Combustible Dust Fire and Explosion Protection:
NFPA 654 Requirements, Explanations and Issues

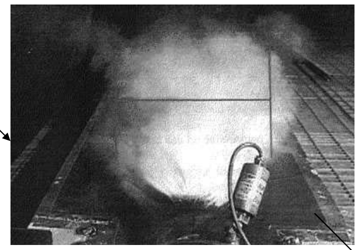
Georgia State Fire Marshal
Fire Safety Seminar
Robert Zalosh Presentation
Thursday, July 16, 2009

Presentation Outline

1. Dust fire and explosion risk evaluations per NFPA 654 chapter 7.
2. Controlling Ignition Sources: NFPA 654 Chapter 9 and beyond
3. Process equipment explosion protection
   - Inerting per NFPA 69
   - Dust deflagration venting per NFPA 68
   - Dust explosion suppression per NFPA 69
4. Dust control and housekeeping (NFPA 654 Chapter 8): requirements and available equipment .

Combustible Powder/Dust Layer

+ Disturbance =



Dust Cloud

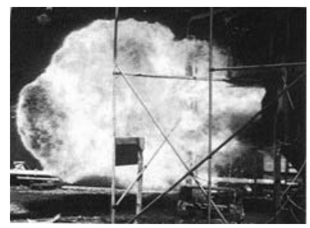
C > MEC

Minimum Explosible Concentration

+ Ignition Source

And Confinement =

Vented Explosion Fireball



Risk Evaluation Requirements per NFPA 654

- **7.1.1** A **documented** risk evaluation acceptable to the authority having jurisdiction shall be permitted to be conducted to determine the level of protection to be provided.
- **A.7.1.1** A means to determine protection requirements should be based on a risk evaluation, with consideration given to the size of the equipment, consequences of fire or explosion, combustible properties and ignition sensitivity of the material, combustible concentration, and recognized potential ignition sources. See AIChE Center for Chemical Process Safety, *Guidelines for Hazard Evaluation Procedures*.

AHJ Review of Risk Evaluation

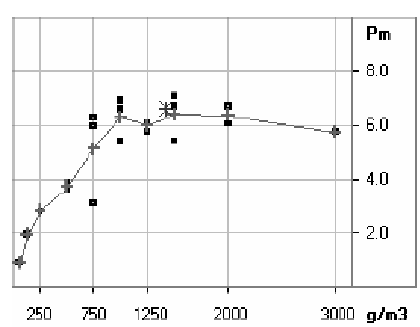
- Who performed risk evaluation: qualifications of author relative to combustible dust and risk analysis methods.
- When was analysis conducted? Before or After Equipment Protection Determined?
- Have powder/dust materials (composition or size) and associated combustibility properties changed since risk evaluation?
- Does risk evaluation discuss likelihood and consequences of dust explosion (with and w/o protection) in that particular equipment and by propagation to connected equipment?

Combustible Dust Material Explosibility Properties

- Pmax = Maximum Pressure in Closed Vessel Deflagration. Depends on dust concentration, and also on particle size.

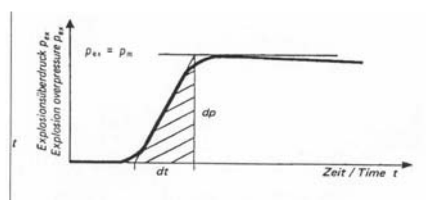
Test data for non-dairy creamer powder, particle size < 75 µm.

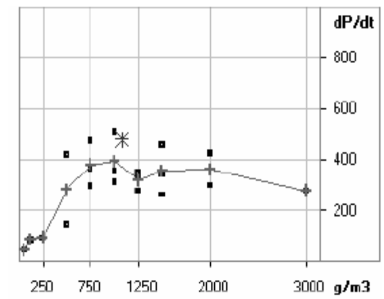
Pmax = 6.6 bar g = 96 psig



Combustible Dust Material Explosibility Properties

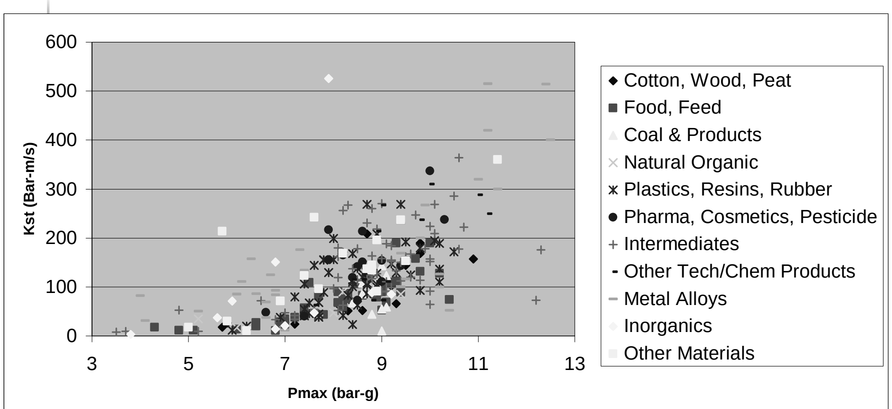
- K_{ST} = volume-scaled maximum rate of pressure rise in closed vessel = $(dP/dt)_{max}V^{1/3}$
- Depends on concentration, particle size, ignition source strength, and turbulence level at time-of-ignition





Non-dairy creamer < 75 µm: K_{ST} = 130 bar-m/s

P_{max} and K_{ST} data summary in Eckhoff Table A.1



Combustible Dust Material Explosibility Properties

- Explosion Severity Index (E.S.I.)

▪If E.S.I. ≥ 0.5, material is classified as Class II dust

▪ If E.S.I. < 0.5, should use Ignition Sensitivity Index to make Class II classification determination (per NFPA 499); OSHA SLC Lab does not run Ignition Sensitivity tests unless 0.4 < E.S.I < 0.5

Ignition Sensitivity Parameters

- MIE = Minimum Ignition Energy (in millijoules) = minimum electric spark energy required to ignite most-easily-ignitible dust cloud concentration
- Dust Cloud Minimum Ignition Temperature: Measured by injecting dust sample into either a horizontal or vertical oven with a pre-set air temperature.
- Dust Layer Hot Surface Ignition Temperature; usually much lower than cloud ignition temperature

Combustible Dust Explosibility Property Databases

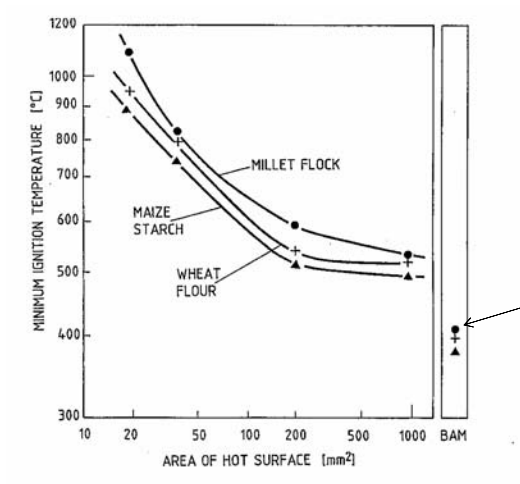
- Although data should be obtained for plant-specific dust samples, the following two public data bases provide numerous examples for many materials.
- Eckhoff's Dust Explosions in the Process Industries, Table A.1 accessible online via Knovel Electronic Library (free via AIChE)
- BGIA GESTIS-DUST-EX Online Database
  - Data for over 4000 materials searchable by name
  - Data from German labs; database is EC funded
  - Data for P_{max}, K_{ST}, MEC (lower exp limit), MIT, MIE
  - http://bgia-online.hvbg.de/STAUBEX/explosuche.aspx?lang=e

Hot Equipment Ignition Sources: Example of Dust Explosion Ignited in Oven

- Employees "blowing down dust" in vicinity of oven with temperature > cloud ignition temp
- Oven door left open to facilitate cooling between shifts.

Figure 13. Interior of line 405 oven.

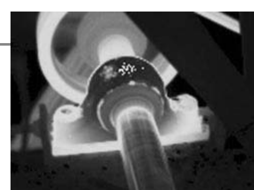
Hot Surface Ignition Temperatures



BAM Oven Ignition Temperatures

Examples of Hot Surfaces

- Hot Bearings



- Foundry Furnace

- Hot steam pipe or heat transfer fluid pipe

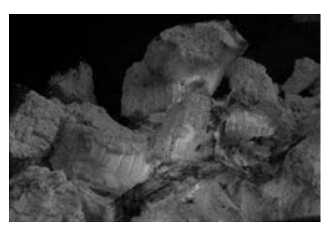
Ignition Sources: Hot Surfaces

- Cutting and Welding – Hot Work
  - Example: Cutting down old ducting containing aluminum dust

- Hot Work Permits required for old/abandoned equipment as well as operational equipment

Burning Embers and Agglomerates

- Burning embers created by
  - Frictional heating, e.g. from sanding
  - Radiant heating, e.g. during curing of wood panels
  - Convective heating, e.g. in dryers



Dust Clouds Ignited by Burning Embers/Nests

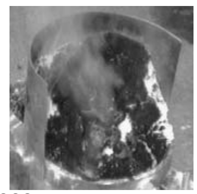
- Direct ignition of dust clouds requires flaming embers/nests rather than smoldering.
- Can occur when embers/nests are transported downstream to dust collector or hopper

Can ignite most dust clouds

Flaming milk powder agglomerates: 960^{o}C

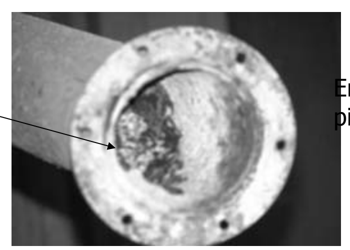
Can not ignite most dust clouds

Smoldering milk powder agglomerates: 700^{o}C. MIT = 410^{O}C



From Gummer & Lunn, 2003

Example of Dust Explosion Caused by Flaming Embers



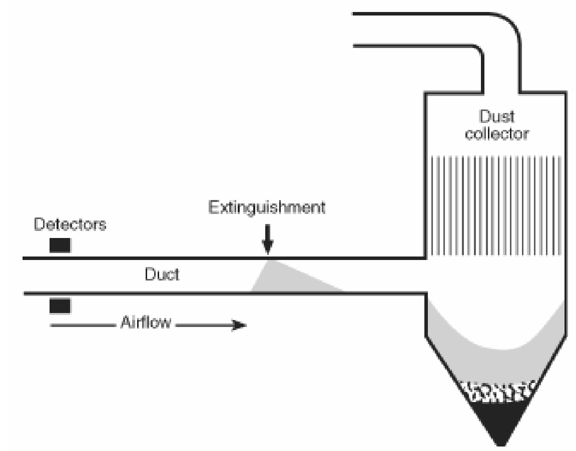
Embers in dust pickup pipe

Animal Feed Pelletizer:

Small Fire due to blockage

Dust collector explosion damages building

Prevention via Burning Ember Extinguishing System



See NFPA 654 Annex C for System Description

Self-Heating Ignitions

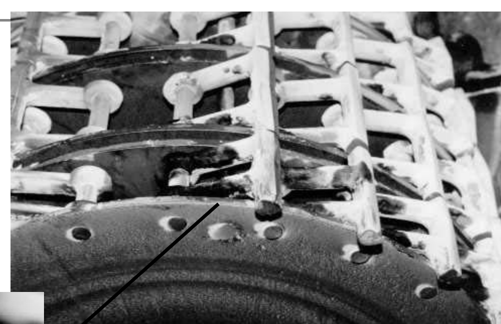
- Self-Heating Mechanisms
  - Low level oxidation
  - Heat of condensation
  - Microbiological processes
- Pertinent Applications
  - Product accumulations in dryers
  - Extended storage in large silos or outdoor piles
  - Over-dried product suddenly exposed to moist atmosphere
- Self-ignition leads to burning, which can then ignite dust cloud if burning product is flaming.
- Critical temperature for self-heating decreases with increasing size of pile or layer.

Impact/Friction Ignition

- During size reduction operations in various types of mills.
- During mixing and blending if impeller is misaligned or deformed or has inadequate clearance, or tramp metal enters mixer.
- During grinding and polishing operations.
- Tramp metal in a particle classifier, mill or conveyor; NFPA 654 paragraph 9.1.3 requires tramp metal removal by magnetic or other separators.

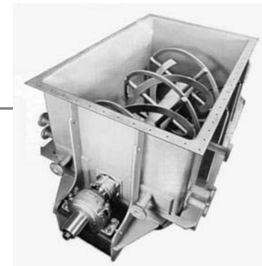
Ignition Sources: Friction/Impact Sparks

Sugar Hammermill: Ignition Evidence



Impact/Friction Ignitions in Blenders and Grinders

Reference: Jaeger, 2001



Ribbon/Paddle Speed	Friction Ignition Threat
< 1 m/s	None
1 – 10 m/s	Depends on Dust MIE and MIT
> 10	Great

No ignition threat when fill level > 70%

Electrical Equipment for Class II Locations

- Dust ignitionproof for Division 1 locations

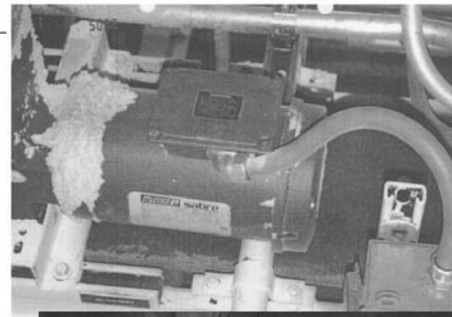
Dust ignitionproof video camera with adjustable positioning mount

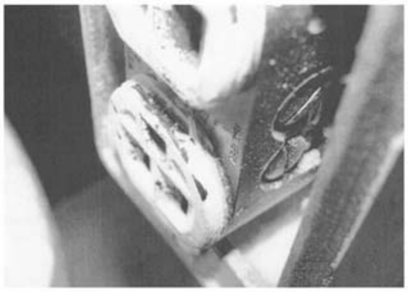
- Dustproof for Division 2 locations

Dustproof light fixture

Ignition Sources: Electrical Equipment not Rated for Class II Areas

Paper dust accumulations on motor and outlet

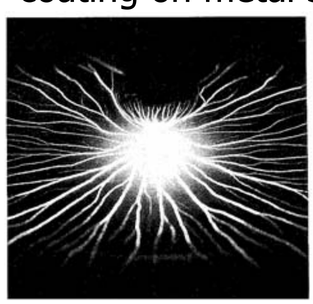




Saw dust on motor

Ignition Sources: Electrostatic Discharges

- Propagating Brush Discharge from insulated layer or coating on metal surface



- Sparks from ungrounded boots on pipes and ducts
- Bulking brush discharge from large piles of high resistivity powder loaded into bins or blenders

MIE Data for Different Dusts: Implications for Electrostatic Ignition Threat

Minimum Ignition Energy of the Powder (mJ)	Comment
500	Low sensitivity to ignition: Ground plant when ignition energy is at or below this level.
100	Consider grounding personnel when ignition energy is at or below this level.
25	The majority of ignition incidents occur when ignition energy is below this level. The hazard from electrostatic discharges from dust clouds should be considered.
10	High sensitivity to ignition. Take the above precautions and consider restrictions on the use of high resistivity materials (plastics). Electrostatic hazard from bulk powders of high resistivity should be considered.
1	Extremely sensitive to ignition. Precautions should be as for flammable liquids and gases when ignition energy is at or below this level.

From Chillworth Technology laboratory test report

Electrostatic Ignition Sources: Flexible Intermediate Bulk Containers (FIBCs) aka Supersacks

- Used for loading, transporting, and unloading bulk powders
- Four different types with different electrostatic properties

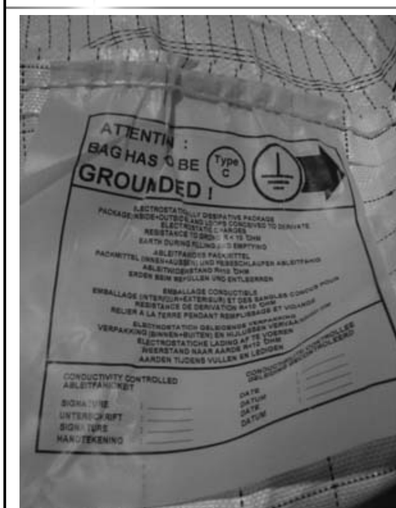
Type A,B,C, and D FIBCs

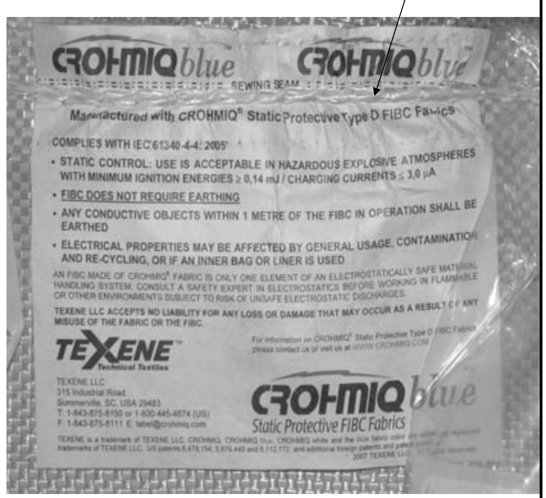
- Type A allows high electrostatic charges and has no electrostatic controls.
- Type B has walls that cannot sustain a voltage of more than 4 kV; can be used if powder Min Ign Energy > 3 mJ.
- Type C is made with conductive fabric and must be grounded to prevent electrostatic charge accumulation.
- Type D dissipates electrostatic charges and can be used for any dust/powder.

FIBC Label

Type C FIBC label

Type D designation





Explosion Protection Measures: Prevention

- Inerting – NFPA 69-2008
- Deflagration Containment – NFPA 69
- **Deflagration Venting** – NFPA 68-2007
- Explosion Suppression – NFPA 69

Explosion Isolation for Interconnected Enclosures

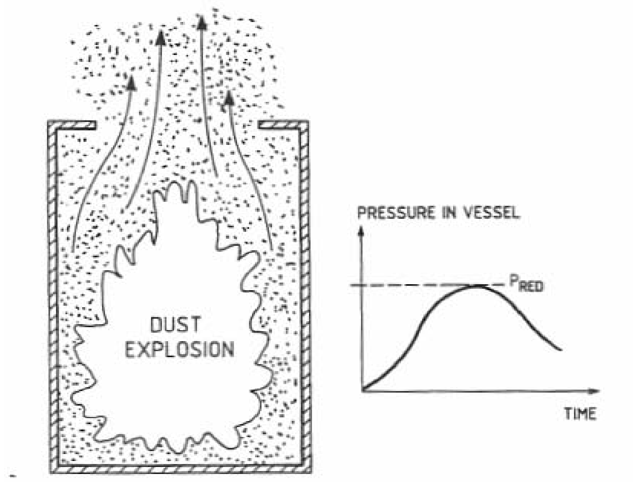
Inerting Requirements per NFPA 69

- Determine Limiting Oxygen Concentration (LOC) for combustible dust/powder; defined as oxygen concentration below which a deflagration cannot occur (typically 9 – 12 v% O_2 for nitrogen inerting.
- Maintain safety margin below LOC:
  - 2 volume % if oxygen concentration is monitored
  - No more than 60 % of LOC if oxygen concentration is not continuously monitored
- See NFPA 69 Section 7.7 for details.

Vented Dust Explosion

Eckhoff:

Fig. 1.94



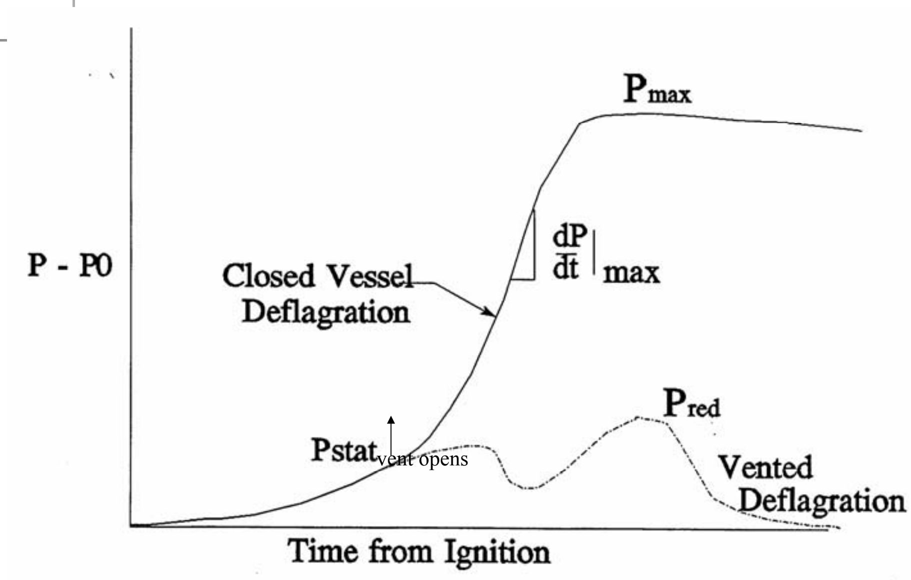
Explosion Venting Objective

To limit the pressure and minimize structural damage in a deflagration by allowing dust and combustion gases to flow out of the enclosure during the deflagration.

The deflagration vent can be initially covered and then fully opened at a pressure well below the damage threshold pressure

The vent area must be sufficiently large to accommodate the rate of combustion gases generated during the deflagration.

Pressure Development in Vented Explosion



Later Stage of Vented Corn Starch Explosion

Vented Coal Dust Explosion

Dust Explosion Vent Design Parameters

- Dust K_{ST}, P_{MAX}
- Enclosure Volume
- Enclosure Strength
- Vent Opening Pressure
- Vent Closure mass/area
- Enclosure Length/Diameter Ratio
- Vent Duct Length if Duct Needed

Vented Aluminum dust explosion test

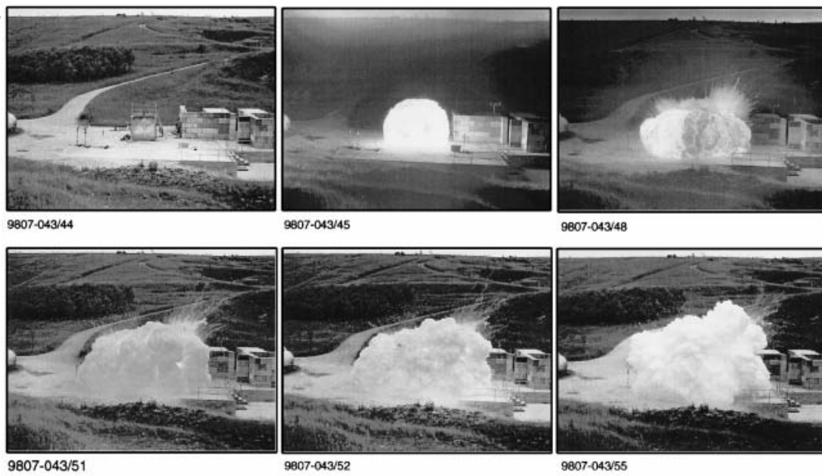


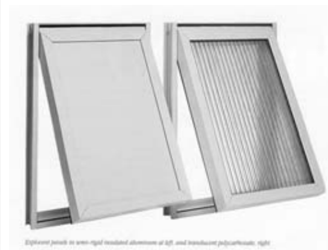
Fig. 4. Example of a vented aluminium dust explosion.

Actual Vented Coal Dust Collector Explosion Incident

Six employees inside dust collector at time of explosion suffered severe burn injuries.

Explosion venting does not prevent flame from propagating within the vented enclosure.

Approved / Listed Vent Panels



Hinged Vent Panels have decreased venting efficiency per NFPA 68 Section 5.6.14; Efficiency determined by testing.

Higher Strength Vent Panels and Disks

Fike Rectangular Explosion Vents

DESCRIPTION

The CV type vent is a composite membrane, high performance explosion vent. CV vents are lightweight and specifically designed for dynamic operation during venting of explosions from industrial equipment. All

Conventional Prebulged (P) Rupture Disc (before and after rupture).

Improper Vent Attachment and Restraint

Roof-mounted cyclone dust collector after animal food explosion

Cyclone vent on ground near building

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Explosion Venting for Equipment inside Buildings

- Need vent ducts to channel burning dust outside building; use of ducts requires larger vent area.

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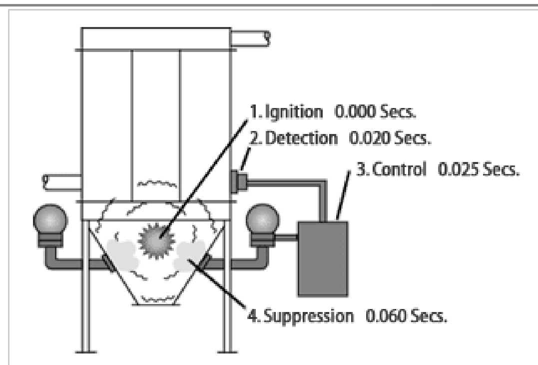
Alternative: Flame Arresting Explosion Vent Installed on Combustible Powder Hopper

AHJ Inspection of Explosion Vents per NFPA 68 Chapter 11

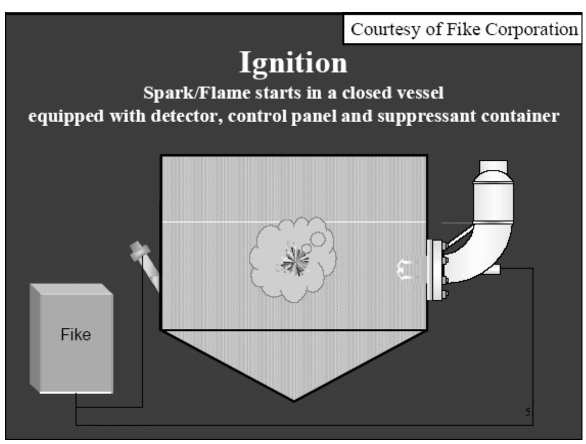
- Design parameter/calculation documentation showing compliance with NFPA 68 design.
- Installation per manufacturer specs with vent restraints (if entire vent panel is intended to blow off), no obstructions near vent outlet, personnel exclusion zone, and warning label.
- Documentation on inspection and maintenance records (required at least annually).

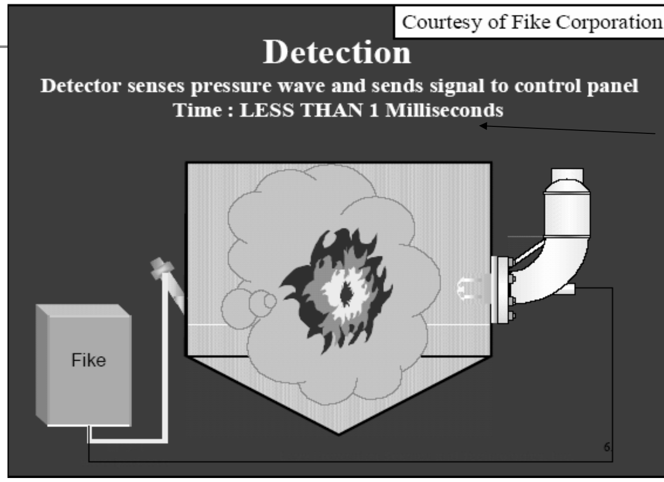
Explosion Suppression System Schematic



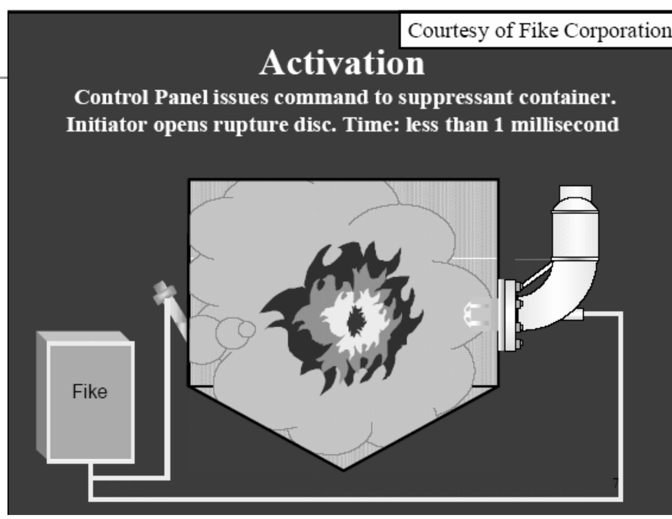
Detection and Suppression Times depend on application and system design and installation details

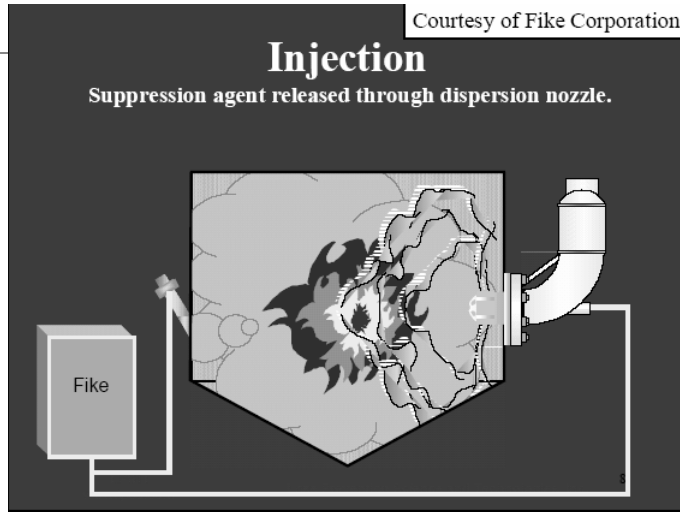
Suppression Sequence Schematic

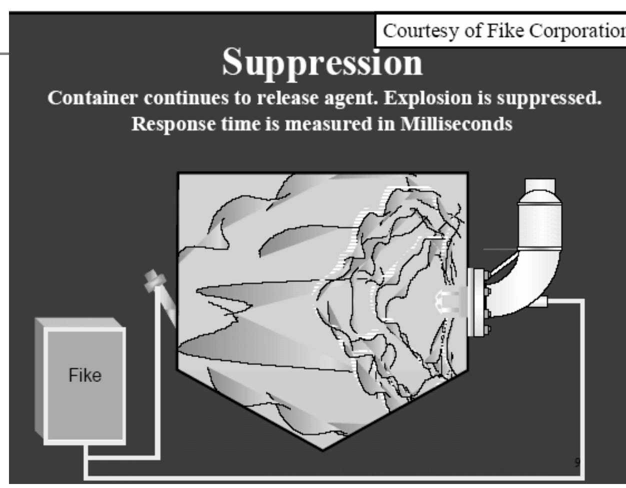




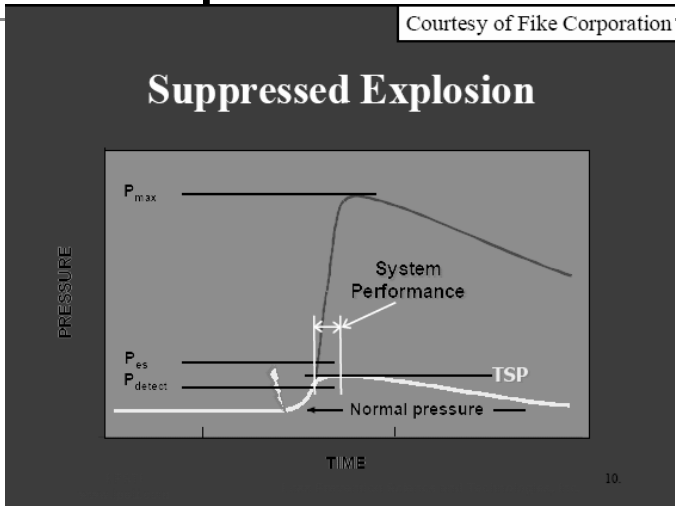
Detection time depends on application and detector set pressure.




Courtesy of Fike Corporation
Injection
Suppression agent released through dispersion nozzle.
Fike


Courtesy of Fike Corporation
Suppression
Container continues to release agent. Explosion is suppressed.
Response time is measured in Milliseconds
Fike

Pressure Development during Suppressed Explosion

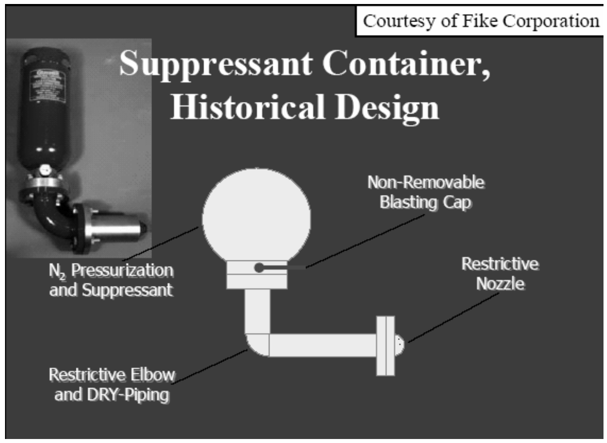


P_{es} = enclosure strength

TSP = total suppressed pressure

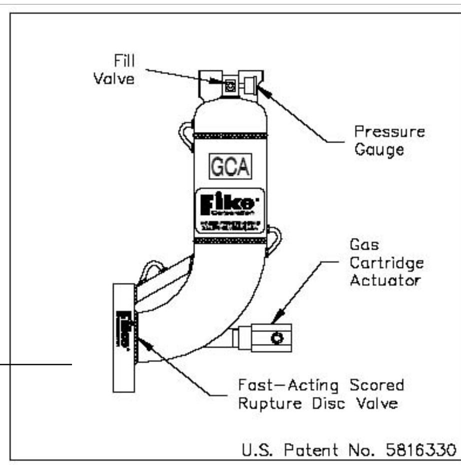
Installed Suppression Agent Container

Suppressant Containers



Fike Elbow Shaped Suppressant Containers

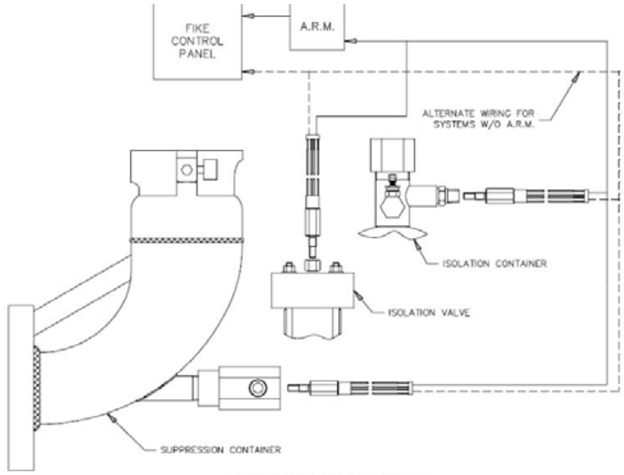
Agent Discharge



Suppressant Container

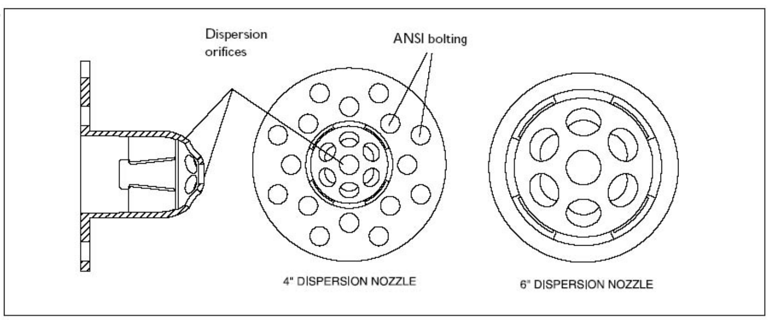
Gas cartridge actuator contains reactive chemicals triggered by heated wire.

Suppressant Container Actuation by Control Panel



CONNECTION DIAGRAM

Suppressant Dispersion Nozzles



Dispersion Nozzle

Sodium Bicarbonate Based Suppression Agent Discharge

Explosion Suppression System Design Parameters

- Similar to design parameters for explosion vents
- Detection pressure setting replaces vent actuation pressure.
- Suppression systems are designed by commercial vendors
- Choice of suppression agent: sodium bicarbonate (available in food grade), monammonium phosphate, water.
- Number and location of suppressors depends on equipment size and strength and material K_{ST} value.
- NFPA 69 requires that system be certified by independent testing organization.

Certification Testing of Suppression Systems

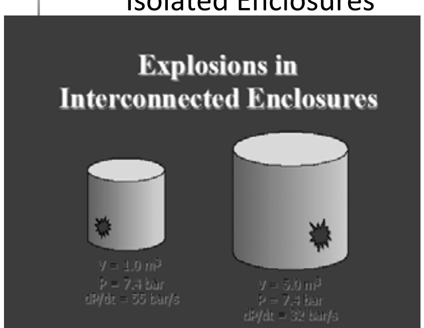
- CEN Draft Standard prEN 14373 March 2002; European Atex certification basis
- FM approval Standard Class Number 5700, 1999.
- NFPA 69-2008 – Testing required, but does not specify the test method.
- AHJ should request copy of certification report for proposed/installed suppression systems

Need for Deflagration Isolation

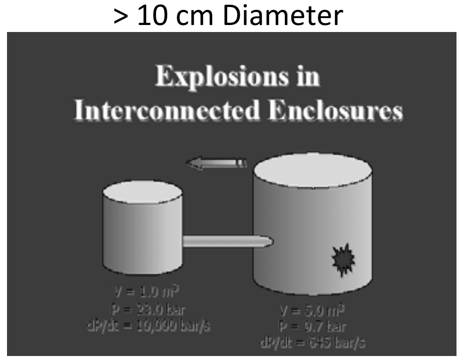
- To prevent propagation into interconnected equipment.
- To prevent flame jet ignitions that could render deflagration venting and suppression ineffective.
- Flow induced by primary deflagration can facilitate transition to detonation in ducts.
- Flow induced by primary deflagration can pressurize interconnected equipment. Deflagrations initiated at elevated pressure produce higher reduced pressures.

Explosion Pressures for Interconnected Vessels

Isolated Enclosures



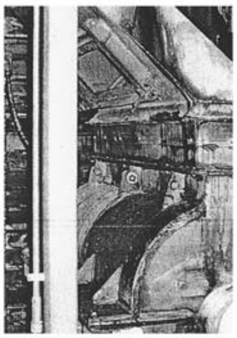
Connecting Pipe/Duct
> 10 cm Diameter

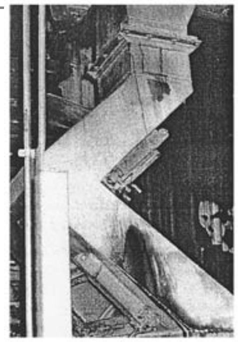


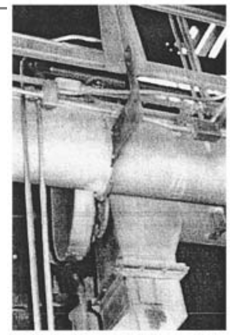
Isolated 1 m³	Isolated 5 m³	Connected 1 m³	Connected 5 m³
$V = 1\ m^3$	$V = 5\ m^3$	$V = 1\ m^3$	$V = 5\ m^3$
P_{max}= 7.4 bar	P_{max}= 7.4 bar	P_{max}= 23 bar	P_{max}= 9.7 bar
$(dP/st)_{max}$ = 55 bar m/s	$(dP/st)_{max}$ = 32 bar m/s	$(dP/st)_{max}$ = 10,000 bar m/s	$(dP/st)_{max}$ = 645 bar m/s

Example of Casualties due to Explosion Propagation though Interconnected Equipment

Ignition in/near Hammermill propagates up into feed duct







Propagation continues through overhead ducting

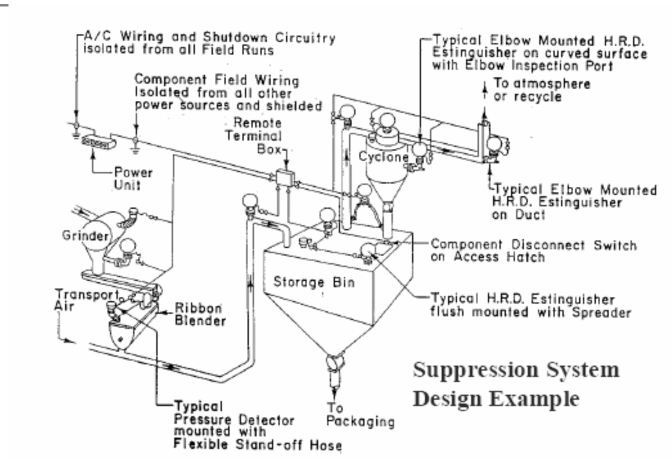
2nd casualty located at baler far downstream of mill

Fatality occurs in raw material warehouse; separate building with feedbox for blower and mill

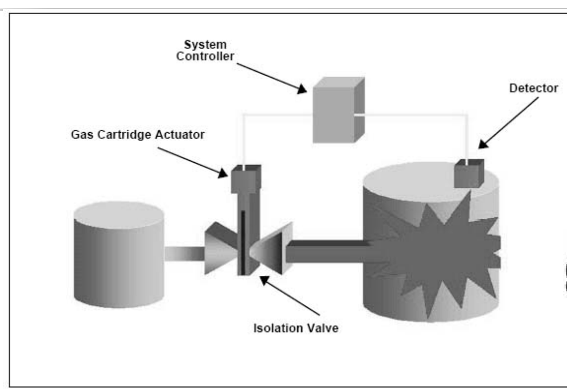
Explosion Isolation Systems Can Prevent Propagation to Interconnected Equipment

- A variety of active and passive explosion isolation devices commercially available.
- NFPA 69 requires isolation devices to be certified by independent authority.
- No certification test organizations in U.S. provide testing for isolation systems.
- Certification tests conducted in several European facilities.

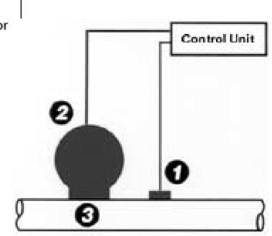
Multiple Suppression/Isolation System Installation



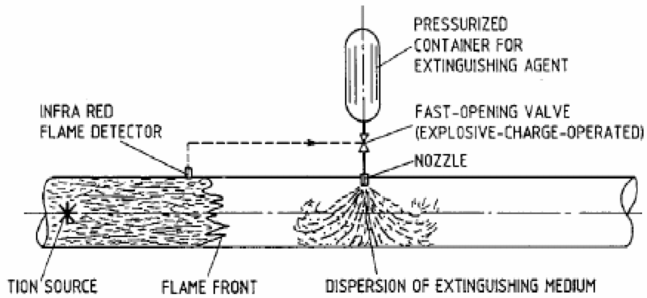
Isolation System 3D Schematic



Schematic of Explosion Isolation System. Detector senses onset of deflagration, sends signal to control panel which in turn closes valve and stops flame and pressure transmission.

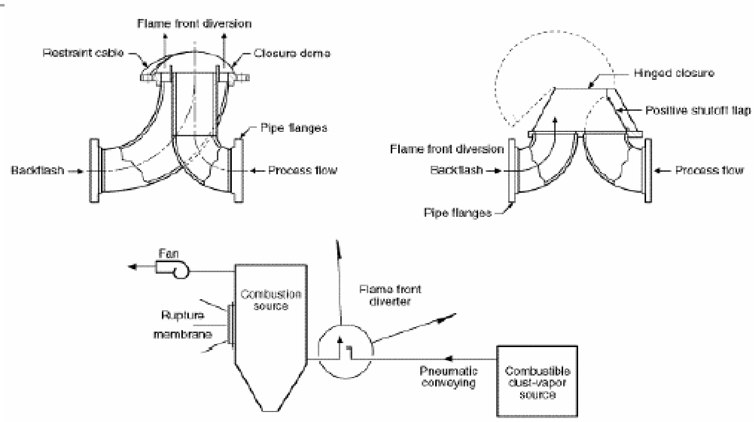


Extinguishing Isolation System



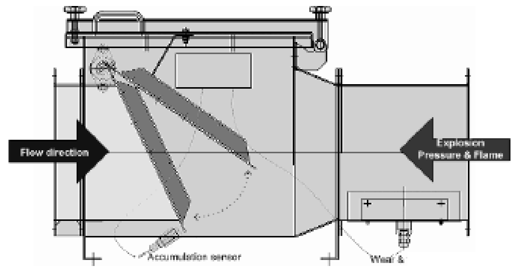
;ure 1.90 *Illustration of system for interrupting dust explosions in ducts by fas extinguishing agent ahead of the flame*

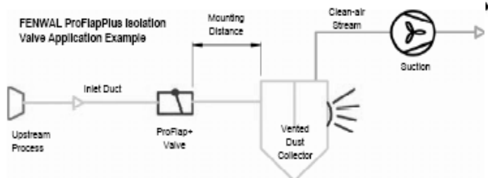
Flame Front Diverters



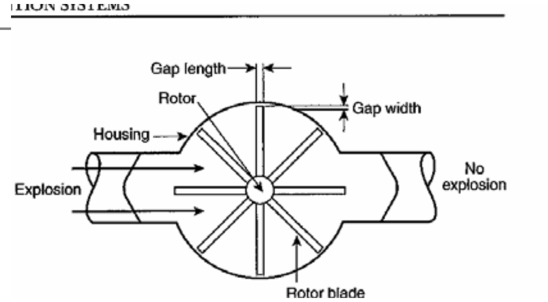
Low-Cost Passive Explosion Isolation Valve for Dusts

-way protection





Rotary Valve for Dust Explosion Isolation



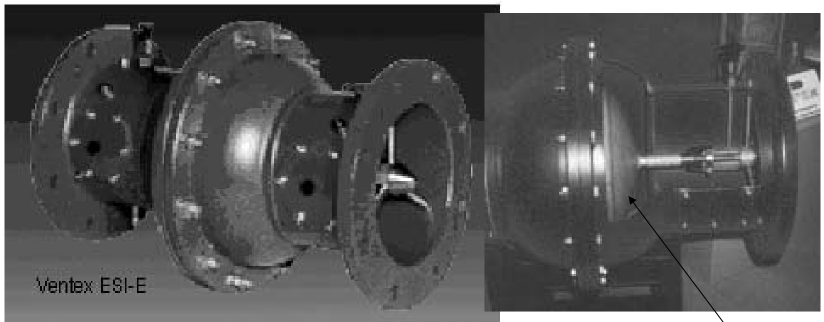
NFPA 69 Requirements for Isolation:

•At least 6 vanes on rotor, diametrically opposed

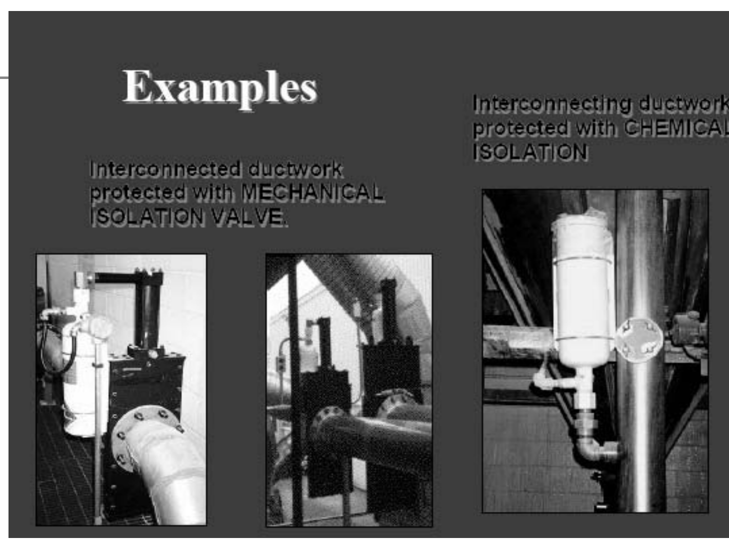
• At least 2 vanes on each side of valve in position of minimum clearance ≤ 0.2 mm at all time.

Passive mechanical isolation valve:

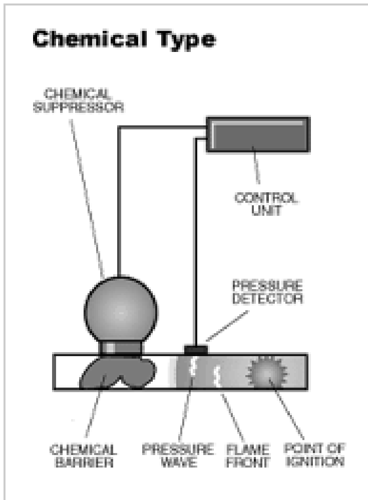
Deflagration pressure wave actuates valve to provide isolation



Deflagration pressure causes valve to slam shut

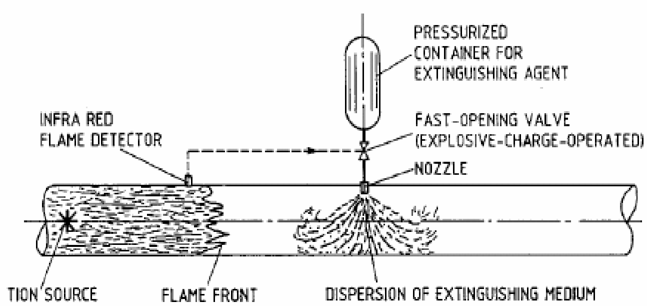


Chemical (Extinguishing) Isolation System



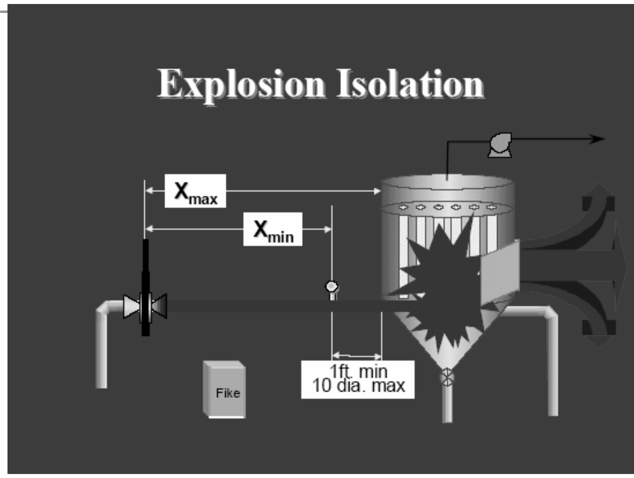
Design requires knowledge of flame speeds and distance between pressure wave and flame front.

Extinguishing Isolation System

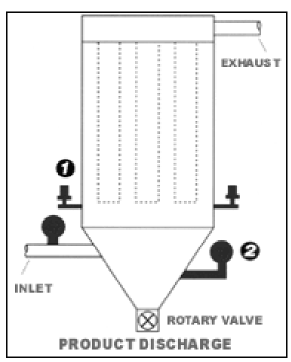


;ure 1.90 *Illustration of system for interrupting dust explosions in ducts by fas extinguishing agent ahead of the flame*

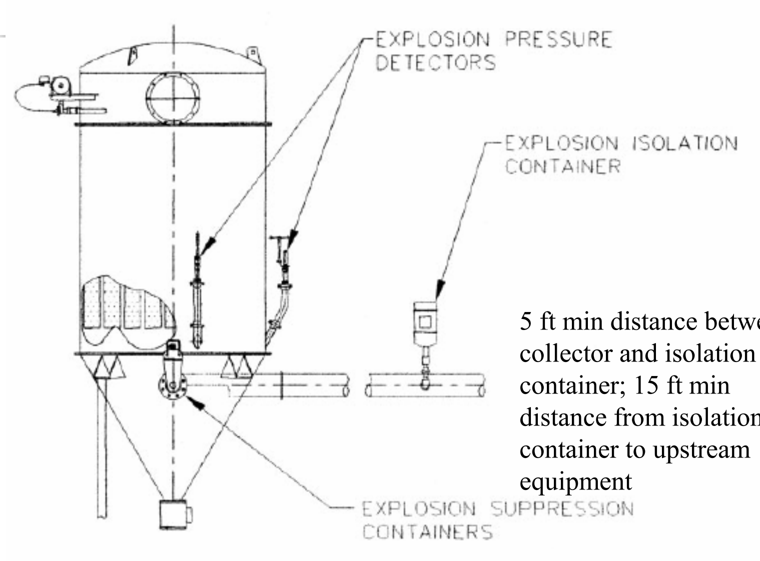
Isolation Device Location Limits



Combined Isolation and suppression system



Example Suppression + Isolation Application for Dust Collector



5 ft min distance between collector and isolation container; 15 ft min distance from isolation container to upstream equipment

Explosion Suppression and Isolation Device Manufacturers

- **ATEX Explosion Protection**
- **BS&B**
- **CV Technology**
- **Fenwal Protection Systems**
- **Fike**
- **Rembe**
- GreCon and PyroGuard make duct backdraft dampers and abort gates for dust explosion isolation.

Preventing Dust Clouds During Cleanup

- Prohibit use of compressed air blowing during equipment operation, and in vicinity of energized electrical equipment and hot surfaces from recent operations.
- Limits on air pressure during blowing

Air hoses and fans for dust blowing

Dust Housekeeping: Allowable Dust Layer Thickness

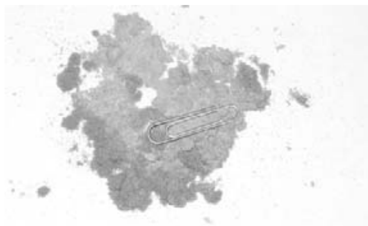
- NFPA 654 limits dust layer depth to 1/32nd inch (0.8 mm) for dusts with bulk density ≥ 1200 kg/m^3 (75 lb/ft^3)
- Hazardous condition if layer accumulates on more than 5% of floor area

1 mm deep layer

2 mm deep layer

Layers of cellulose fiber dust from an animal feed plant that had recent dust explosion.

0.8 mm depth is abour the thickness of a paper clip (NFPA 654 Appendix D)



A more reliable measure of dust accumulation is the dust mass per unit surface area on which it accumulates. Try to measure.

Proposed New Dust Accumulation Criteria for NFPA 654 2010 Edition

- 6.1.2* Unless supported by calculations per 6.1.3 and 6.1.4, respectively, dust explosion hazard volumes and dust fire hazard areas shall be deemed to exist when total accumulated dust mass exceeds 1 kg/m^2 multiplied by 5% of the building or room footprint.
- A.6.1.2 This is equivalent to 0.8 mm (1/32 in.) based upon a settled bulk density of 1200 kg/m3 (75 lb/ft3). The following equation provides a means to estimate an equivalent depth from a known value of settled bulk density.

$$Equivalent\_Depth\ (mm) = \frac{1000 \bullet Accumulation(kg/m^2)}{Bulk\ Density\,(kg/m^3)}$$

$$M_{\exp} = P_{red}\left[\frac{C_w}{P_{\max}}\right]\frac{A_{floor}\,H}{\eta_D}$$

New NFPA 654 Equation for maximum allowable dust per unit area

6.1.3 It shall be permitted to evaluate the threshold dust mass establishing a building or room as a dust explosion hazard volume, mi, per equation 6.1.3.

$$M_{\exp} = P_{red}\left[\frac{C_w}{P_{\max}}\right]\frac{A_{floor}\,H}{\eta_D}$$

where:

M_{exp} is the threshold dust mass (g) based upon building damage criterion,

c_w is the worst case dust concentration (g/m3) at which the maximum rate-of-pressure-rise results in tests conducted per ASTM E1226,

P_{red} is the allowable pressure (bar g) developed during a deflagration per NFPA 68,

P_{max} is the maximum pressure (bar g) developed in ASTM E1226 tests with the accumulated dust sample,

A_{floo}r is the enclosure floor area (m2),

η_D is the entrainment fraction

and H is the enclosure ceiling height (m).

Dust Housekeeping Requirements

- Use portable vacuums rated for Class II Division 1 or Division 2 areas (depending on level of dust accumulation).
- Or use plant central vacuum with hose connections.
- Or compressed air operated vacuums instead of electric; Vacuum not blower

Dust ignitionproof portable vac for Class II Div 1 areas

Portable vacuum that runs off plant compressed air; no electric parts

Oscillating Ceiling Fans to Prevent Dust Accumulation on Elevated Surfaces

Fan slowly rotates 360° and slowly oscillates up & down

Other Resources: NFPA & FM Standards

Issue	NFPA Standard	FM Standard
General Comb Dust Protection	654*	7-76
Woodworking Industry	664	7-10
Agriculture – Food Processing	61	7-75
Combustible Metals	484	-
Deflagration Venting	68	1-44

* New draft edition expected in fall