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Safety Aspects of Silicon as a Clean Energy Transition Element

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Abstract – The shift to clean energy from fossil fuels will depend heavily on metals. Silicon is one of the top elements, playing a key role in the transition to green energy due to its abundance and importance in developing essential technologies. The main energy sectors are the PV industry and the new application of Si-anode elements in EV production. These industries will increase silicon output and promote new recycling methods. Economic and security concerns are present, as China holds a monopoly on production, and Europe must address the challenge of energy costs associated with smelting and refining silicon. Because of its high energy density and specific energy, silicon is also an excellent candidate as a metal fuel. Its widespread availability in silica form, commonly used in glass manufacturing, is environmentally friendly and non-toxic, requiring no specialized waste processing. Furthermore, a clean, energy-efficient method for producing hydrogen from silica has been demonstrated. Still, little is known about the combustion behaviour and explosibility parameters of pure silicon dusts or Si-H2 mixtures. This work will provide data on explosibility characterization and establish a reliable, reproducible dataset for use in risk assessment of silicon metal powder-based energy processes. The silicon powder sample tested exhibited relatively high values for overpressure and rate of pressure rise, respectively, 8.1 bar and 440 bar/sec.

1. INTRODUCTION

Metals will play a central role in the energy transition by supporting the EU in building its clean energy value chain and driving it towards achieving the goals of the Sustainable Development Scenario 2050. In this scenario, elements could be sorted by their relevance and application: renewable technologies such as electric vehicles, photovoltaic modules, wind turbines, and hydrogen energy applications require a high load of specific materials relative to their conventional counterparts. Silicon is listed in the first tier for its relevance in the KU Leuven (2022) report on critical materials for the energy transition, and an increase of about 60 per cent in its production is forecast if the SDS scenario is to be reached within the 2050 deadline.

Silicon will likely drive the energy transition due to its potential enhanced utilisation in two sectors: the photovoltaic modules industry (JRC, 2024), and silicon adoption in replacing carbon-based anodes (graphite) in electric vehicle batteries (Feyzi, 2024). In these perspectives, the EU silicon market has a potential growth of 600-700 ktonn/y in 2030 to 900 ktonn/y in 2050 (KU Leuven, 2022). Actually, this further rise in PV production is connected to the perspectives of decarbonising the EU according to the Paris Treaty, thus requiring about 60% more silicon than is now required.

The current silicon market consists mostly of chemical and metallurgical applications. Silicon is widely used as a fluidising agent in the aluminium melting process and is included in the production of Al--Si alloys. A significant share of silicon extraction is used in silicones and silane production, while electronic applications account for a small contribution.
Both metallurgical-grade and solar-grade polysilicon (>99.9999%) are produced from silica mineral ore extraction followed by carbothermal reduction, a process generating 4.3 ton CO2 per ton of Si produced (Hoover, 2024), making decarbonisation of Si production one of the most pressing open challenges. Metallurgical grade silicon is converted to a volatile compound that is condensed and refined by fractional distillation. Ultra-pure silicon is then extracted from this refined product (CRM Alliance, 2026).

Alternative reduction pathways have been proposed, such as bio-carbon coupled with CCU/CCS (Hoover, 2024), solid-state electrolysis with molten salts (Maldonado2020), and high-temperature solar furnaces (Loutzenhiser, 2010), though these remain at lab or pilot scale. Silicon, together with Aluminium, iron, and magnesium, is among the best potential candidates as an energy carrier, due to its high energy density, high abundance, non-toxic oxidised form, and high transportability (see also Wronksy & Sciacovelli, 2024).

A promising pathway for silicon's high energy content is its direct combustion in air or by steam to generate heat and power outputs. This process is among the most effective metal-enabled energy cycles (MeCRE, see Figure 1), although renewable sources are demanded to close the silica-to-silicon metal loop effectively.

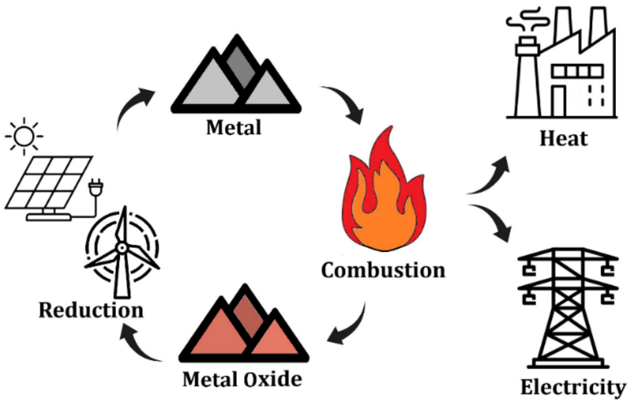

Figure 1: Schematic of the cycle using metals as an energy carrier: If renewable energy is available in surplus, the metal oxide gets reduced. If energy or heat is needed, the metal is burned, from Semenova, (2026)

The technical feasibility of a silicon powder burner has recently been demonstrated (Heng, 2025a, Heng, 2025b), laying the foundation for silicon as a direct energy carrier, a concept first proposed by (Bardsley, 2008).

In selecting silicon as an energy carrier, several criteria must be assessed: availability, cost, energy storage density, safety in handling, potential for closing the material cycle, reactivity during activation, and simple, loss-free storage (Bergthorson, 2018).

While technical constraints have been addressed, and intrinsic properties give this metal relevant advantages among others, availability and accessibility are still problematic. According to the European Commission report (JRC, 2024) and Ramírez-Márquez, C. (2025), China produces over 65% of the world's metallurgical-grade silicon (silicon metal) and accounts for over 80% to 90% of global solar-grade polysilicon output. China is associated with significant overcapacity, raising concerns about supply security and sustainable pricing rather than material abundance. European Union demand currently relies on imports from Norway (EU Commission, 2023), with Scandinavian supply offering sustainability advantages through green energy availability (Akyıldız, 2024). Silicon end-of-life recycling rates remain near zero today (KU Leuven, 2022), though this will become increasingly important as the first large volumes of PV module waste arise around 2040.

1.1 The safety perspective

Given these supply-chain and market constraints, the safe handling and processing of silicon and its compounds are critical and often underappreciated dimensions of any large-scale silicon energy economy. It is clear from the literature (Kletz & Amyotte, 2010) that increasing the adoption scale of a hazardous material (or a hazardous process) without any adequate risk assessment will produce a coherent increase in related accidents, as maximising the inventory of a hazardous material would increase the cumulative exposure of targets (workers, installations, and surrounding communities).

The risk level is heightened by several factors, such as underestimating actual risks, assuming that "green processes" are intrinsically safer (Casson Moreno, 2019), and uncritically relying on proven materials or processes while disregarding site-specific variables and variability in conditions. In the Silicon industrial chain, certain hazards could exacerbate the risk of explosions and fires, as demonstrated by recent accidents discussed below.

Silicon and its key process intermediates, including silane (flashpoint 27 °C, pyrophoric) and trichlorosilane, are highly flammable, and fine silicon powder forms explosive dust clouds with ignition energies in the range of 5--100 mJ and minimum explosive concentrations of approximately 100-200 g·m-3.

Actually, the specific process layout for polysilicon manufacturing requires chemical engineering know-how and strict process management due to the use of flammable, toxic, and hazardous materials. Three significant industrial accidents illustrate these hazards across more than five decades of Silicon processing.

In 1972, a catastrophic silicon dust explosion at Elkem's Bremanger plant in Norway killed five workers and severely injured four more, destroying the entire grinding facility; the cause was a hot-work operation on a powder-conveying pipe that had not been cleaned, which dispersed and ignited a fine dust layer and propagated a secondary explosion throughout the building (Eckhoff, 2003). This case reflected some key common failures while dealing with combustible dust: i) poor housekeeping, letting dust pile up; ii) inadequate hot-work procedure, providing an efficient ignition source; iii) unawareness or failure to recognise material-specific hazards.
In January 2014, a fire and explosion occurred at the Mitsubishi Materials polysilicon plant in Yokkaichi, Japan, during maintenance cleaning of a heat exchanger in the hydrogen recycling section; chlorosilane polymer residues had accumulated inside the exchanger, and their hydrolysis under dry, low-temperature conditions produced highly ignition-sensitive compounds whose decomposition — identified as involving Si8H10O14— triggered the explosion when the cover was opened (Kudo et al., 2016).

A recent series of major accidents across the polysilicon supply chain — the 2024 explosion at OCI's plant in Malaysia and the 2020–2021 fires and explosions at Xinjiang facilities (Bernreuter, 2020, 2024; Crawford, 2025a, 2025b; Wood-Black et al., 2021) — shows that solar-grade silicon production still handles highly hazardous materials with little cross-industry safety information sharing. Although these events concerned chlorosilane, hydrogen, and siloxane process hazards rather than silicon metal powder, their concentration in Xinjiang, which holds most of the world's polysilicon capacity, means even localised incidents can disrupt global PV feedstock supply. This context motivates a fuller characterisation of the fire and explosion behaviour along the silicon value chain, including the silicon-particle hazards addressed here. Taken together, these cases demonstrate that the hazards of silicon chemistry — whether in powder grinding, reactive gas processing, or maintenance operations — demand the most rigorous process safety discipline, and that this dimension must be integral to any strategy for scaling Silicon in the renewable energy transition.

1.2 Metal dust explosions

Metal dust explosions present particular hazards compared to organic dust: the high heat of combustion per mole of oxygen, exceeding that of carbon by a factor of two to three, drives adiabatic flame temperatures above 3000 K, generating intense thermal radiation and severe burn injuries (Reding, 2018).

Yet safety literature on silicon combustion behavior and its metal-to-energy cycle remains scarce, and the assumption that silicon powder is harder to ignite than aluminum or magnesium should not be equated with low explosion sensitivity under all conditions.

This latter statement came with the actual difficulty of maintaining stable silicon particle flames in burner applications (Weiser et al., 2026, Heng et al., 2025b). Even Eckhoff's pioneering work (Eckhoff, 1986) underlined the lower ignition sensitivity of Si compared with Al powders, but this should be regarded as a relative assumption, consistent with the specific testing in terms of materials and equipment.

Among other metal dusts, silicon was less tested, and scarce data could be found in the literature. The science community has recently focused on silicon-to-energy applications, investigating combustion behavior, while the safety parameters have been less in the spotlight, according to the authors' literature analysis. This could have reflected on ultimate safety assumptions, or underestimation of the actual explosibility characterization of a combustible powder, which resulted in a misunderstanding of the ignition sensitivity ranking of silicon metal particles.

Jacobson and coworkers (Jacobson, 1964) tested several elemental metal powders. A silicon sample, defined as collected from a bag filter before grinding, exhibited Pmax = 5.6 bar and $(dp/dt)_{max}$ = 827.4 bar·sec^{-1}, corresponding to a K_{St} value of about 225 bar·sec^{-1}·m^{-1}. The sample was sized 100% under 74 µm.

In the aftermath of the reported accident, Eckhoff (1986) conducted an experimental campaign in which very fine silicon samples were analysed. In this, the explosion testing was conducted in the modified Hartmann tube, with an electric spark as the ignition source, as was common at the time. He concludes that fine silicon powders could present a significant explosion hazard, although not as severe as that of equally fine aluminium powders. This is reflected in both the rate of pressure rise and the MIE values. By decreasing the particle size, Silicon ignited more easily and generated higher rates of pressure rise, although these were lower than those of Al at any given particle diameter. In terms of $(dp/dt)_{max}$, this gap is almost equal to four times.

The explosion behaviour of silicon powders in vented tubes is investigated later (Eckhoff, 1988) to identify the actual response of bag-filter equipment to internal overpressure and the reliability of the VDI 3673 standard for explosion-venting design. The silicon sample reported a d50 of about 50 µm and was also tested for its explosibility parameters. When the silicon dust cloud was ignited by a silicon dust flame, the measured reduced overpressure (p_{red}) was correctly predicted by the standard, whereas with a nitrocellulose flame, the p_{red} was very low and inconsistent with the standard.

Skjold (2013) also studied the silicon flame propagation behaviour using a 20 L spherical device by measuring the impact of the ignition delay time (and hence the turbulence level in the vessel) on overpressure and pressure rise over time. A relevant finding was the rapid decrease in dust concentration with increasing ignition delay time, which could be regarded as a critical constraint on the applicability of results from constant-volume explosion vessels at the laboratory scale. Both particle size and shape would have impacted the dust settling in the vessel.

Hybrid mixtures of silicon dust and hydrogen were also investigated. They demonstrated how typical parameters used in the design of explosion protection systems, such as p_{max} and $(dp/dt)_{max}$, are affected by mixture composition and can vary significantly when hydrogen is introduced.

2. MATERIALS AND METHODS

Dust explosion safety characteristics are conventionally grouped into three groups according to their physical meaning and practical role in hazard assessment (Eckhoff, 2003, Bartknecht, 1993). Primary characteristics define the fundamental boundaries of the explosive regime: the lower explosion limit (LEL, also called the minimum explosible concentration, MEC) and the limiting oxygen concentration (LOC) (EN14034-3, EN14034-4). Together they describe the compositional space — in terms of fuel concentration and oxygen availability — within which a self-sustaining deflagration can exist, and they are therefore the quantities most directly relevant to the design of inerting, dilution, and ventilation strategies aimed at preventing an explosive atmosphere from forming in the first place. Secondary characteristics describe the sensitivity of the dust cloud to ignition once an explosive atmosphere is present: the minimum ignition energy (MIE) and the minimum ignition temperature (MIT) of the dust cloud (EN13821, ISO 80079). These determine the type and strength of ignition source capable of initiating an explosion, and so govern the selection of electrical equipment categories, the permissibility of hot-work operations, and the adequacy of electrostatic bonding and earthing measures. Tertiary characteristics quantify the destructive severity of the explosion event itself and are the parameters on which passive and active explosion protection systems such as venting, suppression, and containment are dimensioned. The two principal tertiary parameters are the maximum explosion pressure pmax and the maximum rate of pressure rise (dp/dt)max, from which the scale-normalized deflagration index KSt = $(dp/dt)_{max} \times V^{1/3}$ is derived (EN14034-1, EN14034-2). These were determined experimentally using the standardized 20-liter sphere (see Fig. 2).

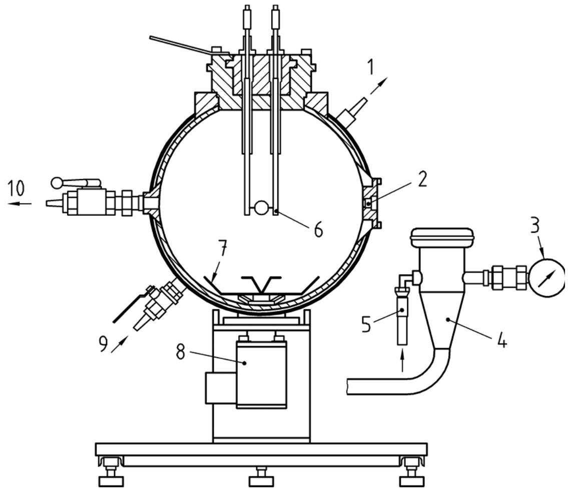

Figure 2: Schematic of the standard 20-L sphere apparatus for the determination of safety characteristics of dusts (EN14034-1), 1) Cooling water outlet 2) Pressure transducers 3) Manometer 4) Dust container 600 ml 5) Air inlet 6) Ignition source 7) Nozzle 8) Fast-acting valve 9) Cooling water inlet 10) Vent (Air, reaction products)

In this vessel, a weighed quantity of dust is loaded into an external 0.6-liter pressurized reservoir (4) at approximately 20 bar, while the sphere is simultaneously pre-evacuated to around 0.4 bar absolute, ensuring that the combined initial condition at the moment of dispersal is atmospheric. Upon actuation of the solenoid valve (8), dust is ejected through a rebound nozzle within the sphere, generating a turbulent suspended cloud representative of worst-case process plant conditions. After a standardized ignition delay time of 60 ms, two opposing pyrotechnic chemical ignitors mounted at the geometric center of the sphere (6) fire simultaneously, supplying a combined ignition energy of 10 kJ. Two piezoelectric pressure transducers flush-mounted in the vessel wall (2) record the complete pressure–time trace of the event, from which p_{max} is extracted as the highest pressure attained and $(dp/dt)_{max}$ is determined as the maximum slope of the rising portion of that trace. The procedure is repeated three times across a systematic range of dust concentrations spanning from low concentrations up to fuel-rich compositions, since neither p_{max} nor $(dp/dt)_{max}$ necessarily occurs at the same concentration for all materials, and both the stoichiometric and the moderately fuel-rich regimes must be covered to ensure the true peak values are captured. The average of the three highest values recorded across the entire concentration series is reported as the characteristic severity parameters of the material. The cubic-root normalization embedded in K_{St} is what enables results measured in the 20 L laboratory vessel to be applied to the sizing of explosion protection systems on vessels of arbitrary industrial scale.

The $(dp/dt)_{max}$ is converted to the K_{St} form through the cubic-root normalisation equation, as this latter value is independent of testing vessel size and could be used as a design parameter for protection systems on vessels of arbitrary industrial scale. In this work, the safety characteristics of a silicon dust sample were tested using a 20 L sphere, in air and mixed with hydrogen, to assess the enhanced synergistic effect of the hybrid mixture (see tests specifications in Table 1). The sample was a 99% pure commercial silicon powder, with a mean diameter of about 20.2 um.

For the silicon-hydrogen tests, the 20L sphere was evacuated to a pressure below the initial 0.4 bar and then filled with hydrogen so that the desired concentration is reached after the dust-air mixture is injected (DIN/TS 31018-1).

Table I: Tests performed and standards of reference

Parameter	Standard
Maximum explosion pressure p_{max}	EN 14034-1:2011
Maximum rate of pressure rise $(dp/dt)_{max}$	EN 14034-2:2011
Maximum explosion pressure p_{max} (hybrid mixture)	DIN/TS 31018-1:2024-05
Maximum rate of pressure rise $(dp/dt)_{max}$, (hybrid mixture)	DIN/TS 31018-1:2024-05

3. RESULTS AND DISCUSSION

This work's results are presented in Figures 3 and 4, respectively, for the maximum pressure and the maximum pressure rise at any tested dust concentration.

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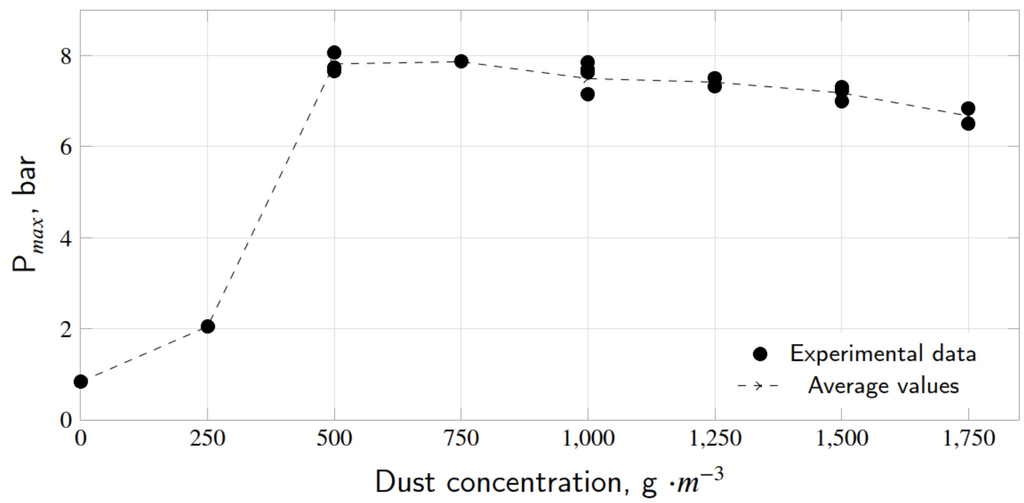

Figure 3: Rate of pressure rise test for this work's silicon sample

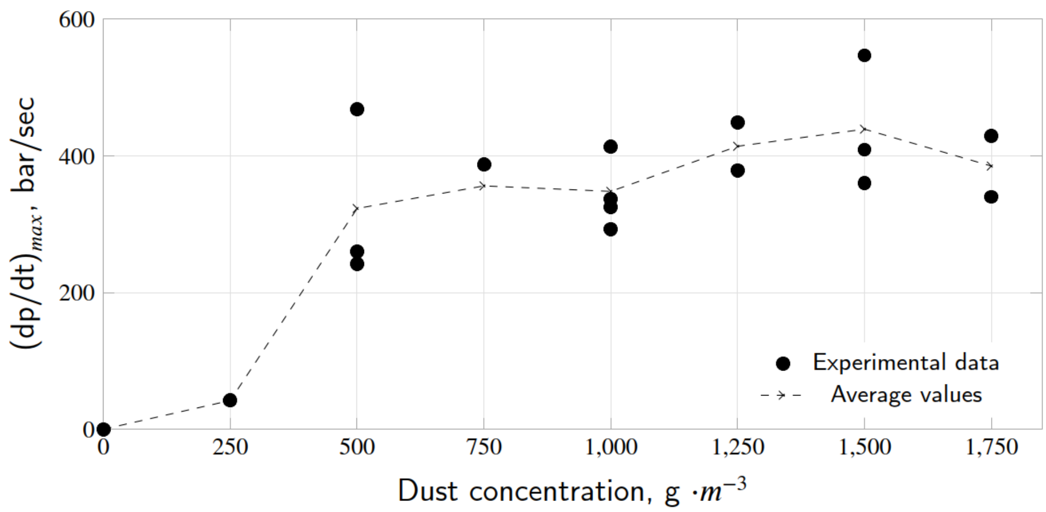

Figure 4: Rate of pressure rise test for this work's silicon sample

The maximum overpressure found was 8.1 bar at 500 g/m3, and the maximum rate of pressure rise was about 440 bar/sec at 1500 g/m3 (these are averages of the maximum values obtained across the different test series). The explosion curve obtained is typical for a metal powder, as it peaks, then settles or slightly decreases in a plateau-like shape. Higher concentrations will likely result in a decrease in both parameters, as they enter a rich fuel mixture and the mass exceeds the dispersion device's effectiveness.

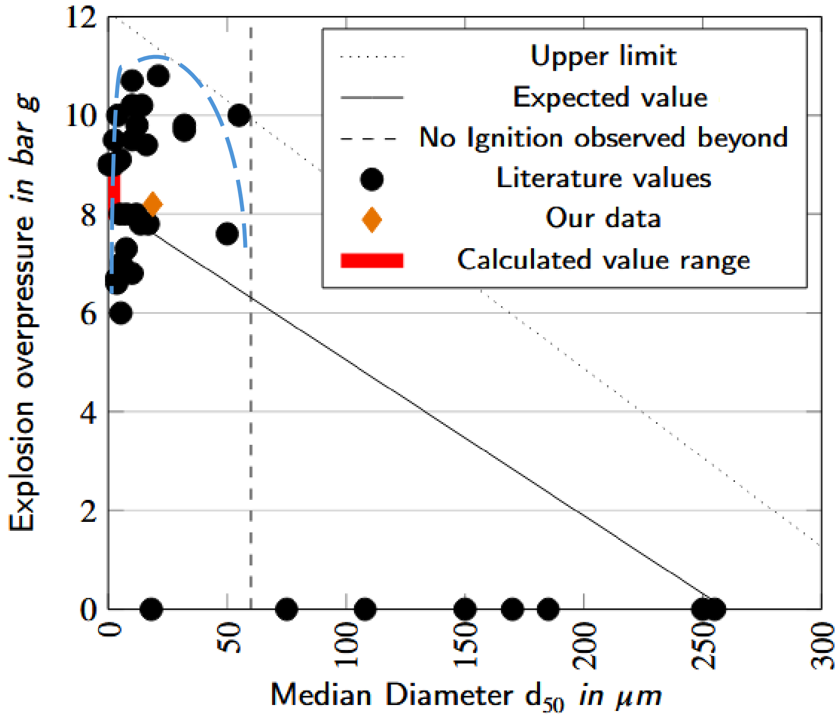

Figure 5: SSE-Chart: Explosion pressures for several silicon dusts against the stated $d_{50,}$ data collected from Lucas (1994), Eckhoff, (1988 & 1992), Cashdollar, (2007), Matsuda, (2001), Taveau, (2018), Hertzberg, (1992), and GESTIS (2026).

Data from explosion testing are collected and organised in the plot in Figure 5, which reports the maximum overpressure against the 50th percentile of the dust particle size distribution. This is a coherent and reliable representation of combustible dust safety parameters, since PSD strongly affects both pmax and $(dp/dt)_{max}$.

From a closer look at the curve in the vicinity of the lower size area, the curve seems to assume a bell-shaped form, with a peak at about 20 microns (around 10 bars, the blue dashed line in Figure 5). Smaller sizes reported lower overpressures. The reasons could be associated with: higher agglomeration (as inter-particle forces grow with reducing diameters), so that agglomerates accounted for the explosion dynamics and then lower overpressures than expected were found; or with passivation enhancement at smaller size, this has been reported by Mittal (2014), for magnesium, but could likely be concerning silicon (although Mittal's data dealt with micro- and nanometric dust samples too). Another alternative explanation could be as a result of data scattering, since some referenced values (such as those from GESTIS database) only reported a median value, but any other information was not disclosed. Particle size distribution parameters could refer to the 50th percentile or average diameter based on volume or weight distribution or even refer to Sauter diameter (the diameter of a sphere that has the same ratio of volume to surface area as the whole group of particles).

For relatively larger diameters, the agglomeration seemed negligible, and higher overpressures are reported, in the range 15-20 μm, while larger diameters tend to give lower overpressures, coherently with the literature, up to a likely threshold where no explosion is reported anymore. This threshold could be identified from the dataset around 70 um. Only one point stood as an outlier at 18 um, with no ignition; this corresponded to a test of Eckhoff (1986) using a different ignition source and device, as reported above. Silicon has clearly lower sensitivity to ignition, as stated before, even though the ignition type is crucial.

The calculated range values are derived from different methods, from analytical to adiabatic equilibrium models, such as CANTERA (Goodwin et al., 2025) and the CEA-NASA codes (Gordon et al., 1994). The predicted pressure range of approximately 7.9–10.5 bar g is particularly uncertain, as the experimental data show large scatter values exceeding the calculated upper bound. This may be due to additional high-temperature reaction pathways, such as silicon nitride formation and the further oxidation of SiO to SiO2, as well as pressure-piling effects in the confined vessel. Therefore, the upper limit should be regarded as preliminary, and further tests considering particle size, morphology and oxidation state are needed before using these values for explosion protection design (see also Morra, D. et al., 2026).

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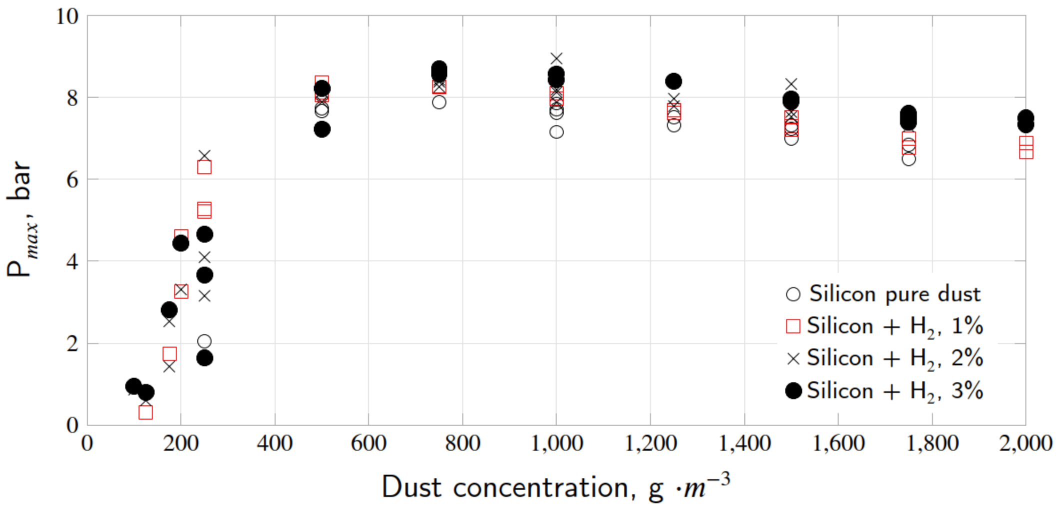

Figure 6: Preliminary results of hybrid silicon-Hydrogen mixtures, overpressure against dust concentration.

Figure 6 presents the preliminary test results for hybrid mixtures (Si-H2). Here, only 3 hydrogen concentrations were tested, all below its LEL (4%). Although further validation and testing are needed, some considerations are warranted. At lower dust concentrations (around the silicon dust LEL), hydrogen addition has a higher effect on the overpressure. As dust mass increases, the differences between pure dust explosions and hybrid mixtures become less relevant, although it seems that the higher the hydrogen share, the higher the overpressure at any given concentration. These assumptions pointed to the existence of a “synergistic” zone, where, despite neither component's LEL being reached, the explosion parameters exceed those of the individual components.

4. CONCLUSIONS

Silicon dust has been investigated for its explosion pressure and maximum rate of pressure rise. This sample exhibited 8.1 bars and 440 bar/sec, respectively, for p_{max} and $(dp/dt)_{max}$. It has also been compared with literature data, and the first upper-bound estimates of its safety characteristics were presented. Further tests are needed to verify the presented approach, but eventually, this will lead to predictable safety characteristics that are easy to implement and remain reliable and independent of the testing facility.

The future perspective is to further examine silicon powders with coarser diameters (in the 70-100 um range), to replicate the different sizes across the silicon processing industry and verify the diameter vs overpressure correlation. Even though no ignition has been observed thus far above median particle sizes above ~70 µm, it is too early to regard silicon powders exceeding that diameter as safe. Other metals such as aluminium and iron show rather flat behaviour, similar to the dotted and straight lines of Fig. 5; hence, further investigation is needed to clarify which assumption is most correct. An experimental campaign is planned in the next research step with coarser samples.

Future work will also focus more on hybrid mixtures of silicon dust and hydrogen. These materials are encountered in the same process facilities along the silicon metal industrial chain, and a synergistic effect on the overpressure of the pure single components is possible (Spitzer, 2026). Preliminary results have already demonstrated that, even with hydrogen content below its LEL (4%), the overpressure of the silicon-H2 mixture increases, confirming the synergistic effect between the two materials.

5. ACKNOWLEDGEMENTS

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