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...minum Figure 5. Bagfilter before (top picture) and after (bottom left and right pictures) the alu... dust explosion (Marmo et al., 2015)

Metal Dust Explosions by Dave Burn

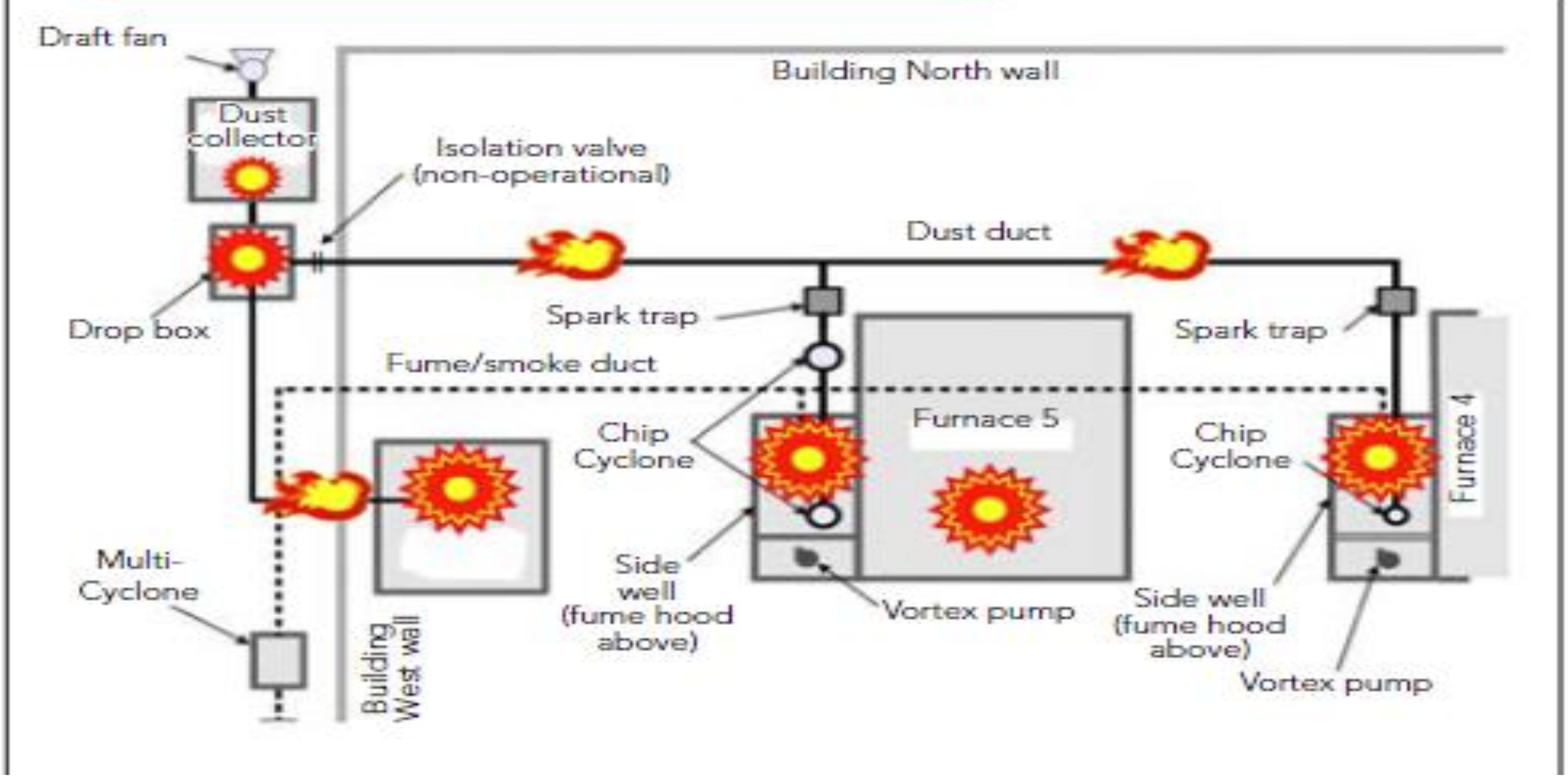
A Review of Metal Dusts Explosion Incidents

Following several major dust explosions, the Chemical Safety Board (CSB) published a dedicated study in 2006: 281 dust explosions were reported between 1980 and 2005 in the USA killing 119 workers and injuring 718 Metal dusts were involved in 20% of these incidents (Chemical Safety Board, 2006).

According to the Center for Chemical Process Safety (2005), FM Global identified 19 explosions involving metal dusts between 1985 and 1995, representing 13% of all incidents (Feb, 2001).

Metal dust deflagrations have also been regularly reported in Europe, Japan, and recently China.

ACCIDENT 1: HUNTINGTON, IN (2003)

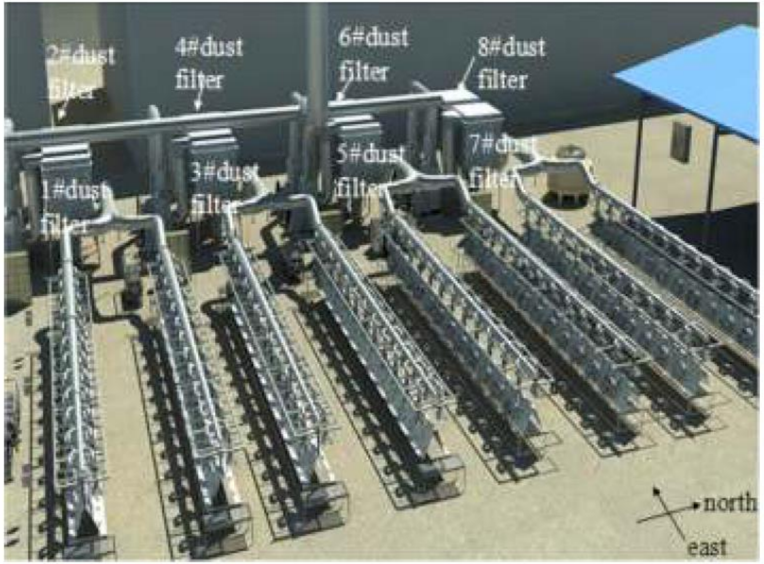


1. Furnace No. 5 Wall
2. Fume Hood ove Side Well
3. Side Well
4. Aluminum Ingots
5. Dry Chip Hopper
6. Dust Duct
7. Fume Duct
8. Reject Wheels for Remelting

Figure 3. View of the dust collector (outside) and the facility (inside) after a dust explosion at a manufacturing plant in Huntington, Ind., in 2003. *Source: U.S. Chemical Safety and Hazard Investigation Board.*

Kunshan, Jiangsu, China (2014)

On August 2nd, 2014, an aluminum dust deflagration took place in an automotive parts factory of Jiangsu province, killing 146 people and injuring 114 people (Li et al., 2016). The explosion was heard several kilometers away, and shattered glass up to 500 meters away (Figure 9).



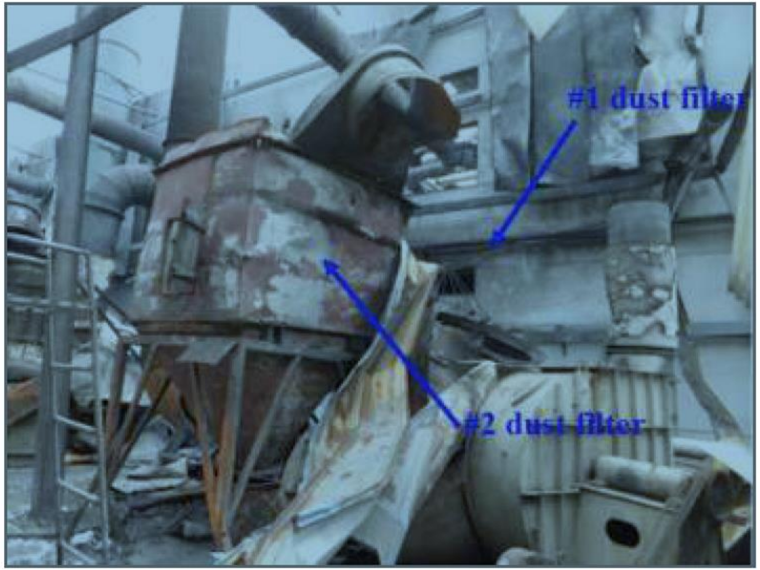


Figure 9: Results of the aluminum dust explosion that occurred in Kunshan, China (Li et al., 2016). From left to right: Production lines with work stations, damaged dust collectors, process line (2nd floor), and eastern wall of the main building

ANATOMY OF METAL DUST EXPLOSIONS

Metal dusts are similar to organic dusts in that they, once ignited, undergo oxidation reactions and the combustion can propagate through a dust cloud. They differ in the nature of the products formed: while all organic fuels form primarily carbon dioxide and water vapour (Eq. 1), each metal dust forms a particular metal oxide (Eq. 2):

$$(C_6H_{10}O_5)_x + O_2 \rightarrow CO_2 + H_2O + \text{Heat}\ , \quad (1)$$

$$2Al + \tfrac{3}{2}O_2 \rightarrow Al_2O_3 + \text{Heat}\ . \quad (2)$$

As a result, organic dusts have quite similar combustion properties, whereas metal dusts exhibit more variability and extremes [9], as illustrated in Table 1.

Table 1. Physical properties of selected metal dusts compared to carbon. [9, 10]

Element	T_f	P_{max}	K_{st}
Al	3,550	13	800
Ti	3,450	5.7	35
Mg	3,100	17.5	500
Si	2,870	9.5 - 10.8	100 - 168
Fe	2,250	4.5	29
Zn	1,860	4.4	17
C	2,320	5 - 9	50 - 350

Explosibility tests

Previous investigations (HSL)

- 20-L sphere and 1-m^3 vessel tests
- 4 organic dusts + aluminum dust

Dust	20 L sphere			1 m^3 vessel		
	C (kg/m^3)	K_{St} (bar.m/s)	P_{max} (bar)	C (kg/m^3)	K_{St} (bar.m/s)	P_{max} (bar)
Coal	500	144	8.4	500	144	8.5
Aspirin	1,000-1,500	220-254	8.6-8.7	1,000	254	8.3
Toner	250	236	9.3	250	236	8.8
Polyethylene	250	193	8.8	500	106	7.9
Aluminum	500-1,000	272-333	8.8-9.3	250	630	11

Lunn, G., Crowhurst, D., Hey, M., The effect of vent ducts on the reduced explosion pressures of vented dust explosions. Journal of Loss Prevention in the Process Industries. 1988. 1(4): p. 182-196.

Explosibility tests

Previous investigations (FSA)

- 20-L sphere and 1-m^3 vessel tests (FSA)
- Two types of aluminum dust with different particle size distributions were used (AS011, AS081)

Dust	20 L sphere C (kg/m^3)	20 L sphere K_{St} (bar.m/s)	20 L sphere P_{max} (bar)	1 m^3 vessel C (kg/m^3)	1 m^3 vessel K_{St} (bar.m/s)	1 m^3 vessel P_{max} (bar)
AS011	1,750	94	7.3	1,500	284	9.2
AS081	1,250	193	8.5	1,500	423	10

Explosion Protection

The management of dust explosion risk includes the implementation of both preventive and protective measures. An overview of explosion protection techniques applied to metal dusts, including Venting including flameless, suppression, and isolation, will presented in the next slides.

Explosion Venting

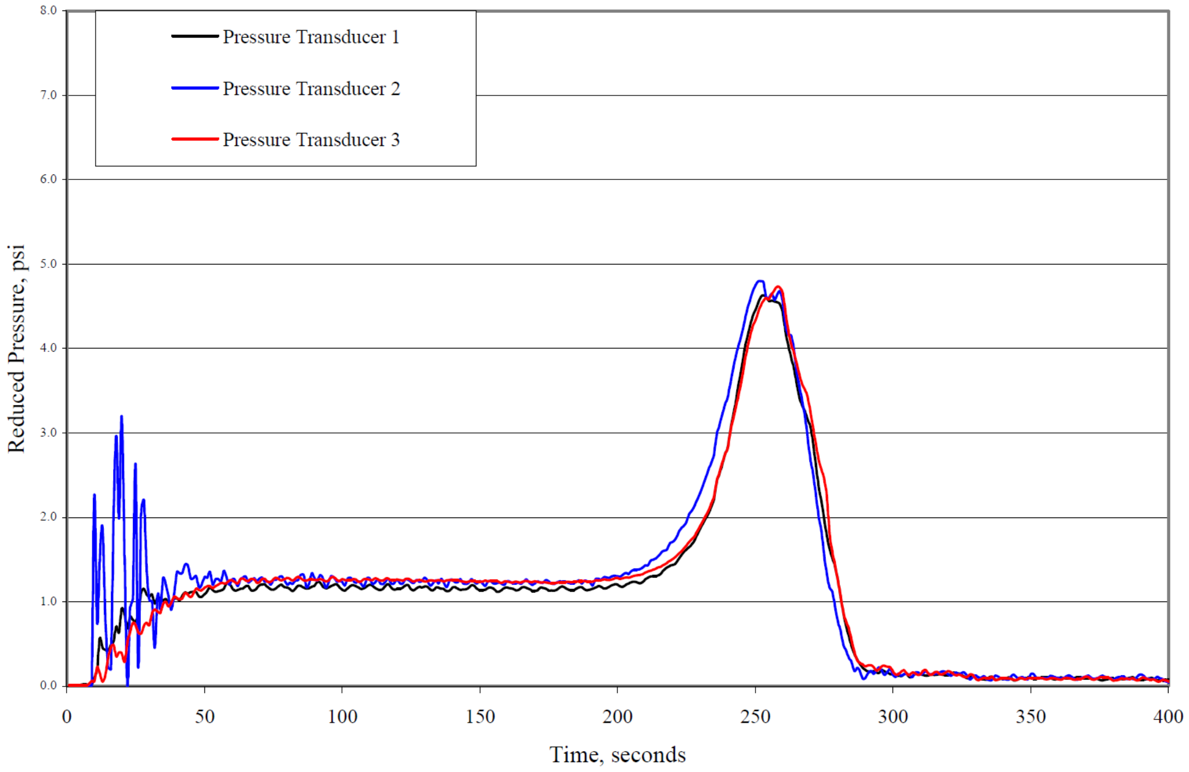
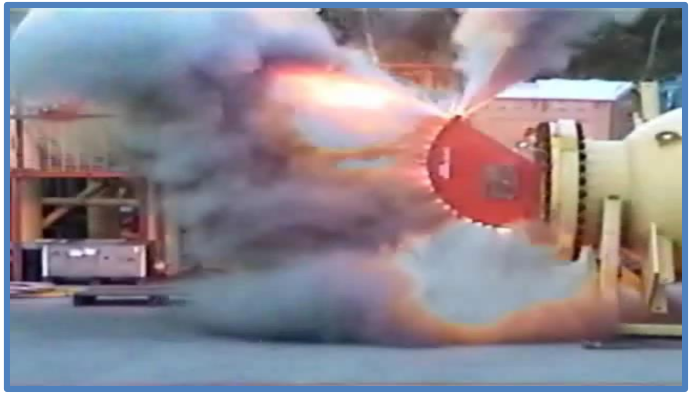


Figure 5. Venting of Aluminum Powder Deflagration

Flame-less – Fuel Limitations

Substance	Oxidation Products	KJ/mole O_2
Coal	CO_2 and H_2O	400
Sucrose	CO_2 and H_2O	470
Starch	CO_2 and H_2O	470
Polyethylene	CO_2 and H_2O	390
Zn	ZnO	700
Al	Al_2O_3	1100



Failure to flameless vent aluminum dust

Suppression of Metal Dusts - History

1988 – Moore & Cooke undertook tests in a 6.2m^3 vessel @ 500g/m^3 with 12.9kg/m^3 Sodium Bicarbonate.

1989 – Bartnecht undertook tests in a 1m^3 vessel, Low concentrations OK. High concentrations > 500g/m^3 failed.

2002 – Going & Snoeys undertook tests in 1m^3 .

2014 – Snoeys undertook tests at FSA in 1m^3 & 4.4m^3 with aluminium at various concentrations.

1 m^3 vessel suppression tests with organic dusts.

Dust	Dust concentration (g/m^3)	K_{St} (bar.m/s)	P_{max} (bar)	Suppressant type	Suppressant concentration (kg/m^3)	P_{act} (bar)	TSP[a] (bar)
Coal	500	100	7.2	SBC	2.3	0.035	0.19
Wheat starch	750	150	8.0	SBC	2.3	0.035	0.22
Corn starch	500	220	8.2	SBC	2.3	0.035	0.26

[a] Total suppressed pressure is the average of two tests.

Table 3
1 m^3 vessel suppression tests with silicon and aluminum dusts.

Dust	Dust concentration (g/m^3)	K_{St} (bar.m/s)	P_{max} (bar)	Suppressant type	Suppressant concentration (kg/m^3)	P_{act} (bar)	TSP[a] (bar)
Si	1000	120	8.2	SBC	2.3	0.035	0.33
Si	1000	120	8.2	PK	2.3	0.035	0.27
Si	1000	120	8.2	PK	4.5	0.035	0.30
Al	1750	300	8.5	SBC	4.5	0.035	2.05
Al	1750	300	8.5	SBC	9.1	0.035	0.84
Al	1750	300	8.5	PK	4.5	0.035	1.25
Al	1750	300	8.5	PK	9.1	0.035	0.89

[a] Total suppressed pressure is the average of two tests.

Table 4
1 m^3 vessel suppression tests with silicon dust (varying Pact and suppressant concentrations).

Dust	Dust concentration (g/m^3)	K_{St} (bar.m/s)	P_{max} (bar)	Suppressant type	Suppressant concentration (kg/m^3)	P_{act} (bar)	TSP[a] (bar)
Si	750	144	8	SBC	2.3	0.05	0.37
Si	750	144	8	SBC	2.3	0.1	0.73
Si	750	144	8	SBC	2.3	0.2	>6
Si	750	144	8	SBC	4.5	0.05	0.45
Si	750	144	8	SBC	4.5	0.1	0.65
Si	750	144	8	SBC	4.5	0.2	1.36
Si	750	144	8	SBC	6.8	0.05	0.41
Si	750	144	8	SBC	6.8	0.1	0.64
Si	750	144	8	SBC	6.8	0.2	1.03

[a] Total suppressed pressure is the average of two tests.

Table 7
1 m³ and 4.4 m³ vessels suppression tests with aluminum (FSA).

Dust	Vessel	Dust concentration (g/m^3)	K_{St} (bar.m/s)	P_{max} (bar)	SBC concentration (kg/m^3)	TSP[a,b] (bar)
AS011	1 m^3	250			12.5	0.62
AS011	1 m^3	500			12.5	0.67
AS011	1 m^3	1000	256	8.7	12.5	1.24
AS011	1 m^3	1750	220	9.2	12.5	2.16
AS081	1 m^3	250	110	7.2	12.5	0.65
AS081	1 m^3	500	240	10.7	12.5	1.03
AS081	1 m^3	1000	322	9.9	12.5	1.59
AS011	4.4 m^3	250			9.5	0.51
AS011	4.4 m^3	500			9.5	0.79
AS011	4.4 m^3	1000	256	8.7	9.5	1.45
AS081	4.4 m^3	250	110	7.2	9.5	0.61
AS081	4.4 m^3	500	240	10.7	9.5	1.32

[a] Detector activation pressure was 0.035 bar.
[b] Total suppressed pressure is the highest one when more than one test was performed.

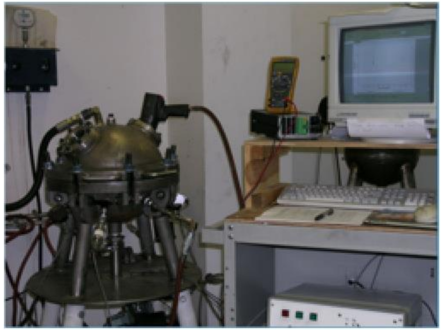
Explosibility tests

5 metal dusts:

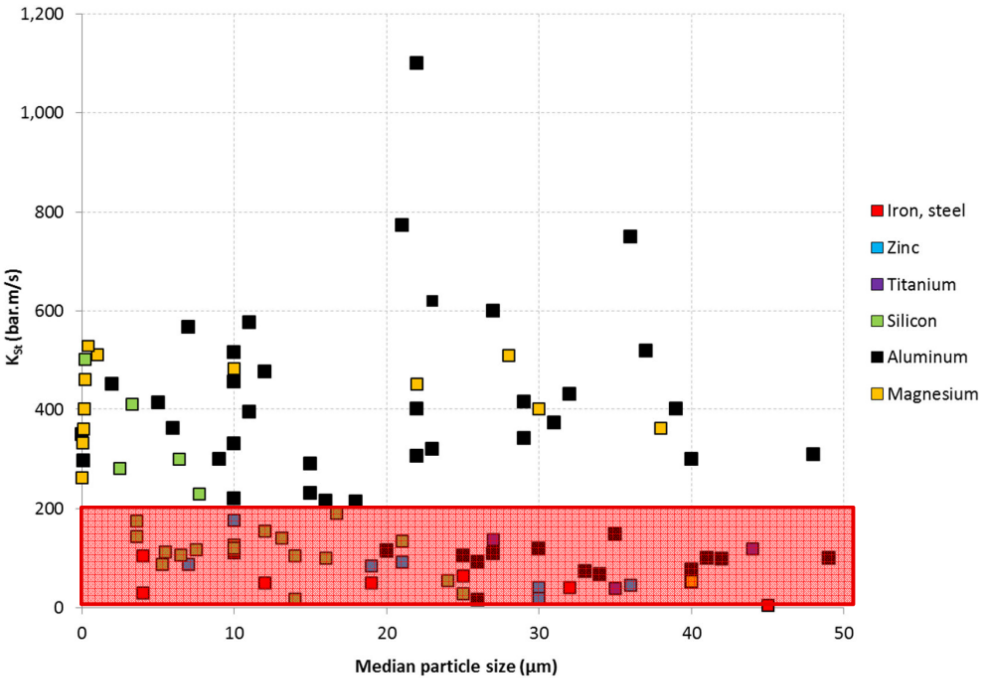
- iron, zinc, silicon, aluminum (2)
- + cornstarch (reference dust)

> 100 tests performed in 1-m^3 vessel

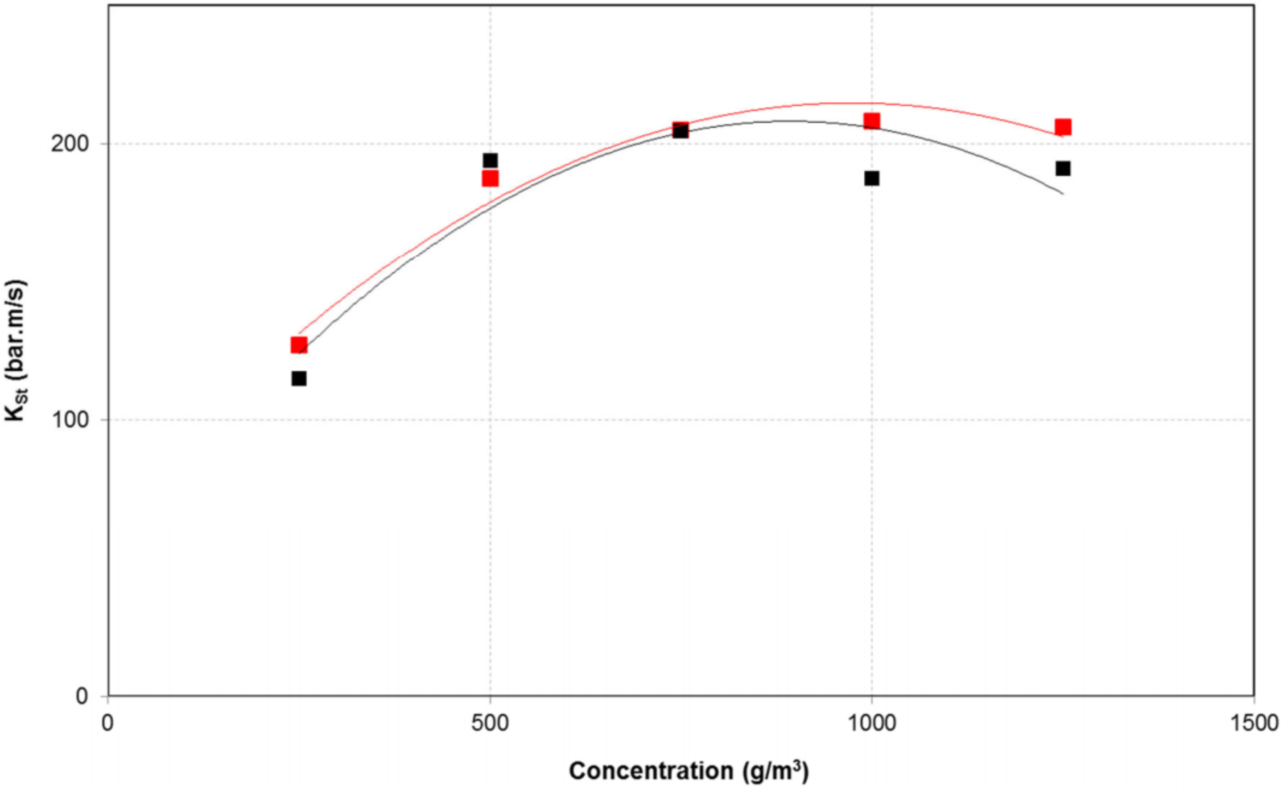
> 100 tests performed in 20-L sphere



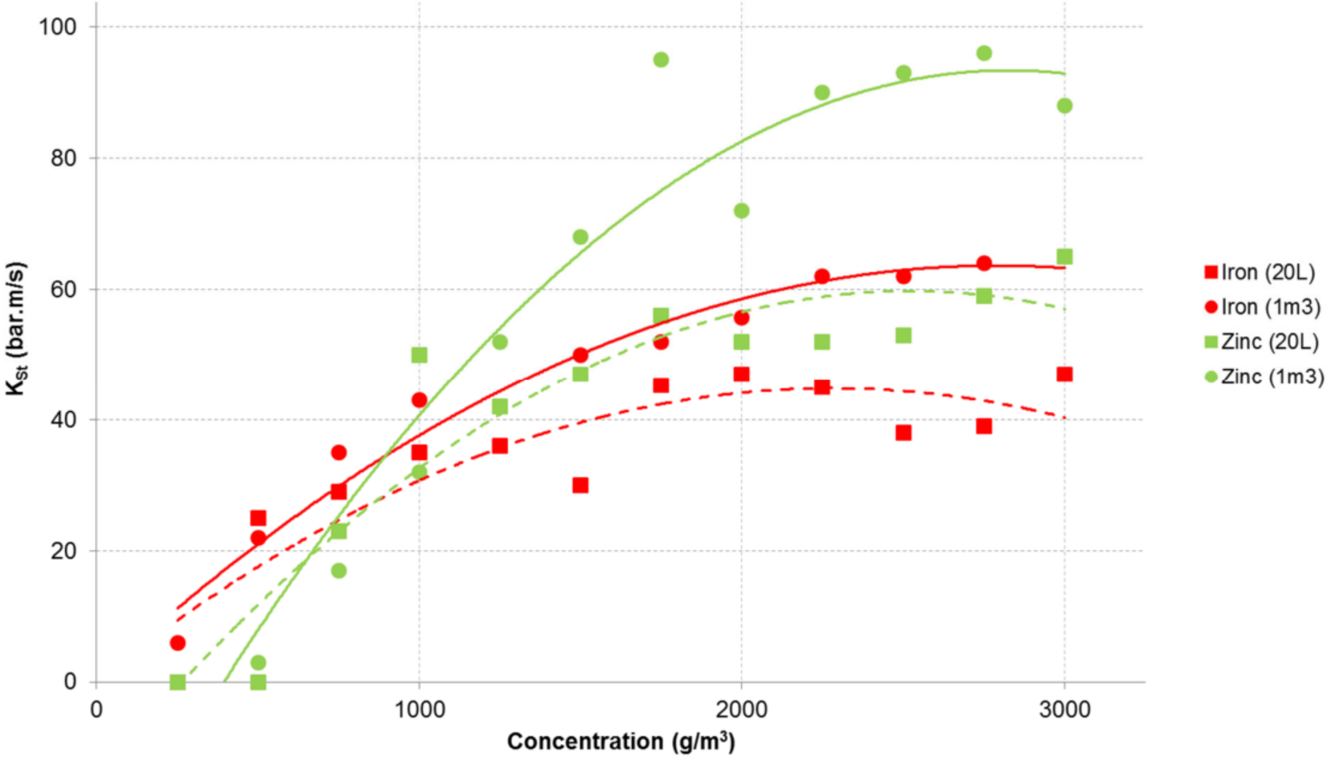
K_{St} (metals)


1,200
1,000
800
600
400
200
0
K_{St} (bar.m/s)
0
10
20
30
40
50
Median particle size (µm)
Iron, steel
Zinc
Titanium
Silicon
Aluminum
Magnesium

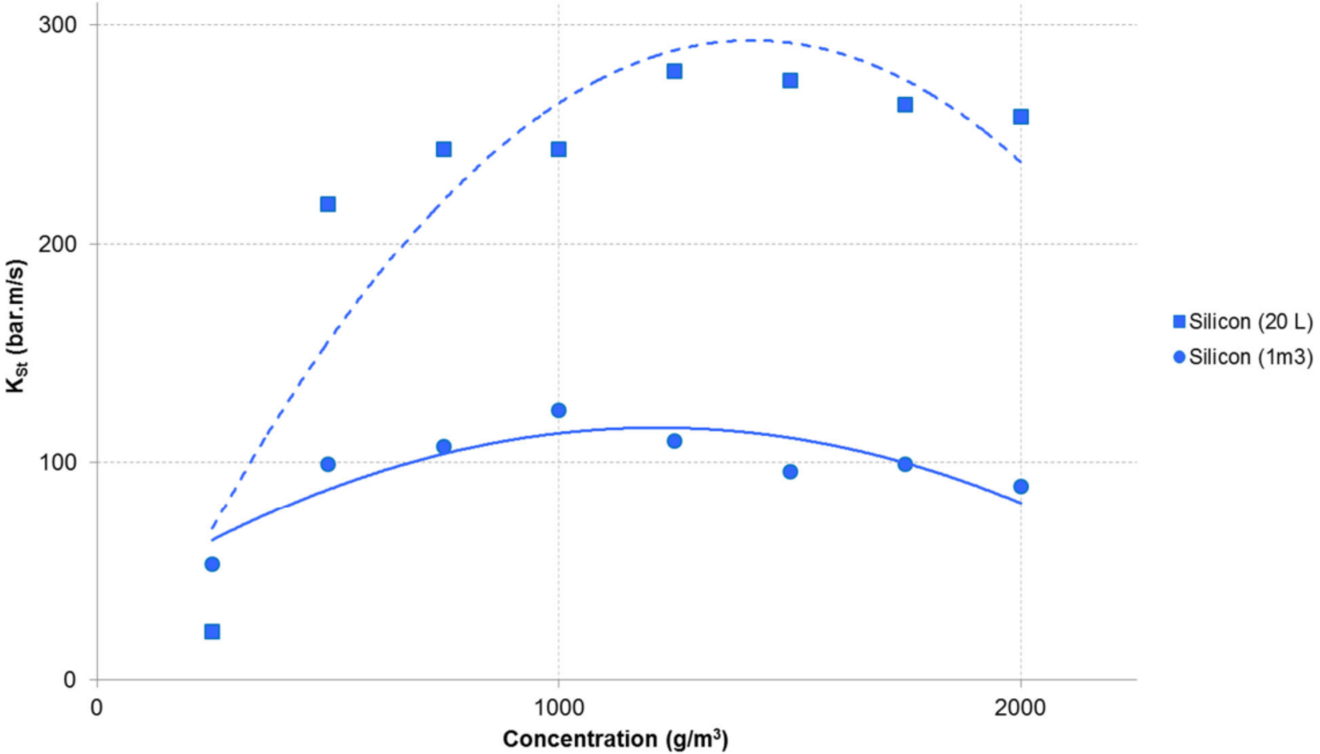
Explosibility tests (cornstarch, reference)



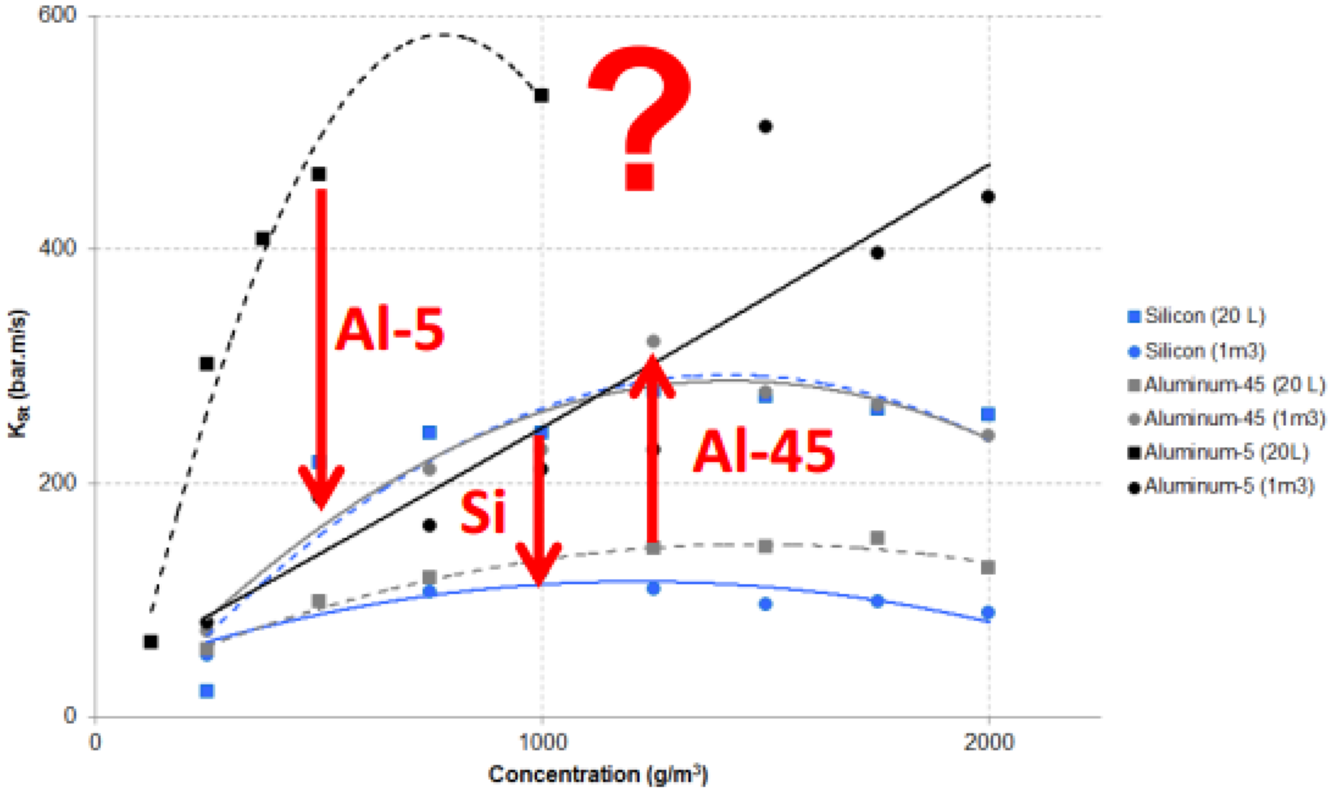
Explosibility tests (iron and zinc)



Explosibility tests (silicon)



20-L and 1-m³ testing do not agree



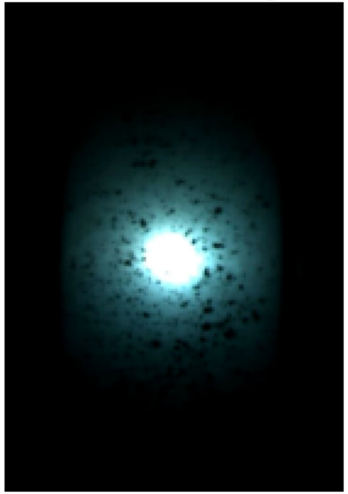
Aluminum 5 µm

Fine particles may agglomerate in the 1-m³ vessel

"Homogeneous" cloud

Aluminum 45 µm

Aluminum 5 µm



Larger particles
Coagulation

Conclusions

- Metal dust explosions differ from organic dust explosions and must be treated accordingly even for venting as the P_{red} will be higher than predicted using standard sizing methods.
- Venting can be used with care based on true understanding of the hazard. Extrapolation to large volumes needs to be limited.
- Flameless venting; Yes but with low volatility metal dusts e.g. Iron.
- Suppression can achieve reduced pressures of <1bar for metal dusts up to K_{max} 300. No testing of magnesium has been reported.
- Isolation; If detection is early and the barrier placement is close to the origin then isolation can be achieved.

• 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 Kmax 650.

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