Dust Explosions

SAChE Workshop

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Topics

- Dust Combustion Characteristics.
- Pressure Piling
- Primary/secondary Explosions and Hybrid Mixtures
- Dust Explosion Video
- Explosion Protection

Dust Combustion Characteristics

Definition of Dust

A finely divided powdered solid less than 420μm, ie the largest particles that will pass through a US 40 sieve.

Which Dusts Can Burn Explosively?

Materials which, if finely divided and dispersed in air can burn explosively, include:

Most organic materials,

Many metals eg Fe, Al, Zr, Ti.

Some non metals eg, S, Si, P_2S_5

Nature of Dust Explosions

- Generally they are deflagrations, ie the flame fronts propagate into the unburned cloud at subsonic speeds, by a combination of heat and mass transfer, (P_{max} approx. $8P_0$).

- Given favorable conditions, such as long, large diameter pipework, "energetic" dusts, may detonate, i.e the flame front propagate into the unburned cloud by compression caused by shock waves traveling at, or above, sonic velocity (P_{max} approx. $20P_0$ but can be higher)

Conditions Required For a Dust Explosion

- A suspension of dust within its flammable range

- Sufficient air, or other oxidizer.

- An effective ignition source

Typical Dust Explosion Characteristics

- Large excess of fuel.

- If vented forms large fireball,

  NFPA 68 predicts the diameter "D" from an enclosure volume "V" as:

  D= 10($V^{1/3}$)   i.e Considerably larger than for a gas explosion.

  Also note the fireball extends upwards and down similar distances.

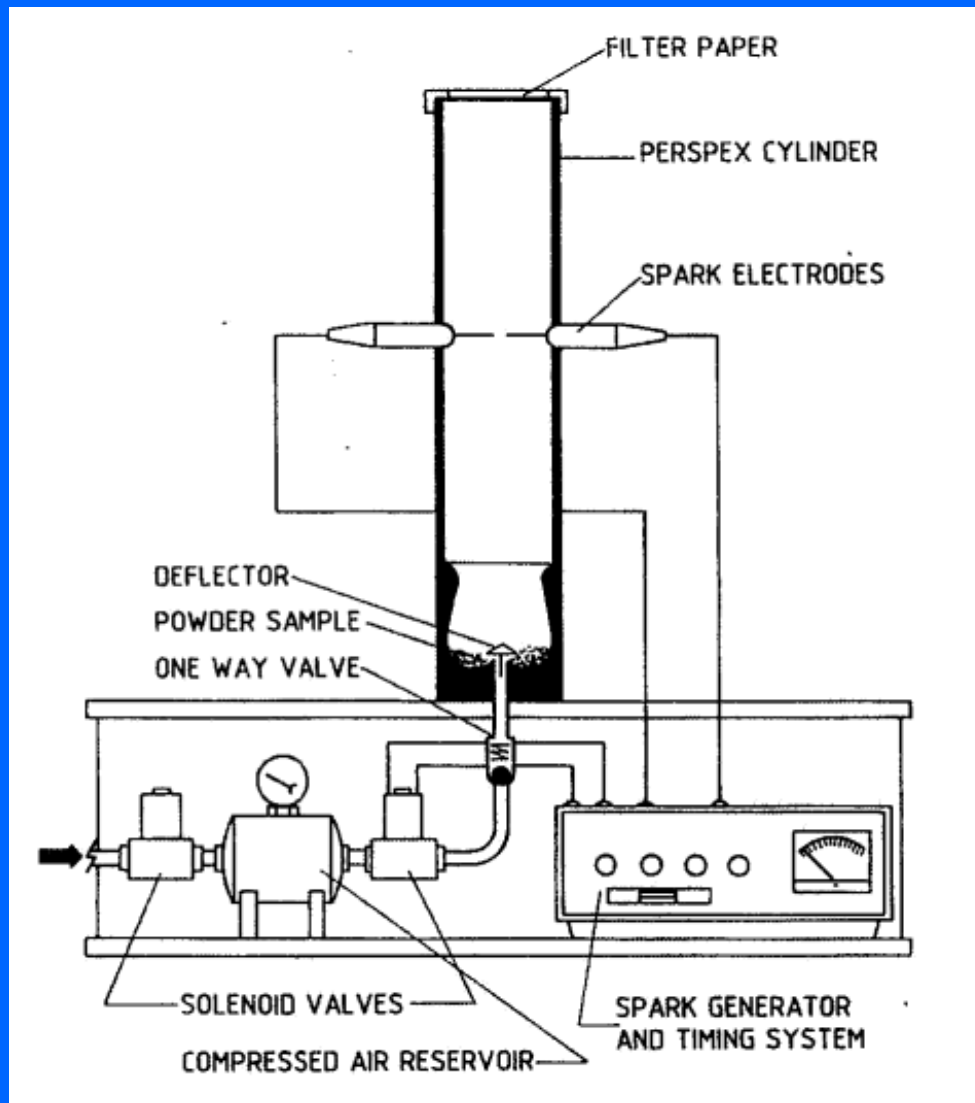# Properties Which Influencing Dust Explosion Hazards

- Minimum ignition energy

- Flammable limits

- Deflagration Index, K_{St}.

- Maximum Explosion Pressure

- Ease of dispersion in air

Minimum Ignition Energy (MIE)

- The MIE of a dust cloud depends on various factors including:
  - Particle size.
  - Chemical composition.
  - Temperature.
  - Moisture
  - Turbulence.
  - Oxygen concentration.
  - Test method used.
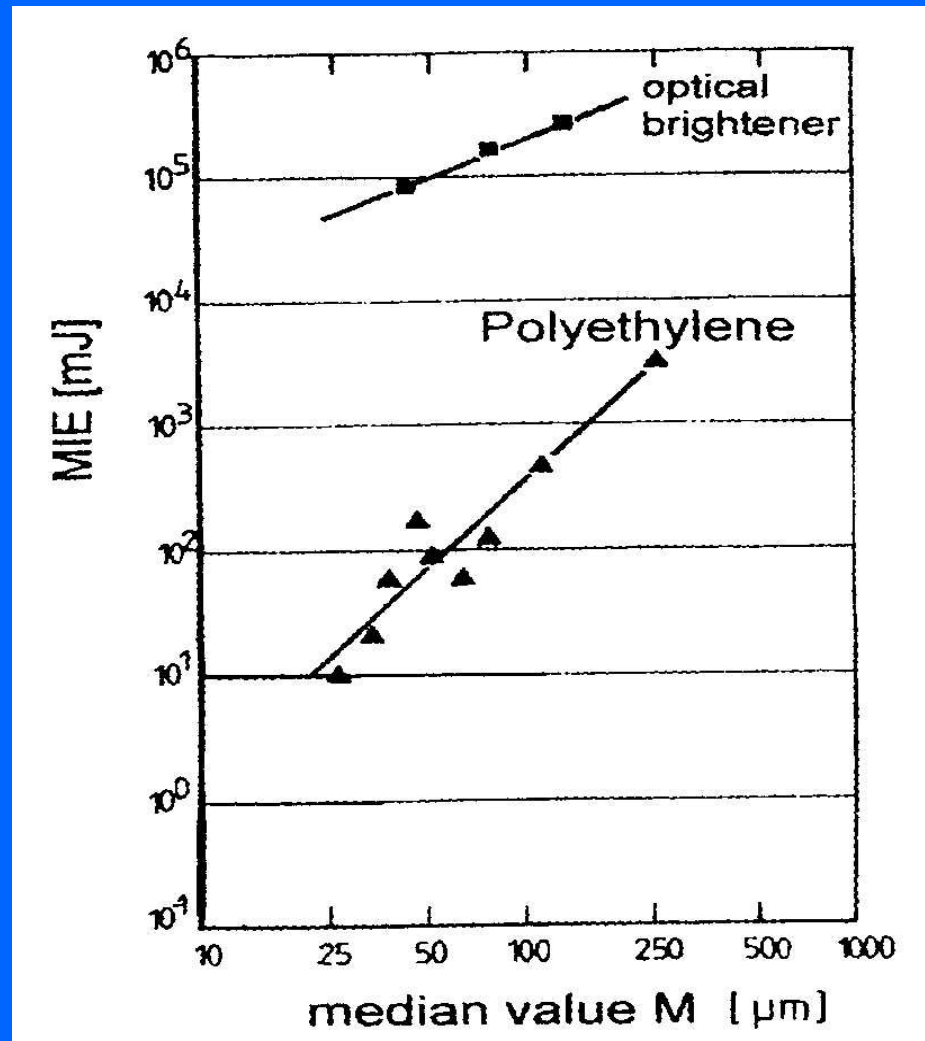
Modified Hartmann Apparatus
(typically used for MIE Measurements)

MIE - Effects of Particle Size.

- In general, dusts with particle size above 400 microns will not ignite, i.e if the particles are greater than 0.4 mm diameter, dust explosions will not occur.

- For many dusts the MIE is approximately proportional to the particle diameter cubed.
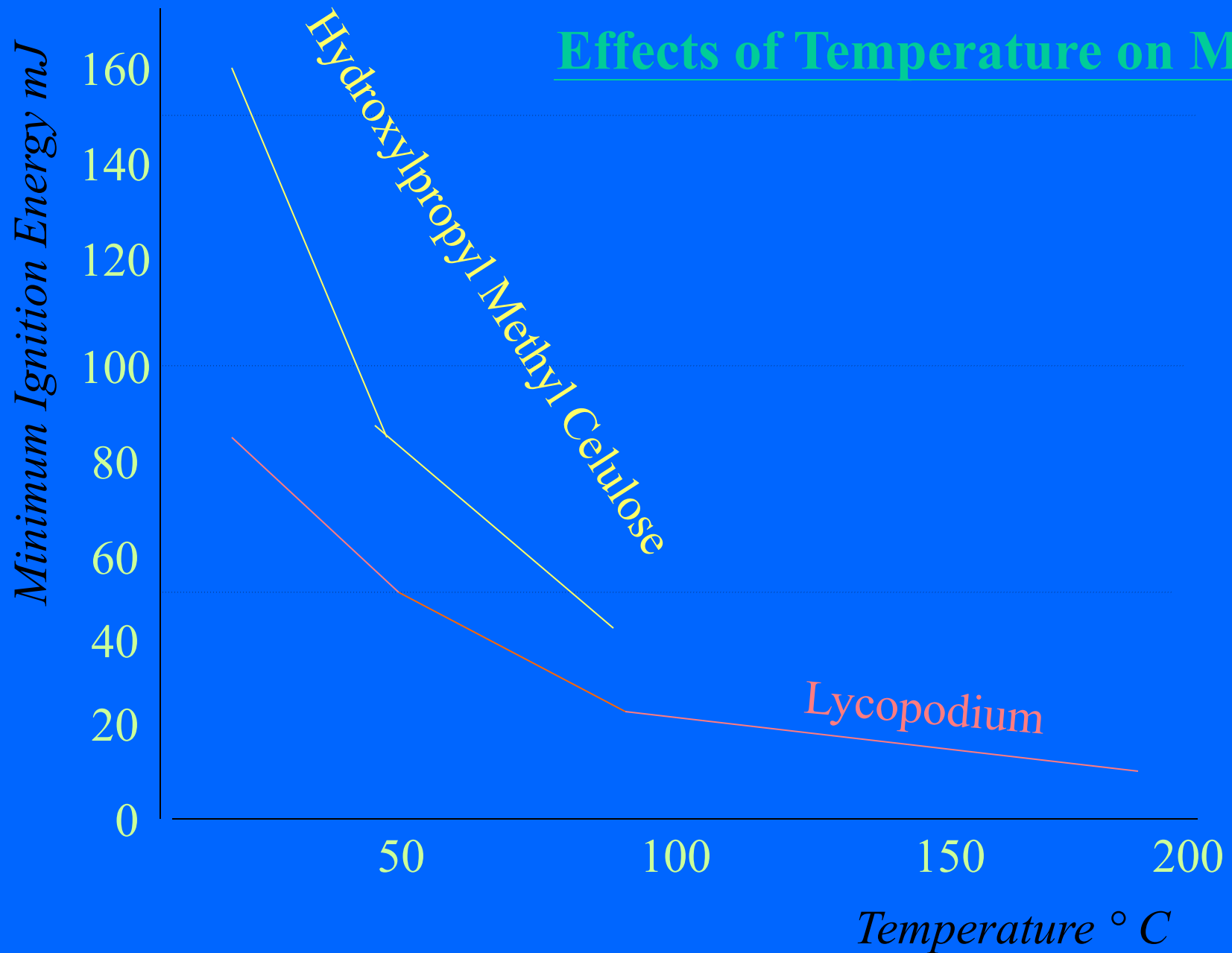
MIE - Effect of Particle Size

MIE - Effects of Temperature.

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Temperature	Lycopodium MIE
Ambient	90 mJ
50° C	50 mJ
90° C	20 mJ
180° C	12.5 mJ

Source, Gibson and Rogers 1980
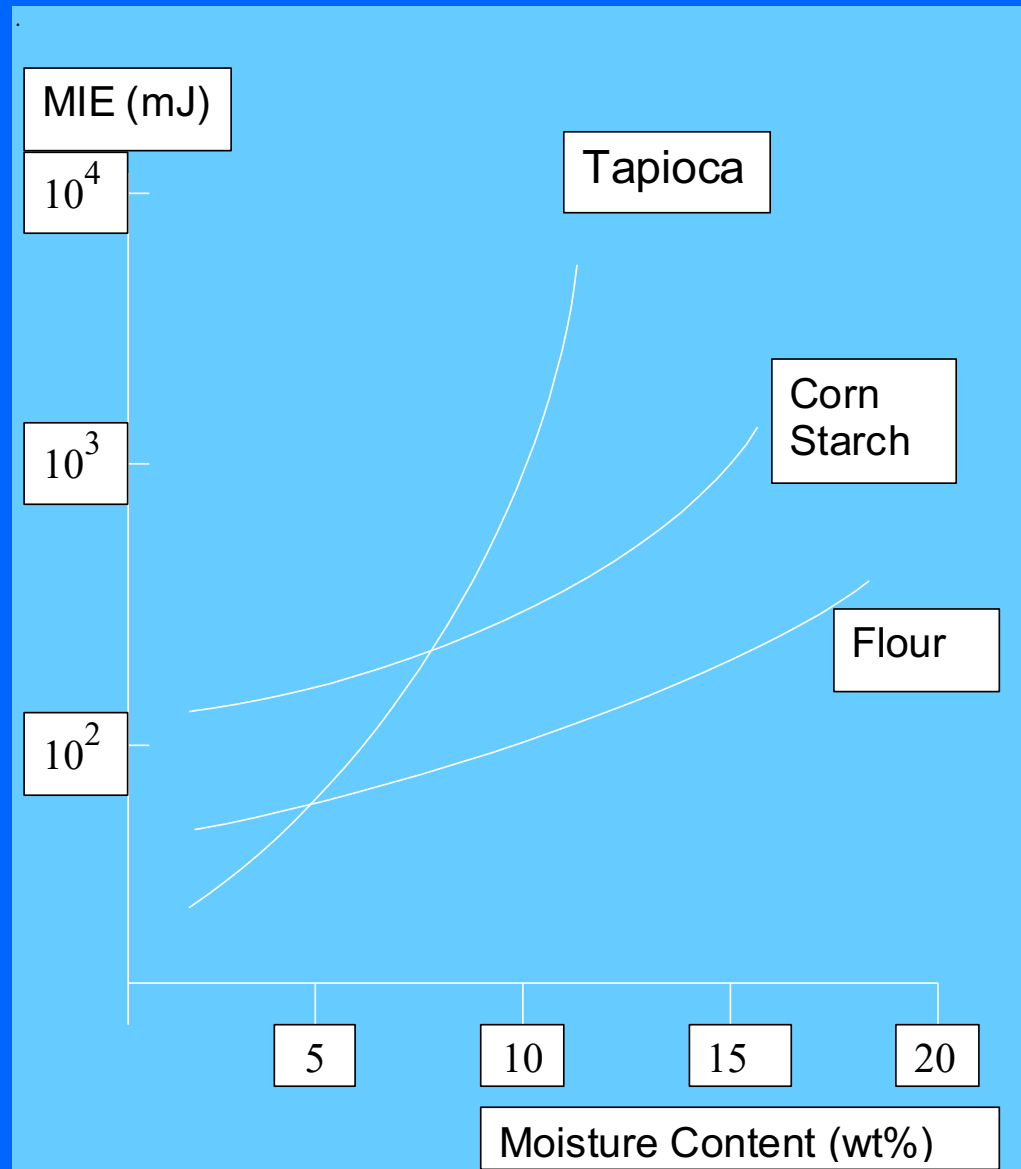
MIE - Effects of Moisture

- Increasing Moisture:
  - Increases the MIE.
  - Reduces the Explosion Severity $(dP/dt)_{max}$.
  - Inhibits dispersion of the dust.

MIE - Effects of Moisture.

MIE - Effects of Turbulence.

- Turbulence increases the heat losses from the ignition source.

  Consequently the MIE for a dust cloud typically increases with increasing turbulence.

MIE - Oxygen Concentration

- Most dusts will not burn if the air pressure is reduced below 50 mbar.

- Reducing the oxygen concentration in "air" increases the energy required for ignition.

- Most organic materials cease to be ignitable in the range 9 – 14% O_2.

- The MIE reduces if the O_2 concentration in the "air" is increased above 21%.

MIE Testing.

- The ASTM Standard for MIE measurements of dust suggests three different electrical circuits, and permits some latitude in the choice of electrodes.

  – This can result in significant variability between test laboratories.

MIE – Allowable Range of Calibration Results

ASTM E2019-99 for Measuring MIE.
- Permitted Range for Calibration Tests.

Material	Allowable MIE Range*
Irganox 1010	1 – 5 mJ
Anthraquione	1 – 11 mJ
Lycopodium	10 – 30 mJ
Pittsburgh coal	30 – 140 mJ

*(Measured without inductance)

Flammable limits

- ASTM Standard E1515-98 provides the test method for the LFL of dusts using a 20L, or greater, spherical test vessels.

- Many dusts must be at their stoichiometric (C_{St}) concentration, or higher for an explosion to occur, and optimum concentrations can be 2-3 times the C_{St}.

 - As a guide[1], dust clouds at their LFL are dense and typically a 25 W light would not be seen through 6 feet.
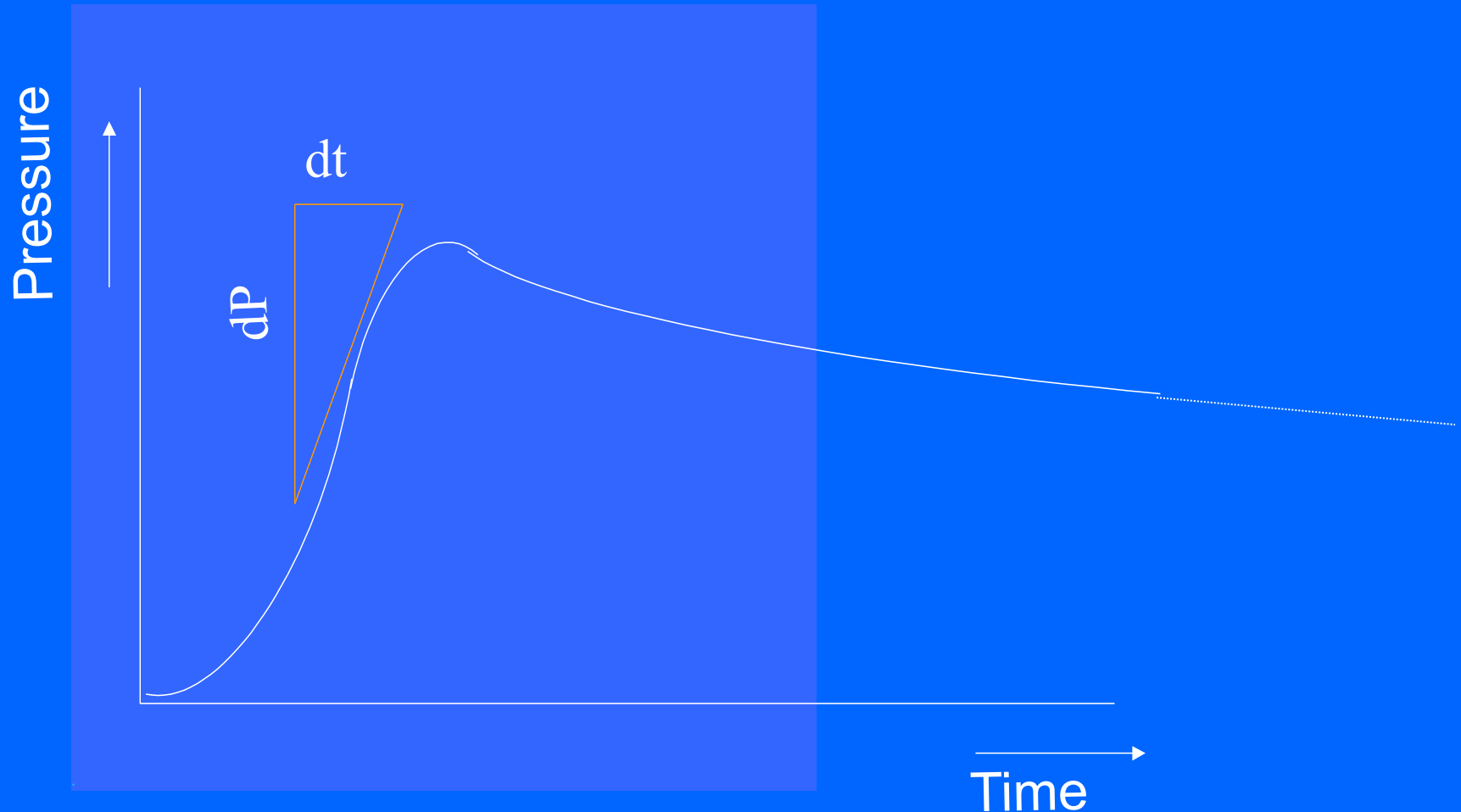
Flammable limits (UFL).

- Dust clouds have have upper flammable limits which are dependant on both the composition and the particle size.

- For example a narrow size fraction corn starch with a particle distribution of 106 to 125 μm, is reported to have an UFL of 800 to 1000 gm/m^3.

- Note, as dust cloud settles it will enter the explosive range, also dust layers can smolder.

Deflagration Index (K_{St})

The Deflagration Index (K_{St}) is used to quantify the explosion violence for a specific dust, and is needed when specifying explosion relief vents.

Numerically the K_{St} is the maximum rate of pressure rise for a deflagration of an optimum dust/air mixture in a 1 m^3 spherical vessel, at an established level of turbulence and ignition energy .

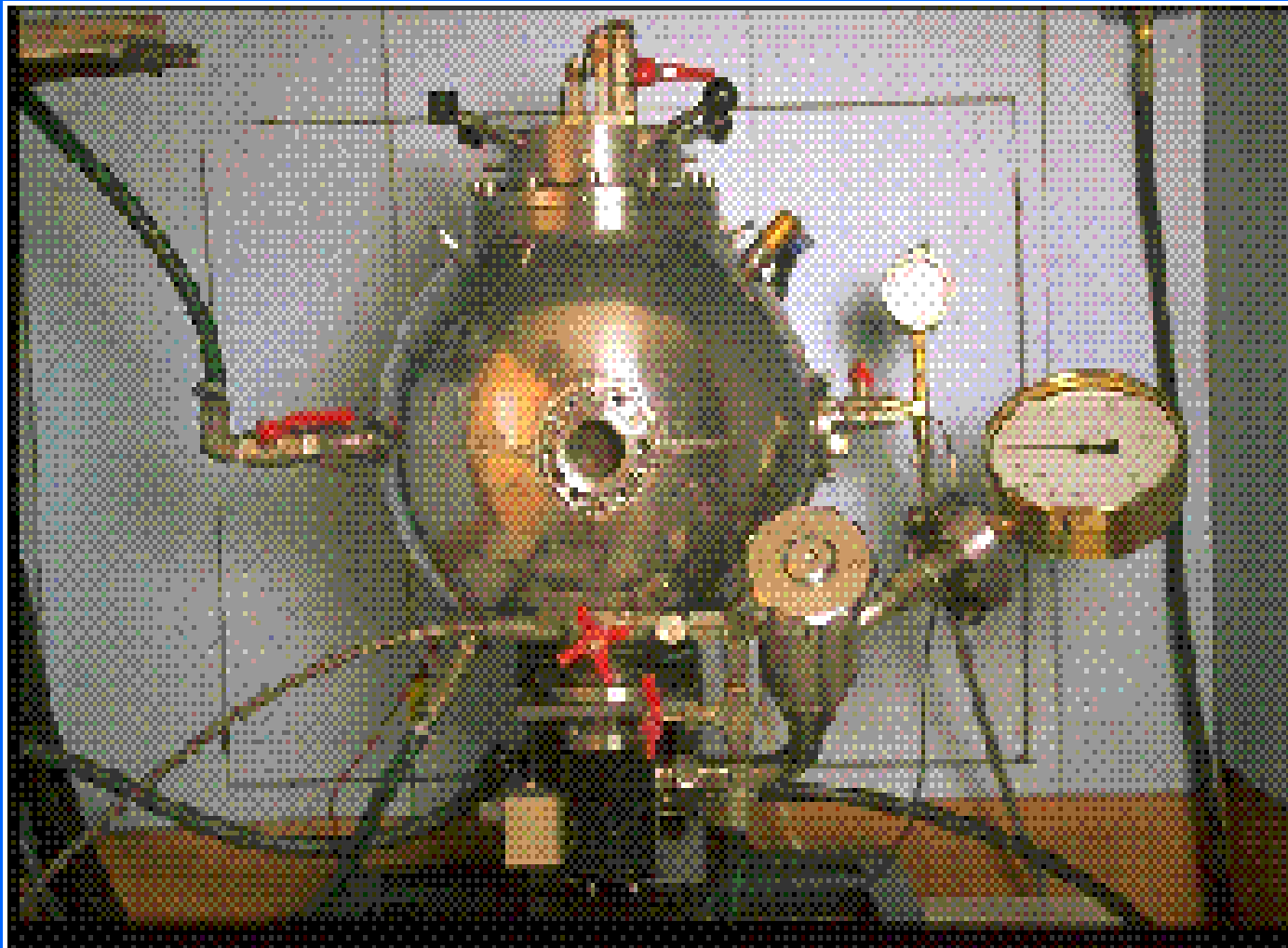Pressure/time History for a Contained Dust Deflagration

Deflagration Index (K_{St})

- For a specific dust the maximum rate of pressure rise in vessels of different volumes can be predicted by the "Cubic Law".

$$(dP/dt)_{max} \cdot V^{1/3} = \text{constant} = K_{St}$$

- This rule has been shown to be effective for vessels of 20 liters and greater, hence testing is normally conducted in 20 liter vessels.

20 Liter Test Vessel

Variables Influencing the Deflagration Index (K_{St})

Factors influencing (K_{St}) include but not limited to:

- Chemical properties – dust & oxidizer

- Dust particle size and shape

- Turbulence

Deflagration Index (K_{St})
(Continued)

- Combustion occurs at the surface of the dust consequently the rate of combustion, ie the explosion violence, is normally a function of its specific surface area (m^2/gm).

 - For convenience particle size (mesh) is used to categorize dust, however, this neglects the shape of the particles.

Deflagration Index (K_{St})((continued)

Dust combustion rate is a determined by:
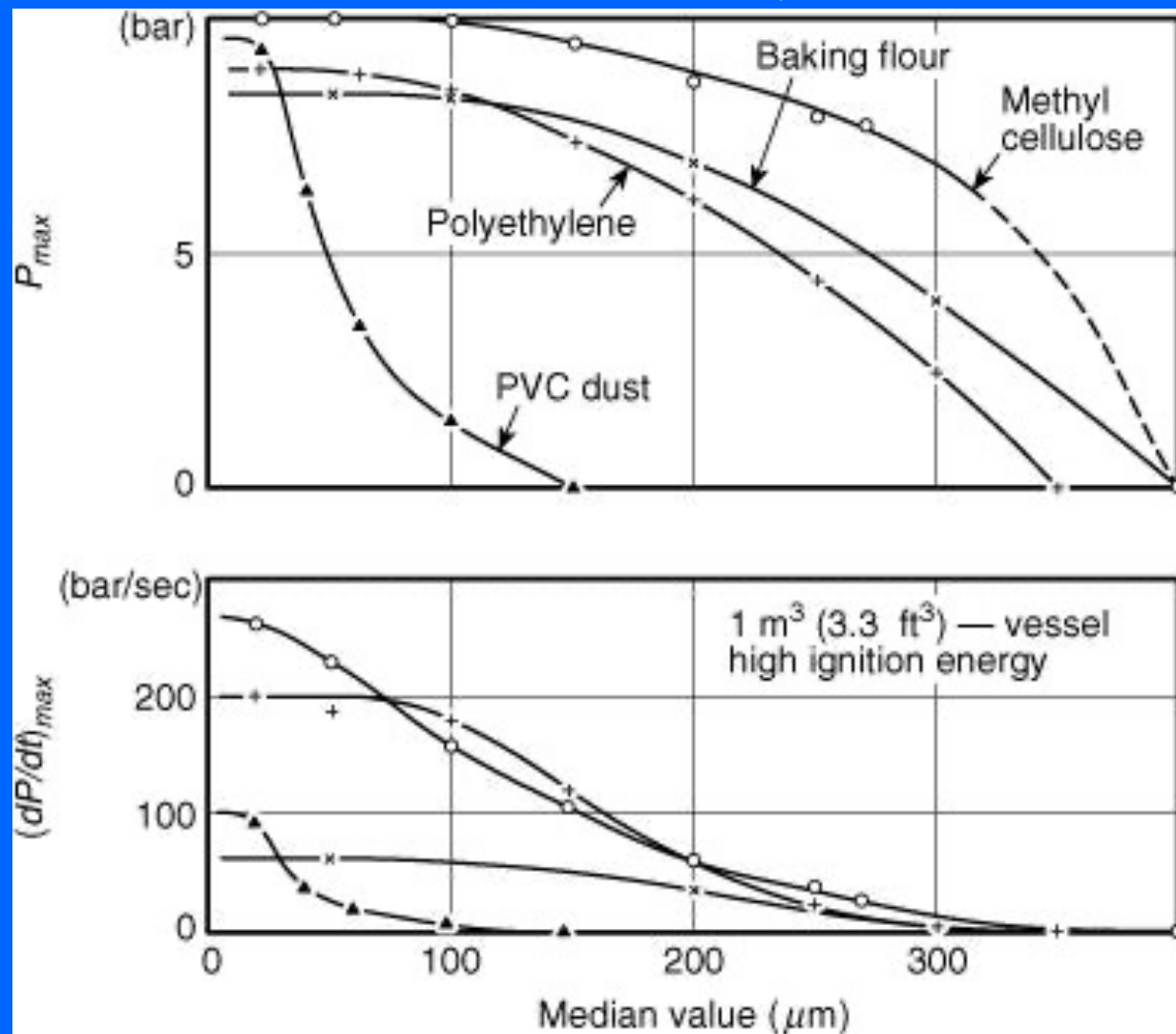
      (a) - devolatization rate

      (b) - gas phase mixing rate

      (c.) - gas combustion rate.

As long as (a) is limiting, reducing particle size will increases the combustion rate.

K_{St}, and P_{max} - Effects of Particle Size and Shape

- Decreasing particle size increases K_{St}, and to a lesser degree, increases the explosion pressure P_{max}.

- In general dusts with particle size above 400 microns will not form combustible clouds.

- For most organic dusts the explosion pressure, and rate of pressure rise, tend to "plateau" at 10 to 40 microns.

Effect of Particle Size on P_{max} and $dP/dT_{max,}$ (K_{St})

Implications of Particle Size

- Large particles in dust clouds drop out rapidly, consequently a small fraction of fines can determine explosion properties.

- Unless specified otherwise, testing is typically conducted on material thro 200 mesh. Note for many materials this is not the "worst possible case".

Turbulence

Turbulence plays a primary role in deciding the rate with which a given dust cloud will burn"

Rolf Eckhoff

Turbulence

- Test equipment for measuring K_{St} is calibrated by adjusting the ignition delay. For a given dust reducing the ignition delay increases the the level of turbulence and the K_{St} reading.

- In pipework and elongated vessels turbulence caused by the expanding products of combustion enhances the explosion severity.
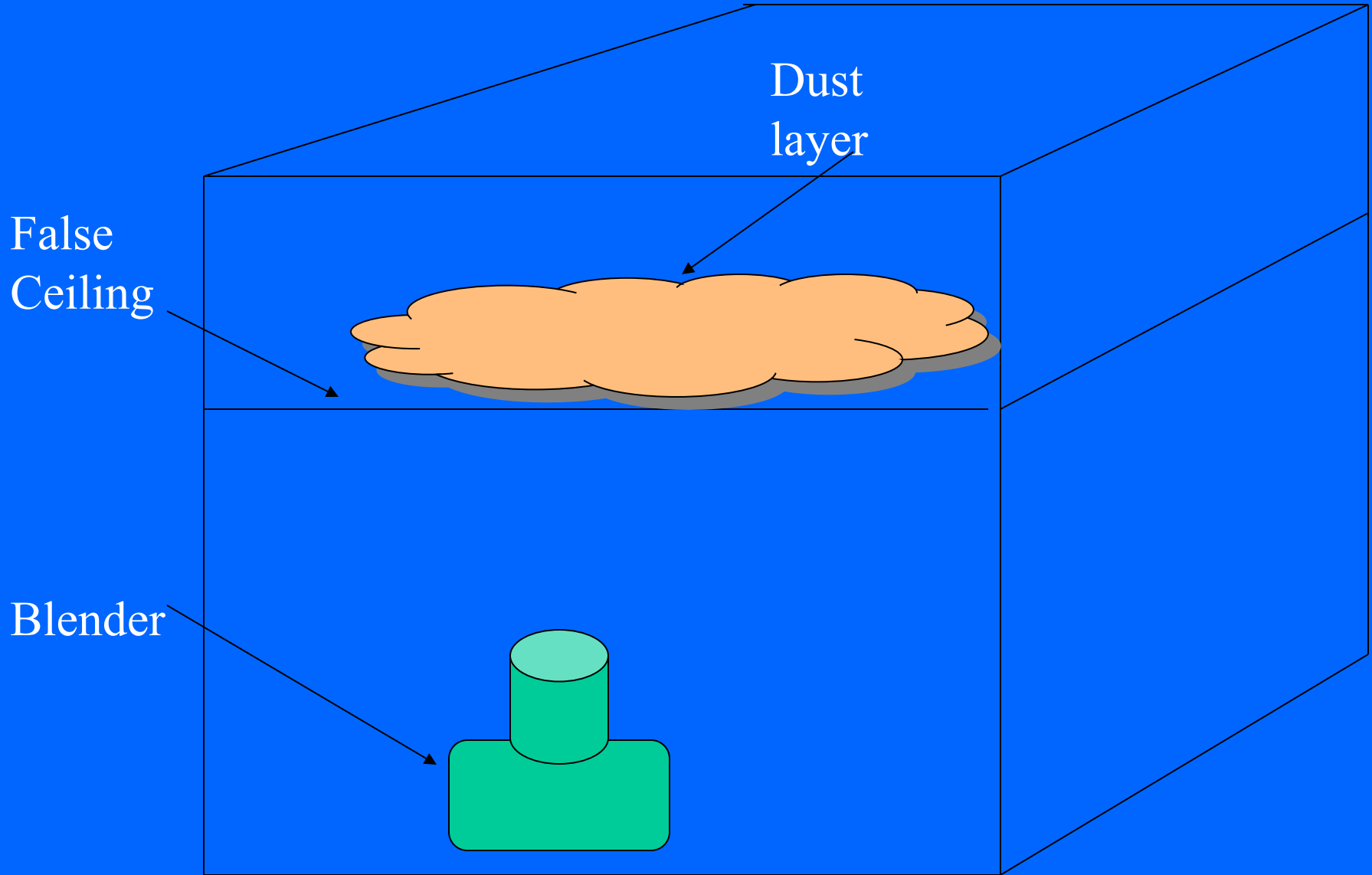
Primary and Secondary Explosions

In order for a dust explosion to occur it is necessary for the dust to be in suspension, and within its flammable range.

A unique characteristic of dusts is their potential to accumulate on surfaces, and then to be re-suspended, a strong air movement or shock wave.
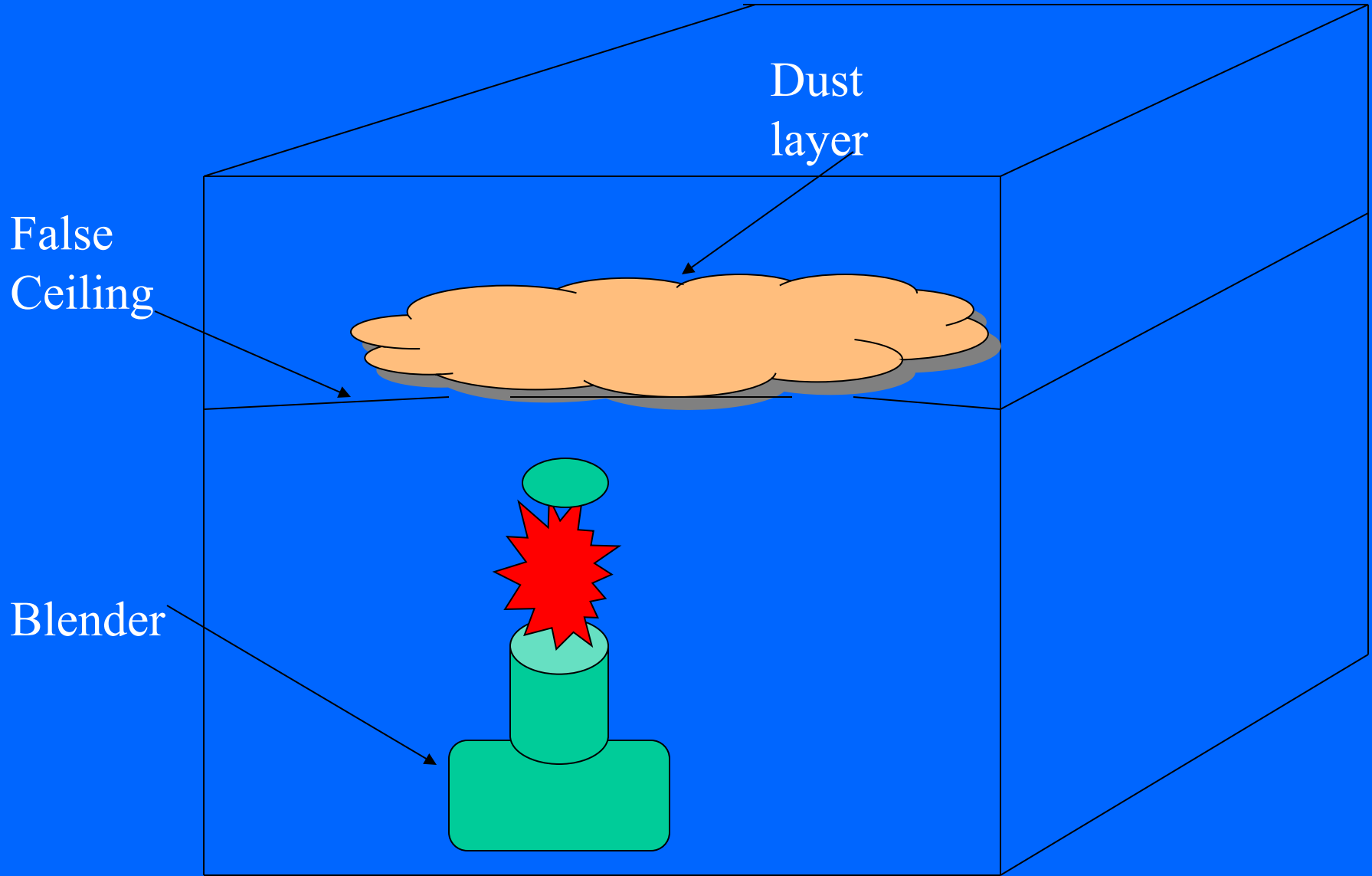
Primary and Secondary Explosions (Continued)

- If a small dust explosion occurs in an area where there is dust, a secondary explosion may occur which could be significantly more severe than the primary event.

- As little as $^1/_{32}$ inch of dust layer is sufficient to cause this, and the mechanism has historically been responsible for explosions propagating between interconnected buildings, equipment, etc.

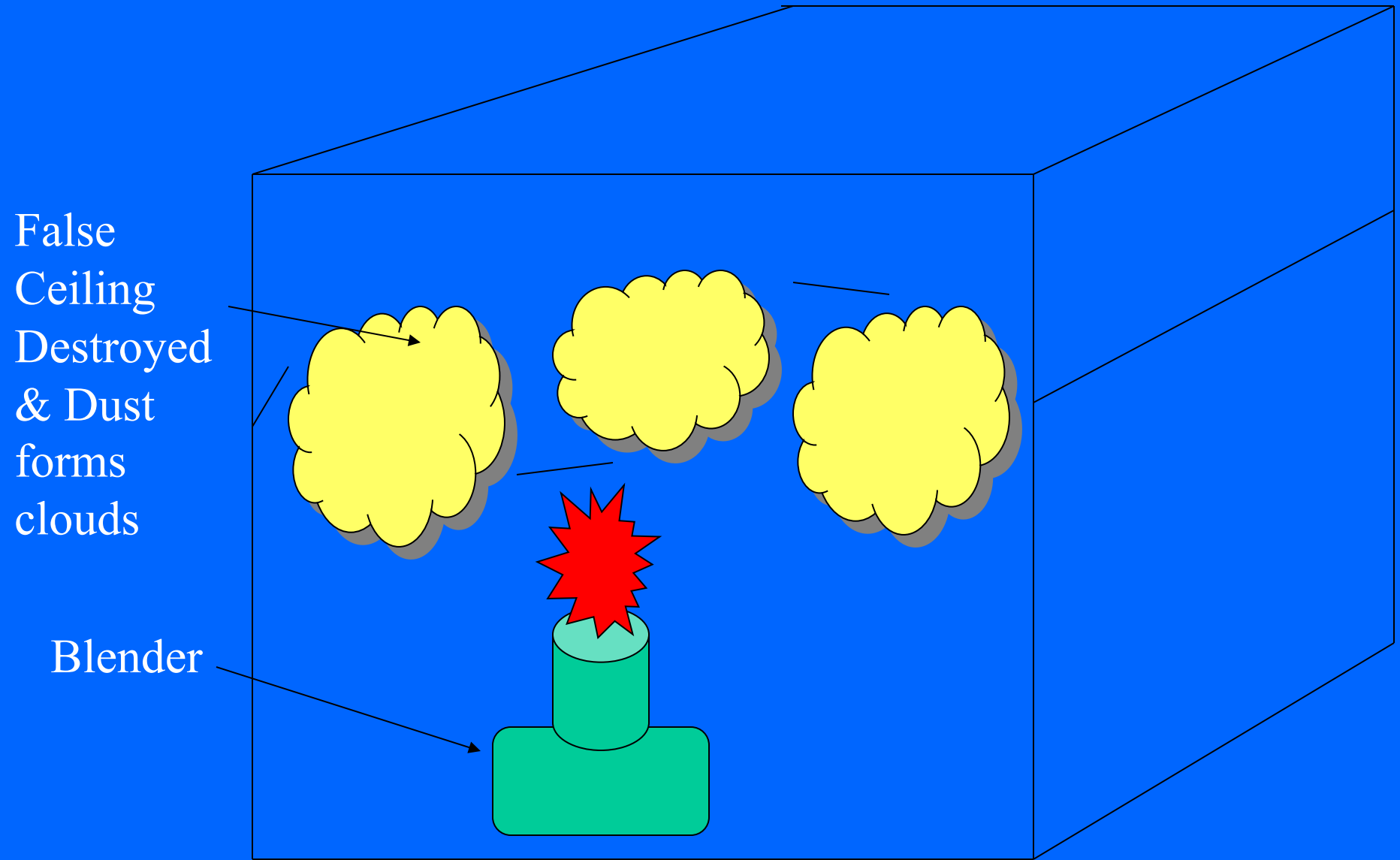# Example of Primary and Secondary Dust Explosion

Dust layer

False Ceiling

Blender

Additives Blending Room

Example of Primary and Secondary Dust Explosion

Dust layer

False Ceiling

Blender

Additives Blending Room

Example of Primary and Secondary Dust Explosion

False Ceiling Destroyed & Dust forms clouds

Blender

Additives Blending Room

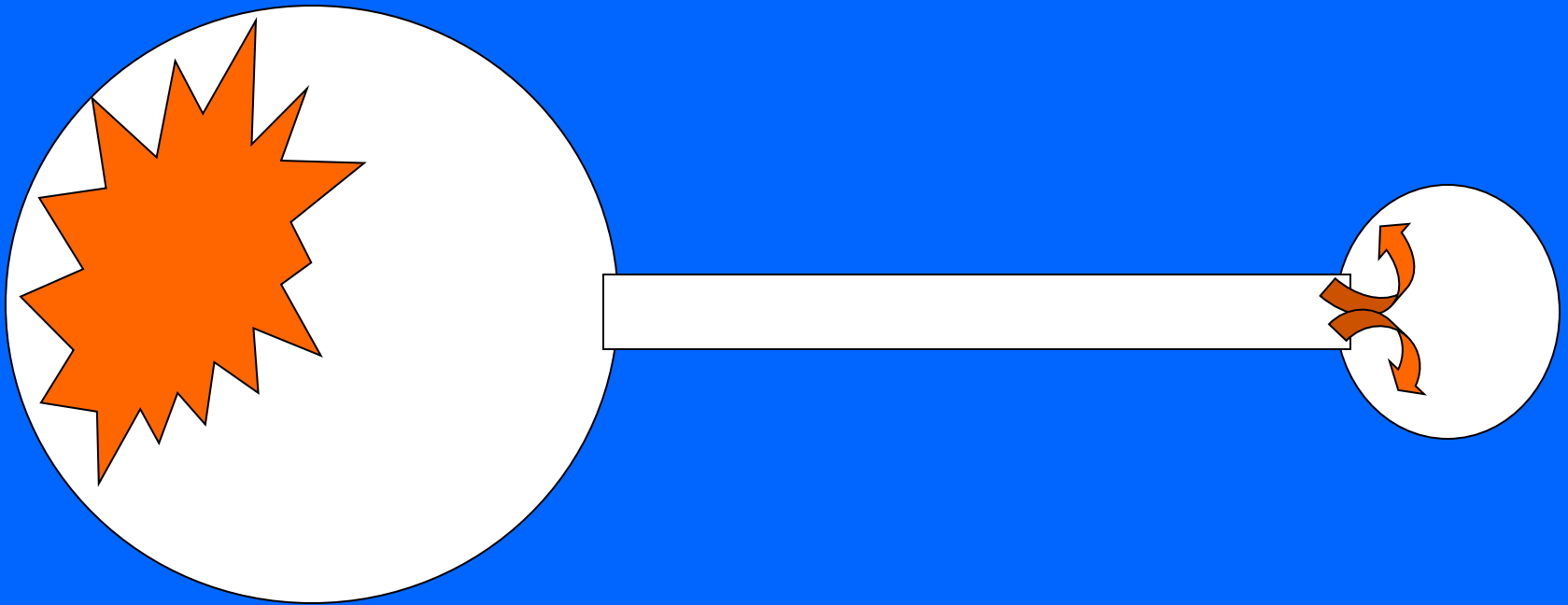# Example of Primary and Secondary Dust Explosion

Bender

Additives Blending Room

Pressure Developed in Interconnected vessels.

Typically dust handling processes involve multiple items of equipment that are interconnected.

This can result in "pressure piling" which results in higher explosion pressures, and/or can reduce the effectiveness of explosion venting.

Pressure Developed in Interconnected vessels.

Expanding gases in the first vessel displaces unburned gases into the second, pre-compressing the mixture and increasing the peak explosion pressure

Pressure Developed in Interconnected Vessels

Ignition Path		Pressure Developed	
		Large Vessel $20m^3$	Small Vessel $4m^3$
Large to Small Vessel		75.9 psi	210.0psi
Small to Large Vessel		95.0psi	83.4psi

Material; coal dust K_{St} 168. P_{max} = 112psig.
Interconnecting pipe; 0.25m dia x 5.0m long

Hybrid Mixtures

- Mixtures of dust and flammable gas or vapor are referred to as Hybrid Mixtures.

- The dust and gas phase contribute to flammability.

- Both could be below their LFL and the mixture be capable of exploding.

- Small amounts of gas can greatly reduce the MIE of the dust

Recent Dust Explosion Incidents

- C T Acoustics, Corbin Ky, Feb 20 2003.

- West Pharmaceuticals, Kingston, NC, Jan 29, 2003.

Hybrid Mixtures

- The presence of the flammable gas/vapor :
  - Increases the flammable limits.
  - Can reduce the MIE to a level such that electrostatic brush discharges can ignite the cloud.

    Note adding dust to flammable liquids is one of the most common cause of injury.

Video

- Pause to show a few minutes from the video "Deadly Dusts II" by Dr. R Schoeff

US Chemical Safety and Hazards Investigation Boards Report, on:-

CTA Incident Summary

- Occurred on 2/20/2003 at about 7:30 AM

- Injured employees - 44
  - 12 flown to hospital burn units
  - 7 of those died

- Local impacts
  - Neighborhood and elementary school near plant evacuated
  - Interstate 75 closed briefly

- Fire smoldered for several days

Preliminary Findings

- A dust explosion originated at Line 405 near the oven

- Combustible phenolic resin dust was likely the fuel

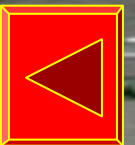- Line cleaning dispersed the dust into the area

Preliminary Findings

- Initial explosion disturbed the dust that had settled on building surfaces

- Dust ignited causing a flash fire

- Secondary dust explosions occurred

Southeast Wall of Building

West Pharmaceuticals

Occurred Jan 29, 2003

Six Fatalities, and "dozens" injured.

Operation involved the application of polyethylene dust to rubber sheets.

Some of the dust separated from the sheets and was captured by the ventilation.

Over time, dust built up in the space above the suspended ceiling.

West Pharmaceuticals

West Pharmaceuticals

West Pharmaceuticals Responders

Explosion Protection

Deflagration Venting

Oxidant Concentration Reduction

Deflagration Suppression

Deflagration Pressure Containment

Combustible Concentration Reduction

Deflagration Venting

- NFPA 68 Guide for Venting Deflagrations

- For enclosures with L/D $\leq$ 2.0
- $A_v = (8.535 \times 10^{-5})(1+1.75P_{Stat})K_{St}V^{0.75}[(1-\prod)/\prod]^{1/2}$

- For enclosures with L/D > 2.0 add,
- $\Delta A = 1.56\ A_v[1/P_{red} - 1/P_{max}]^{0.65} \times \log[L/D - 1]$

NFPA 68 Venting Nomenclature

- A_v = Required vent area, m^2
- P_{Stat} = Vent, static opening pressure, bar
- K_{St} = Deflagration index of dust, Bar.m/sec
- V = Volume of enclosure, m^3
- $\prod$ = P_{red}/ P_{max}
- P_{red} = Reduced pressure with deflagration venting
- P_{max} = Maximum confined deflagration pressure
- L = length & D = diameter of enclosure, m

Explosion Relief Vent

Mass/unit area must not exceed 2.5 lb/ft^2.
P$_{red}$ will always exceed the vent opening pressure

Explosion Venting Isolation Requirements

- If two vessels are interconnected, a dust explosion in one of them could result in enhanced pressure due to pressure piling in the other.

- To protect against this isolation using a high speed isolation valve, or chemical isolation should be provided between them.

Oxidant Concentration Reduction

NFPA 69 Explosion Prevention Systems.

If oxygen concentration in head space is continuously monitored, maintain it at least 2 volume % below the Limiting Oxygen Concentration (LOC).

Unless LOC is <5%, in which case operate ≥ 60% of the LOC

Oxidant Concentration Reduction

- If oxygen concentration in head space is not continuously monitored design system to operate at no more than 60 % of the LOC. Unless LOC is <5% in which case operate $\geq$ 40% of the LOC.

- If the head space is not continuously monitored, it must be checked on a scheduled basis.

Oxidant Concentration Reduction

- For many organic materials the LOC for nitrogen inerted systems lies between 9.0 and 14.0% oxygen.

- If CO_2 is used in place of nitrogen the LOC typically rises by 1 to 2% due to its higher specific heat. Note this does not apply to some metals which may even burn in CO_2.

Deflagration Suppression

NFPA 69 Explosion Prevention Systems.

Systems comprise of

Instruments to detect the incipient explosion

A control system to analyze the signal and activate the suppressors

High rate suppressant discharge units.

Deflagration Suppression

- Deflagration suppression functions by detecting the initial combustion, typically by a pressure rise and then discharging a suppressant, commonly sodium bicarbonate into the equipment.

- The suppressant units are typically pressurized to 500 – 1000psi with nitrogen

Deflagration Suppression

- The suppressant units are typically pressurized to 500 – 1000psi with nitrogen.

- A rupture disk is used to "seal" the unit from the protected equipment and a blasting cap if used to burst the disc discharging the suppressant.

Deflagration Pressure Containment

NFPA 69 Explosion Prevention Systems.

The peak deflagration pressure for most organic dusts range between 100 and 160 psig.

Provided pressure piling is prevented and the operating pressure is known it is possible to design equipment to withstand the deflagration.

Deflagration Pressure Containment

- Depending on the P_{max} of the dust. For a process that operates at ambient pressure deflagration pressure containment can be achieved by designing vessels in accordance with ASME (1998 edition) Sec. VIII Div 1, with a maximum operating pressure of between 40 and 70 psi.

  See NFPA 69 (2002 Edition) Section 10.

Combustible Concentration Reduction

- NFPA 69 Explosion Prevention Systems.

- Explosion protection in equipment can be achieved by maintaining the dust concentration to less the 25% of the lower flammable limit.

Combustible Concentration Reduction

- The design of buildings should facilitate keeping the area free dust build up. For example by avoiding horizontal ledges, cable trays, and unsealed suspended ceilings, in dust processing areas.

- It should be possible to wash down or vacuum clean areas. Do not clean by "air blowing" dust.