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RESEARCH ARTICLE

REVISED Towards standardized safety protocols for iron-based energy carriers: International alignment through round robin testing on safety characteristics

[version 2; peer review: 2 approved with reservations]

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Abstract

Background

Iron powder appears to be a promising solution for long-term energy storage and (inter-) continental transport, as it is safe to store and does not require energy to maintain its state, unlike, for instance, liquefied hydrogen. However, while the fundamental research is well underway, large-scale implementation is still in its early stages, with a growing number of promising demonstrators emerging.

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Methods

This article contributes to the large-scale implementation of iron as an energy carrier by presenting a round-robin test of four iron powders currently used in research and larger-scale demonstrators. These powders were tested on their safety characteristics in the standard 20 L apparatus across eight European countries.

Results

The resulting data are intended to support future standardization efforts using different iron samples as standardized fuel. All tested powders were classified either as non-explosible or as belonging to the category of marginally explosible dusts (Class 1). This provides a clear picture of the level of explosion protection measures that need to be considered for the safe use of iron powders in energy carrier applications.

Conclusions

Along with that, the study detected variations in the results and pointed to shortcomings in the current standards that may cause such discrepancies. These findings emphasize the importance of improving testing procedures to support standardization and ensure the safe use of iron powder as an energy carrier using an a-priori-approach rather than subsequent testing.

Keywords
MeCRE, Safety Characteristics, Chemical Energy Carriers, Clean Energy Transition, Standardized Iron Fuel, Dust explosions

HE This article is included in the Horizon Europe gateway.

2. **Aki Fujinawa**, University of Cambridge, Cambridge, UK

Any reports and responses or comments on the article can be found at the end of the article.

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REVISED **Amendments from Version 1**

San Cristobal, 21st of May 2026

The revised manuscript addresses a broad range of methodological, presentational, and scientific concerns raised by the reviewers.

On the methodological side, the authors clarified how explosion parameters are determined in line with EN 14034 and ASTM E1226 standards, and updated tables to include standard deviations where multiple experimental series were available. Graphical representations of explosion overpressure and rate of pressure rise as a function of dust concentration were added, accompanied by a discussion of the observed deviation from typical literature trends, particularly the absence of a distinct pressure maximum for iron dust. The injection dynamics at high dust concentrations are now more explicitly addressed.

Particle size data, previously presented in a potentially misleading box-plot format, have been replaced with a table reporting d10, d50, and d90 values per laboratory along with the measurement method used which is a clear improvement in transparency. The discussion of sources of experimental scatter has been expanded, and concrete recommendations for future studies are now included.

Structural and presentational issues have also been resolved: figure–text alignment was corrected, y-axes now correctly indicate overpressure, K_{St} values were added to the tables, and the comparison of iron with other energy carriers was moved from the conclusion to the introduction where it belongs. Several phrasing improvements were implemented throughout. In total, ten figures were added to the revised manuscript, and one existing figure was modified, reflecting the extent of the visual revisions made.

Two points merit continued attention: the introduction's literature survey, while revised, should be carefully verified for referencing accuracy; and the absence of EDX analysis on regenerated samples, though acknowledged, remains a limitation the authors attribute to practical constraints rather than scientific reasoning.

Stefan H. Spitzer sr. (on behalf of all authors)

Any further responses from the reviewers can be found at the end of the article

1. Introduction

The need for alternative carbon-free energy sources is becoming increasingly crucial in achieving the goals of the Paris Climate Agreement. Although solar and wind power are promising solutions for energy production, their inherent intermittency in both time and location requires efficient energy storage and transport.

The use of metals as energy carriers to decarbonize the energy sector appears to be a promising solution. This approach offers several key advantages: metals are among the most energy-dense zero-carbon energy carriers, are non-toxic in bulk form, relatively easy to recycle, and allow energy to be stored over long periods without losses.[1–3]

In particular, iron is not classified as a critical or conflict material[4] and is abundantly available across all continents and countries.[5] If renewable energy is available, the iron energy carrier cycle can operate in a loop, allowing the stored chemical energy to be released as heat (see Figure 1). Alternatively, it is also possible to react iron powder with water vapor, resulting in the release of hydrogen. Thereby, the iron powder effectively acts as a hydrogen carrier.

The chemical reactions governing combustion (Equation 1) and hydrogen production (Equation 2) are:

$$4Fe + 3O_2 \rightleftharpoons 2Fe_2O_3, \Delta_R H_{298K} = -1640\,kJ/mol \quad (1)$$

$$3Fe + 4H_2O_{(v)} \rightleftharpoons Fe_3O_4 + 4H_2, \Delta_R H_{298K} = -129\,kJ/mol \quad (2)$$

The re-charging phase with hydrogen reduces the iron oxide formed during combustion back to iron and water (Equation 3):

$$Fe_2O_3 + 3H_2 \rightleftharpoons 2Fe + 3H_2O_{(v)}, \Delta_R H_{298K} = +86\,kJ/mol \quad (3)$$

The concept of using iron for long-term energy storage has been known for more than a century[6] and is now gaining renewed momentum due to the need for a safe and dense energy carrier to solve the inherent intermittency of renewable energy. Although iron as an energy carrier is largely absent from mainstream discussions,[7–9] the landscape is rapidly changing. Start-ups such as RIFT, AMBARtec AG, Fenix Energy, and Iron+ are actively rolling out pilot plants and launching the first commercial installations.[10]

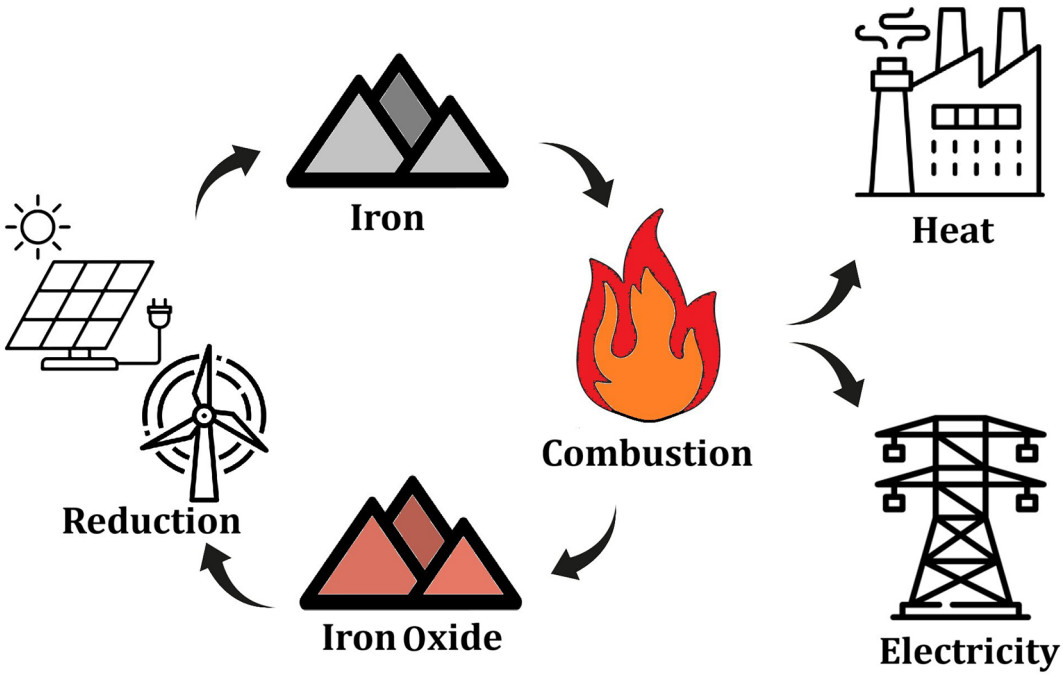

Figure 1. Schematic of the cycle using iron as an energy carrier: If renewable energy is available in surplus, the iron oxide gets reduced. If energy or heat is needed, the iron is burned.

Table 1. Comparison of selected energy carriers with respect to energy density and explosion characteristics.

Energy carrier	Energy density (MJ/kg)	MIE (mJ)	p_{max} (bar g)	$K_{St/G}$ (bar·m/s)
Iron	7 [11]	n.a.	5.2 [12]	50 [12]
Aluminium powder	31 [13]	3 [14]	12.5 [12]	1100 [12]
Brown coal (dust)	10 [15]	160 [12]	9.1 [12]	143 [12]
Bituminous coal (dust)	24 [16]	60 [17]	9.1 [12]	86 [12]
Wood dust	17 [18]	7 [12]	9.2 [12]	102 [12]
Crude oil	47 [15]	n.a.	n.a.	n.a.
Gasoline	44–46 [15]	0.8 [19]	7.9 [20]	47.66 [21]
Diesel	42–46 [15]	n.a.	7.4 [20]	n.a.
Methane	50–55 [15]	0.29 [20]	7.1 [20]	56.7 [20]
Hydrogen	120–142 [15]	0.017 [20]	7.3 [20]	976.6 [20]

However, as with many energetic materials, iron powder can pose an explosion hazard when dispersed in air, for example during handling or transport, where it may form explosible dust–air mixtures. Table 1 provides an overview of the key explosion characteristics of iron and other common energy carriers. Compared to many conventional solid, liquid and gaseous energy carriers, iron dust generally exhibits a lower explosion severity.

In order to enable large-scale deployment, it is essential that the safety characteristics of iron dust are well understood, and that appropriate explosion protection measures are formally addressed through standardised guidelines. This paper makes an important contribution by establishing a solid foundation for such efforts through international round-robin testing, providing valuable and reliable data to support the development of dedicated safety standards for applications involving iron energy carriers.

Safety characteristics for gases, vapors, and dusts are typically found in databases, but contrary to gases and vapors, available data for dusts show a large spread and cannot be applied directly, as the results are less reproducible and difficult

to implement in practice without conducting additional experiments. This is due to four influencing parameters that significantly affect their safety characteristics.

- Chemical properties (see 3.1)
- Moisture content (see 3.2)
- Particle size distribution (see 3.3)
- Particle morphology

In contrast, this study employs iron powders that were produced under identical conditions and characterized by the same chemical composition, moisture content, particle size distribution, and morphology. This minimizes variability and enables a clear assessment of whether the powders can be considered explosible under standardized testing, with safety aspects integrated from the beginning.

To date, driven by the increasing application of iron powders in emerging energy and industrial systems, research on the combustion behaviour of iron powders has expanded significantly. A substantial body of work has focused on single-particle combustion,[22–28] providing fundamental insights into ignition mechanisms, burning rates, and oxidation pathways under well-controlled conditions. Beyond single-particle combustion, further studies have addressed the behaviour of particles in clusters, suspensions and powder beds,[25,29–32] as well as combustion modes, including laminar flame propagation.[33–38] These studies improve the understanding of collective combustion phenomena, such as particle–particle interactions and heat transfer within reacting clouds. However, they are typically conducted under controlled, idealized conditions, which limits their direct applicability to industrial dust-explosion scenarios. In contrast, studies directly addressing the explosion behaviour of iron dust and safety-related characteristics of iron dust, such as standard explosion parameters (e.g., maximum explosion pressure and rate of pressure rise), are reported,[12,39–48] but remain comparatively limited. According to a previous study,[39] which summarises the available literature, iron dust is generally classified as St1, representing the lowest explosion class and meaning it is marginally explosible. It has been previously investigated and stated that the reproducibility of safety characteristic measurements of marginally explosible dusts, especially iron dusts, can be poor.[49–51] Therefore, despite significant progress in understanding the fundamental mechanisms of combustion and flame configurations, a consistent, safety-oriented understanding of explosion behavior under standardised testing conditions — as required for industrial safety assessments — is still lacking.

After a first general approach to an a-priori-prediction of the safety characteristics of pure iron energy carriers,[39] this article represents a second step towards the development of a standardized iron powder as a dense energy carrier with the safety aspect implemented from the beginning. The aim is to establish an internationally harmonized understanding of the potential explosion hazards associated with this emerging technology and to define appropriate safety measures, fostering a holistic safety culture from the very beginning of its implementation. These data are also essential in a regulatory context, for example, within the framework of TDG/ADR for transport, REACH for substance registration and Safety Data Sheets, ATEX for the management of explosive atmospheres, and national regulations such as ICPE in France for industrial safety.

2. Experimental

2.1 Experimental materials

The dust samples were provided by Pometon S.p.A. and Eindhoven University of Technology. Four types of iron dusts were tested: MT63, MT150, MT63reg, and MT150reg. The term “reg” indicates regenerated powders that have already undergone one combustion–reduction cycle.

The original MT63 and MT150 powders are produced by water atomization from molten scrap metal. For the regenerated powders, the reduction was performed in a mesh belt furnace operating at temperatures between 1000–1100°C with the addition of hydrogen, following combustion of the original MT63/150 powder in a 500-kWth pilot-scale industrial burner described in[52] (Figures 2 and 3). After the reduction process, the iron is hammer-milled to produce a suitable particle size for combustion. Regenerated samples have a flaky shape due to the hammer-milling. The MT63reg sample has a



Figure 2. **Picture of the reduction belt furnace.**



Figure 3. **Picture of the MP500 iron powder boiler.**

*d*50 of about 50 μm, while the MT150reg sample would fall outside some standards because it is too coarse to be considered dust [1]. However, all powders have been successfully combusted in the pilot-scale MP500 burner and are therefore representative of iron powder for future power plants.

[1]According to the European and International standards for the determination of safety characteristic of dusts, dust is defined as solid particles with a diameter below 500 μm.[53–57] The American standard applies for particles below 75 μm[58] and the German compulsive regulatory differentiates between dust layers (particles below 250 μm) and elevated dusts (particles below 63 μm).[59] However, the superordinate German regulatory again defines everything below 500 μm as a dust.[60]

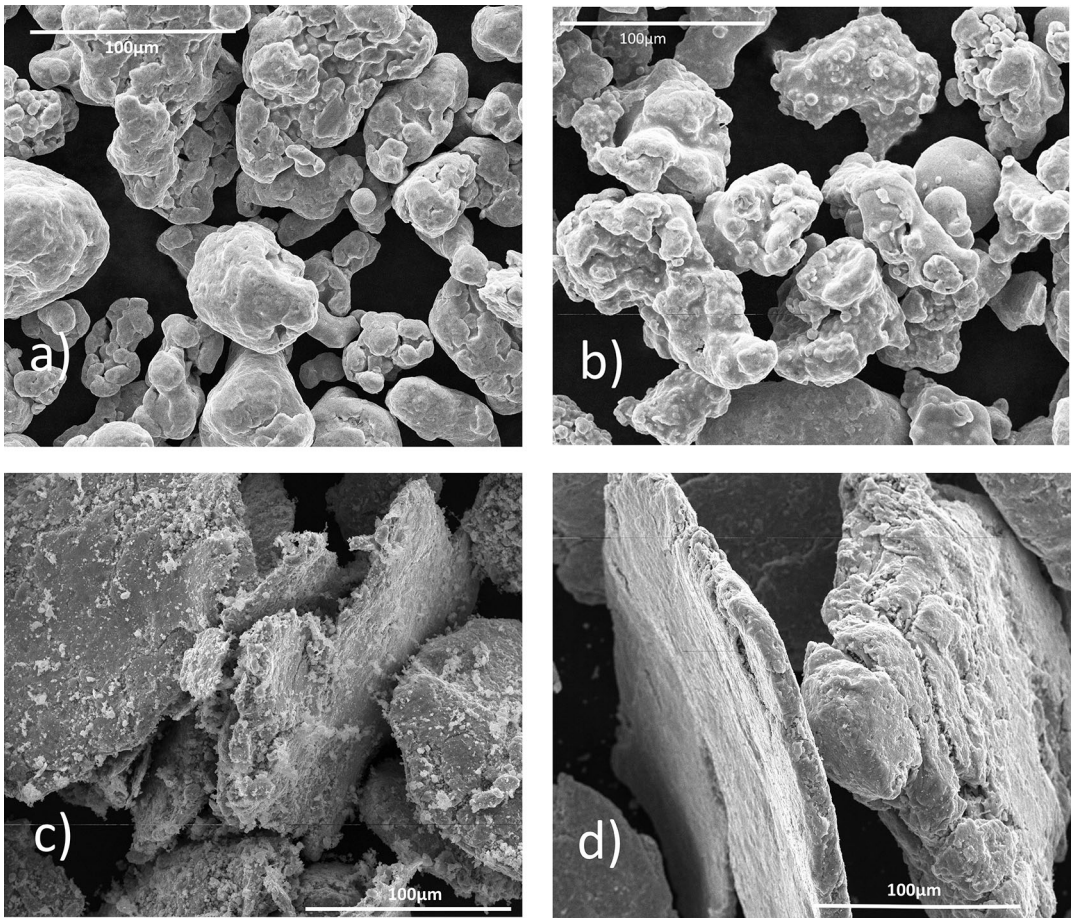

Figure 4. Scanning Electron Microscopy (SEM) images showing a) MT63, b) MT150, c) MT63reg, and d) MT150reg.

All samples were characterized by their water content and particle size distribution (see Chapters 3.2 and 3.3). Although the surface morphology is not discussed further, the SEM images are provided in Figure 4 for reference. The tested iron dusts include:

- MT63: Iron dust freshly produced via water atomization, characterized by irregular, "potato-shaped" particles that are nonporous.
- MT150: Iron dust freshly produced via water atomization, characterized by irregular, "potato-shaped" particles that are nonporous, but coarser than MT63.
- MT63reg: Iron dust regenerated in a belt furnace following one combustion–reduction cycle, resulting in porous, thin, flake-like particles.
- MT150reg: Iron dust regenerated in a belt furnace following one combustion–reduction cycle, with porous, flake-like particles, but coarser than MT63reg.

2.2 Chemical composition

The chemical composition of the MT63 and MT150 powders was analyzed at the Bundesanstalt für Materialforschung und -prüfung (BAM) using energy-dispersive X-ray spectroscopy (EDX). The measurements were conducted in a Phenom XL G3 SEM (Thermo Fisher Scientific Inc.) with an acceleration voltage of 15 kV at a reduced pressure of 1–6 *bar*. For each sample, several measurements at different spots were carried out. In addition, line scans and mappings were recorded to investigate the elemental distribution. The level of impurities in the MT63reg and MT150reg powders can be assumed to be similar to the original MT63 and MT150, respectively, considering that no impurities were added

during the combustion process. During the first combustion–reduction cycle, only minor changes in impurity concentrations can be expected to occur.[61,62] All powders were also tested for their crystalline composition using X-ray diffraction (XRD) and for their oxygen content using inert gas fusion (IGF) at Eindhoven University of Technology.

2.3 Experimental procedures

The dust samples were shipped to the Technical University of Leoben. There, the moisture contents, particle sizes, and safety characteristics were analyzed and subsequently packed and distributed to the other participating institutions:

- VSB – Technical University Ostrava, Czech Republic
- Slovak University of Technology in Bratislava, Slovakia
- ADINEX NV, Belgium
- Otto-von-Guericke University Magdeburg, Germany
- Bundesanstalt für Materialforschung und -prüfung (BAM), Germany
- Politecnico di Torino, Italy
- CMI – National Research Institute – Experimental Mine "Barbara", Poland
- INERIS, Verneuil-en-Halatte, France

In general, round-robin particle characterization and explosion tests were carried out in nine facilities from eight different countries (see Figure 5).

As part of the coordinated effort, the institutes provided measurements of the moisture content, the particle size distribution, and the safety characteristics: explosibility, p_{max}, and $(dp/dt)_{max}$, or rather K_{st}, for the four dusts, determined according to standardized procedures described in ISO 80079-20-2 and the EN 14034 series.[53,54,57]

These safety characteristics were determined in standard 20-L spheres from different manufacturers. The main steps for the determination of safety characteristics are as follows (see also Figure 6):

1. Evacuation of the explosion vessel to a defined vacuum (0.4 *bar* absolute)
2. Pressurizing the dust chamber to a defined overpressure (21 *bar* absolute)
3. Opening of the fast-acting valve
4. Triggering the ignition source (2×1 kJ for explosibility, 2×5 kJ for p_{max} and $(dp/dt)_{max}$ after a defined ignition delay time of 60 ms
5. Recording and evaluating the pressure development

The dust is classified as non-explosible if no ignition test with an ignition energy of 2×1 kJ shows a pressure rise above 0.5 *bar g* over a wide dust concentration range[57] (see Figure 7).

To determine p_{max} and $(dp/dt)_{max}$, the explosion overpressure p_{ex} and the rate of pressure rise $(dp/dt)_{ex}$ are determined for each dust concentration and plotted as a function of dust concentration until a maximum value is obtained. The tests are performed for at least two consecutive concentrations on both sides of the maximum. This maximum corresponds to the maximum explosion overpressure p_{ex} and the maximum rate of pressure rise $(dp/dt)_{max}$. If the procedure does not yield a clearly defined maximum, the test series is repeated in the region of the maximum. In such cases, the arithmetic mean of the peak values obtained in each test series is taken as maximum explosion overpressure p_{ex} and $(dp/dt)_{max}$. The maximum explosion overpressure is processed with Equations 4 and 5 to determine p_{max}.[54,58] The K_{st} value is calculated from $(dp/dt)_{max}$ according to Equation 6.[53]

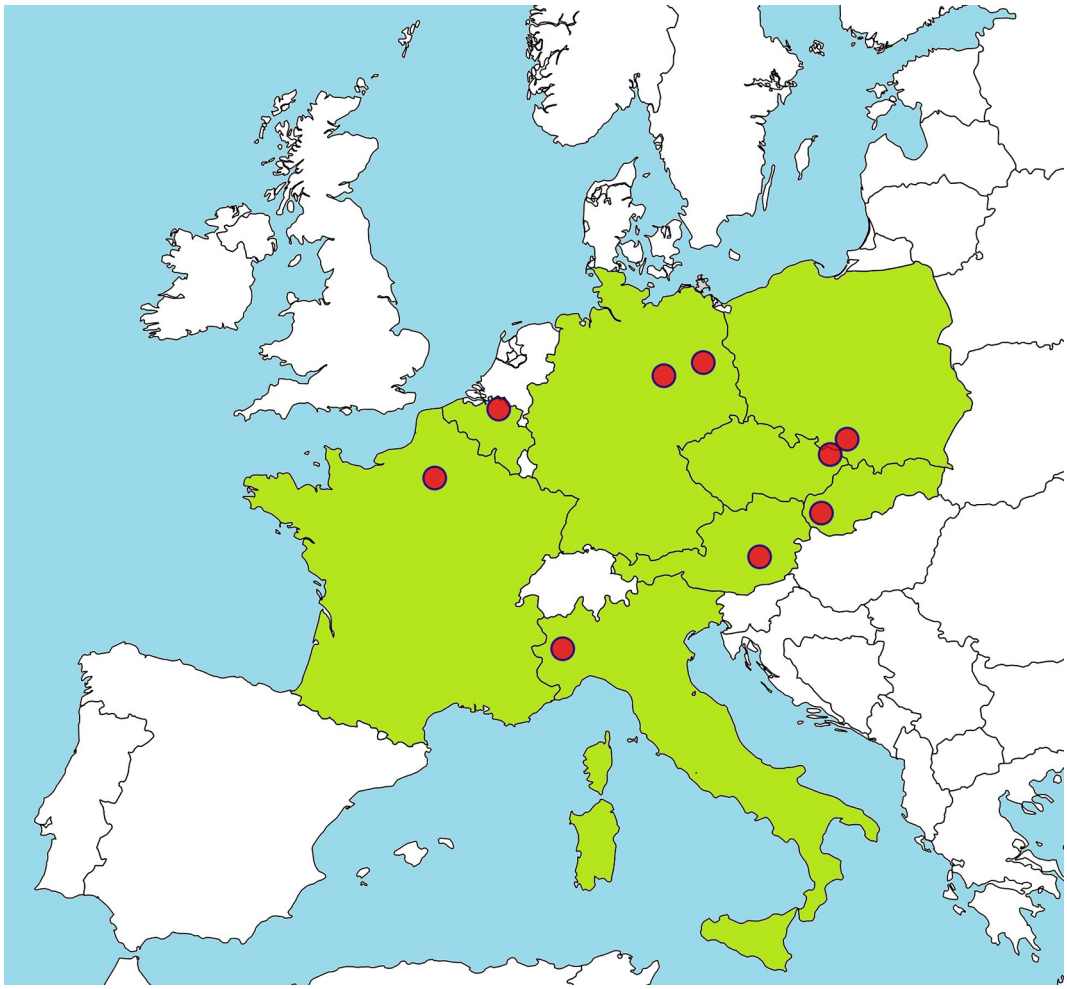

Figure 5. Location of the nine participating facilities in central Europe.

$$p_{max} = 5.5 \cdot \frac{p_{ex,max} - p_{ci}}{5.5 - p_{ci}} \tag{4}$$

$$p_{ci} = \frac{1.6 \cdot E_i}{10000} \tag{5}$$

$$K_{St} = \left(\frac{dp}{dt}\right)_{max} * V_{\text{TestVessel}}^{1/3} \tag{6}$$

Although the test procedure is clearly defined in the standards, certain degrees of freedom in their execution, combined with the specific characteristics of iron dusts, can lead to deviations in the test results.

First, iron has a high density, and flame propagation can be observed at concentrations that are higher than for other dusts (e.g., coal or organic dusts such as flour). The dust concentrations in EN 14034–1/2 are not strictly predefined; instead, a recommendation is given: *"The dust concentration is varied over a wide range from 250 g/m³ to 1500 g/m³ (typically 250 g/m³, 500 g/m³, 750 g/m³, 1000 g/m³ and 1500 g/m³) and the pressure increase is measured"*.[53,54] It is further stated that in the case of high-density materials such as metals, higher concentrations (e.g., up to 2500 g/m³) are permitted. However, the testing procedure has practical limitations due to the need to inject the dust into the vessel using an overpressure (21 *bar* absolute) through an outlet valve and a rebound nozzle. The pressure increase in the sphere is typically around 0.6 *bar*, within a permissible range of 0.55–0.75 *bar*. Variations within this range may introduce small differences in the initial conditions.

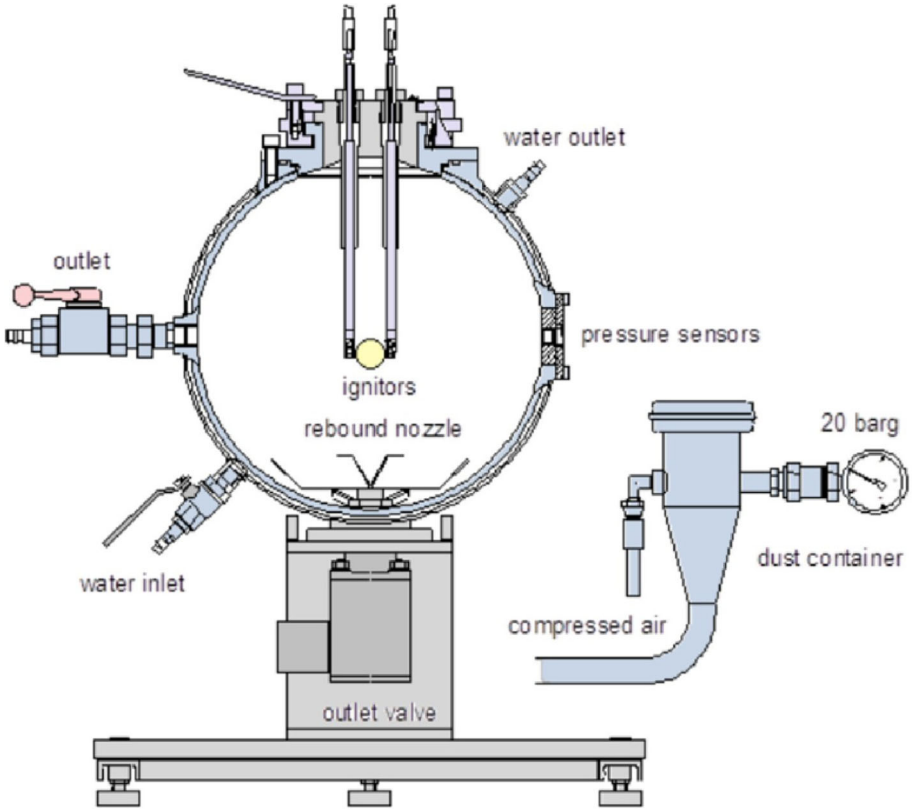

Figure 6. **Schematic of the 20 L-sphere. Taken from.**[63]

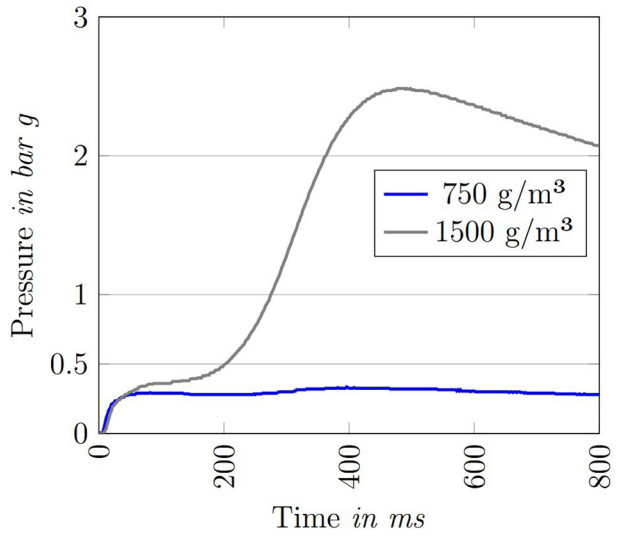

Figure 7. **Example of the measured pressure development for an iron dust sample: At a concentration of 750 g/m^3 there is no ignition, whereas at 1500 g/m^3 the pressure exceeds the threshold value of 0.5 *bar g*.**

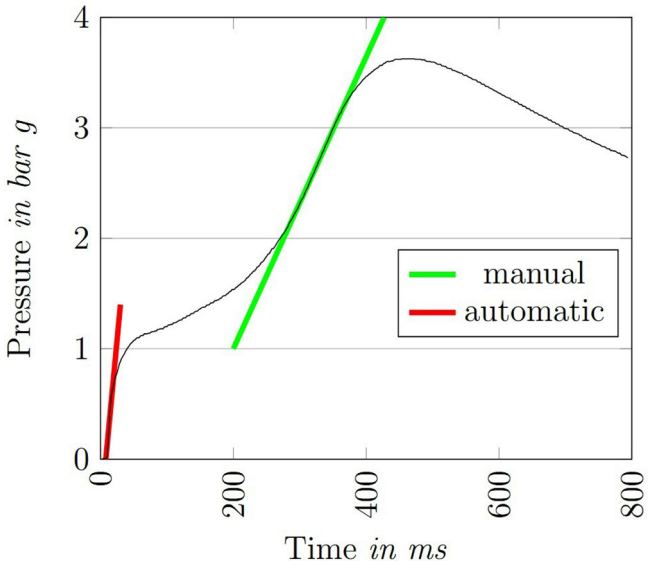

Figure 8. Example of the measured pressure development for MT63 at a concentration of 2000 g/m³: difference in automatic and manual determination of dp/dt.

At high dust concentrations and for high-density materials such as iron dust, not all of the injected air expands uniformly into the vessel before ignition. At concentrations above 1000 g/m^3, the injection pressure is no longer sufficient to convey all dust into the sphere while still ensuring an initial pressure of 1 *bar* abs. As a result, ignition can occur at pressures below atmospheric conditions, leading to an underestimation of the measured pressure rise. Several approaches can be considered to address this limitation; however, most of them are restricted by standard test procedures:

- Increasing the pressure in the dust container to pressures above 21 *bar* (not allowed according to the standard)
- Increasing the initial pressure in the sphere before injection (also not allowed according to the standard)
- Testing the dust at pressures below ambient pressure (allowed but not recommended)
- Placing some of the dust sample or all of it in the container (allowed but not commonly applied; this also influences all safety characteristics[64,65])

In addition to these experimental constraints, the application of correction methods can further influence the interpretation of the results. Equation 4 stretches the measured values from a range of $5.5 - p_{ci}$ to 5.5 (p_{ci} is the pressure increase due to the igniters), which leads to an increase in the scattering of 41%. This means that small differences between individual measurements become amplified in the corrected values. This amplification should be considered when interpreting the results, since it may introduce additional variability that is not present in the raw measurements.

While the above aspects relate to the testing procedure, additional complexity arises from the intrinsic combustion behavior of iron dust. Iron dust is known for its relatively slow ignition behavior. It is often observed that a first pressure increase, caused by the igniters, is followed by a delayed second increase when iron dusts are tested.[41,44] When the rate of pressure increase is determined automatically by the software, the first slope is used to determine the rate of pressure rise, while the iron itself reacts at a slower rate (see Figure 8).

Given the possible deviations caused by different determination techniques, all raw data were collected and analyzed in a consistent way. In this article, the rate of pressure rise is always determined from the second slope, not the first, which is allowed according to the American standard,[58] but not stated in the European standard.[53] For datasets where only values based on the first peak were initially reported, the corresponding values were re-evaluated by the authors using the second pressure rise peak from the available raw data.

3. Results and discussion

3.1 Chemical composition

The results of the chemical analysis for the powders are shown in Tables 2 and 3.

The EDX analysis data show that, as expected, the samples consist mainly of iron. However, MT63 and MT150 also contain significant amounts of oxygen, which indicates that some of the iron is present in oxidized form. The EDX mappings in the supplementary material, which show the distribution of elements, reveal that, unlike iron, oxygen is not distributed evenly throughout the sample, but rather occurs in distinct oxygen accumulations. This suggests the presence of discrete iron oxide accumulations within the powders.

Apart from oxygen, the samples contain no significant impurities. Although other elements such as copper and molybdenum were detected, their fractions are in very low range of less than 1 per cent.

The XRD measurements, conducted at TU Eindhoven, also show high values of iron and little to no impurities.

3.2 Moisture content

All facilities tested the dusts for their moisture content. The moisture content was analyzed using the DIN EN ISO 18134-1 method.[66] The results showed moisture contents for all samples ranging from 0.0 to 0.5 wt%, which is notably low and therefore neglected during further evaluation. The variations in the results presumably arise from differences in the testing methods, environmental conditions during transportation, or the relative humidity of the surrounding air in the laboratory during testing.

Table 2. EDX analysis for MT63 and MT150, averaged values from 14, respectively 11 analyses. The full analysis with all tests for each sample can be found in the Supplementary Material.

	Atomic fraction in %	Weight fraction in %
MT63		
Iron	89.2	95.9
Oxygen	9.5	3.1
Aluminum	0.4	0.2
Silicon	0.3	0.1
Copper	0.3	0.4
Molybdenum	0.1	0.2
Sulfur	0.1	0.0
MT150		
Iron	77.5	91.5
Oxygen	21.5	7.8
Aluminum	0.3	0.2
Silicon	0.5	0.3
Chromium	0.1	0.1

Table 3. Crystalline composition and oxygen mass fraction of the four powders. No other compounds were found in the XRD pattern.

Powder	Fe [wt%]	FeO [wt%]	O wt% by XRD	O wt% by IGF
MT63	98.8	1.2	0.3	0.6
MT150	97.3	2.7	0.6	0.9
MT63reg	82.6	17.4	3.9	4.5
MT150reg	96.7	3.3	0.3	2.3

The values are so low that their impact on the safety characteristics can be considered negligible, as the mass of water is insufficient to act as a heat sink or influence the dispersion of the powder. Most investigations on the influence of moisture content on the explosion characteristics of dusts deal with values of several percent and higher, not below 1 wt%.[67,68]

3.3 Particle size distribution

All facilities analyzed the particle size distribution using the laser diffraction method (ISO 13320:2020)[69] or mechanical sieving (ÖNORM EN 15415–1).[70] The characteristic particle size parameters d_{10}, d_{50}, and d_{90} reported by the laboratories are summarized in Table 4 and Figure 9. Figure 9 presents the statistical distribution of particle sizes (D10, D50, D90) for all investigated powder samples. The graph was constructed using data obtained from both laser diffraction and mechanical sieving methods. The corresponding numerical values are summarized in Table 4, where the results are additionally distinguished based on the measurement technique (sieving and laser analysis).

The results demonstrated a similar size distribution with only minor differences between laboratories for MT63, MT150, and MT63reg (see Table 4). Larger deviations are observed for MT150reg, particularly for d_{90}, which indicates the presence of coarse particles in some subsamples and suggests a lower homogeneity of this powder.

In cases where both measurement methods were applied, the values obtained by laser diffraction tend to be higher than those obtained by sieve analysis, particularly for the upper percentile d_{90}. This difference reflects the fundamental differences between the methods. Laser diffraction determines an equivalent spherical volume diameter and is sensitive to irregularly shaped particles or agglomerates, which can increase the upper percentiles of the distribution. In contrast, sieve analysis is based on the smallest particle dimension that allows passage through the mesh opening and may therefore underestimate the contribution of irregular or weakly agglomerated coarse particles.[71]

For the interpretation of the explosibility data, it is essential to have reliable information on the particle size range. At the same time, it must be emphasized that different characterization techniques come with inherent limitations. Thus, the observed deviations between laboratories do not indicate different samples but rather reflect method-specific sensitivities (e.g., laser diffraction vs. sieve analysis).

3.4 Safety characteristics

3.4.1 Explosibility

First, all samples were tested for explosibility according to ISO 80079-20-2 using two 1 kJ ignitors. If an explosion was detected, further tests were conducted to determine explosion parameters according to EN 14034–1/2,[53,54] using two 5 kJ ignitors.

Table 4. Characteristic particle size parameters (*d*10, *d*50, *d*90) reported by the participating laboratories.

Sample/Lab. number	MT63			MT150			MT63reg			MT150reg		
D, μm	d_{10}	d_{50}	d_{90}	d_{10}	d_{50}	d_{90}	d_{10}	d_{50}	d_{90}	d_{10}	d_{50}	d_{90}
1	6	48	153	20	58	139	1	31	69	0	66	254
2	27	54	96	41	87	154	-	-	-	-	-	-
5	24	51	90	40	85	141	13	38	69	33	80	139
6	26	47	84	34	72	133	12	39	67	29	69	137
7	26	52	97	32	74	145	20	42	73	37	83	168
8	26	51	86	31	68	128	-	-	-	33	73	151
9	25	52	126	32	76	169	14	40	69	29	72	157
Min. value	6	47	84	20	58	128	1	31	67	0	66	137
Max. value	27	54	153	41	87	169	20	42	73	37	83	254
Median	26	51	96	33	74	141	13	39	69	31	72	154
3*	15	36	70	20	57	108	15	32	54	25	60	113
4*	17	40	68	24	63	110	19	36	58	28	63	116

The asterisk (*) denotes values obtained by sieve analysis. Min, max, and median values were calculated excluding results obtained by sieve analysis. All values were rounded to the nearest integer.

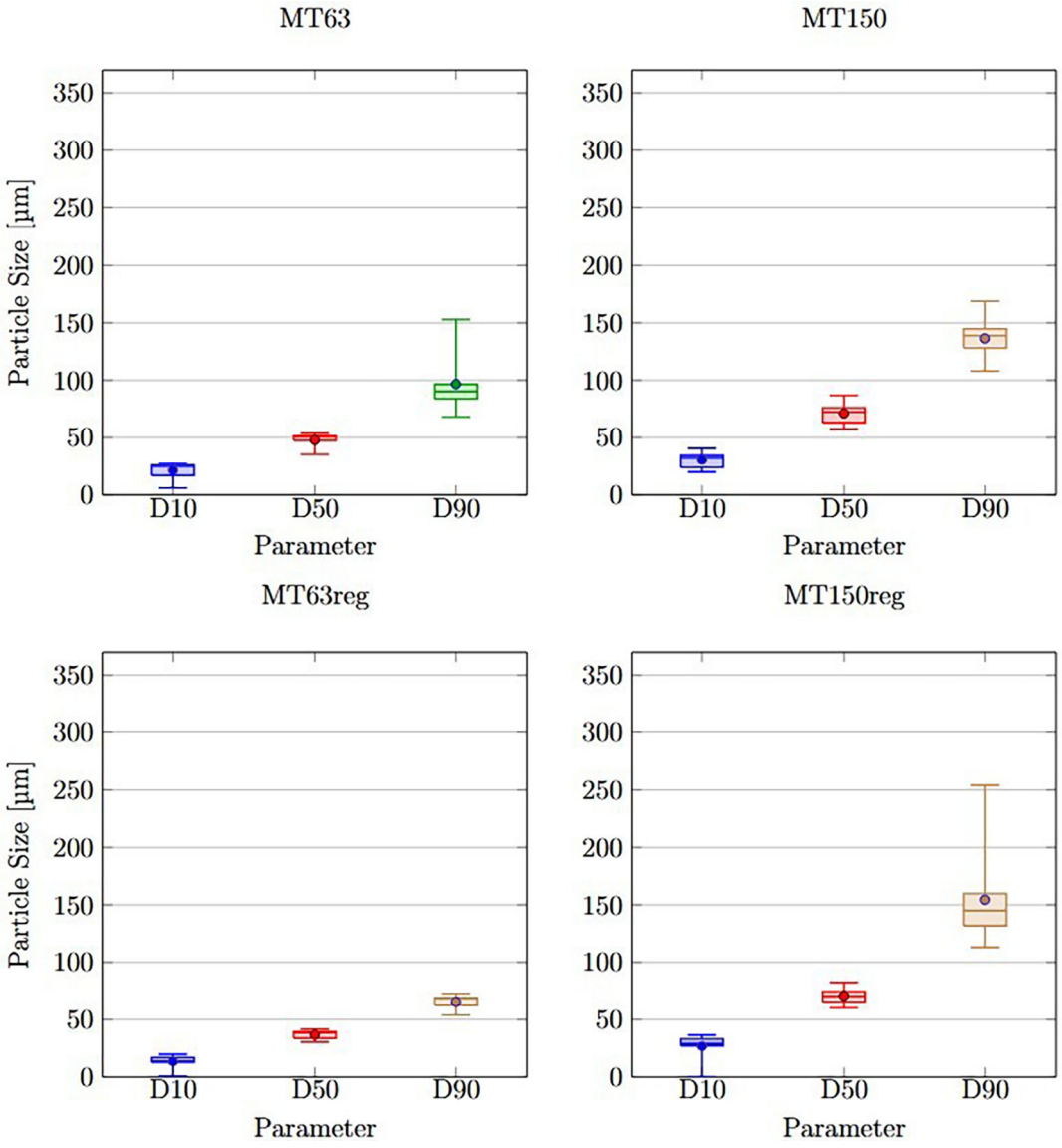

Figure 9. Statistical distribution of particle sizes (D10, D50, D90) for all investigated powder samples (MT63, MT150, MT63reg, MT150reg). The boxplots represent the interquartile range (25th–75th percentile), with the median indicated by a horizontal line inside the box. Whiskers denote the minimum and maximum values. The marker (•) indicates the mean particle size.

The explosibility results for all four dusts are summarized in Table 5. The results of the round-robin test indicate variability in the classification of dust explosibility among laboratories. MT63 was considered non-explosible by six out of nine laboratories, and MT150 by seven out of nine. MT63reg was classified as non-explosible by only one laboratory, whereas MT150reg was classified as non-explosible by six out of nine laboratories. A comparison of the particle size distributions reported by each laboratory (Table 4) with the corresponding explosibility results (Table 5) did not reveal any clear correlation between the characteristic particle size parameters (d_{10}, d_{50}, d_{90}) and the observed explosion behavior.

The observed variations in explosibility results between laboratories may be attributed to the degrees of freedom in the execution of the tests allowed by the standardized procedures, as described in detail in the methodology section. On the one hand, different concentration ranges were considered for the determinations (e.g., up to 1500 or 2500 g/m^3). On the other hand, the initial pressures at which ignition occurred were not always consistent. To overcome the challenge of conveying high-density dust at elevated concentrations (above 1000 g/m^3) into the sphere, some laboratories accepted

Table 5. Explosibility of all four dust samples.

N.	MT63	MT150	MT63reg	MT150reg
1	Explosible	Non-explosible	Explosible	Non-explosible
2	Explosible	Explosible	Explosible	Non-explosible
3	Non-explosible	Non-explosible	Explosible	Non-explosible
4	Non-explosible	Non-explosible	Explosible	Non-explosible
5	Non-explosible	Non-explosible	Explosible	Explosible
6	Non-explosible	Non-explosible	Explosible	Explosible
7	Explosible	Explosible	Explosible	Explosible
8	Non-explosible	Non-explosible	Explosible	Non-explosible
9	Non-explosible	Non-explosible	Non-explosible	Non-explosible

ignition at reduced initial pressures, which may lead to false-negative results. The detailed results of all dust explosion tests conducted by all participating laboratories are provided in the Supplemental Material.

It can be observed that the regenerated samples (MT63reg, MT150reg) showed positive explosion results more frequently than the non-regenerated samples (MT63, MT150). Since only minor differences in particle size distribution were observed, this behavior is more likely associated with differences in particle morphology, as the more porous and flake-like structure increases the specific surface area and thus enhances reactivity.[72]

3.4.2 Explosion severity

For the cases where an explosion was recorded, the safety characteristics such as the maximum explosion pressure p_{max}, the maximum rate of pressure rise $(dp/dt)_{max}$, and the volume-normalized deflagration index K_{st} were determined (Tables 6–9).

Table 6. Evaluation of MT63 explosion indices based on data reported by three participants. Pressure values were rounded to one decimal place, whereas rate of pressure rise values and percentages were rounded to integers.

Parameter [N. participant]	Mean value ± standard deviation	Relative standard deviation [%]
p_{ex} in *bar g*	3.3 ± 0.6	±19
p_{ex} in *bar g* (Lab 1)	3.8 ± 0.6	±17
p_{ex} in *bar g* (Lab 2)	3.6 ± 0.1	±3
p_{ex} in *bar g* (Lab 7)	2.6 ± 0.1	±6
p_{max} in *bar g*	2.5 ± 0.9	±38
p_{max} in *bar g* (Lab 1)	3.1 ± 0.9	±29
p_{max} in *bar g* (Lab 2)	2.9 ± 0.2	±5
p_{max} in *bar g* (Lab 7)	1.4 ± 0.2	±14
$(dp/dt)_{max}$ in *bar/s*	26 ± 7	±27
$(dp/dt)_{max}$ in *bar/s* (Lab 1)	26 ± 8	±31
$(dp/dt)_{max}$ in *bar/s* (Lab 2)	19 ± 5	±27
$(dp/dt)_{max}$ in *bar/s* (Lab 7)	33 ± 6	±17
K_{st} in *bar·m/s*	7 ± 2	±29
K_{st} in *bar·m/s* (Lab 1)	7 ± 2	±31
K_{st} in *bar·m/s* (Lab 2)	5 ± 1	±27
K_{st} in *bar·m/s* (Lab 7)	9 ± 2	±17

Uncertainty in the results also appeared during the determination of the explosion characteristics. According to the standards, duplicate measurements within one laboratory should agree within 5% for the maximum explosion pressure p_{max}, while the reproducibility between laboratories should be within 10%.[54] For the deflagration index K_{st} or the maximum rate of pressure rise $(dp/dt)_{max}$, standards specify a repeatability and reproducibility of 30%.[53] However, as shown in Tables 6–9, the observed deviations partially exceed these limits. It should be emphasized that the particle size distributions of the tested samples were very similar (Table 4) between the laboratories, indicating that the observed differences are unlikely to originate from variations in particle size. A plausible explanation for this behavior lies in the specific combustion characteristics of iron. Iron is often classified as a St 1 Class dust, indicating weak explosibility and typically resulting in poorer reproducibility,[49–51] as discussed above.

The standard deviation for the maximum explosion pressure (p_{max}) between the laboratories is a lot higher than 10% (Tables 6–9). This can be attributed to the data evaluation procedure specified in both American and European standards, where the correction applied according to Equations (4) and (5) increases the scattering by approximately 41%, potentially leading to higher deviations than actually measured. In addition, the signal-to-noise ratio is inherently low: a typical scattering of 0.5 *bar* corresponds to a much larger relative deviation when the maximum pressure is 2 *bar* for weakly reactive iron dust than when it is 10 *bar* for other commonly tested dusts.

Moreover, it should be noted that the actual pressure increase caused solely by the ignitors (p_{ci}) is not always exactly 1.6 *bar* but generally assumed (Equation 5). This phenomenon was described in.[73] Laboratories often rely on manual assessment of their ignitors, and the resulting values can deviate; for example, instead of 1.6 *bar*, values as low as 1.1 *bar* are reported.[73] The scattering of the pressure increase caused solely by the ignitors from one batch to another is about 0.1 *bar* and has a relatively stronger effect in case of weak explosiveness.[74] This re-evaluation contributes to the discrepancies observed between laboratories in terms of p_{max}.

For this reason, the row data were additionally processed by the authors and the corresponding p_{ex} values were included in the Tables 6–9. As can be seen, the standard deviation between laboratories decreases after this re-evaluation. For MT63 and MT150, the standard deviation between laboratories exceeds the acceptable limits, but remains lower than that observed for p_{max}. For MT63reg and MT150reg, the deviations between laboratories remain within the acceptable range.

The deviations observed between laboratories can be attributed to the remaining degrees of freedom in the execution of the tests, as described in the methodology section, as well as to specific characteristics of iron dust. In particular, the selection of dust concentrations for testing was not uniform across laboratories. Since the concentration range is not strictly predefined and is adapted based on the occurrence of the first positive explosibility result, different concentration ranges were applied, which influenced the subsequent determination of explosion parameters. In addition, practical limitations related to the injection of high-density dust at elevated concentrations further contributes to these variations.

Tables 6–9 also provide the standard deviation with in individual laboratories. It should be noted that these values were calculated only for laboratories that performed multiple test series. In these cases, the standard deviation was determined based on the maximum values obtained from the individual test series within the same laboratory.

As shown in Tables 6–9, the standard deviation within individual laboratories exceeds the 5% limit in several cases. This indicates that significant variability is present not only between laboratories but also within individual laboratories. Such deviations highlight the influence of the dust injection system and its limited repeatability on the measured results. This effect becomes particularly significant at low pressure levels, where even small absolute deviations (e.g., around 0.1 *bar*) correspond to relative differences exceeding 5%.

With regard to the differences observed in $(dp/dt)_{max}$, all samples exhibited values that did not exceed 50 *bar/s*. As shown in Tables 6–9, the standard deviation between laboratories for the rate of pressure rise remains within the acceptable limits for MT63 and MT63reg. For MT150 and MT150reg, however, the deviations reach approximately 39%, which is around 9% above the recommended limit, but not considered critical. At the same time, the deviations within individual laboratories remained within the 30% range in all cases. This is particularly noteworthy, as it indicates a good repeatability of the measurements for the second pressure rise within individual laboratories.

A separate comparison of the deflagration index K_{st} was performed; however, as this parameter is directly derived from the rate of pressure rise by applying a scaling factor, a separate discussion does not provide additional insight. The corresponding values are included in Tables 6–9.

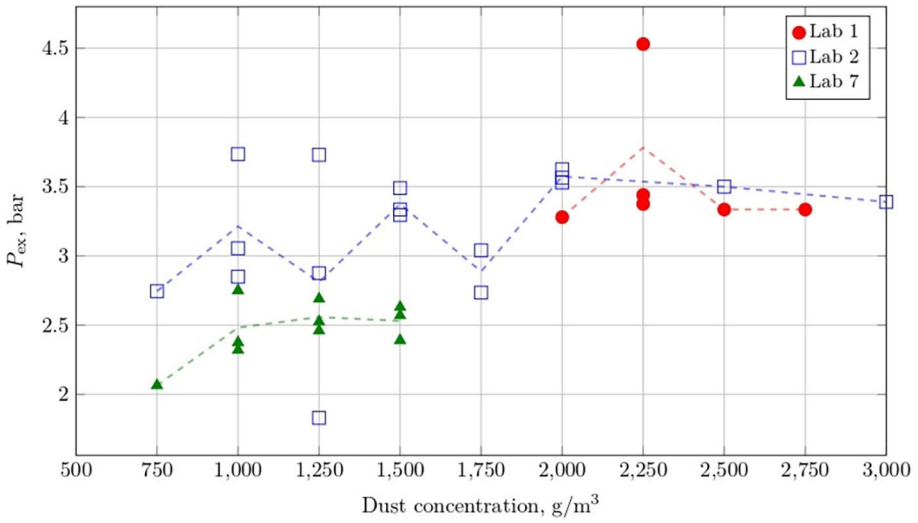

Figure 10. Explosion overpressure p_{ex} for MT63 as a function of dust concentration measured by Lab. 1, 2, 7.

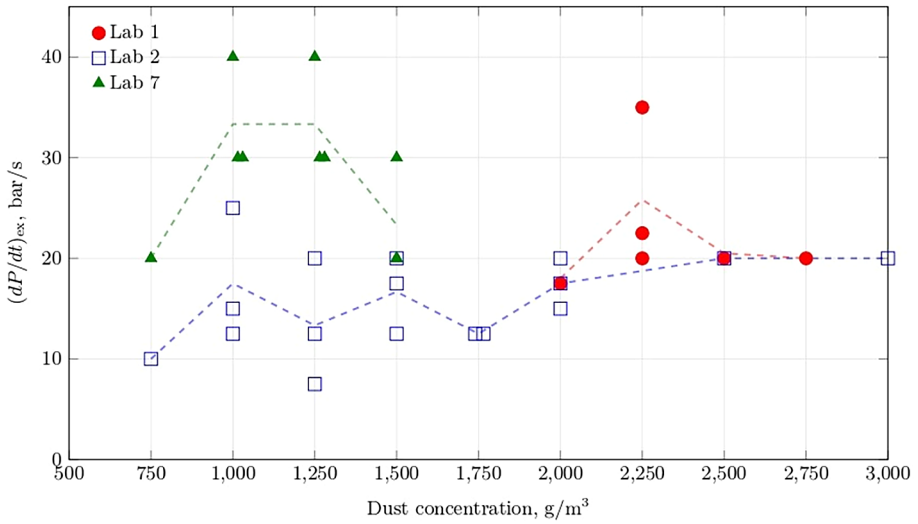

Figure 11. Rate of pressure rise $(dp/dt)_{ex}$ for MT63 as a function of dust concentration measured by Lab. 1, 2, 7.

Figures 10–19 show the individual experimental results p_{ex} and $(dp/dt)_{ex}$ plotted as data points. For improved readability, lines representing the average trend are additionally included, based on the average values at each concentration or on single test results, depending on the data reported by each laboratory.

Based on theoretical considerations, these plots are generally expected to exhibit a curve with a local maximum at a certain dust concentration, after which maximum values should decrease due to the excess thermal mass of unreacted powder.[41,75] However, when examining the $p_{ex}/(dp/dt)$–concentration plots obtained in this work, a different behavior can be observed. Instead of a pronounced maximum followed by a decrease, the curves rather show an increase in pressure values followed by a plateau with some fluctuations.

An important aspect in this context to consider is that the maximum explosion pressure for iron-based dust is reported to occur at relatively high dust concentrations (around 2500 g/m^3),[44] whereas the oxygen available in the 20-L vessel can theoretically oxidize only approximately 660 g/m^3 (Fe_2O_3), 740 g/m^3 (Fe_3O_4), or 990 g/m^3 (FeO).

This discrepancy arises because the theoretical stoichiometric concentration assumes that the entire amount of added dust is uniformly dispersed within the 20-L spherical vessel. In reality, this condition is difficult to achieve, especially for

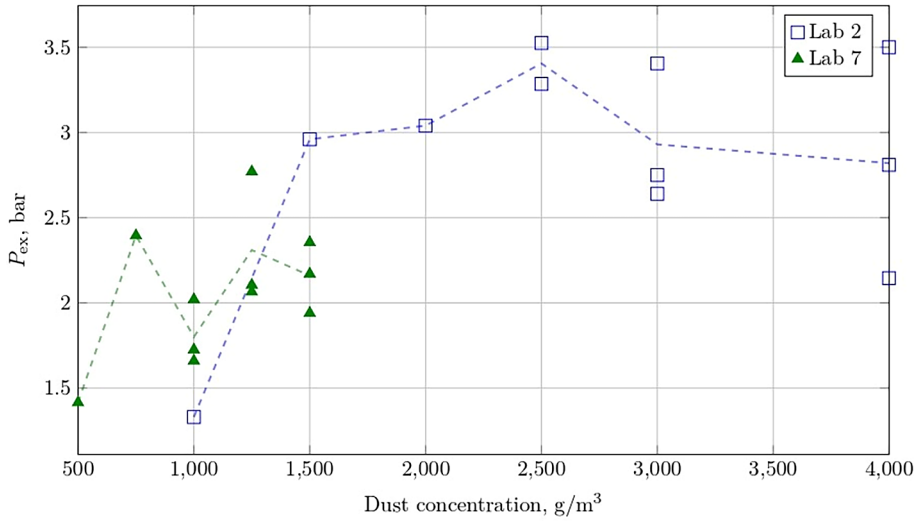

Figure 12. Explosion overpressure p_{ex} for MT150 as a function of dust concentration measured by Lab. 2, 7.

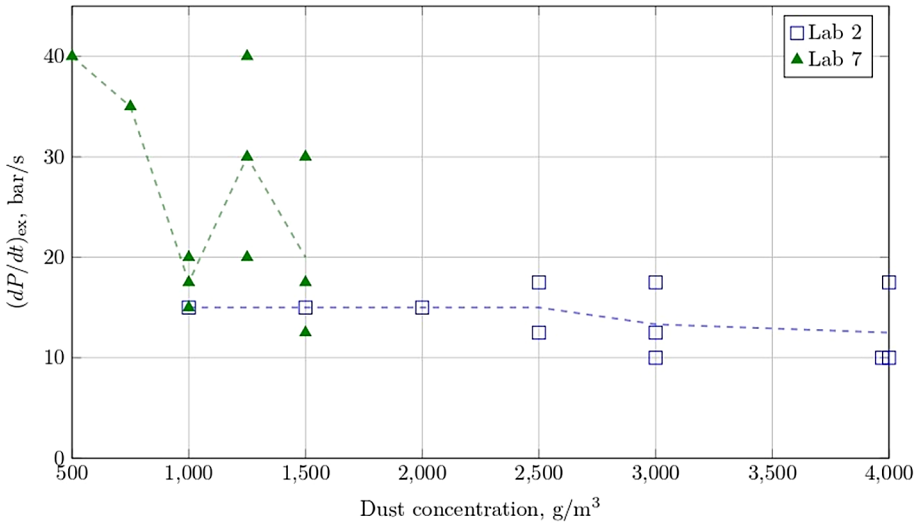

Figure 13. Rate of pressure rise $(dp/dt)_{ex}$ for MT150 as a function of dust concentration measured by Lab. 2, 7.

dense dusts at high concentrations. This behavior suggests that only a fraction of the nominal dust mass participates in heat absorption. This can be attributed to several factors, including incomplete material injection into the vessel, as well as strongly non-uniform particle dispersion within the sphere. All these aspects contribute to the fact that iron dust exhibits significant deviations in the measured explosibility parameters.

Figures 10 and 11 present the explosion overpressure p_{ex} and the maximum rate of pressure rise $(dp/dt)_{ex}$ for MT63 obtained in three laboratories. It should be noted that the selection of dust concentrations for further testing depends on the concentration at which a positive explosion test is obtained using 2 kJ igniters. For example, a positive result was observed at 2000 g/m^3 in the first laboratory. Consequently, the first laboratory focused on concentrations above 2000 g/m^3, while the seventh laboratory limited its testing to concentrations up to approximately 1500 g/m^3. In contrast, the second laboratory investigated a broader range, covering concentrations from 750 to 3000 g/m^3. As discussed in the methodology section, testing at such high concentrations is limited by the 20-L apparatus's injection capacity. Therefore, the differences in the selected concentration ranges for the four powders are due to these practical constraints.

A comparison of the MT63 results shows that the first and the second laboratories exhibit relatively similar behavior in p_{ex}. In contrast, the seventh laboratory reports lower maximum explosion pressure, which leads to higher standard

Table 7. Evaluation of MT150 explosion indices based on data reported by two participants. Pressure values were rounded to one decimal place, whereas rate of pressure rise values and percentages were rounded to integers.

Parameter [N. participant]	Mean value ± standard deviation	Relative standard deviation [%]
p_{ex} in *bar g*	2.9 ± 0.8	±27
p_{ex} in *bar g* (Lab 2)	3.4 ± 0.1	±3
p_{ex} in *bar g* (Lab 7)	2.3 ± 0.4	±16
p_{max} in *bar g*	1.9 ± 1.1	±57
p_{max} in *bar g* (Lab 2)	2.6 ± 0.2	±7
p_{max} in *bar g* (Lab 7)	1.1 ± 0.6	±52
$(dp/dt)_{max}$ in *bar/s*	24 ± 9	±39
$(dp/dt)_{max}$ in *bar/s* (Lab 2)	17 ± 1	±9
$(dp/dt)_{max}$ in *bar/s* (Lab 7)	30 ± 8	±27
K_{st} in *bar·m/s*	7 ± 2	±33
K_{st} in *bar·m/s* (Lab 2)	5 ± 0.4	±9
K_{st} in *bar·m/s* (Lab 7)	8 ± 3	±33

deviation between laboratories (Table 6). With regard to the rate of pressure rise, the opposite trend is observed, as the highest values were observed in the seventh laboratory. Standard deviation for highest values between laboratories in $(dp/dt)_{ex}$ is in acceptable range, as well as inside each laboratory.

Figures 12 and 13 present the results obtained for MT150. The general trend is similar to that observed for MT63. As described previously, different dust concentrations were tested. The second laboratory investigated a wider concentration range (1000–4000 g/m^3) with larger step intervals, whereas the seventh laboratory focused on concentrations up to 1500 g/m^3 with smaller step sizes. The measured explosion overpressures are generally higher in the 2nd laboratory, whereas the 7th laboratory reports higher values of the maximum rate of pressure rise. The repeatability of the maximum pressure within the 2nd laboratory remains within the acceptable range, whereas within the 7th laboratory exceeds the limit. Between-laboratory reproducibility is outside the acceptable range. The repeatability of the maximum rate of pressure rise within individual laboratories remains within the acceptable range according to the standard. However, when comparing the maximum values between laboratories, the standard deviation reaches approximately 39%, slightly exceeding the recommended limit of 30% (Table 7).

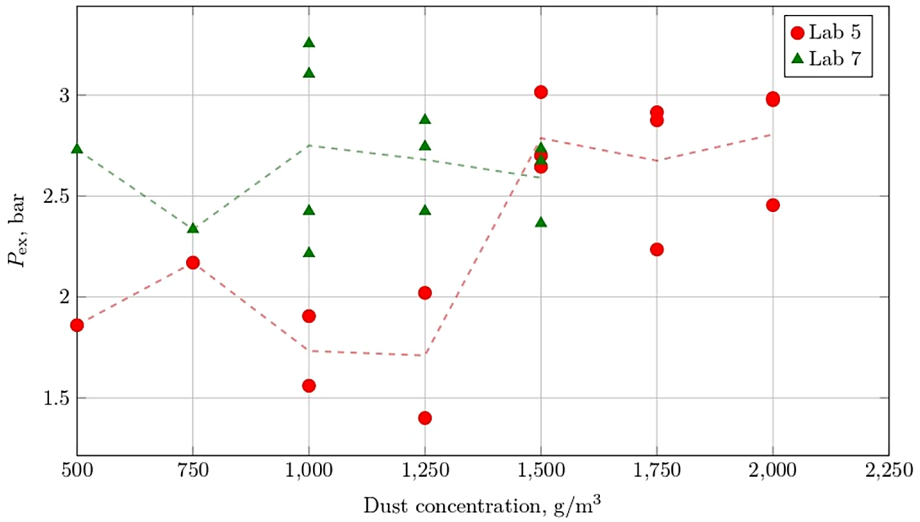

Figure 14. Explosion overpressure p_{ex} for MT150reg as a function of dust concentration measured by Lab. 5, 7.

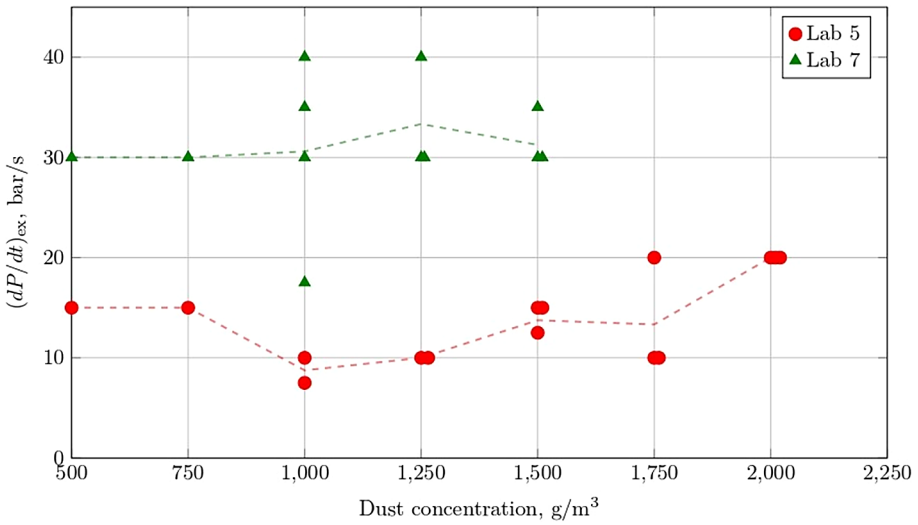

Figure 15. Rate of pressure rise $(dp/dt)_{ex}$ for MT150reg as a function of dust concentration measured by Lab. 5, 7.

Figures 14 and 15 present the results obtained for MT150reg. In this case, both laboratories tested within largely comparable concentration ranges. It can be observed that at concentrations of 1000 and 1250 g/m^3, the values for both explosion parameters differ significantly between the laboratories. Nevertheless, when considering the average of the maximum values for each parameter in each series, the between-laboratory reproducibility remains within acceptable limits for the maximum explosion pressure, while it is slightly above the recommended range for the maximum rate of pressure rise (Table 8).

Figures 16–19 show the explosion overpressure (p_{ex}) and the rate of pressure rise for MT63reg. As summarized in Table 9, all deviations remain within the acceptable range. Nevertheless, it can be observed that the pressure peaks occur at different dust concentrations. As this sample was classified as explosible by the majority of the participating laboratories, a larger dataset is available compared to the other powders. Over a wide concentration range (500–5000 g/m^3), a consistent overall trend can be observed, with no clear decline in the measured values at higher concentrations. Instead, both parameters increase at lower concentrations and then reach a plateau with some fluctuations.

Table 8. Evaluation of MT150reg explosion indices based on data reported by two participants. Pressure values were rounded to one decimal place, whereas rate of pressure rise values and percentages were rounded to integers.

Parameter [N. participant]	Mean value ± standard deviation	Relative standard deviation [%]
p_{ex} in *bar g*	3.0 ± 0.1	±2
p_{ex} in *bar g* (Lab 5)	3.0 ± 0.1	±2
p_{ex} in *bar g* (Lab 7)	2.9 ± 0.4	±13
p_{max} in *bar g*	1.9 ± 0.1	±7
p_{max} in *bar g* (Lab 5)	2.0 ± 0.1	±3
p_{max} in *bar g* (Lab 7)	1.8 ± 0.5	±28
$(dp/dt)_{max}$ in *bar/s*	28 ± 11	±39
$(dp/dt)_{max}$ in *bar/s* (Lab 5)	20 ± 0	±0
$(dp/dt)_{max}$ in *bar/s* (Lab 7)	35 ± 4	±12
K_{st} in *bar·m/s*	7 ± 3	±40
K_{st} in *bar·m/s* (Lab 5)	5 ± 0	±0
K_{st} in *bar·m/s* (Lab 7)	9 ± 1	±12

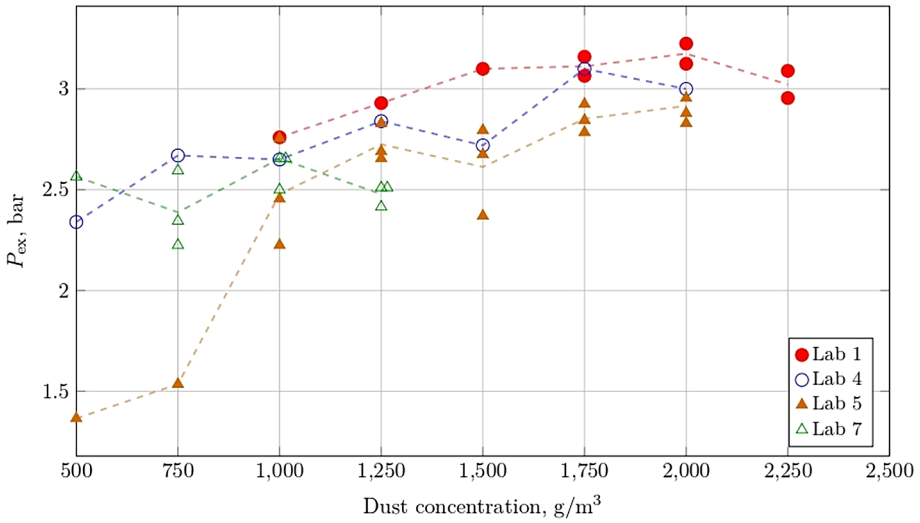

Figure 16. Explosion overpressure p_{ex} for MT63reg as a function of dust concentration measured by Lab. 1, 4, 5, 7.

This behavior highlights the limitations of the 20-L sphere when testing marginally reactive dusts, where further increases in dust concentration do not result in lower explosion severity.

Overall, all powders exhibited similar levels of explosion overpressure (p_{ex}), with average maximum values of approximately 3 *bar*, regardless of whether the material was regenerated or not. Although it was expected that the regenerated samples would show higher explosion severity due to changes in particle morphology and structure,[72] this effect is not clearly observed in the results.

The same applies to the rate of pressure rise $(dp/dt)_{ex}$, for which the average maximum values are around 30 *bar/s* across all samples, with no significant differences between regenerated and non-regenerated powders. This suggests that, despite morphological changes, the overall explosion severity remains comparable.

In summary, the round-robin test revealed variability in the determination of explosion parameters for weakly explosive iron dust, despite consistent sample properties and standardized procedures. These findings highlight the limitations of the current testing procedure, particularly for low-reactivity dusts. They show that variations in the safety characteristics

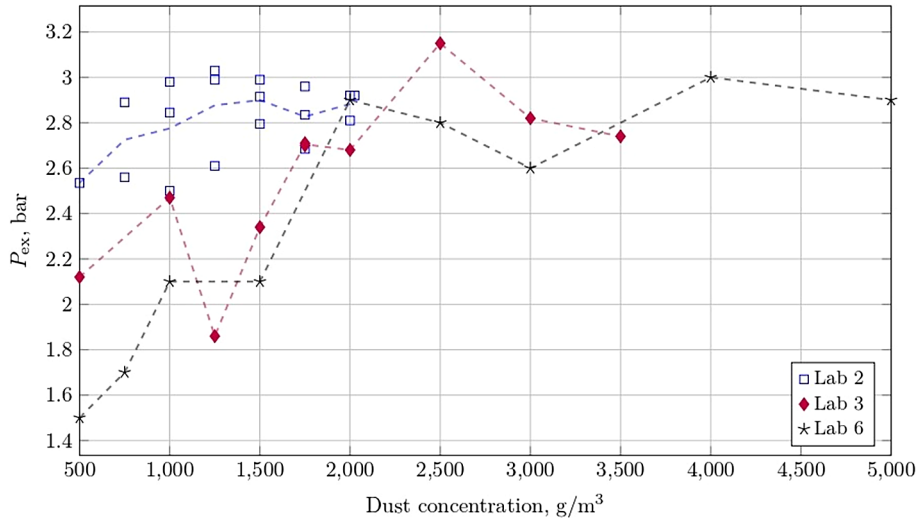

Figure 17. Explosion overpressure p_{ex} for MT63reg as a function of dust concentration measured by Lab. 2, 3, 6.

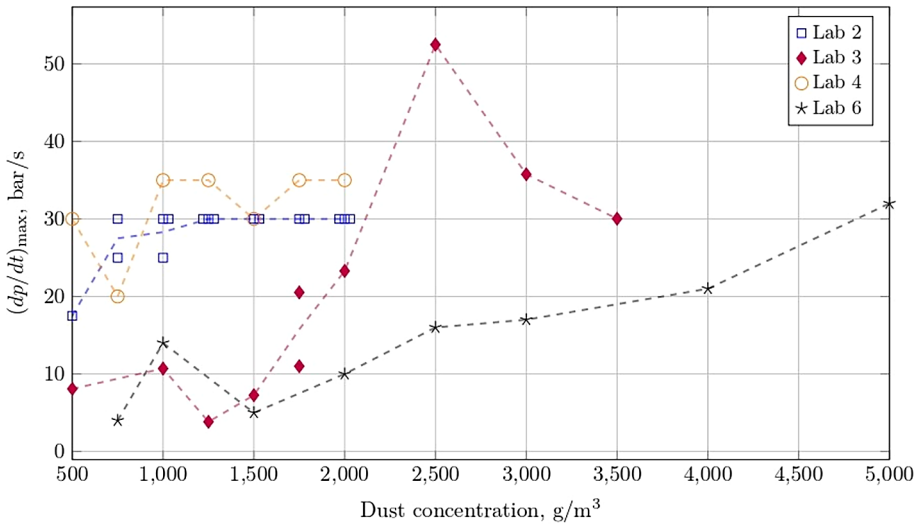

Figure 18. Rate of pressure rise $(dp/dt)_{ex}$ for MT63reg as a function of dust concentration measured by Lab. 2, 3, 4, 6.

of different iron dust samples with different properties may be overshadowed by the limited reproducibility of the test methods.

As long as these limitations in the explosion standard persist, the establishment of general safety concepts for a standardized, non-explosive iron energy carrier — intended for large-scale distribution across Europe — remains a challenge. One way to overcome this difficulty is to classify all iron dusts as St 1 ($K_{st} < 200$) or to use an a-priori approach as suggested previously[39] (see Figure 20) in which the expected value is the linear regression for all the data points, the upper limit is the linear plot between the highest observed data points. The theoretical value was calculated with the assumption that a full conversion from Fe to Fe_2O_3 at the stoichiometry with air takes place when the particles are infinitely small and are evenly suspended in air. Further assumptions/values for the calculation were a constant heat capacity for iron of 0,55 kJ/kg/K and 1,01 kJ/kg/K for air, and a latent heat of melting for iron of 13,8 kJ/kg.

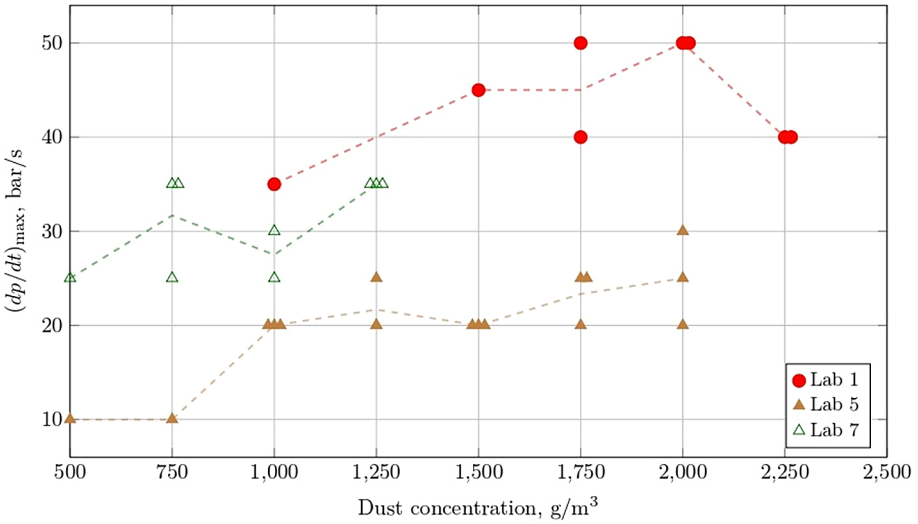

Figure 19. Rate of pressure rise $(dp/dt)_{ex}$ for MT63reg as a function of dust concentration measured by Lab. 1, 5, 7.

Table 9. Evaluation of MT63reg explosion indices based on data reported by seven participants. Pressure values were rounded to one decimal place, whereas rate of pressure rise values and percentages were rounded to integers.

Parameter [N. participant]	Mean value ± standard deviation	Relative standard deviation [%]
p_{ex} in *bar g*	3 ± 0.2	±7
p_{ex} in *bar g* (Lab 1)	3.2 ± 0.1	±2
p_{ex} in *bar g* (Lab 2)	3.0 ± 0.03	±0.9
p_{ex} in *bar g* (Lab 3)	3.2	-
p_{ex} in *bar g* (Lab 4)	3.1	-
p_{ex} in *bar g* (Lab 5)	2.9 ± 0.1	±2
p_{ex} in *bar g* (Lab 6)	3.0	-
p_{ex} in *bar g* (Lab 7)	2.6 ± 0.1	±3
p_{max} in *bar g*	2.1 ± 0.4	±18
p_{max} in *bar g* (Lab 1)	2.3 ± 0.1	±3
p_{max} in *bar g* (Lab 2)	2.0 ± 0.1	±3
p_{max} in *bar g* (Lab 3)	2.6	-
p_{max} in *bar g* (Lab 4)	2.1	-
p_{max} in *bar g* (Lab 5)	1.8 ± 0.2	±8
p_{max} in *bar g* (Lab 6)	2.4	-
p_{max} in *bar g* (Lab 7)	1.5 ± 0.1	±4
$(dp/dt)_{max}$ in *bar/s*	37 ± 10	±27
$(dp/dt)_{max}$ in *bar/s* (Lab 1)	50 ± 0	±0
$(dp/dt)_{max}$ in *bar/s* (Lab 2)	30 ± 0	±0
$(dp/dt)_{max}$ in *bar/s* (Lab 3)	53	-
$(dp/dt)_{max}$ in *bar/s* (Lab 4)	35	-
$(dp/dt)_{max}$ in *bar/s* (Lab 5)	27 ± 3	±11
$(dp/dt)_{max}$ in *bar/s* (Lab 6)	32	-
$(dp/dt)_{max}$ in *bar/s* (Lab 7)	35 ± 0	±0
K_{st} in *bar·m/s*	10 ± 3	± 28
K_{st} in *bar·m/s* (Lab 1)	14 ± 0	± 0
K_{st} in *bar·m/s* (Lab 2)	8 ± 0	± 0
K_{st} in *bar·m/s* (Lab 3)	14	-
K_{st} in *bar·m/s* (Lab 4)	9	-
K_{st} in *bar·m/s* (Lab 5)	7 ± 1	± 11
K_{st} in *bar·m/s* (Lab 6)	9	-
K_{st} in *bar·m/s* (Lab 7)	9 ± 0	± 0

Further work is required to populate this plot with additional data, but eventually it may allow a classification without the need for further testing of iron energy carriers. Simultaneously, a better understanding of dispersion, turbulence, and combustion/explosion in a 20-liter vessel - for instance, through comparison with numerical simulations, as demonstrated in[32] - could help explain the observed variation and support the development of an improved standard.

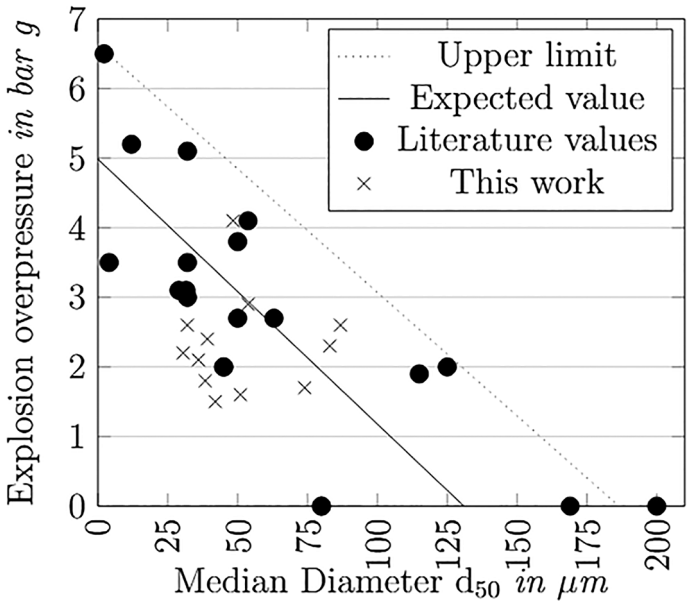

Figure 20. SIE-Chart: Explosion pressures for several iron dusts against the stated *d*50, Data taken from.[39,40,76]

4. Conclusion

Four powders currently used in pilot-scale reactors for the iron powder energy carrier concept were tested for their explosion characteristics by performing a round-robin experiment. The round-robin test confirmed that all nine participating laboratories received and analyzed dust samples with consistent physical properties, particularly in terms of moisture content and particle size distribution. Standardized testing procedures were applied for the initial screening for explosibility and the subsequent determination of the explosion parameters, according to ISO 80079-20-2[57] and EN 14034–1/2.[53,54]

The results revealed variability in the classification of dust explosibility, where disagreement between laboratories was evident even though all laboratories followed the same standard procedures. The reasons for these variations may arise from differences in the dust concentrations tested or lower starting pressures. A scenario in which this may cause severe problems is easy to imagine: a producer tests the dust in one laboratory and it is classified as non-explosible, then ships it to another company for application. If an accident occurs, the second company may test the dust again in another laboratory, which then classifies it as explosible—despite both following the ISO 80079-20-2[57] standard. In addition to differing classifications regarding explosibility, deviations were observed in the values of the maximum explosion pressure and the maximum rate of pressure rise, partially exceeding the tolerances defined in the standards.

These discrepancies can be attributed to the specific combustion behavior of weakly reactive iron dusts. For the maximum explosion pressure, the main contributing factors are:

- A lower signal-to-noise ratio, with a typical scattering of 0.5 *bar* on a maximum pressure of approximately 2 *bar* for weakly reactive iron dusts, compared to about 10 *bar* for other commonly tested dusts.
- Correction of the measured pressures to the standardized reference pressure below 5.5 *bar* g. This correction increases the scattering by 41%, which may lead to higher deviations than actually measured.
- The inherent scattering of the overpressure generated by the ignitors, typically around 0.1 *bar* from one igniter batch to another.
- Differences in the initial pressure arising from friction in the injection process.[56]
- The concentration limits unto which the samples were tested.

For the maximum rate of pressure rise, the dual pressure-rise pattern should be addressed in the standards, and it should be clearly indicated which pressure rise has to be taken. Inconsistencies in the evaluation methods (manual vs. automated) otherwise lead to a wide spread of the data.

The findings reveal limitations in current explosion testing procedures for low-reactivity dusts, highlighting the need for methodological improvements and clearer evaluation criteria. However, the round-robin test confirmed that all four powders investigated were classified either as non-explosible or as Class 1 marginally explosible dust. This provides a clear picture of the level of explosion protection measures that need to be considered for the safe use of iron powders in energy-carrier applications. Despite the discrepancies in the explosion parameters measured between laboratories, the overall results demonstrate that the explosibility of iron powders remains low.

This round-robin test, which represents one of the very few inter-laboratory studies on iron powders, contributes both to improving our understanding of iron dust explosibility and to supporting future refinement of safety standards.

An a priori approach, such as the one presented in this study, could provide a viable solution for the characterization of pure dusts, reducing uncertainties and complementing standardized methods. Together, the results not only show where methodologies can be improved but also provide confidence that iron powders can be handled safely as a recyclable energy carrier in large-scale applications, provided that appropriate protective measures are implemented.

Ethics and consent

Ethical approval and consent were not required.

Data availability statement

Underlying data

Zenodo: CESAR. IRON ROUND ROBIN Semenova and Spitzer 2026. CESAR. https://doi.org/10.5281/zenodo.19726825.[77]

The project contains the following underlying data:

- EDX_MT150_250429_neu_2.pdf contains the EDX measurements for MT150.
- EDX_MT63_250429_neu_2.pdf contains the EDX measurements for MT63.
- Expl.tests.pdf contains the test results from all eight facilities.
- RoundRobin_Explosion_Parameters.xlsx

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgments

The corresponding author would like to thank Paul Geoerg for drawing the map of Europe.

Courtesy to Tom Siebelt and Bart van Overbeeke for providing the photograph displayed in Figure 3.

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Aki Fujinawa
University of Cambridge, Cambridge, UK

The manuscript by Semenova *et al*. describes the results of international round robin testing for the safety characteristics of iron powder. Two size fractions of both virgin and regenerated iron powders were used. SEM imaging revealed that virgin powders resembled round agglomerates and regenerated ones appeared flake-like. EDX was used to probe the surface composition of virgin powders, while XRD and IGF was conducted for all powders to determine bulk crystalline composition and oxygen content, respectively. Nine facilities independently performed explosibility tests using the standard 20-L sphere apparatus, revealing significant variability in the classification of dust explosibility of powders, as well as the explosion indices for dusts characterised as explosible.

This work is an important step towards reaching international alignment in the classification of metal dust explosibility, in the context of using micrometric iron powder as a recyclable energy carrier. However, there are several shortcomings of the work that undermine the quality of the manuscript. In particular, the limited reproducibility of experiments conducted at the institution-level is not adequately discussed and uncertainties are not properly propagated in the discussion of values reported across laboratories. The manuscript cannot be approved for indexing in its current state. My suggestions for improving the manuscript are provided in detail below. Suggestions specific to the questions above are shared first, followed by general comments.

If applicable, is the statistical analysis and its interpretation appropriate? Are the conclusions drawn adequately supported by the results?
1. The way in which explosion indices are calculated and presented (Tables 4-7 in the manuscript, experimental results in Supplementary Material) can be improved. Details follow:
- The tabulated format of $(p)_{max}$ and $(dp/dt)_{max}$ at different dust concentrations in the Supplementary Materials is difficult to interpret quantitatively. A graphical representation of the dependence of $(p)_{max}$ and $(dp/dt)_{max}$ on dust concentration, with the spread of data points at each dust concentration shown as error bars, would facilitate interpretation. These plots should normally resemble a curve with a local maximum at some dust concentration (*e.g.* Figure 3 in [1]), beyond which flame propagation should slow down, either due to the excess thermal mass of

unreacted powder or the flame front losing heat by radiation to an optically thick unburnt mixture (see Fig. 9 in [2]). If experimental trends deviate from results in literature or theory, this should be mentioned and discussed.
- The three highest recorded p and dp/dt values averaged to give values in Tables 4-7 seem to be extracted from experiments conducted at different dust concentrations. This lacks a physical basis as $(p)_{max}$ and $(dp/dt)_{max}$ should occur at a fixed dust concentration where the mixture is most explosive, and three independent measurements at this concentration should be averaged to give the final reported $(p)_{max}$ and $(dp/dt)_{max}$. If different dust concentrations gave $(p)_{max}$ or $(dp/dt)_{max}$, or different institutes reported $(p)_{max}$ or $(dp/dt)_{max}$ to occur at different dust concentrations, both indicating limited reproducibility, this should be made explicit and elaborated in the manuscript.
- Following the point above, the underlying spread in p and dp/dt values used to calculate $(p)_{max}$ and $(dp/dt)_{max}$ must be incorported in the calculation of uncertainties reported in Tables 4-7. The contribution of uncertainties from the underlying scatter on a *per-laboratory basis*, and the scatter *between* laboratories, should be clarified. The discussion on acceptable deviations, and conclusions drawn on the spread of data with respect to standard tolerances, should be updated.

Are sufficient details of methods and analysis provided to allow replication by others?
2. Authors mention that some laboratories conducted experiments at a lower initial pressure to facilitate tests at high dust concentrations, but no further details are provided, rendering the experimental study not fully reproducible. Can the authors tabulate and publish all details pertaining to test conditions at each institution?

Is the work clearly and accurately presented, and does it cite the current literature?
3. The literature survey on the combustion of metal powders in the introduction is superficial and contains many erroneous references, *e.g.* ref 12 deals with 1-D dust flames under strain (not single particle), ref 22 has nothing to do with metal combustion, most references made on "process-related parameters" do not pertain to process/operation, *etc*. This is unfortunate as there is a growing body of literature on iron combustion that informs about dust explosions and safety (*e.g.* ignition characteristics, flame propagation in closed vessels, see references below) that the authors did not take advantage of. Please carefully revise the introduction to accurately reflect the knowledge in current literature.

General comments:
4. In Sect. 2.1 authors mention that MT63reg powder has a wide particle size distribution while Fig. 9 suggests that MT63reg is more narrowly distributed than MT63. Can the authors please clarify?

5. While the authors acknowledge that particle morphology significantly affects safety characteristics, and show differences in particle morphology between virgin and regenerated iron powders by SEM imaging, no discussion of the effect of particle morphology/porosity on reactivity is offered. In addition, the flake-like particles will likely be dispersed more uniformly in experiments due to the higher specific surface area enhancing drag. Can the authors comment on the expected effects of morphology on the explosibility tests and whether any trends were observed or if the lack of reproducibility overshadowed any physical effects? A recent work by Cen *et al*. discusses the effect of particle morphology on ignition [3].

6. Why was EDX not performed on the regenerated samples? Ref 43 only demonstrates that the change in impurity concentrations after combustion was minor in their lab-scale burner. This result cannot be blindly extrapolated to the current study since powders used here are combusted

in a pilot-scale apparatus and subsequently regenerated through hydrogen-based reduction with additional mechanical processing to produce powders. Whether combustion/reduction cycling in these facilities resulted in increased concentrations of surface impurities should be quantitatively assessed for completeness.

7. In Figure 9, please describe what is being plotted - what values do the centrelines, whiskers, and the filled dots represent? The presentation is also misleading, since discrepancies in particle size distribution arising from systematic effects induced by the selection of the measurement method is presented as a statistical distribution. As a result, the true width of the size distribution of the particles is unclear. Either all samples need to be assessed using the same measurement technique or results obtained by different measurement techniques should be shown separately, *e.g. as* separate boxes and whiskers side-by-side in the same plot, or in a histogram-style plot with different colours for each method, or all d_{10}, d_{50}, d_{90} values at each institution reported in a table, etc.

8. The discussion on reasons for uncertainties in the results (pg 14-16) can be improved. In particular, when discussing differences observed in $(dp/dt)_{max}$, the authors mention the use of the second portion of the dp/dt curve, although this was a methodological choice that should have eliminated deviations, hence not explaining at all the lack of repeatability of results. A more in-depth discussion on the sources of scatter in experimental results is demanded, along with concrete recommendations for future experiments characterising the explosibility of iron dust. How wide was the particle size distribution of the powders used in the current set of experiments (unclear due to presentation of data in Fig. 9), and could this have resulted in minor variations of reactivity in the powder suspension each time an experiment is conducted? Upon an initial characterisation of the particle size distribution in a given batch, should the powder be sieved to produce a batch with a narrower size distribution centred at either d_{10} or d_{50}? Experiments with a narrower distribution of particle sizes might promote repeatability and one centred at d_{10} would be representative of the worst-case scenario for explosibility.

9. The broad comparison of iron to other energy carriers in Table 8, presented for the first time in the conclusion, seems more appropriate in the Introduction.

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Is the work clearly and accurately presented and does it cite the current literature?

Partly

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?
No

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Metal combustion; hydrogen combustion; gas-solid flows.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 14 May 2026

Stefan Spitzer

16.04.2026 Letter to Aki Fujinawa (University of Cambridge, Cambridge, UK) Dear Mr. Fujinawa, Thanks a lot for the critical comments and for putting your precious time in the review. We have incorporated all your remarks in the revised version and hope this new version meets your expectations. Most of all we hope you enjoyed reading and can benefit from the publication. Kind regards Aleksandra Semenova & Stefan Spitzer **Comment 1:** The tabulated format of p_{max} and $(dp/dt)_{max}$ at different dust concentrations in the Supplementary Materials is difficult to interpret quantitatively. A graphical representation of the dependence of p_{max} and $(dp/dt)_{max}$ on dust concentration, with the spread of data points at each dust concentration shown as error bars, would facilitate interpretation. These plots should normally resemble a curve with a local maximum at some dust concentration (e.g. Figure 3 in [1]), beyond which flame propagation should slow down, either due to the excess thermal mass of unreacted powder or the flame front losing heat by radiation to an optically thick unburnt mixture (see Fig. 9 in [2]). If experimental trends deviate from results in literature or theory, this should be mentioned and discussed. **Response 1:** Thank you for this helpful suggestion. Following the reviewer's recommendation, graphical representations of both the explosion overpressure *P*ex$P_{ex}$and the rate of pressure rise *dp/dt)*ex$(dp/dt)_{ex}$as a function of dust concentration have now been added to the revised manuscript. In addition, a discussion of the observed curve shape has been included in the manuscript. In contrast to the typical trend reported in the literature, where the maximum explosion pressure for iron dust is reported at nominal dust concentrations $\geq$ 2500 g/m^3 [1], the oxygen available in the 20-L vessel can theoretically oxidize only approximately 660 g/m^3 (Fe_2O_3), 740 g/m^3 (Fe_3O_4), or 990 g/m^3 (FeO). This discrepancy arises because the theoretical stoichiometric concentration assumes a well-dispersed, homogeneous dust

cloud within the 20-L sphere, which is difficult to achieve in practice, particularly for high-density dusts and elevated concentrations. The results of the present study also deviate from the commonly reported trend. No distinct maximum is observed; instead, after an initial increase, the explosion pressure reaches a plateau with fluctuations at higher dust concentrations. It is assumed that not all of the nominal material is effectively injected into the vessel due to limitations of the injection system. Guo, Y., Ren, K., Wei, A., Tao, C., Huang, W., Zhao, P., & Wu, D. (2022). Iron dust explosion characteristics with small amount of nano-sized Fe2O3 and Fe3O4 particles. *Fuel*, *324*, 124786. https://doi.org/10.1016/j.fuel.2022.124786 **Comment 2:** The three highest recorded p and dp/dt values averaged to give values in Tables 4-7 seem to be extracted from experiments conducted at different dust concentrations. This lacks a physical basis as p_{max} and (dp/dt)max should occur at a fixed dust concentration where the mixture is most explosive, and three independent measurements at this concentration should be averaged to give the final reported p_{max} and $(dp/dt)_{max}$. If different dust concentrations gave p_{max} or $(dp/dt)_{max}$, or different institutes reported p_{max} or $(dp/dt)_{max}$ to occur at different dust concentrations, both indicating limited reproducibility, this should be made explicit and elaborated in the manuscript. **Response 2:** Thank you for this comment. According to the standards (EN 14034 ASTM 1226), *p*maxp_{max} and *dp/dt)*max$(dp/dt)_{max}$ are determined as the highest values observed across the tested concentration range, and these maxima do not need to occur at the same dust concentration in repeated tests. When several experimental series are conducted, the reported values are obtained as the arithmetic mean of the maximum values from each series, rather than by averaging results obtained at a single concentration. However, these values typically do not vary more than one concentration interval between test series. To clarify this point, the manuscript has been revised to explicitly state this evaluation procedure and to highlight the observed variability. **Comment 3:** Following the point above, the underlying spread in p and dp/dt values used to calculate p_{max} and $(dp/dt)_{max}$ must be incorporated in the calculation of uncertainties reported in Tables 4-7. The contribution of uncertainties from the underlying scatter on a per-laboratory basis, and the scatter between laboratories, should be clarified. The discussion on acceptable deviations, and conclusions drawn on the spread of data with respect to standard tolerances, should be updated. **Response 3:** Thank you for this comment. Regarding the scatter within individual laboratories, ASTM E1226 and EN 14034 1/2 provide guidance on acceptable deviations. According to these standards, duplicate measurements within one laboratory should agree within 5 % for the maximum explosion pressure *pmax*p_{max}, while the reproducibility between laboratories should be within 10 %. For the deflagration index *Kst*K_{st} or the maximum rate of pressure rise *dp/dt)max*$(dp/dt)_{max}$, standards specify a repeatability and reproducibility of 30 % For clarity, the scatter of duplicate tests performed at the same dust concentrations can be directly observed in the graphical representation of the results. In addition, the tables reporting the maximum values have been updated to include the standard deviation within the experimental series (for maximum values in each series) where multiple series were performed by a given laboratory. For laboratories that conducted only a single experimental series, no standard deviation can be calculated, and these entries are therefore indicated with a dash. **Comment 4:** Authors mention that some laboratories conducted experiments at a lower initial pressure to facilitate tests at high dust

concentrations, but no further details are provided, rendering the experimental study not fully reproducible. Can the authors tabulate and publish all details pertaining to test conditions at each institution? **Response 4:** Thank you for this important comment. Before each test, the 20-L vessel is evacuated (0.4 bar abs) to ensure that, after dust injection and expansion of the pressurized air from the dust reservoir, the initial pressure in the sphere is approximately atmospheric (≈1013 mbar abs). The dust is dispersed using compressed air from a reservoir typically pressurized to 21 bar (absolute), which is regulated by the system. The dust storage expansion pressure is typically around 0.6 bar, with a permissible range of 0.55–0.7 bar. Variations within this allowable range can introduce minor differences in the resulting initial conditions inside the vessel, which are allowed. Also, in practice, especially at high dust concentrations and for high-density materials such as iron dust, not all of the injected air expands uniformly into the vessel before ignition. As a result, slight deviations from the nominal initial pressure may occur, and ignition can take place at pressures somewhat below atmospheric conditions. This effect is linked to the dynamics of the injection system and the limited time between dust dispersion and ignition. The observed variations in initial pressure are therefore not due to intentional changes in test conditions but arise from physical limitations of the dispersion process at high dust loadings. To clarify this point, the methodology of the manuscript has been revised to explicitly state the procedure and to highlight the observed variability. **Comment 5:** The literature survey on the combustion of metal powders in the introduction is superficial and contains many erroneous references, e.g. ref 12 deals with 1-D dust flames under strain (not single particle), ref 22 has nothing to do with metal combustion, most references made on "process-related parameters" do not pertain to process/operation, etc. This is unfortunate as there is a growing body of literature on iron combustion that informs about dust explosions and safety (e.g. ignition characteristics, flame propagation in closed vessels, see references below) that the authors did not take advantage of. Please carefully revise the introduction to accurately reflect the knowledge in current literature. **Response 5:** Thank you for this detailed and valuable comment. The introduction has been thoroughly revised. **Comment 6:** In Sect. 2.1 authors mention that MT63reg powder has a wide particle size distribution while Fig. 9 suggests that MT63reg is more narrowly distributed than MT63. Can the authors please clarify?
Response 6: Totally right, we cut that sentence. The main point is that the other one falls outside some standards. **Comment 7:** While the authors acknowledge that particle morphology significantly affects safety characteristics and show differences in particle morphology between virgin and regenerated iron powders by SEM imaging, no discussion of the effect of particle morphology/porosity on reactivity is offered. In addition, the flake-like particles will likely be dispersed more uniformly in experiments due to the higher specific surface area enhancing drag. Can the authors comment on the expected effects of morphology on the explosibility tests and whether any trends were observed or if the lack of reproducibility overshadowed any physical effects? A recent work by Cen et al. discusses the effect of particle morphology on ignition [3]. **Response 7:** Thank you very much for this valuable comment. A discussion on the influence of particle morphology and porosity on the explosibility behavior has now been added to the revised manuscript. **Comment 8:** Why was EDX not performed on the regenerated samples? Ref 43 only demonstrates that the change in impurity concentrations after combustion was minor in their lab-scale burner. This result cannot be blindly extrapolated to the current study since powders used here are combusted in a pilot-scale apparatus and subsequently regenerated through hydrogen-

based reduction with additional mechanical processing to produce powders. Whether combustion/reduction cycling in these facilities resulted in increased concentrations of surface impurities should be quantitatively assessed for completeness.
Response 8: We thank the reviewer for this important comment. We acknowledge that no EDX analysis was performed on the regenerated samples which is simply the cae because there was nothing left at the end of the explosion tests. Also, potential changes in impurity concentrations during combustion–reduction cycling cannot be excluded. However, all powders were carefully homogenized prior to testing and identical batches were distributed across participating laboratories, ensuring consistent sample preparation. Even if minor impurities were introduced during the combustion–reduction cycle, their effect is considered negligible in the context of this study. All samples, including regenerated ones, exhibited comparable explosion severity (p_{ex} and (dp/dt)). **Comment 9:** In Figure 9, please describe what is being plotted - what values do the centrelines, whiskers, and the filled dots represent? The presentation is also misleading, since discrepancies in particle size distribution arising from systematic effects induced by the selection of the measurement method is presented as a statistical distribution. As a result, the true width of the size distribution of the particles is unclear. Either all samples need to be assessed using the same measurement technique or results obtained by different measurement techniques should be shown separately, *e.g. as* separate boxes and whiskers side-by-side in the same plot, or in a histogram-style plot with different colours for each method, or all d_{10}, d_{50}, d_{90} values at each institution reported in a table, etc. **Response 9:** We thank the reviewer for this valuable comment. In order to avoid potential misinterpretation of the particle size data, Figure 9 has been replaced with a table reporting the characteristic particle size values (d10, d50, and d90). In addition, the particle size analysis method used by each participating laboratory has now been explicitly indicated.
Comment 10: The discussion on reasons for uncertainties in the results (pg 14-16) can be improved. In particular, when discussing differences observed in $(dp/dt)_{max}$, the authors mention the use of the second portion of the dp/dt curve, although this was a methodological choice that should have eliminated deviations, hence not explaining at all the lack of repeatability of results. A more in-depth discussion on the sources of scatter in experimental results is demanded, along with concrete recommendations for future experiments characterising the explosibility of iron dust. How wide was the particle size distribution of the powders used in the current set of experiments (unclear due to presentation of data in Fig. 9), and could this have resulted in minor variations of reactivity in the powder suspension each time an experiment is conducted? Upon an initial characterisation of the particle size distribution in a given batch, should the powder be sieved to produce a batch with a narrower size distribution centred at either d_{10} or d_{50} ? Experiments with a narrower distribution of particle sizes might promote repeatability and one centred at d_{10} would be representative of the worst-case scenario for explosibility.
Response 10: Thank you for this valuable comment. Following the reviewer's suggestion, the discussion of possible sources of scatter in the experimental results has been expanded in the revised manuscript. In addition, the particle size data are now presented in a tabulated format to provide a clearer overview of the particle size distribution. **Comment 11:** The broad comparison of iron to other energy carriers in Table 8, presented for the first time in the conclusion, seems more appropriate in the Introduction.
Response 11: The comparison of iron with other energy carriers has been moved from the conclusion to the Introduction in the revised manuscript.

Competing Interests: No competing interests were disclosed.

Reviewer Report 28 February 2026

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David Pallarès
Chalmers University of Technology, Gothenburg, Sweden

This manuscript presents a highly relevant work about the characterization of iron powder in terms of safety for its transport and storage when used as energy carrier. The work presents test data from different partners in the EU following the same regulations and showing that different categorization is yield for several parameters due to the test protocols not being suitable or becoming ambiguous for the case of iron powder.

The presentation of the work can be improved significantly by the following means:

- The manuscript mentions and discussed different test parameters and steps (page 5) before the whole test procedure is introduced to the reader (page 9). This has to be corrected so that the reader experiences a consistent information flow.
- Text and figures and strongly misaligned. The text refers/discusses to them in a different order than the one they are presented. This is general, but the case of Fig.5 is specially problematic, as it is shown much later than all discussion it supports.
- The y-axis of Figs 5 and 7 should indicate an overpressure in relation to a reference one, rather then simply “Pressure”.
- The data in Tables 4 and 7 should be divided into categories for each parameter – as done in Tables 5 and 6.
- Why are the different values of K_St not shown in the tables?
- Fig.10: Provide explanation (and reference if possible) to the “Upper limit” and “Expected value” lines drawn in the figure. Provide a discussion about these in the text – it is very odd to show these in the figure but not use them to support the text.
- Fig.10: Not at all clear what is meant by the data point “Theoretical value” at x=0. A theoretical value derived for infinitely small particle? How is it calculated? Is there a reference to that? How does it differ from the “Expected value” line?
- Page 7: MT150 is not in the list.
- Page 11: “This supports the assumption that small amounts of iron oxide are present in the samples.”. This sentence repeats the same message provided previously in the paragraph. Further, the presence of iron oxide is not an assumption.

Phrasings: “Increasing the beginning pressure in the sphere” à “Increasing the initial pressure in the sphere”. “It has also been investigated previously that marginally explosible dusts - and especially iron dusts - cause large deviations when tested” à “It has also been previously shown

that marginally explosible dusts - and especially iron dusts – exhibit large deviations in AAAAAA, BBBB, CCCCC when tested". "which causes a lower measured pressure increase" à " which causes a smaller increase of the measured pressure increase.". "safety characteristic of dusts they are solid particles" à "safety characteristic of dusts, dust is defined as solid particles...".

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Gas-solids flows, particulate matter

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 14 May 2026

Stefan Spitzer

16.04.2026 Letter to David Pallarès (Chalmers University of Technology, Gothenburg, Sweden) Dear Prof. Pallarès, Thanks for your precious time and your comments. We have incorporated all your feedback in the revised manuscript and hope that the new version of our work leaves no questions unanswered. Please see the details for all remarks below. Last but not least we hope you enjoyed reading the article and that you gained something from it for your own work Kind regards Aleksandra Semenova & Stefan Spitzer **Comment 1:** The manuscript mentions and discusses different test parameters and steps (page 5) before the whole test procedure is introduced to the reader (page 9). This has to be corrected so that the reader experiences a consistent information flow. **Response 1:** Thank you for this comment. The manuscript has been revised accordingly. **Comment 2:** Text and figures are strongly misaligned. The text refers/discusses to them in a different order than the one they are presented. This is general, but the case of Fig.5 is especially problematic, as it is shown

much later than all discussion it supports. **Response 2:** The manuscript has been revised to ensure proper alignment between the text and figures. **Comment 3:** The y-axis of Figs 5 and 7 should indicate an overpressure in relation to a reference one, rather than simply "Pressure". **Response 3:** The y-axes of Figs. 5 and 7 now indicate overpressure instead of pressure. **Comment 4:** The data in Tables 4 and 7 should be divided into categories for each parameter – as done in Tables 5 and 6. **Response 4: Thank** you for your comment. The results have now been clearly separated in the revised manuscript. It should be noted that Tables 4 and 7 are based only on the data from two laboratories, as only these laboratories classified the powder as explosible. Therefore, only their results were considered for the calculation of the corresponding explosion parameters. **Comment 5:** Why are the different values of K_St not shown in the tables? **Response 5:** Thank you for your comment. The *KSt* K_{St} values have now been added to the tables in the revised manuscript. **Comment 6:** Fig.10: Provide explanation (and reference if possible) to the "Upper limit" and "Expected value" lines drawn in the figure. Provide a discussion about these in the text – it is very odd to show these in the figure but not use them to support the text. **Response 6:** Thanks for pointing this out, the two lines are described now in the text. **Comment 7:** Fig.10: Not at all clear what is meant by the data point "Theoretical value" at x=0. A theoretical value derived for infinitely small particle? How is it calculated? Is there a reference to that? How does it differ from the "Expected value" line? **Response 7:** We erased that data point. There is no reference and it was initially calculated from the energy release of a stoichiometric mixture assuming full conversion to Fe2O3 only. I have to say that many things were not taken into account for that calculation and we are currently working on a new paper for iron and other metals in which this will be properly inserted...however, since not published yet, its simply erased. **Comment 8:** Page 7: MT150 is not on the list. **Response 8:** Thank you very much for pointing this out. This has been corrected in the revised manuscript. **Comment 9:** Page 11: "This supports the assumption that small amounts of iron oxide are present in the samples.". This sentence repeats the same message provided previously in the paragraph. Further, the presence of iron oxide is not an assumption. **Response 9:** The text has been reformulated accordingly. **Comment 10:** Phrasings: "Increasing the beginning pressure in the sphere" à "Increasing the initial pressure in the sphere". "It has also been investigated previously that marginally explosible dusts - and especially iron dusts - cause large deviations when tested" à "It has also been previously shown that marginally explosible dusts - and especially iron dusts – exhibit large deviations in AAAAAA, BBBB, CCCCC when tested". "which causes a lower measured pressure increase" à " which causes a smaller increase of the measured pressure increase.". "safety characteristic of dusts they are solid particles" à "safety characteristic of dusts, dust is defined as solid particles... **Response 10:** All phrasing issues have been carefully revised in the manuscript according to your recommendations.

Competing Interests: No competing interests were disclosed.