Results for Metal Dust Deflagrations.

Metal Dust	Conc., g/m^3	K_{max} bar.m/s	P_{max} barg	Suppressant (a)		Reduced Pressure (b,c)	
				Type	Conc.lbs/m^3	psig	Barg
Silicon	1000	120	8.16	SBC	5	4.8	0.33
Silicon	1000	120	8.16	PK	5	4.0	0.27
Silicon	1000	120	8.16	PK	10	4.4	0.30
Aluminum	1750	300	8.50	SBC	10	30.2	2.05
Aluminum	1750	300	8.50	SBC	20	12.2	0.84
Aluminum	1750	300	8.50	PK	10	18.4	1.25
Aluminum	1750	300	8.50	PK	20	13.1	0.89

a) SBC = sodium bicarbonate; PK = potassium bicarbonate
b) Detector set pressure was 0.5 psi(50 mbar)
c) Reduced pressure is the average of two tests

The suppression of silicon was easily accomplished and did not depend upon the type of suppressant. Also, there was no improvement when the suppressant concentration was increased from 5 to 10 lbs/m^3. Aluminum, on the other hand, displayed a much higher K_{max} and was more difficult to suppress. The higher concentration of 20 lbs/m^3 is clearly required to accomplish suppression. Figure 4 compares the unsuppressed aluminum deflagration with suppression with sodium bicarbonate at 20 lbs/m^3. While PK is slightly more effective at 10 lbs/m^3, at the recommended concentration of 20 lbs/m^3, there was no difference between PK and SBC. Much of the success of this system is due to the fast responding electronic pressure detector. Earlier results using a mechanical detector were quite similar to those reported by Bartknecht; suppression was not possible at high aluminum concentrations. In summary, metal dust deflagrations can be suppressed to less than 1 barg provided that fast responding equipment is used, the concentration of suppressant is sufficient, and the detector set point is ~0.5 psig (35 mbar).

Venting. The extensive practice of industrial deflagration venting is described in detail in commonly accepted engineering literature and guidelines such as NFPA 68 and VDI 3673 (9,10). With industrial deflagration venting, a rupture diaphragm is placed on a process vessel that could potentially have a deflagration on the inside and cause catastrophic damage to the vessel as well as the surroundings. The rupture diaphragm is designed with a static burst pressure (P_{stat}) or an opening pressure well below the pressure at which the process vessel would be destroyed or damaged and above the operating pressure of the vessel. In addition, the area of the rupture diaphragm (vent area, A_v) is chosen or calculated to be large enough to allow discharge of flame and pressure generated during an explosion. The vent area is chosen such that the pressure inside the process vessel is reduced to a level below the pressure at which the vessel would be destroyed. This pressure is designated as P_{red}. Guidelines are available to calculate the appropriate area for a given vessel with volume V and with a known explosion hazard characterized by the fuel's P_{max} and K_{max} . As an example, the formula for dust explosion venting provided in NFPA 68 Section 7-2.2, the 1998 edition is shown below.

$$A_v = (3.264 \times 10^{-5} \times P_{max} \times K_{max} \times P_{red}^{-0.569} + 0.27 (P_{stat}^{-0.1}) \times P_{red}^{-0.5}) \times V^{0.753}$$

Once the vent area has been calculated, the location of the protected vessel must be reviewed. More accurately, the location surrounding the vessel and specifically the direction of discharge from the explosion vent must be evaluated to make certain that a secondary hazard is not created. Consideration must be given to the size of the flame cloud from the explosion vent and the external pressures created by the explosion discharge.

NFPA 68 allows for the venting of dust explosions with P_{max} up to 12 bar and with K_{max} between 300 and 800 bar.m/s. This could apply to hybrid deflagrations with high K_{max} levels and to metal dusts with both high P_{max} and K_{max}. Very few examples of actual metal dust vent tests are published. Again BMH (4) as part of their suppression study, performed aluminum dust vent tests. The system used was an 18 m^3 vessel with a vent area of 0.95 m^2 and a P_{stat} of 0.2 bar. The aluminum deflagration parameters were P_{max} = ~10.5 barg and K_{max} = 350 bar.m/s and the measured reduced pressure P_{red} was 3.8 barg.

When repeated at a K_{max} of 600 and no vent closure, the Pred was 3.4 bar. The results were generally higher than predicted using VDI venting nomographs.

Fike conducted duplicate tests using a 2.6 m^3 cubical vessel with a 0.56 m^2 vent with a P_{stat} of 0.1 bar. The aluminum dust had a K_{max} of ~170 and P_{max} ~ 10 bar which resulted in a P_{red} of 0.25 barg. The results of one test are shown in Figure 5. Again, the reduced pressure was greater than predicted.

One unique aspect of metal dust venting is the nature of the combustion product. These will be metal oxides solids (e.g., Al_2O_3) in contrast to carbon dioxide and water vapor from carbon based fuels. An extremely large dust cloud will be discharged. Also, the flame temperature may be quite high and the generation of secondary explosions must be considered. If venting is to be a common protection practice for metal dust explosions, further study of its effectiveness and sensitivity to explosibility parameters seems to be warranted.

Isolation. The use of pipelines to connect vessels and transport material is a common practice in the processing industry. The potential of fires and explosions in the process industry has been well recognized and is addressed in consensus guidelines such as NFPA 68 – Guide for Venting of Deflagrations and NFPA 69 – Explosion Prevention Systems. Both of these guides differentiate between vessels and piping systems by providing different rules to address the differences in explosion propagation behavior. For example, NFPA 68 has a separate chapter (#8) on deflagrations in pipes and NFPA 69 has a chapter (#7) on isolation methods for equipment interconnected by pipes. Both NFPA 68 and NFPA 69 are based on an understanding of explosion propagation behavior developed from empirical or experimental evidence. Three types of combustion propagation phenomena in pipes – fires, deflagrations and detonations – must be understood in order to conduct adequate process safety design. Typically, process piping transports combustible materials at a concentration outside the flammable limits although in some instances, the concentration in the pipe may vary and traverse the flammable range. The combustion propagation phenomenon across the entire flammable region is of importance. It is expected that near the rich and lean limits, flame propagation is slow and pressure development is negligible. Near the stoichiometric compositions, flame propagation and pressure development is expected to be representative of deflagrations and detonations.

One important difference between deflagrations and detonations is the mechanism of propagation. Deflagration flame fronts propagate due to heat transfer effects. The deflagration flame heats the unburned fuel in front of it above its ignition temperature and therefore propagates forward into the unburned fuel. Detonations propagate forward due to compression effects. In the deflagration region, pressures typically will not exceed 10 bar for hydrocarbon-air combustion and the rate of pressure rise will be on the order of milliseconds. The accelerating flame will have velocities on the order of 100 – 300 m/s. In the detonation region, pressures can be from 20 – 80 bar and the rate of pressure rise is in microseconds. The flame velocity will rise to 1500 – 2500 m/s. This behavior is illustrated in Figure 6.

Isolation is used to prevent flame travelling from its point of ignition to other parts of the process (see NFPA 69). This is difficult when the flame speed is high, when the conveyance line has bends and when the point of ignition is within a vessel. Previous experiments have shown that flame speed and pressure increases as the explosion propagates. This is especially true if a vessel is built strong enough to contain the explosion and the explosion is allowed to run its course. Turbulence at the walls and obstruction (bends) will stretch the flame. This can enhance the combustion rate resulting in an increase of velocities and transition from deflagration to detonation.

Isolation can be accomplished with a variety of mechanical methods as well as chemical methods. The mechanical system physically interrupts or blocks the passage of flame. Examples include fast acting valves and flame arrestors (gases only). Placement of the device is important for performance. If a mechanical isolator is placed too far from the ignition, the flame front will become a detonation prior to reaching the device. But if the device is placed before the transition point, in the case of a fast acting valve, it may not be able to close before the flame arrives. Chemical isolation is similar to suppression in that an agent such as sodium bicarbonate is injected into the pipeline prior to the arrival of the flame front. It serves as a barrier by extinguishing the arriving flame and preventing ignition of the upstream fuel.

Little has been reported on the propagation of a metal dust down a pipeline or on the chemical or mechanical isolation of that deflagration. Bartknecht (7) tested a 30 m pipe, DN 400, that was closed at the ignition end. Aluminium dust at ~500 g/m^3 was suspended (K_{max} = 625) and flame velocities and explosion pressures were measured. At 20 m, the velocity was ~1500 m/s and the pressure exceeded 25 bar. Chemical isolation was demonstrated in this pipeline using detection at 1 m and the extinguishing barrier at 10 m. The suppressant conditions were not specified however, it appears that 12 Kg (26.4 pounds) of MAP were injected. Flame did not pass the barrier and pressure was reduced to ~3 bar. No tests with pre-volumes were reported.

In a related test with a 33 meter pipe and a 2.4 m^3 pre-volume causing flame jet ignition, the velocity and pressure at 30 m exceeded 3000 m/s and 36 bar respectively. Figure 7 is a representation of the reported data. Attempts at mechanical isolation at 10 m or greater led to massive deformation of the gate. The installation of vents with an area of 4.5 times the cross section was effective at reducing the pressure at the mechanical valve. Placement of vents at 20 m intervals was effective at keeping the pressure below 10 bar.

Tests were conducted for Fike by DMT (Germany) in the system shown in Figure 8. This layout was based on a containment pre-vessel, 16" (DN 400) pipe, an aluminium dust with K_{max} >300 and a maximum distance of 14 m for valve placement as shown. Test indicated that the aluminium dust transitioned into a detonation within the pipe between the vessel and the explosion isolation valve: pressures up to 30 bar (450 psig) and flame speeds over 450 m/sec were measured. It is believed that the pipe layout and the presence of bends in the pipe enhanced this effect. When tested, the explosion isolation valve did stop the explosion flame from propagating down the pipe, however flames escaped through pipe gaskets and valve parts as a result of the excessive heat and pressure.

A system was developed which added 2 chemical isolation containers, each containing 18 pounds (36 pounds total) sodium bicarbonate as the suppression media 4 meters from the containment vessel. This barrier suppressed enough of the flame front so that the pressure experienced at the isolation valves is decreased to an acceptable level, 15 bar, thereby allowing the isolation valve to completely block the flame. This combination of techniques represents a method to safely isolate a metal dust explosion without release of flame or combustion products.

Conclusions

Industrial explosions involving metal dusts may have unique properties that make explosion protection more challenging. Testing has shown, however, that such explosions can be managed safely if the risk is well understood and the design is within established limits.

- Suppression can achieve reduced pressure of <1bar for metal dusts up to Kmax 300. At higher K_{max} levels, suppression alone has not been successful and the addition of venting was only partially successful. No testing of magnesium has been reported.
- Venting has been reported at volumes of 2.6 and 18.5 m^3. In both tests, the reduced pressures observed were higher than predicted from existing methods. While venting is certainly possible, it remains to be shown that accurate vent sizing can be done.
- Isolation has been demonstrated by chemical and mechanical methods, combinations of these methods and by combination of mechanical and venting methods. Chemical isolation was successful in a straight pipe up to K_{max} 650. With a pre-volume, mechanical isolation required the addition of venting to prevent catastrophic damage. The combination of chemical and mechanical isolation with a pre-volume deflagration was also shown to work.

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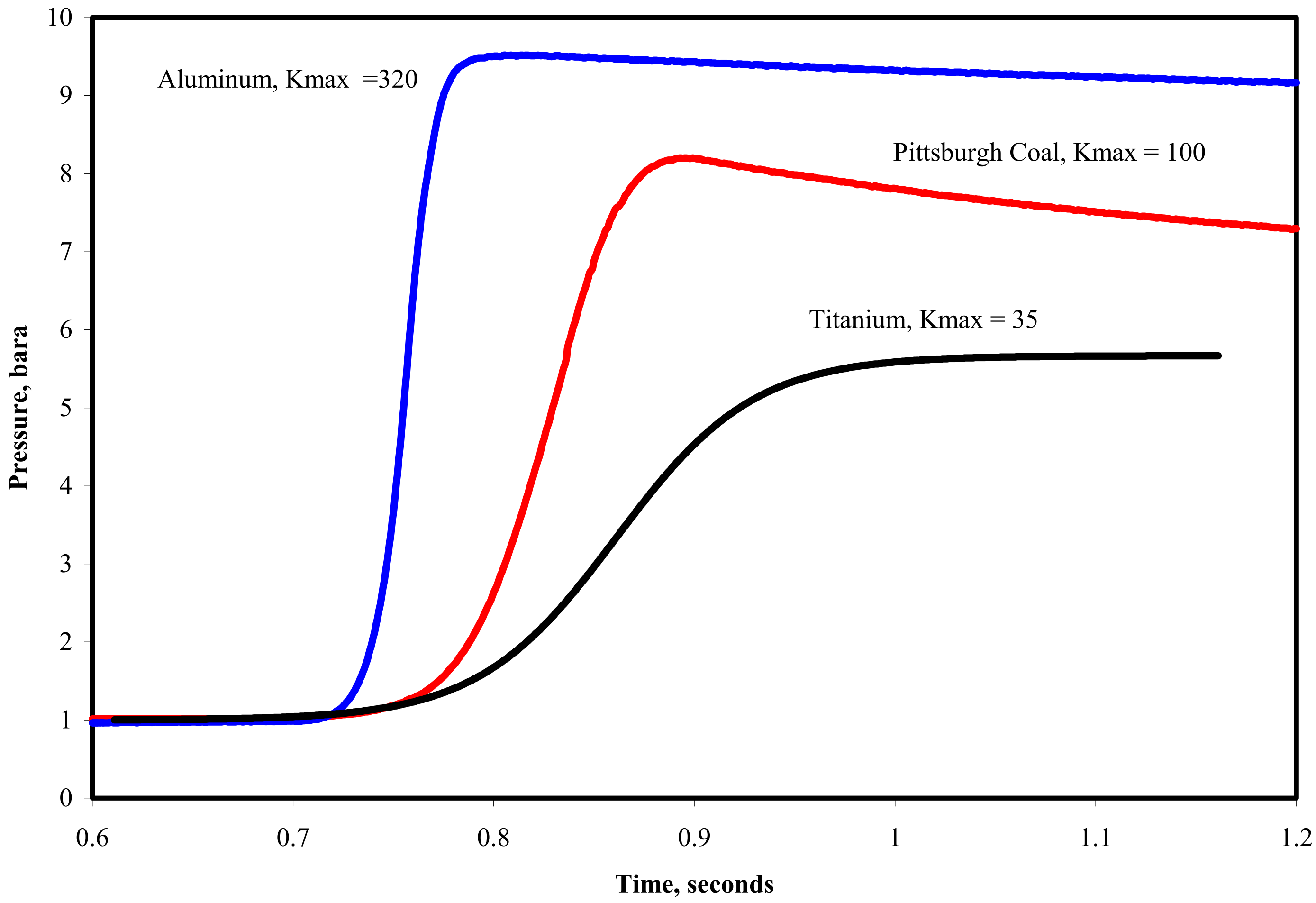

Figure 1. Deflagration Curves for Metal Dusts

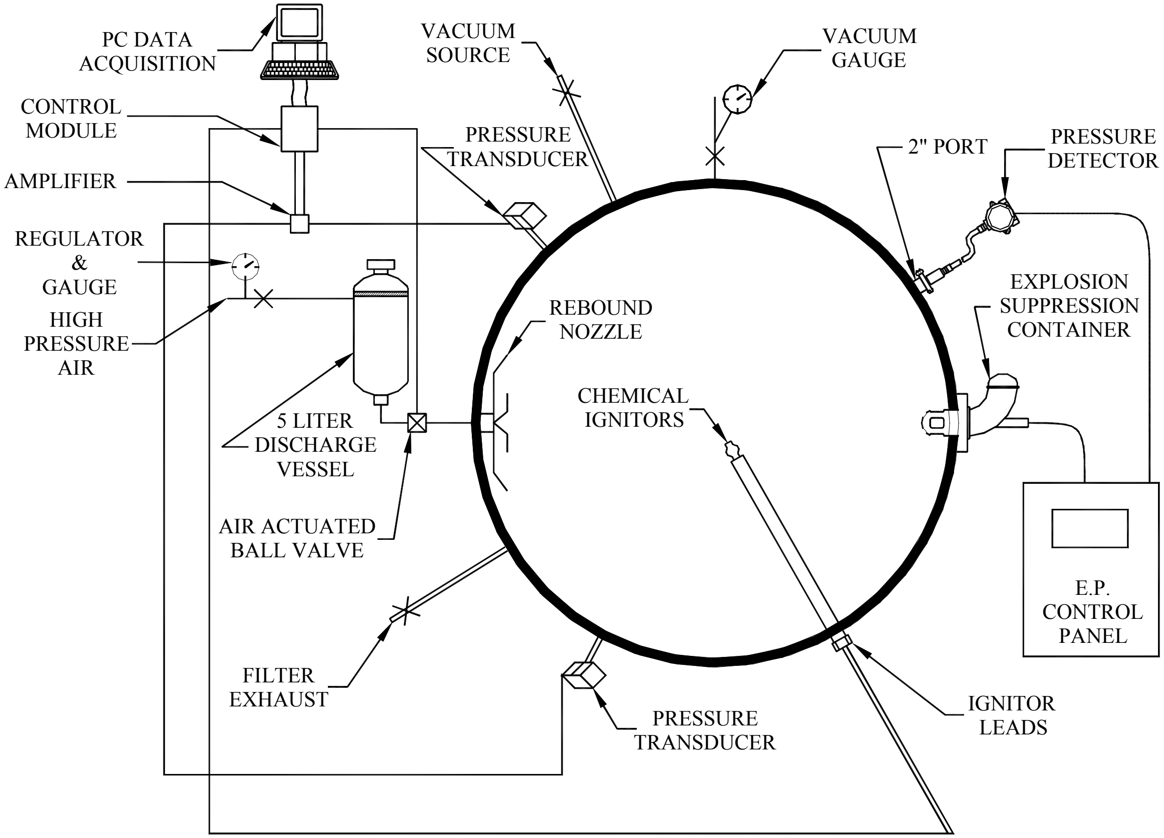

Figure 2. 1 m^3 Vessel Setup for Deflagration Suppression

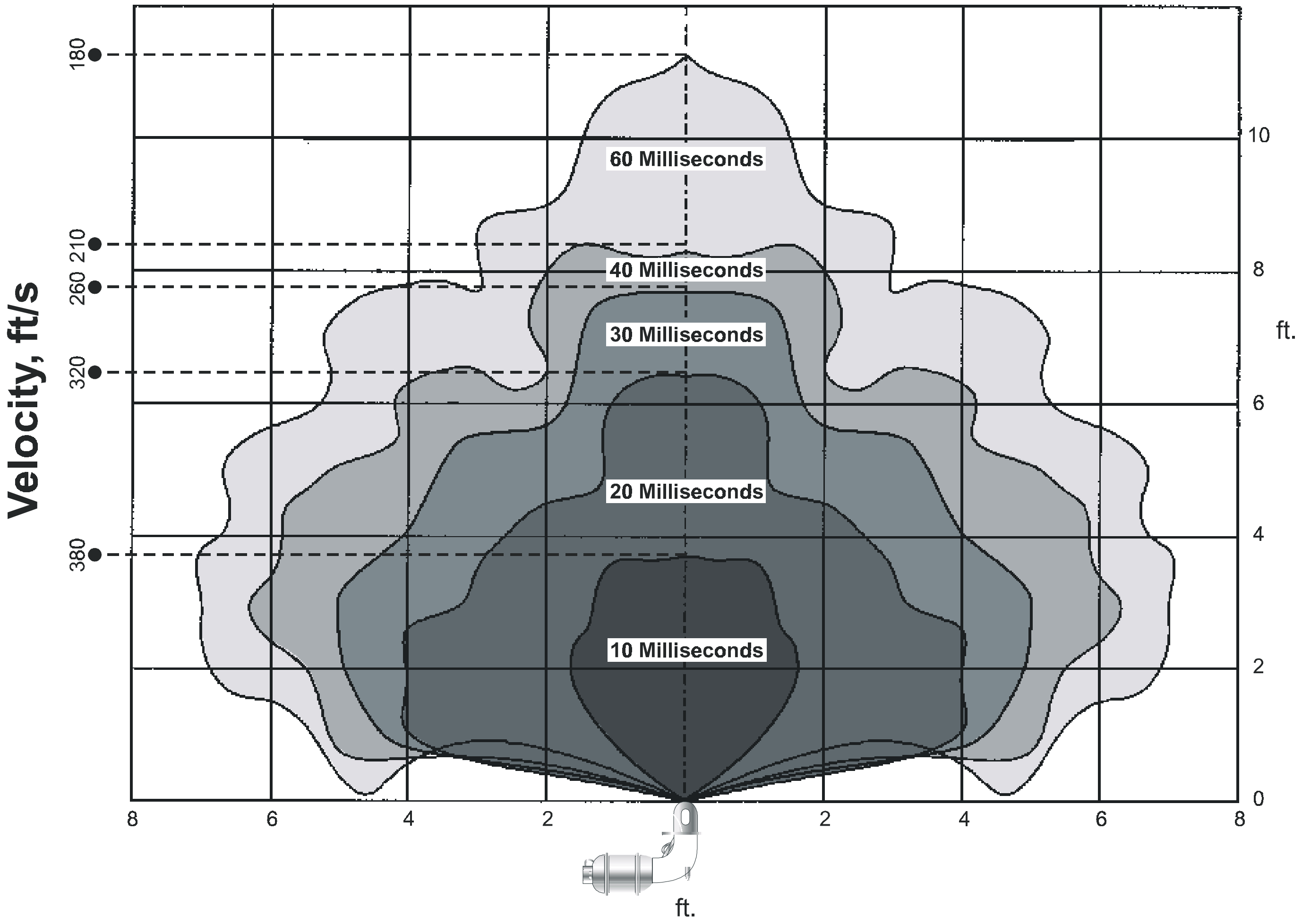

Figure 3. Dispersion Pattern of High Rate Discharge Container

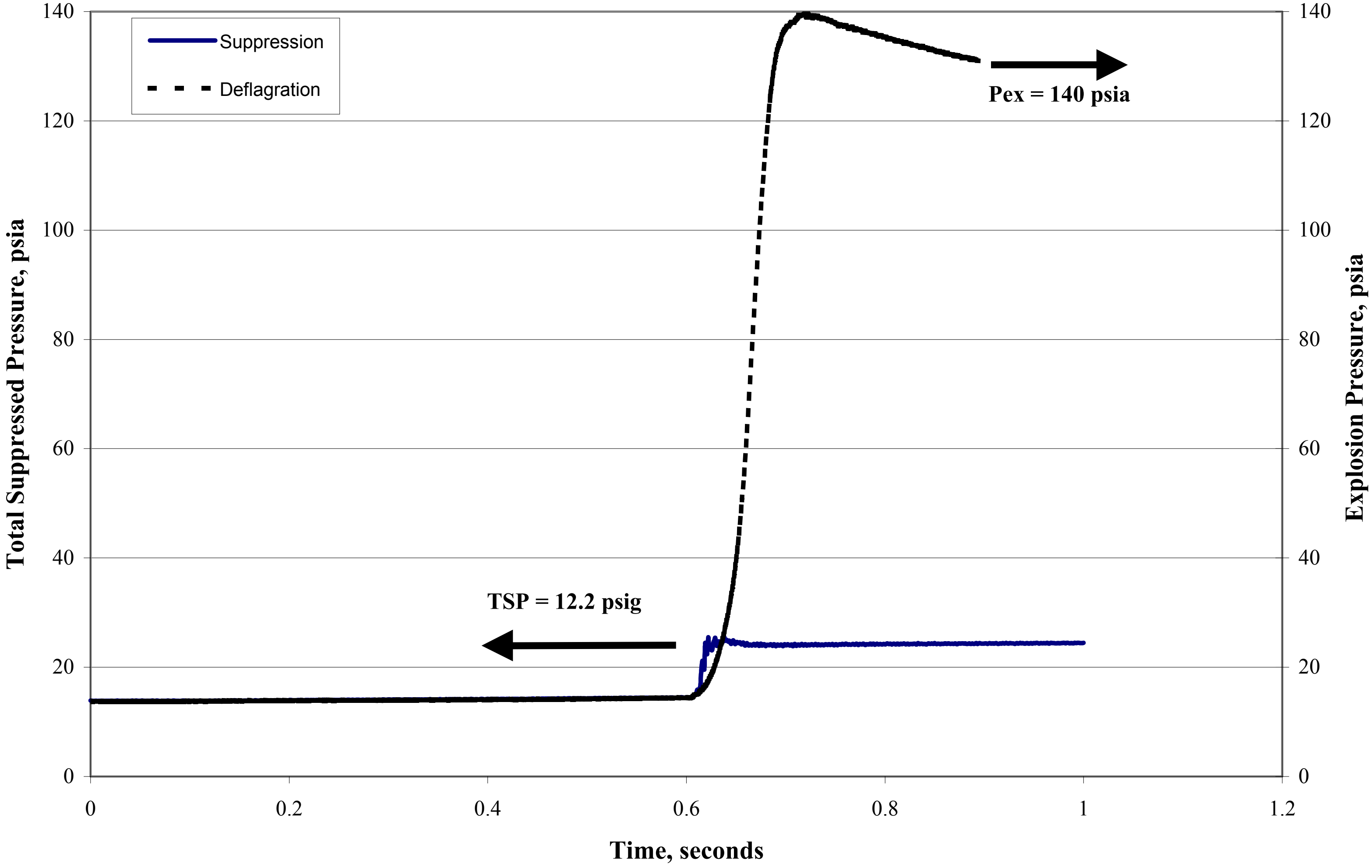

Figure 4. Comparison of Aluminum Deflagration and Suppression Pressure
1 m3, Al = 1750 g/m3; Pset = 0.5 psi; Two 5 L HRD; 20 lbs SBC total

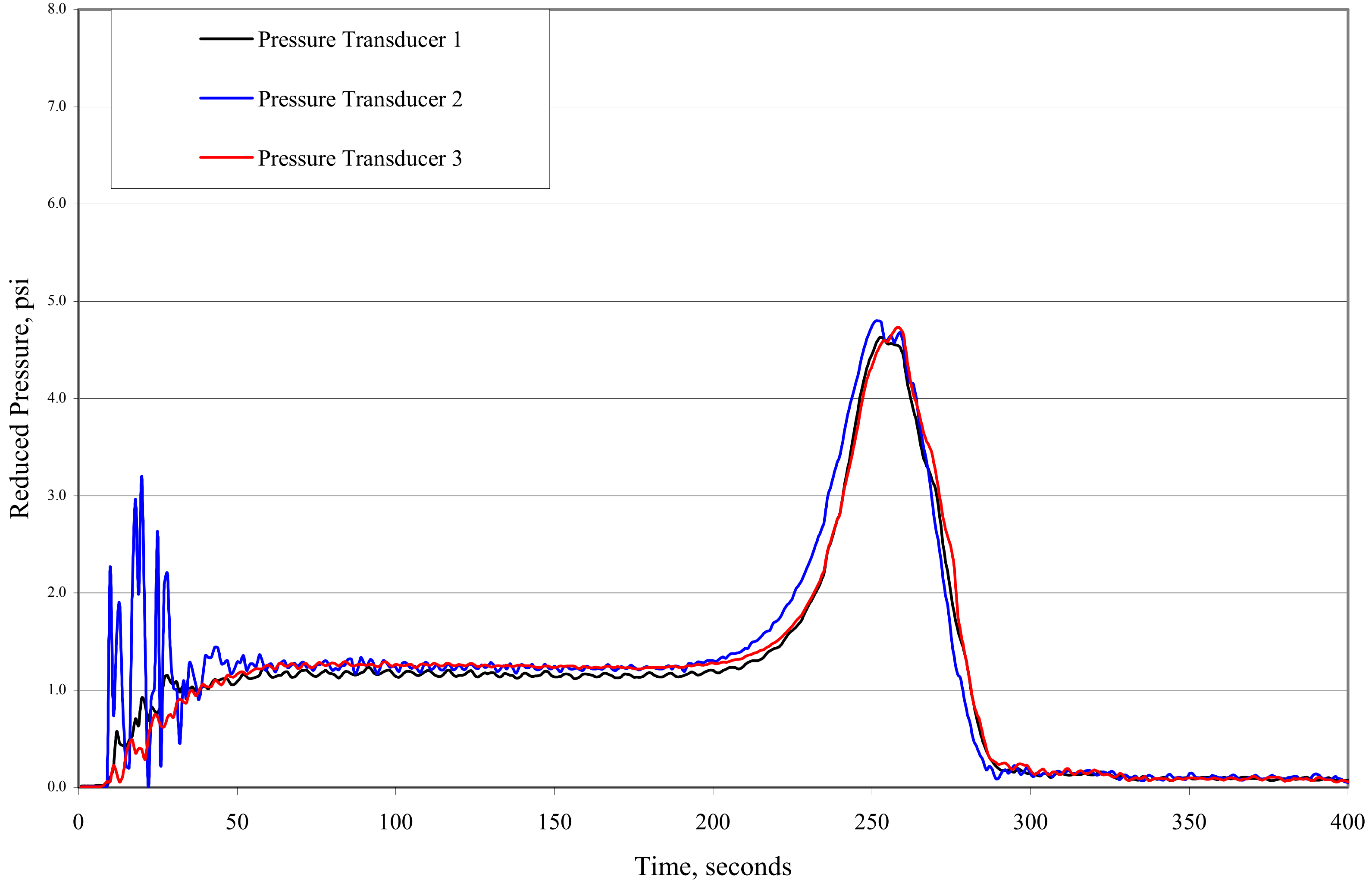

Figure 5. Venting of Aluminum Powder Deflagration

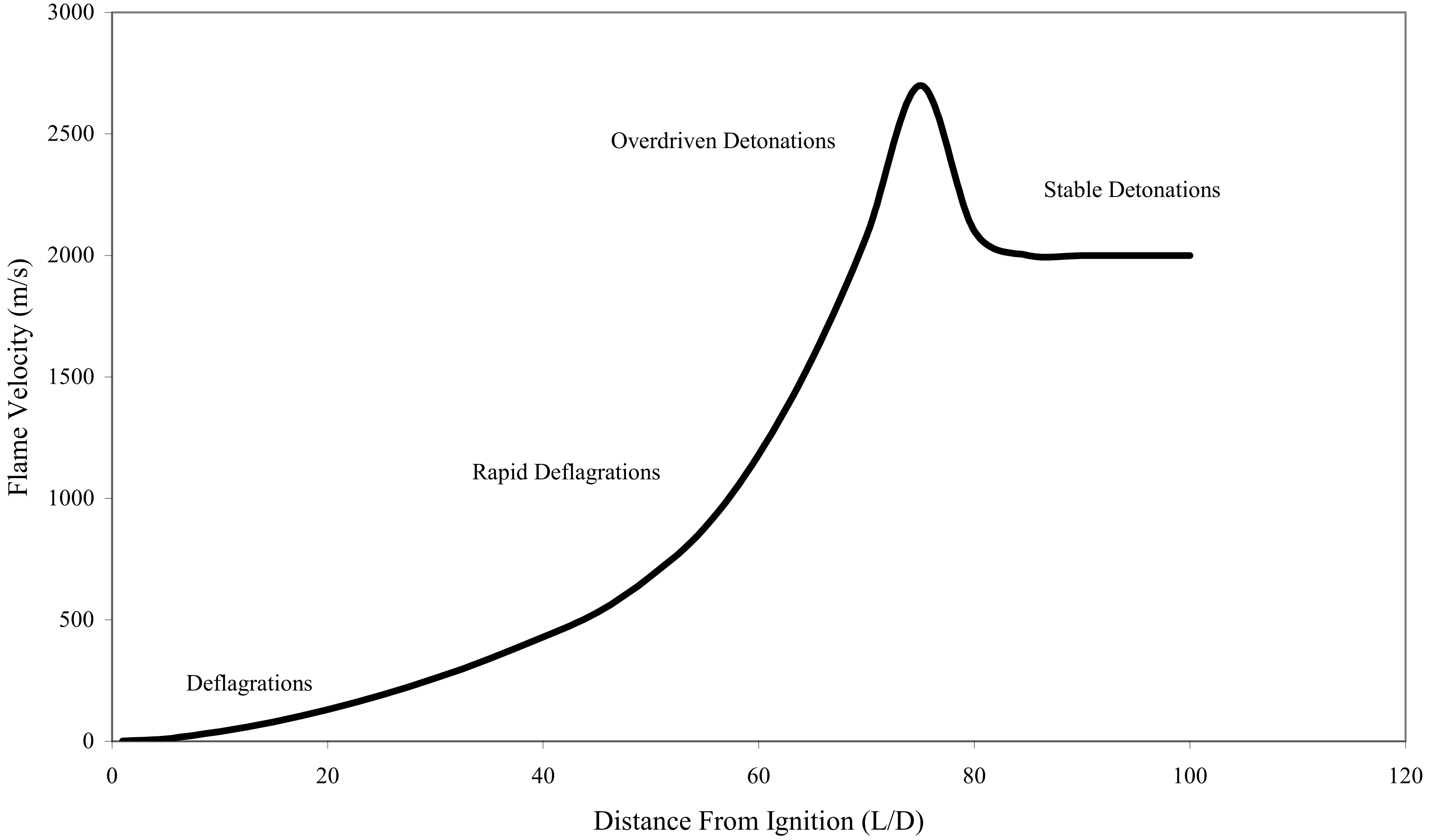

Figure 6: Flame Propagation in Pipes

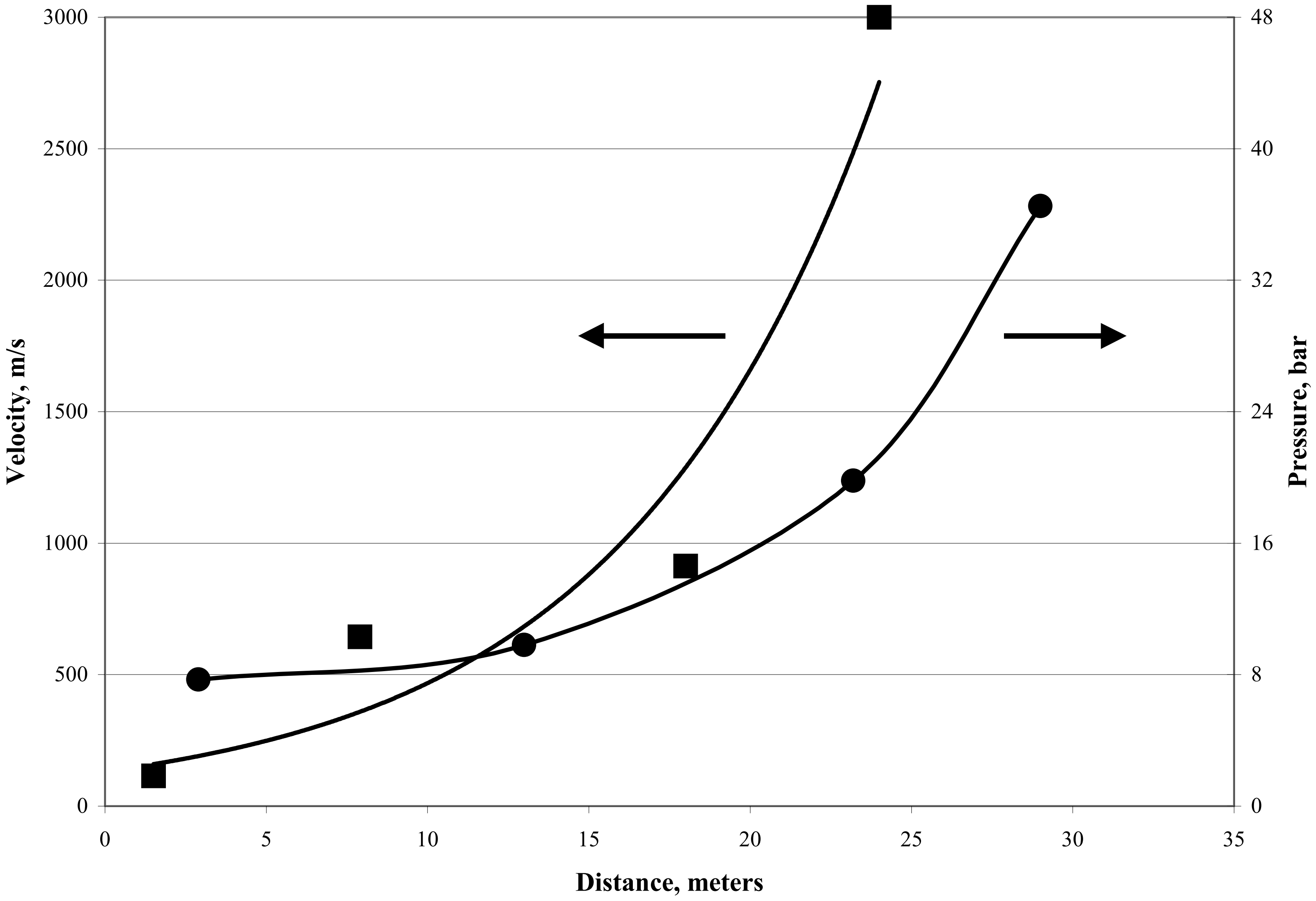

Figure 7. Aluminum Powder Pipeline Deflagration
2.4 m3 Pre-volume, DN 400 Pipe 33 meters

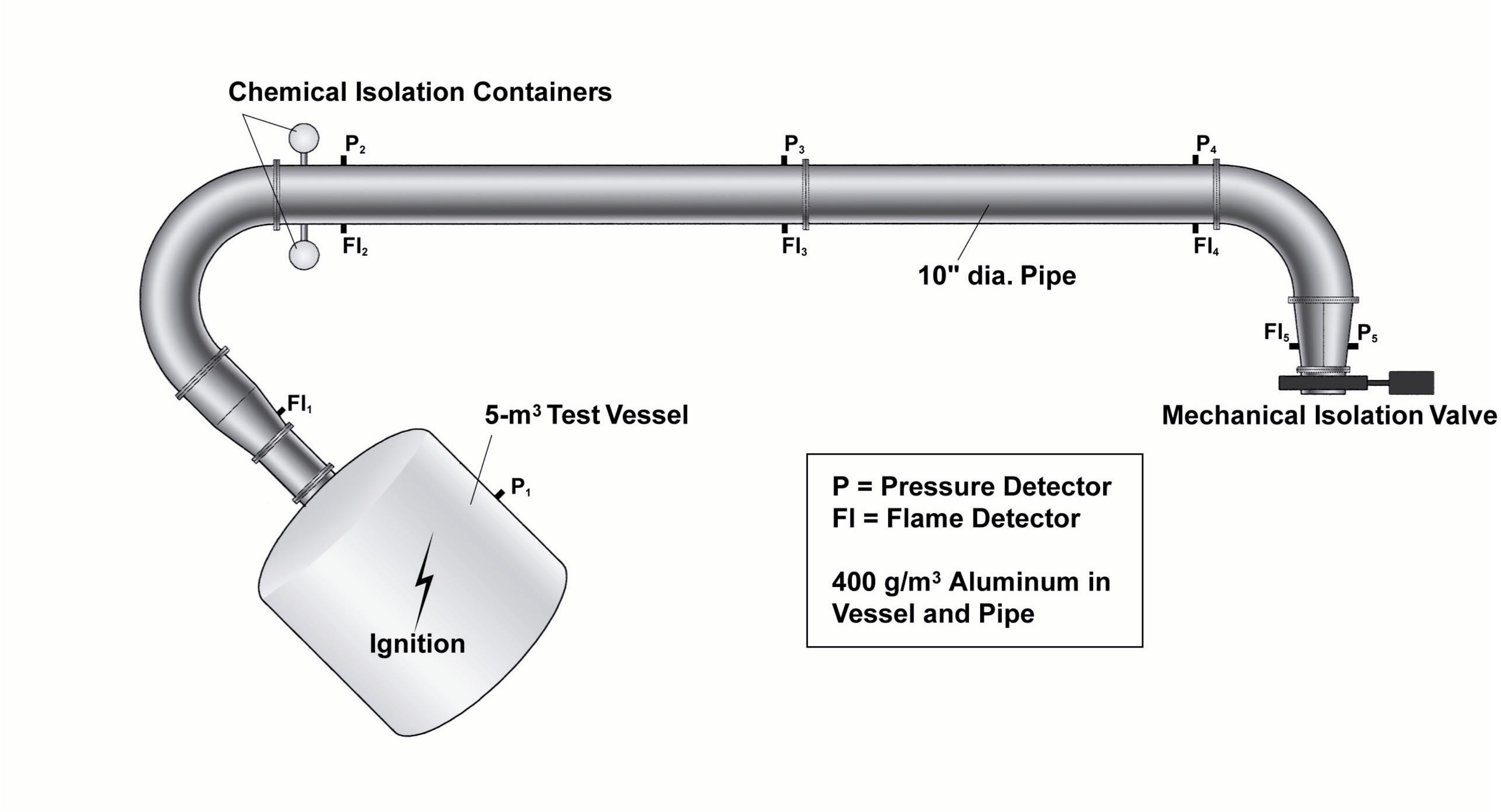

Figure 8 Chemical and Mechanical Isolation of Aluminum