Experimental Investigation into the Explosion Properties of Direct Reduced Iron fines

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WHERE RESEARCH AND TEACHING MEETS THE FUTURE

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- Introduction
- Methodology
- Research Questions
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Introduction

- Currently, the statistic data shows that the transport of DRI materials has increased significantly in recent decades.

- This raises the risk of accidents during transportation, highlighting the need for further investigation into the transportation of Direct Reduced Iron (DRI) products.

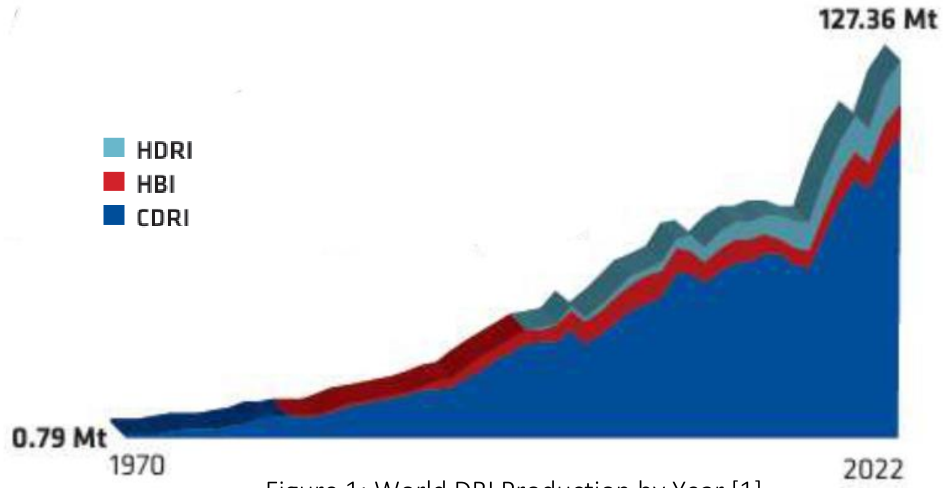

Figure 1: World DRI Production by Year [1].

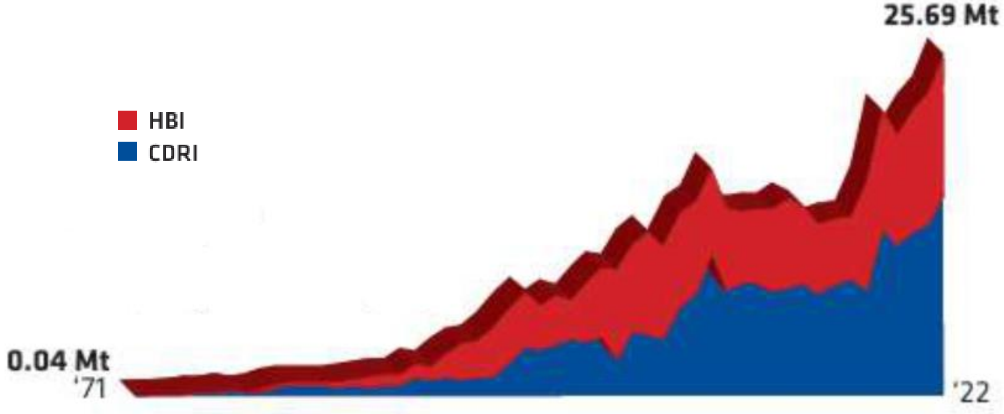

Figure 2: World DRI Shipments by Year [1].

Introduction

Classification of DRI according to The International Maritime Solid Bulk Cargoes Code (IMSBC Code):

- DRI (A) Hot Briquetted Iron (HBI)
- DRI (B) in lumps/pellets
- DRI (C) comprising by-product fines from manufacturing and handling processes of DRI (A) and/or DRI (B)

*** Introduction of DRI (D) Classification as a** by-product with moisture content of at least 2% and particles with an average size less than 6.35 mm, aged for at least 30 days prior to loading [2].

Introduction

DRI D and C fines are a by-product of gas-based shaft direct reduction furnaces and direct reduction process handling. A considerable part of the DRI fines is traded, which requires a safe transport regulation. DRI fines pose serious risks, including:

- Overheating risks
- Fire potential
- Explosion danger

In this research, we'll delve into behavior of DRI D fines dust explosions.

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Sample Preparation

To investigate the explosion characteristics and to obtain DRI (direct reduced iron) grade D, the input material was ground under nitrogen atmosphere to a particle size of less than 500 µm.

Grain size analysis of this ground dust was conducted according to ÖNORM EN 15415-1 standards.

Upon receiving and grinding the sample, the water content was determined at 105°C under vacuum until a constant mass was achieved, following DIN EN ISO 18134-1 standards.

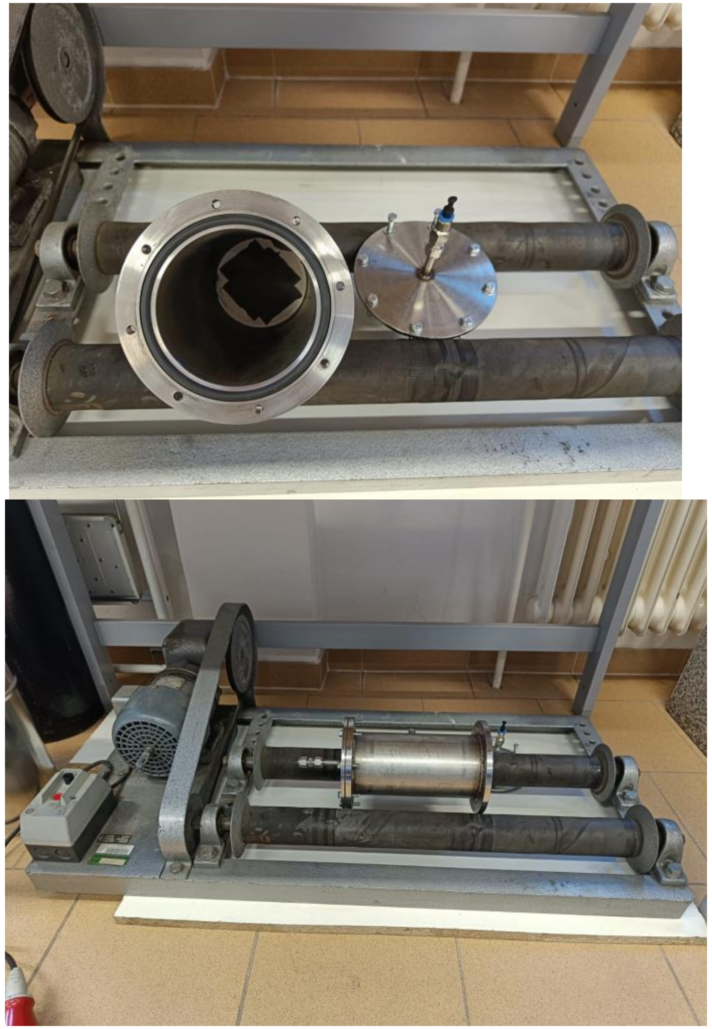


Fig. 1: Drum mill for the production of DRI dust.

Explosion severity

For the efficient prevention of dust explosions by preventive explosion protection (e.g. explosion venting, explosion suppression) it is necessary to know the optimum explosion indices, which can be determined according to a standard procedure in the 20-l laboratory apparatus (fig.2) [3] :

- ASTM E1226: Standard Test Method for **Explosibility** of Dust Clouds
- EN 14034-1: Determination of **the maximum explosion pressure P_{max}** of dust clouds
- EN 14034-2: Determination of **the maximum rate of explosion pressure rise** $(dp/dt)_{max}$ of dust clouds
- EN 14034-3: Determination of the **lower explosion limit** LEL of dust clouds

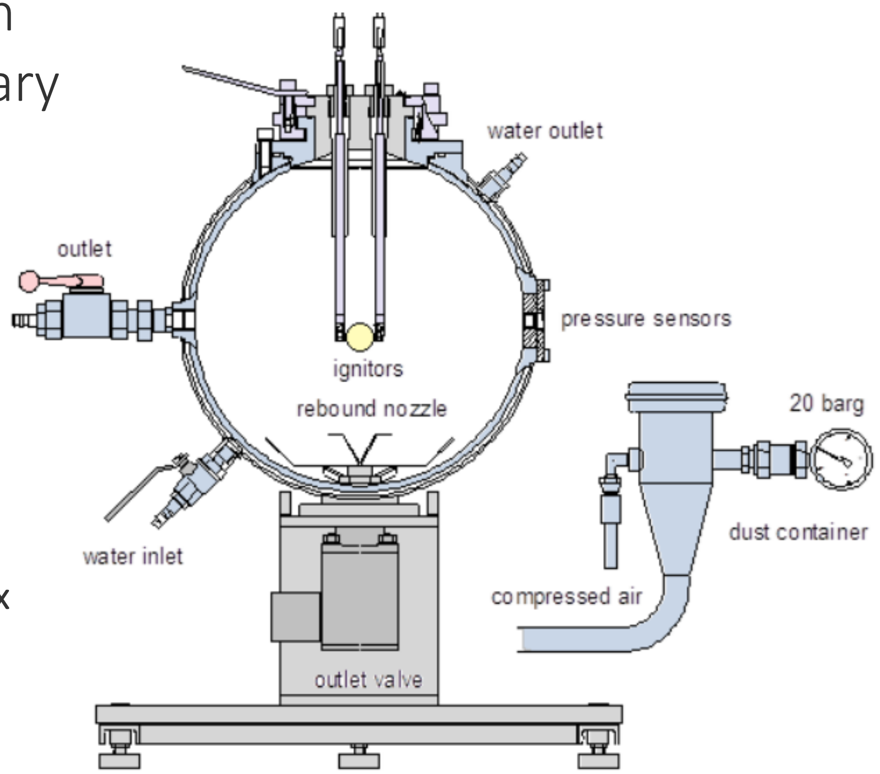


Fig. 2: 20-L-Apparatus (Siwek - Sphere) [3].

Explosion severity

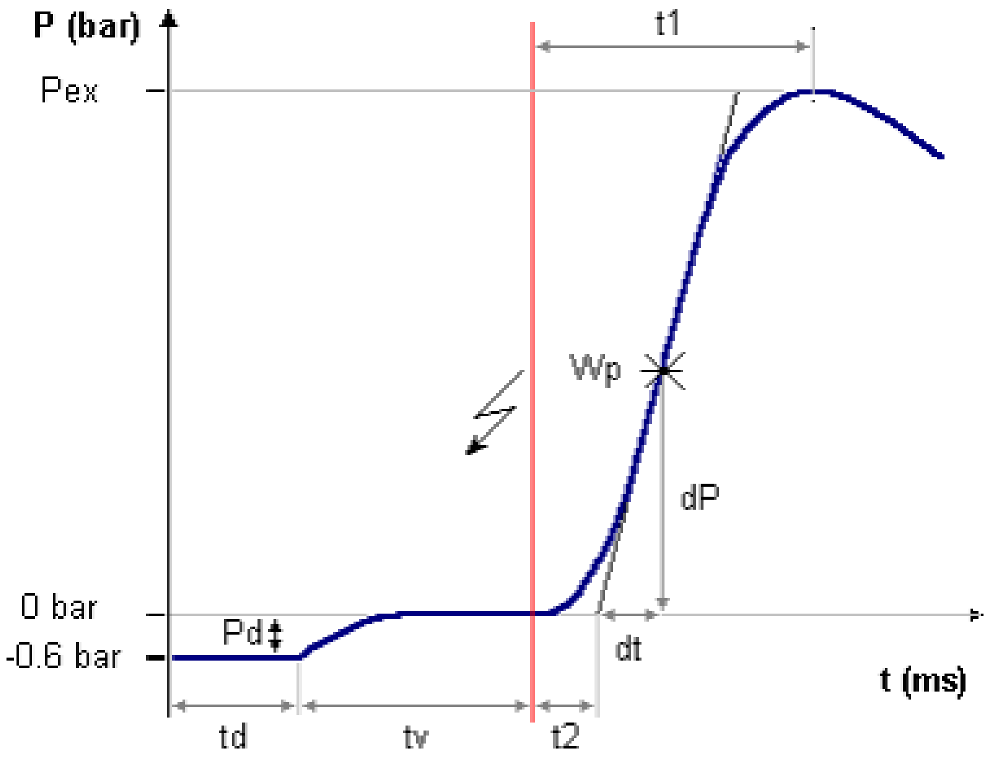


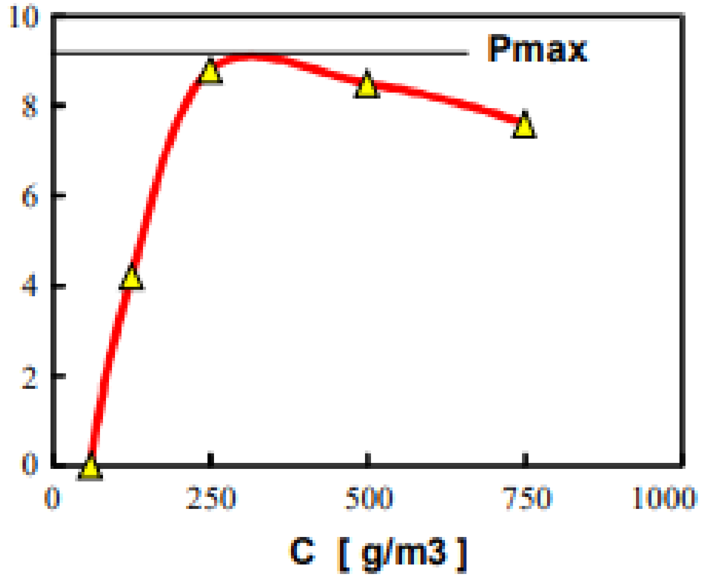
Fig. 3: Pressure/time-diagram of a fuel explosion [4].

P_{ex}: explosion overpressure. The difference between the pressure at ignition time (normal pressure) and the pressure at the culmination point is the maximum explosion overpressure P_{ex} measured in the 20-l-apparatus at nominal fuel concentration.

$(dP/dt)_m$: Rate of pressure rise with time at nominal fuel concentration. It is defined as the maximum slope of a tangent through the point of inflexion (Wp) in the rising portion of the pressure vs. time curve.

Explosion severity

The explosion overpressure P_m and the rate of pressure rise dP/dt describe the violence of reaction of dust/air mixtures of random concentration after ignition in a closed vessel. The maximum explosion pressure Pmax and the maximum rate of pressure rise (dP/dt)max of combustible dusts are determined in closed standard equipment (e.g. 1-m³-vessel or 20-l-apparatus) by means of tests over a wide range of concentrations:



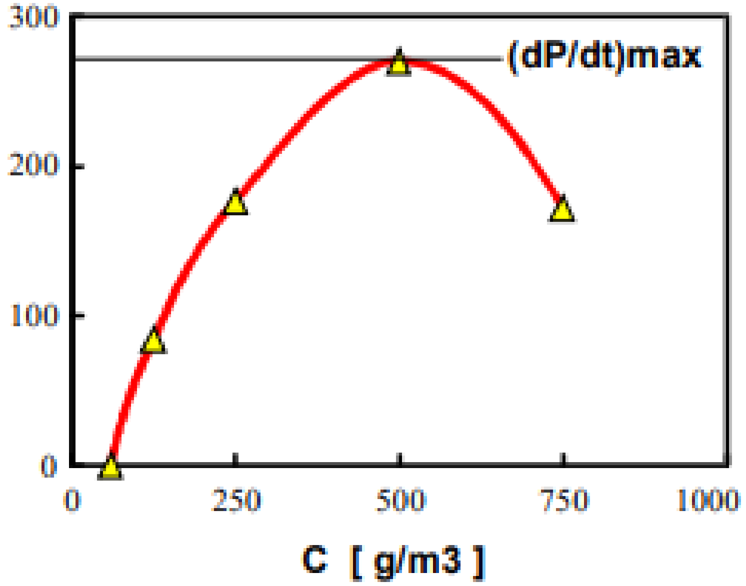


Fig. 4: Determination of the explosion indices [4].

Explosion severity

The K_{max}-value is dust and test method specific but independent of volume. For the 20-l-apparatus the following equation applies [4]:

$$\left(\frac{dp}{dt}\right)_{max} * V^{\frac{1}{3}} = konst. = K_{st}$$

K_{St} – Value [m·bar·s^{-1}]	Dust explosion class [4]
0 – 200	1
200 – 300	2
> 300	3

- No criterion for the probability of occurrence of a dust explosion or the effect of a dust explosion in an operating facility
- Only an indication of which explosion protection concept can be followed, or which type of protection can be used.
- Tells us how to design measures of constructive explosion protection

Minimum ignition energy MIE

- For an assessment of the hazard situation in dust-processing installations, knowledge of the minimum ignition energy is indispensable.

- The minimum ignition energy (MIE) is the lowest energy value of a high-voltage capacitor discharge required to ignite the most ignitable dust/air mixture [5].

- This characteristic can be determined according to international standards: EN 13821 “Determination of minimum ignition energy of dust/air mixtures”.

Fig. 5: Minimum Ignition Energy Apparatus MIKE 3 [5].

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Research Questions

1. What are the explosion characteristics of DRI D fines, including the minimum explosible concentration, maximum explosion pressure (P_{max}), maximum rate of pressure rise $(dp/dt)_{max}$, and dust explosion classification?

2. What is the minimum ignition energy (MIE) of DRI fines?

3. How do various storage conditions influence the explosion properties of DRI fines?

4. What are the current challenges in accurately measuring the explosion characteristics of DRI fines?

Agenda

Results and discussion

Sample Preparation: The HBI material (DRI (A)) ground under nitrogen atmosphere to a particle size < 500 µm

Sample characteristics:

- Median particle size (d_{50}): 53.7 µm (detailed results in Fig. 6)
- Water content: 3.9%

Given the properties of the material and the manner in which the dust was generated, it can be classified as DRI (D).

Further, we will refer to it as DRI (D) dust.

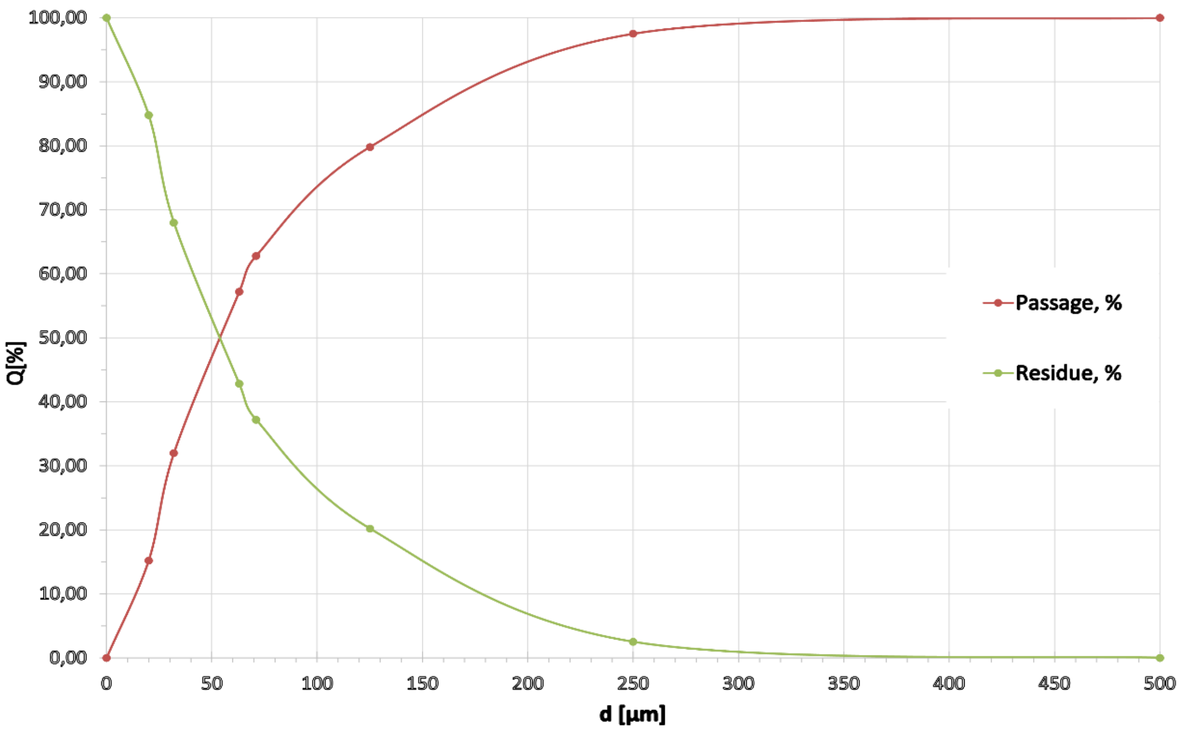

Fig. 6. Particle size distribution of DRI (D) dust.

Results and discussion

- Testing was conducted with an inductance of 1 mH and at ignition delay times of 90, 120, and 150 ms. The investigated sample weight range from 900 to 2,400 mg corresponds to a concentration range of 750 to 2,000 g/m³.

- The minimum ignition energy is not specified, as all tests in the MIKE 3 apparatus were negative. Therefore, the MIE is greater than 1,000 mJ and cannot be determined more precisely.

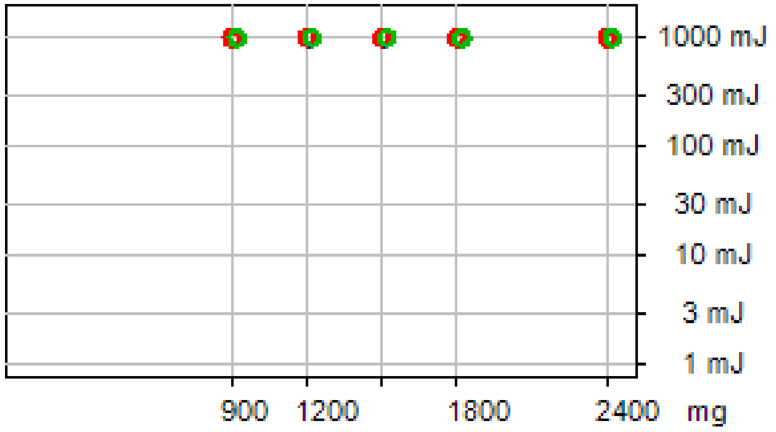

Fig. 7. Measurement results for determining the minimum ignition energy of DRI D fines.

Results and discussion

- In Figure 8, the measurement results for determining the lower explosion limit are shown. The explosion capability is indicated when the red line at 0.2 bar(g) is exceeded.

- Lower Explosion Limit (LEL); = 450 g/m³

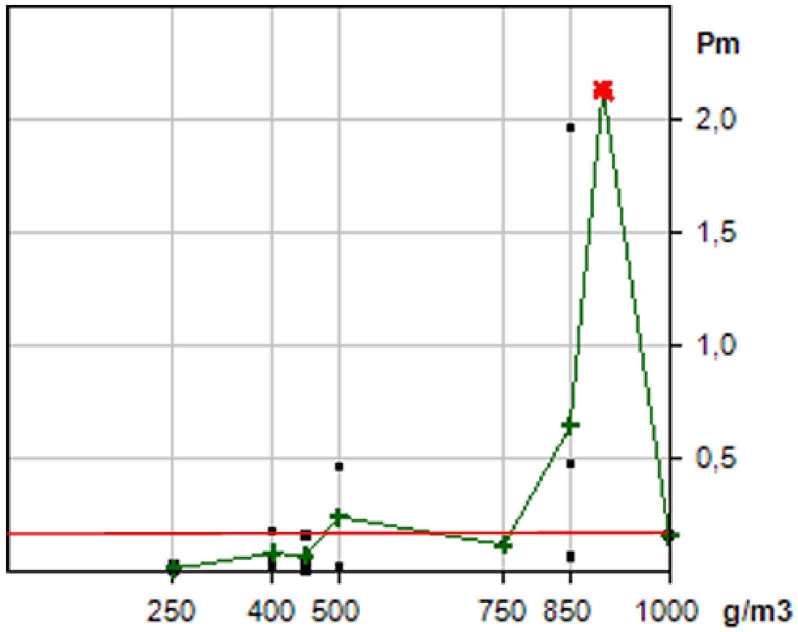

Fig. 8. Measurement results for determining the minimum ignition energy of DRI D fines.

Results and discussion

- The maximum explosion pressure $(P_{ex})_{max}$ was **4.5 bar.**
- The maximum pressure rise rate $(dP/dt)_{max}$ was **130 bar/s.**
- **K_{St} = 35 bar m/s.**
- **1 Dust explosion class.**

- Dust explosion pressure can be divided into **three phases** [8]:
    - Phase 1: Dust injection (t_1 to t_2), including ignition delay (t_{ig}).
    - Phase 2: Dust explosion expansion (t_2 to t_3), including combustion duration (t_c).
    - Phase 3: Following t_3 explosion ceases, pressure decreases due to heat dissipation.

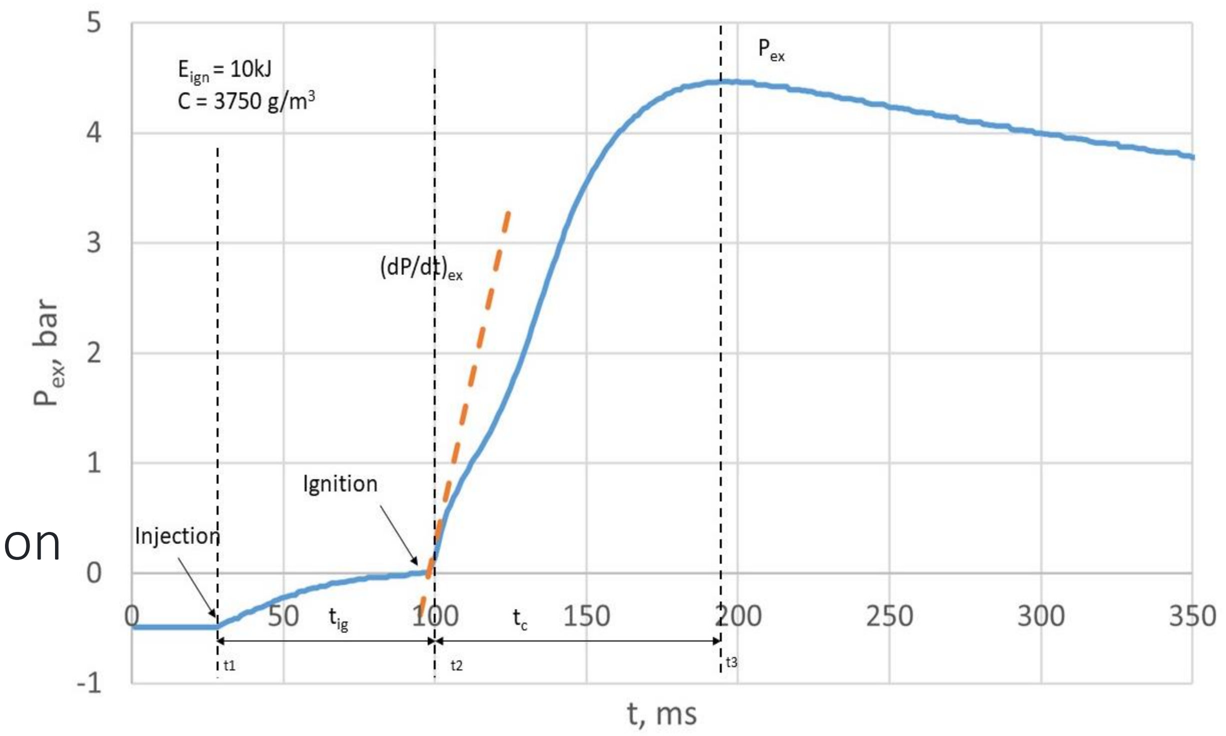

Fig. 9. Explosion process curve of DRI (D) dust in the standardized 20-L spherical chamber.

Results and discussion

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* During the explosion, the **rate of explosion pressure rise reaches its maximum almost immediately after ignition. After that second pressure accelerations occurs.**

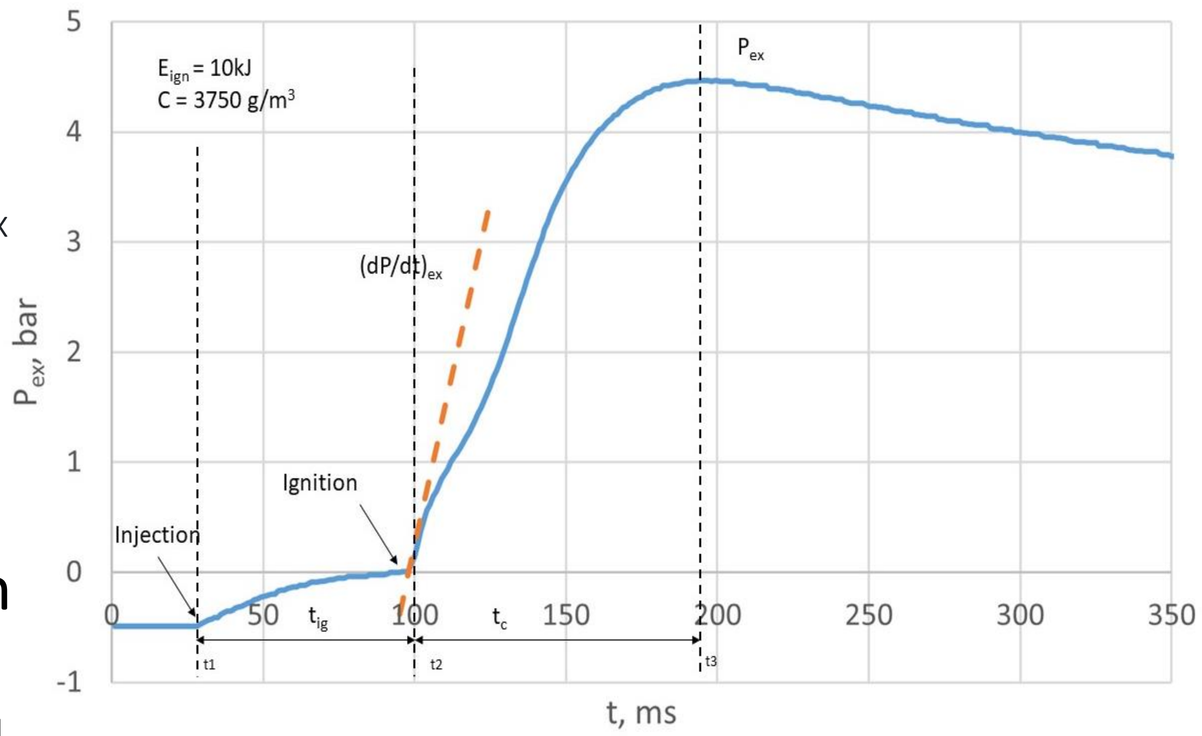

Fig. 9. Explosion process curve of DRI (D) dust in the standardized 20-L spherical chamber.

Results and discussion

Obtained results correlates with the beheviour of iron dust:

- Iron dust is classified as Dust Explosion Class 1, indicating a weak explosion potential [6, 7].
- Unlike other dusts, iron dust exhibits two pressure accelerations during an explosion:
- The first rise in pressure is due to large ignition energy (5kJ · 2).
- The second rise is caused by the subsequent combustion of iron dust [8, 9].

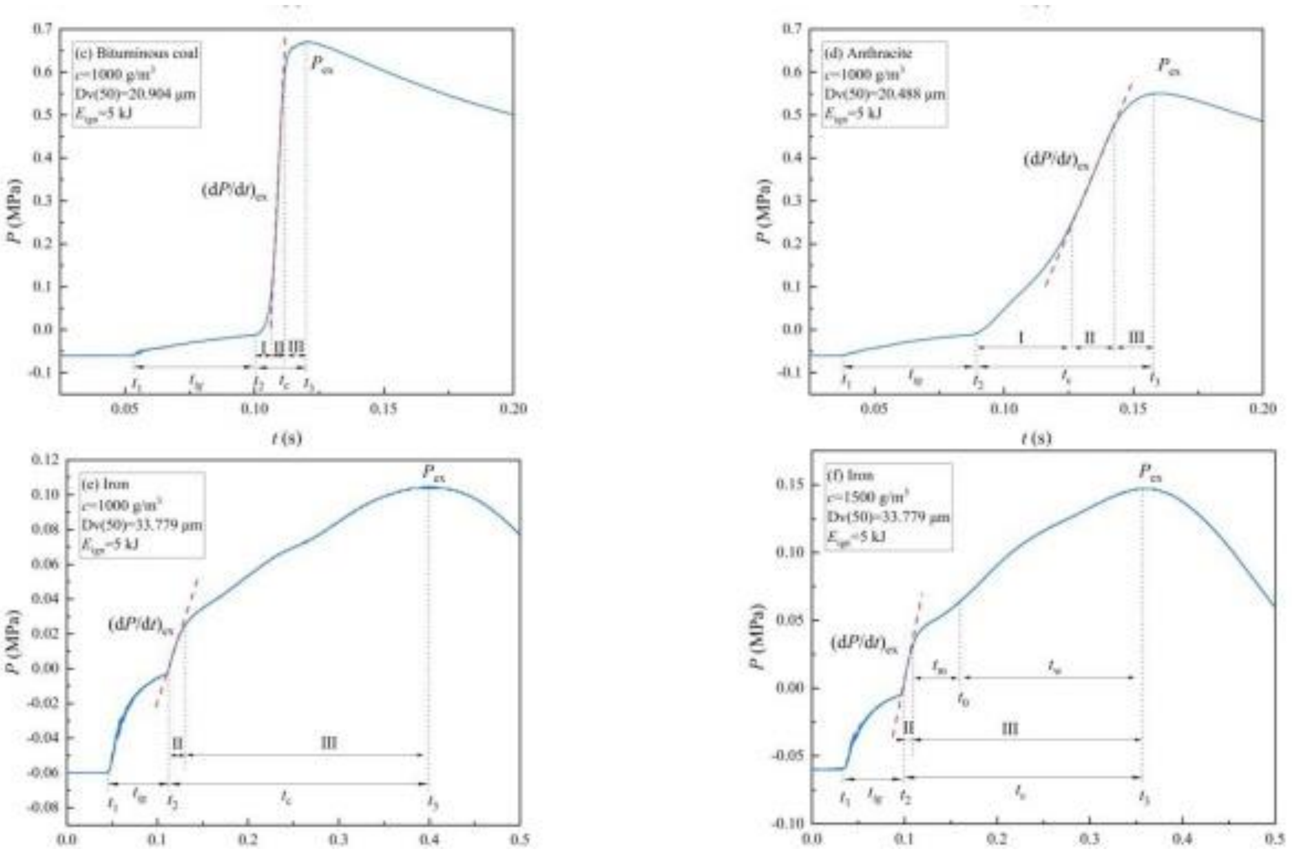

Fig.10: Different dust explosion process curves: (a) bituminous coal; (b) anthracite; (c,d) iron at different concentrations [9].

Results and discussion

- The similar effect of pressure data for a weak dust explosion have been discussed by using the example of volatile bituminous coal dust [10].

- It is important to determine (dP/dt) for the dust explosion itself rather than the ignitor effects.

- **This effect ruins to provide accurate data on actual safety values of low-explosive dust such as DRI D.**

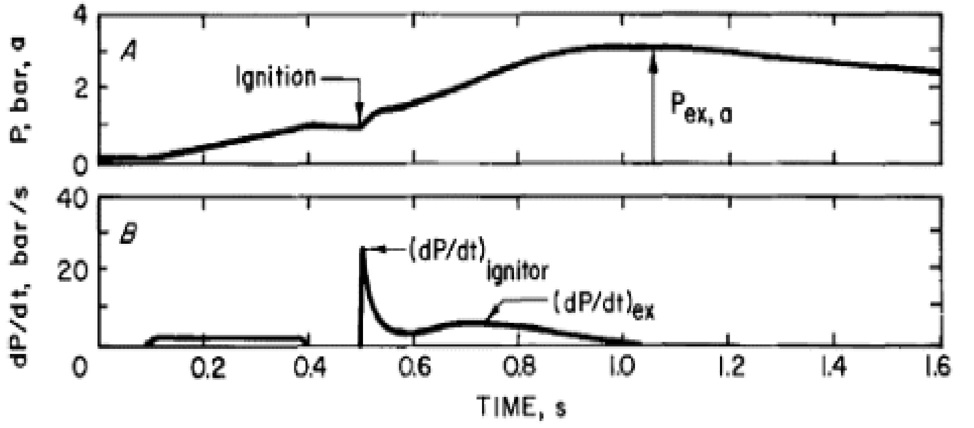

Figure 11: Typical pressure data for a weak dust explosion [10].

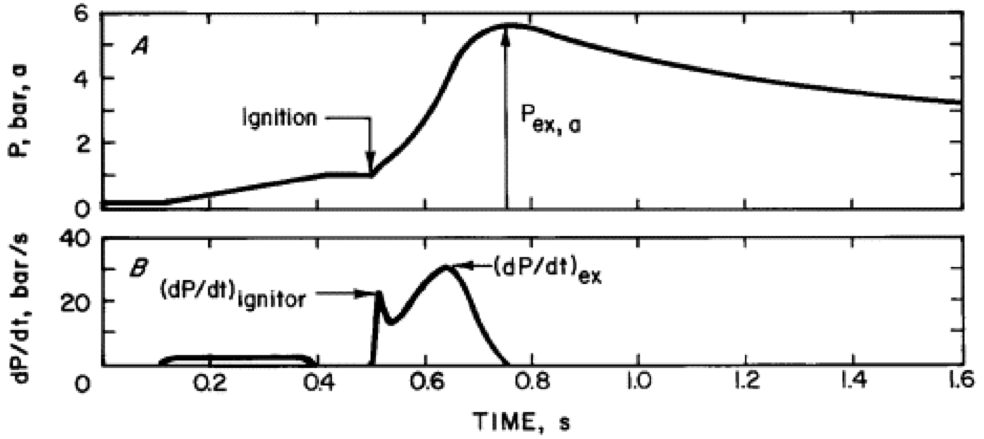

Figure 12: Typical pressure data for a moderate dust explosion [10].

Results and discussion: Storing DRI (D) Dust Under Different Conditions

During the transportation of DRI (D), changes in the storage conditions of the dust may occur [2]. Such as a:

- **DRI (D) can be stored in diverse locations** or containers, including stockyards/warehouses (covered or uncovered) and silos, hoppers, or other confined spaces.

- **Temporary Temperature Increase**: DRI (D) might undergo a transient temperature rise of approximately 30°C above ambient temperature post-bulk handling.

- **Moisture Content Concerns:** DRI (D) could liquefy if transported with a moisture content surpassing its Transportable Moisture Limit (TML), typically ranging from 9-12%.

Results and discussion: Storing DRI (D) Dust Under Different Conditions

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Five distinct climate boxes were used to simulate different storage scenarios (1 week):

- **Box 1 (Control):** DRI dust stored in sealed barrels to prevent oxidation.
- **Box 2 (Water Exposure):** DRI dust exposed to water, allowing for evaporation under normal conditions, followed by one week of exposure to ambient lab air.
- **Box 3 (Elevated Temperature and Humidity):** DRI dust stored in a climate closet at 60°C and 80% humidity.
- **Box 4 (Continuous Water Immersion):** DRI dust continuously immersed in deionized water.
- **Box 5 (Saltwater Immersion):** DRI dust immersed in saltwater (35g salt/1L water) for one week.

Results and discussion: Storing DRI (D) Dust Under Different Conditions

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Table 1. Explosion parameters of the samples

Storage conditions	Storage conditions	$P(ex)_{max}$, bar	Weakening efficiency (WE), %
Box 1	Control	4,5	-
Box 2	Water Exposure	4,3	4
Box 3	Temperature 60°C Humidity	4,2	7
Box 4	Continuous Water Immersion	3,8	16
Box 5	Saltwater Immersion	3,2	29

- The storage conditions have a **decreasing effect** on the maximum pressure as soon as was faced water influence.
- While the effects in **Box 2 and 3** may be deemed insignificant **(up to 7%),** the constant presence of water and saltwater in **Box 4 and 5** does indeed exert a more substantial influence **(up to 29%).**
- Iron oxides exhibit inhibitory effects, which can lessen the severity of iron dust explosions and dampen the combustion process.

Results and discussion: Storing DRI (D) Dust Under Different Conditions

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Table 2. Explosion parameters of the samples

Storage conditions	Storage conditions	$\frac{dP}{dt}_{max}$	Weakening efficiency (WE), %	K_{st}
Box 1	Control	130	-	35
Box 2	Water Exposure	106	18	29
Box 3	Temperature 60⁰C Humidity	135	- 3,8	37
Box 4	Continuous Water Immersion	152	- 16,9	41
Box 5	Saltwater Immersion	124	4,6	34

- The apparatus-specific measurement tolerance for dp/dt values ≤ 185 bar/s is specified as 30%.
- The rate of pressure rise doesn't demonstrate a tendency regarding aging process.
- All measured values are within the limits of the tolerance, which makes it impossible to quantify the difference between the rates of pressure rise of DRI D fines samples.

Results and discussion: Storing DRI (D) Dust Under Different Conditions

- The mechanism of explosion after storage remains the same : **rate of explosion pressure rise reaches its maximum almost immediately after ignition.**
- Notably, the pressure rise profile of the igniters shows a strong similarity to the initial phases of pressure increase during dust explosions. It is likely that the pressure rise rates of DRI/HBI dust are lower than those of the igniters.
- [9] comes to the same conclusion for iron dust and mixtures with iron oxides.
- **As an evaluation parameter, for example, for the effects of aging, this indicator should not be used.**

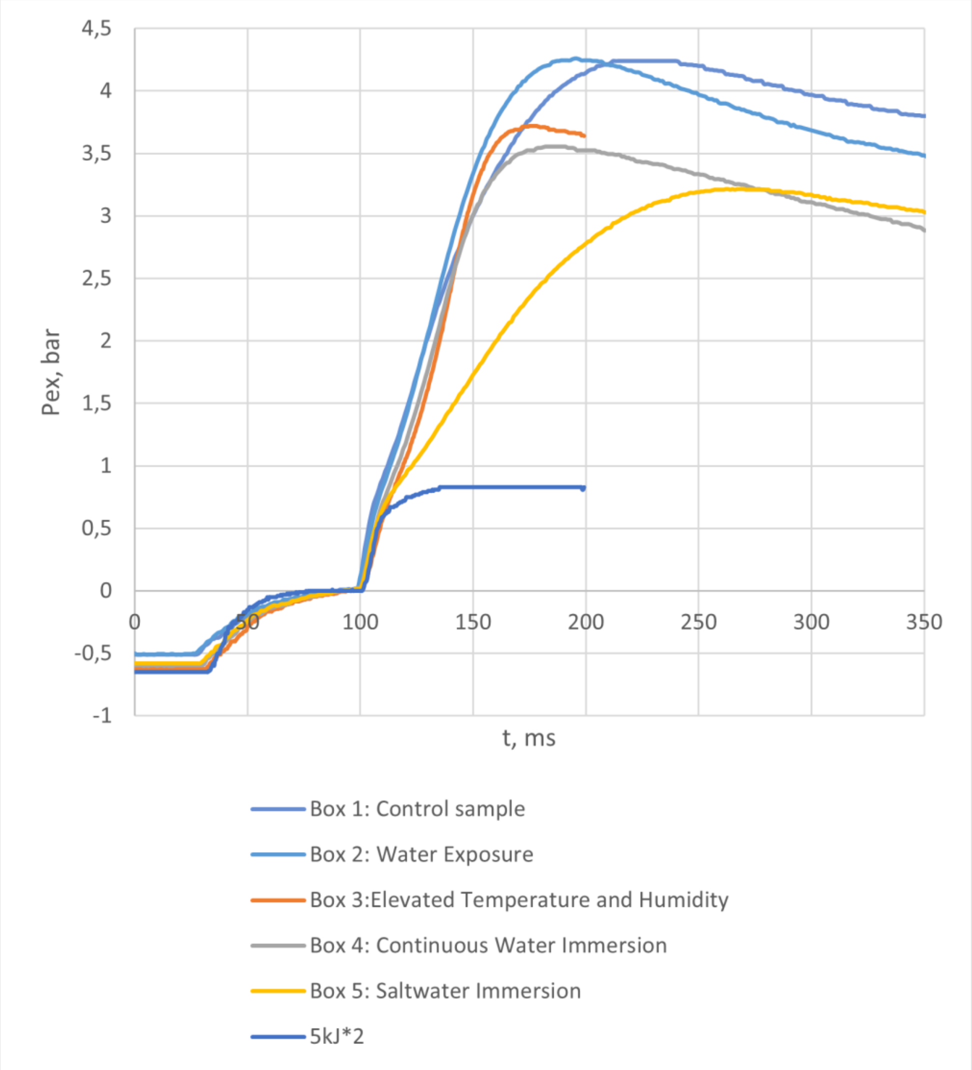

Fig.13. Explosion process curve of DRI (D) dust in the standardized 20-L apparatus after different storage conditionals at the concentration of 3000 g/m^3.

Results and discussion:

- This ignitors effect could lead to the assumption that the ignition effect leads to overdriving phenomena and that in reality DRI D is even less explosive.
- According to the available data, iron powders produced lower K_{St} values in the 20 L, then in the 1-m^3 vessel (table 3) [7].

Table 3 - Explosion safety parameters for iron dust [7].

	Siwek 20-L		Fike 1-m3		
	P_{max}, bar	K_{st}, bar·m/s	P_{max}, bar	K_{st}, bar·m/s	Class
Fe 101	3.1	27	4.5	64	1
Fe 102	3.0	34	4.4	56	1
Fe 103	1.9	2	1.5	5	1

Results and discussion:

- Possible reason for such behavior was explained through simulation process:

- The 20 L vessel shows a non uniform degree of turbulence, due to the following presence of the thermal effect it resulting in not reliable and not repeatable measurements of the explosibility parameters [11].

- Also, 20 L dispersion system, according to [12], demonstrates uneven distribution of the dust cloud, which leads to non-spherical deflagration.

Results and discussion:

Based on the obtained results and literature review, several issues have been identified when measuring DRI D fines explosions:

- Ignitors effect
- Non-Uniform Turbulence
- Uneven Dust Cloud Distribution

- This suggests that **existing testing procedures**, particularly those using 20 L spheres, may underestimate the explosibility of low- explosive dust, highlighting the need for deep evaluation of current standard test procedures and improvement **in order to enable further research on parameters, which influences explosibility of DRI D fines.**

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Conclusion

1. DRI D fines fall into the first explosive class, categorizing them as low-explosive dust—similar to iron dust in general.

2. Here are the key parameters: the Minimum Ignition Energy (MIE) exceeds 1,000 mJ, the Lower Explosion Limit (LEL) is set at 450 g/m³, the maximum explosion pressure $(P_{ex})_{max}$ was 4.5 bar, and the maximum rate of pressure rise $(dP/dt)_{max}$ was 130 bar/s.

3. Due to the low explosiveness of DRI D, the pressure curve is significantly influenced by the effects of the igniter, making it difficult to provide accurate data on the the maximum rate of pressure rise $(dP/dt)_{max}$.

Conclusion

4. The created storage conditions diminish the maximum explosion pressure. While the effects in Box 2 and 3 may be deemed insignificant (up to 7%), the constant presence of water and saltwater in Box 4 and 5 does indeed exert a more substantial influence (up to 29%), which can be attributed directly by oxidation of DRI (D) dust during storage.

5. The effect of ignitors does not allow to estimate the change of maximum rate of pressure rise from aging process. This makes it difficult to evaluate in futher research other influencing factors such as size distribution, specific surface area, moisture content in terms of main trends of they influence on ignitability.

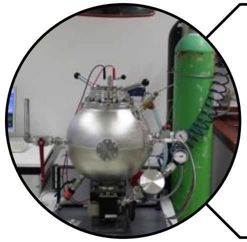
6. Current state of art on the iron dust explosions underlines the necessity of further investigation on accuracy of the current testing methods to enable estimation of change of rase of pressure rise.

EU Project Safe H-DRI

Safe H-DRI project is an essential start to understand how future H_2-based DR will affect the H-DRI transport and supply across Europe and to create guidelines for a safe and stable handling.

Safe transport of H-DRI;

For a safe and stable transport and storage of H-DRI, reactivity in terms of self-heating and H2 formation will be investigated. Two numerical approaches: a simple reactor model and reactive DEM-CFD.



Based on the structure, degree of metallization and size distribution, the fines of H-DRI can deflagrate in air. The explosion behavior of DRI fines will investigated.

Thank you for your attention!

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