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Dust resistivity and hydrogen-enriched atmospheres: a critical factor in hybrid explosion risk assessment

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Abstract. Explosive atmospheres involving dust/air mixtures pose a persistent threat across industries such as food processing, chemicals, pharmaceuticals, and textiles. Despite broad regulatory frameworks, key ignition parameters like dust resistivity are often underemphasized in risk analysis and explosion prevention. With the increasing complexity of industrial processes, hybrid explosive atmospheres—combinations of dust with flammable gases such as hydrogen—have become a growing concern. Hydrogen's unique properties drastically reduce ignition thresholds, making electrostatic charge control essential. This study explores the crucial role of dust resistivity in hybrid explosion risk, aligned with the ATEX Directive 2014/34/EU and supporting international standards.

1 Introduction

Industries that process, convey, or store particulate solids are no longer dealing with single-phase explosion hazards. Increasingly, pneumatic conveying lines discharge solvent-laden powders into dryers, hydrogen leaks — from electrolyzers, pipelines, or storage tanks—permeate packaging halls, and additive-manufacturing facilities disperse metal dust into atmospheres already enriched with process gases. The outcome is a hybrid explosive atmosphere—a transient or persistent mixture in which combustible dust is suspended alongside flammable gases or vapours, dramatically widening the flammability envelope and lowering the minimum ignition energy.

The ignition risk of such dual-phase systems is governed by a web of inter-dependent parameters. Bulk and surface resistivity, particle morphology, moisture content, and charge decay time shape the electrostatic behaviour of dust clouds, while gas composition, temperature, and turbulence control flame acceleration. When these variables are coupled with evolving production layouts, they generate spatially and temporally heterogeneous hazard zones that elude traditional, steady-state area-classification methods.

To address this challenge, modern safety management must transition from checklist-driven compliance to data-centric, systems engineering. Real-time zoning, made possible by dense networks of gas sensors and automated image-based dust mapping,

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complements deterministic models by supplying transient boundary conditions. Predictive simulations integrating both EN ISO/IEC 80079-20-2 (dust property measurement) and EN 60079-10-2 (area classification) are emerging as a linchpin for plant design and incident investigation.

This presentation therefore proposes a systems-based assessment framework for hybrid explosion risk that aligns with the ATEX Directive 2014/34/EU and its harmonised standards. Through industry case studies and actionable design guidance, we illustrate:

- how material properties feed into electrostatic ignition modelling;
- how continuous hydrogen detection reshapes zoning philosophy; and
- how dual-certified equipment and layered protection systems can be specified with confidence.

2 Hybrid atmospheres: formation and dynamics

2.1 Conditions for explosion

Hybrid explosions occur when:

• **An oxidizer** (typically air) is available;

• **Combustible dust and flammable gases/vapours** are simultaneously present at concentrations within their respective explosive ranges;

• **An effective ignition source** (e.g., electrostatic discharge, hot surfaces, mechanical sparks) initiates combustion.

Hydrogen's distinctive characteristics - its exceptionally low minimum ignition energy (MIE), high diffusivity, and broad flammability window - render hybrid scenarios considerably more volatile than dust-only or gas-only events.

2.2 Effect of mixed dust-gas atmospheres on explosion limits

Hybrid atmospheres reduce minimum ignition energy (MIE) and broaden flammability limits, making ignition easier and explosions more violent. Studies such as García Agreda et al. (2011) show that the combination accelerates flame propagation, often exceeding design expectations [4].

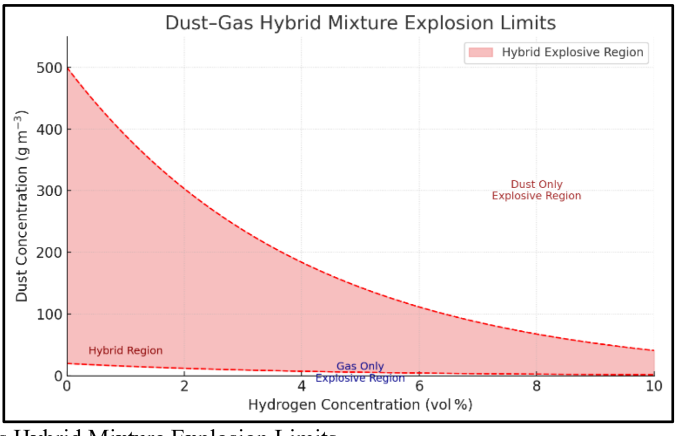

Fig. 1. Dust-Gas Hybrid Mixture Explosion Limits.

2.3 Effect of particle size on dust cloud flammability

Smaller particles (<75 µm):
- Ignite more easily (lower MIE),
- Burn more rapidly due to higher specific surface area,
- Remain suspended longer,
- Contribute more to flame front development.

Agglomerated or moist powders may reduce this risk transiently, but fine dry particles in turbulent flow remain highly explosive [9].

3 Dust resistivity – a critical ignition parameter

3.1 Influence of dust resistivity on ignition risk

Dust resistivity (Ω·m) reflects a material's capacity to accumulate or discharge static electricity. Dusts with resistivity $>10^8$ Ω·m can retain charge long enough to create ignition-capable electrostatic discharges (ESD).

3.2 Thresholds for dust resistivity in explosion risk classification

The thresholds for dust resistivity in explosion risk classification are primarily defined in [6] - "Explosive atmospheres – Part 20-2: Material characteristics - Combustible dusts test methods." [6]:

Table 1. EN ISO/IEC 80079-20-2 – resistivity bands that matter.

Dust sub-group (IEC/ATEX Group III)	Specific electrical resistivity ρ (Ω·m)	Practical meaning
IIIC – conductive dust	$\rho \leq 1 \times 10^3$ Ω·m	Metal powders, graphite, many carbon blacks. Even a very thin layer can bridge clearances or short live parts, so enclosures, cable entries and temperature-limitation measures must assume a low-impedance path to earth.
IIIB – non-conductive dust	$\rho > 1 \times 10^3$ Ω·m	Organics, plastics, foodstuffs, most chemicals. They behave like electrical insulators; the main ignition concern is surface heating or electrostatic charging rather than direct shorting.
IIIA – combustible flyings	Coarse fibres / chips > 500 µm – resistivity not part of the definition	Cotton, wood wool, etc. Settle quickly and normally do not form an explosive cloud; resistivity is therefore not used as a criterion.

3.3 The role of triboelectric charging in explosion hazards

Triboelectric charging occurs due to friction and separation between particles or surfaces. In the absence of adequate charge dissipation mechanisms - such as grounding or controlled humidity—these accumulated electrostatic charges can discharge suddenly, potentially igniting hybrid hydrogen–dust mixtures [2][10].

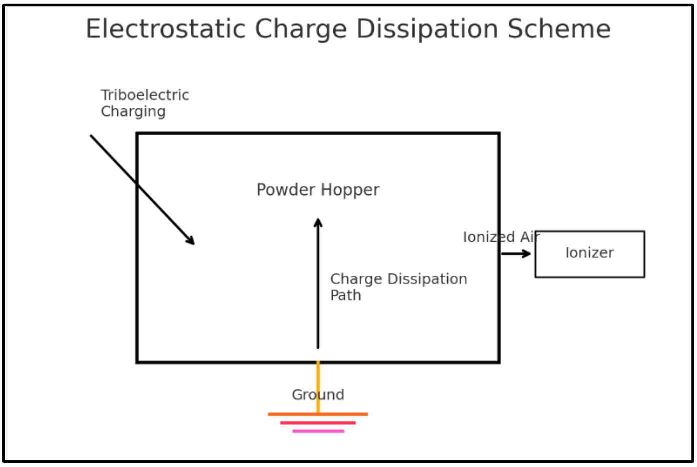

Fig. 2. Electrostatic Charge Dissipation Scheme.

3.4 The role of conductive additives in reducing dust resistivity

Conductive additives—such as graphite, carbon black, or metal flakes—are commonly employed to mitigate electrostatic risks in combustible dusts by improving the material's ability to dissipate accumulated charges.

These additives function through two primary mechanisms:

• **Reduction of Bulk Resistivity**. By incorporating conductive particles into the insulating powder matrix, the overall bulk resistivity of the material decreases significantly. This allows electrostatic charges to dissipate more readily, minimizing the potential for dangerous charge buildup and sudden discharges.

• **Formation of Conductive Networks**. At sufficient loading levels, conductive additives can form percolating networks throughout the powder. These interconnected pathways facilitate efficient electron movement, enhancing the powder's electrostatic conductivity even under low humidity conditions.

These are effective for synthetic powders, polymers, or insulating organic dusts, but may require compatibility checks with product purity and safety goals.

4 Measurement and risk evaluation

4.1 Testing setups for measuring dust resistivity

The measurement of dust resistivity is a critical step in evaluating the electrostatic ignition hazard posed by dust layers and dispersed dust clouds [6]. Specifies the standardized test methods and equipment setups used to determine the volume resistivity and surface resistivity of dusts under controlled laboratory conditions.

Test Chamber and Environmental Conditions. The testing is typically conducted in a climate-controlled chamber to maintain stable temperature (typically 23 ± 2 °C) and relative humidity (typically 50 ± 5%) in accordance with standard conditions. This is necessary as both temperature and especially humidity significantly affect dust resistivity.

• **Volume Resistivity Measurement Setup**.

- Apparatus: A cylindrical or rectangular test cell with electrically conductive electrodes (usually stainless steel or brass) is used.

- Sample Preparation: The dust sample is compacted with a specified pressure (e.g., 20 kPa) to ensure reproducibility. The mass, geometry, and compaction are standardized.
- Electrical Measurement: A DC voltage source (typically 500 V or 1000 V) is applied across the electrodes, and the resulting current is measured using a sensitive electrometer.

Calculation:

$$\rho = \frac{R \cdot A}{L} \tag{1}$$

where:

ρ = volume resistivity [Ω·m]
R = measured resistance [Ω]

A = cross-sectional area of the dust column [m²]
L = length of the dust column between electrodes [m]

• **Surface Resistivity Measurement Setup.**

- Test Plate: An insulating flat surface (e.g., epoxy or ceramic) is coated with a uniform dust layer of controlled thickness (usually 2 mm or less).
- Electrodes: Two parallel ring or strip electrodes are placed on the surface at a specified distance.
- Measurement: A high-resistance meter applies a voltage across the electrodes and records the leakage current through the dust layer.

Calculation:

$$\rho_s = \frac{V}{I} \cdot k \tag{2}$$

where:

ρ_s = surface resistivity [Ω]
V = voltage [V]
I = current [A]
k = geometric constant based on electrode configuration.

4.2 Safety requirements for hybrid explosive atmospheres

Hybrid explosive atmospheres - where combustible dust coexists with flammable gases or vapors (e.g., hydrogen) - pose complex ignition risks due to the combined properties of both phases. Safety measures must address this dual hazard profile using a multilayered approach that integrates the following key elements:

• **Dual-Certified Equipment**: Equipment installed in hybrid atmospheres must comply with both dust and gas explosion protection standards. Typically, this means:

- Ex t (Protection by enclosure) for combustible dust according to [7].
- Ex d (Flameproof) or Ex i (Intrinsic Safety) for gases/vapors under EN 60079-1 or [8], respectively. This dual compliance ensures equipment integrity against ignition sources for both types of explosive media.

• **Continuous Gas Detection** – Especially for Hydrogen: Given hydrogen's low ignition energy and high diffusivity, continuous monitoring is critical. Detectors should:

- Be certified for fast response and low ppm detection thresholds.
- Interface with automated shutdown systems or ventilation triggers.
- Be positioned considering gas buoyancy (typically near the ceiling in enclosed areas).

• **Real-Time Electrostatic Monitoring**: Electrostatic discharges are a significant ignition source, particularly in powder handling and pneumatic transport. Real-time monitoring systems should:

- Detect charge accumulation on surfaces or in bulk material.
- Alert operators when safe limits are exceeded.
- Work in tandem with ionization or neutralization devices where feasible.

• **HAZOP Including Hybrid-Specific Scenarios**: Traditional hazard and operability (HAZOP) studies must be adapted to include:

- Hybrid mixture modeling, including worst-case scenarios.
- Sequential ignition risk analysis, where dust and gas ignite under different conditions.
- Consideration of ignition source interactions, such as dust smoldering followed by gas detonation.

• **Electrostatic Controls – Grounding, Bonding, Humidity Management**:

- Bonding and grounding of all conductive parts and containers is mandatory to prevent static charge buildup.
- Minimum relative humidity (typically above 60%) is recommended to reduce static generation in dust clouds, especially organic or polymeric dusts.
- Antistatic additives or coatings may be used on equipment surfaces and powders.

• **Explosion Protection Documents and Zoning (per ATEX)**:

- A full Explosion Protection Document (EPD) must be developed as per Directive 1999/92/EC, detailing the classification of hazardous zones and preventive measures.
- Zoning must reflect hybrid behavior, possibly requiring Zone 20/1 or Zone 21/1 classifications in transitional areas.

• **Mitigation Systems (Optional but Recommended)**:

- Explosion venting with dual-phase validation.
- Suppression systems rated for both dust and gas.
- Isolation barriers to prevent propagation between equipment sections.

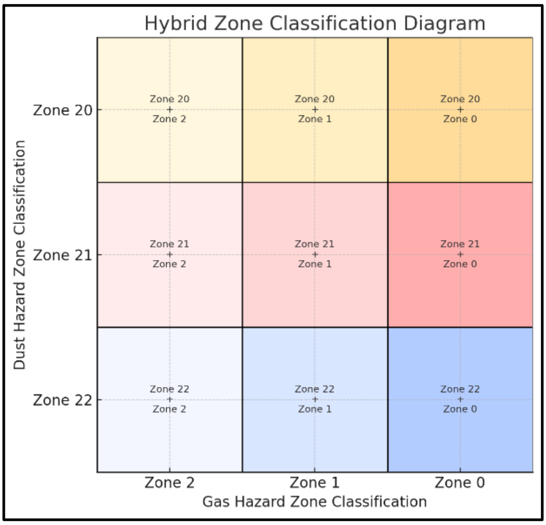

Fig. 3. Hybrid Zone Classification Diagram.

4.3 Integration of hydrogen sensors and electrostatic monitors

In hybrid explosive atmospheres early detection and continuous monitoring are essential for preventing ignition. Integrating hydrogen sensors and electrostatic monitors into a unified safety system enables proactive hazard management by addressing two of the most critical ignition sources: flammable gas accumulation and electrostatic discharge (ESD).

• **Functional Integration Objectives:**

The primary goal of integration is to enable real-time, correlated detection of both gas and electrostatic hazards, which allows:

- Triggering early warning alarms or interlocks before explosive limits are reached,

- Initiating ventilation or inerting systems dynamically,
- Disabling ignition-capable equipment (e.g., conveyors, heaters) when thresholds are exceeded,
- Logging data for HAZOP and incident investigation.

• **Hydrogen Detection Technologies**

Hydrogen sensors suitable for explosive atmospheres must comply with ATEX requirements. Key sensor types include:

- Catalytic bead (pellistor) - robust but limited at low H_2 concentrations.
- Thermal conductivity (TCD) – useful in high-purity environments but less selective.
- Electrochemical cells – accurate and suitable for ppm-level detection.
- MEMS or MOS-based semiconductors - fast response but prone to drift and interference.
- Optical/laser-based TDLAS or NDIR sensors - precise and immune to poisoning, ideal for critical zones.

Sensors must be placed in ventilation dead zones, near leak-prone equipment (e.g., electrolyzers, compressors), or in packaging/handling areas where H_2 may accumulate.

• **Electrostatic Monitoring Technologies**

Electrostatic field monitors detect surface or airborne charge accumulation and can identify:

- High-voltage gradients near equipment,
- Triboelectric buildup on moving dust layers,
- Charging from pneumatic transport or silo filling.

Types of electrostatic monitors include:

- Field meters (static voltmeters),
- Charge decay meters (for evaluating dissipation rates),
- Current-to-ground monitors (detecting leakage through grounding paths),
- Continuous ESD spark counters (especially in silos and ducts).

These devices should be installed on conveyor belts, filter housings, silo walls, or fill lines, especially where low-humidity or synthetic dusts increase ESD risk.

• **Integration Architecture**

A typical integration setup includes:

- Centralized PLC or DCS that receives inputs from both hydrogen sensors and electrostatic monitors,
- Configurable threshold logic (e.g., H_2 > 10% LEL and E-field > 2 kV/m → shutdown signal),
- Relays and interlocks controlling power to motors, heaters, or charging sources,
- Alarm systems with visual/acoustic signals for local personnel,
- Optional SCADA or IIoT connectivity for remote supervision, trend analysis, and predictive maintenance.

• **Compliance and Safety Layering**

- Both sensor types must be certified for Zone 0/1/21/22 as applicable.
- Integration should follow functional safety principles (e.g., SIL 2 minimum for critical applications),
- Must include self-diagnostics, sensor fault detection, and fail-safe states.

By integrating hydrogen sensors with electrostatic monitors, facilities operating in hybrid explosive atmospheres can move from reactive protection to predictive prevention. This dual-monitoring strategy forms a critical component of layered explosion safety under the ATEX framework, enhancing both operational reliability and personnel safety.

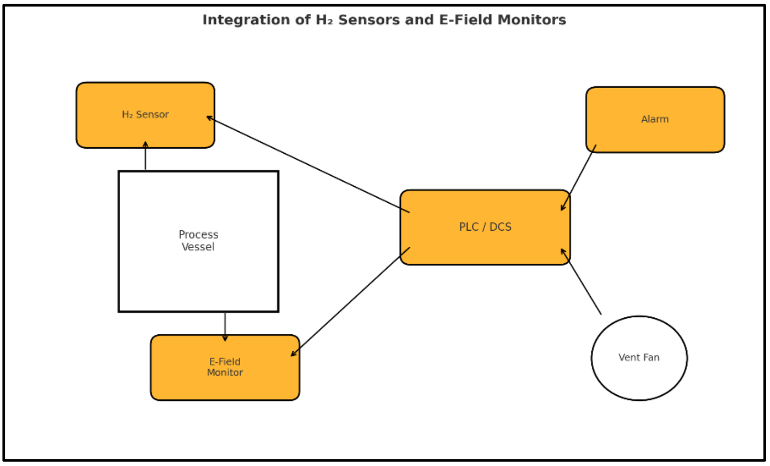

Fig. 4. Integration of H_2 Sensors and E-Field Monitors.

4.4 The role of humidity in electrostatic charge dissipation

Humidity plays a fundamental role in the generation, accumulation, and dissipation of electrostatic charges, especially in environments where combustible dusts or hybrid explosive atmospheres (dust + gas) are present. The level of ambient humidity directly influences the surface conductivity of materials and the electrostatic hazard level in a given process.

• **Mechanism of Influence and Typical Thresholds and Effects**

Humidity affects electrostatic behavior through the following mechanisms:

- Adsorption of Water Molecules: Hygroscopic materials and insulating surfaces (e.g., plastics, dust particles, textiles) adsorb water vapor from the air, forming a thin conductive film on their surfaces,
- Increased Surface Conductivity: This water layer allows charges to dissipate over time instead of building up,
- Charge Relaxation: The presence of moisture reduces the resistance to charge migration, promoting faster neutralization.

In contrast, low humidity environments lead to:

- Reduced surface conductivity,
- Longer charge retention times,
- Increased likelihood of electrostatic discharge (ESD) events.

According to [6] and [10], maintaining RH ≥ 50% is recommended in dust-handling facilities to minimize electrostatic ignition risks.

Table 2. Typical Thresholds and Effects.

Relative Humidity (RH)	Electrostatic Risk Level	Effects
< 30%	High Risk	Charge accumulates rapidly; high ESD probability
30–50%	Moderate Risk	Partial dissipation; materials still prone to charging
> 50%	Low Risk	Charges dissipate quickly; safer operating conditions

• **Material Dependency**

- Organic dusts (e.g., starch, flour, cellulose) are often hygroscopic and dissipate charge more effectively at higher RH.

- Synthetic polymers (e.g., PTFE, polyethylene) remain insulating even at high humidity, requiring additional grounding or additives.

- Metal powders may oxidize in humid air, altering both conductivity and reactivity - important in hybrid atmospheres involving hydrogen.

Humidity is a key control parameter in mitigating electrostatic ignition risks in dust-laden and hybrid explosive atmospheres. Maintaining optimal RH levels ensures faster charge dissipation, lowers the risk of electrostatic discharges, and complements other protective measures like grounding, bonding, and conductive additives.

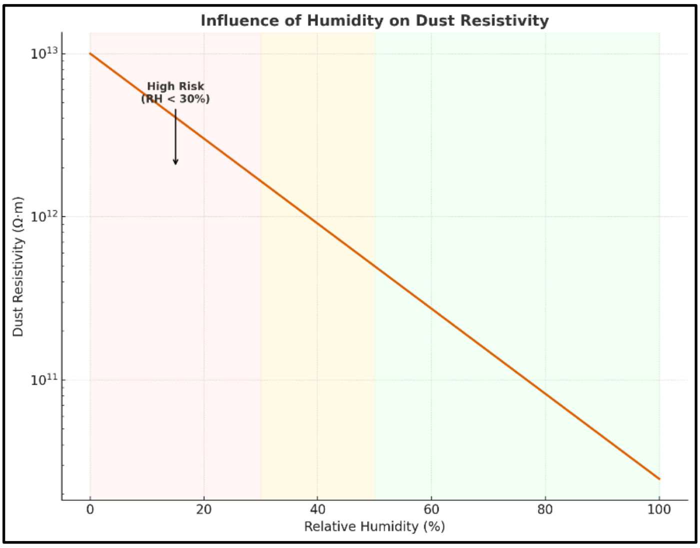

Fig. 5. Influence of Humidity on Dust Resistivity

4.5 Influence of powder moisture content on electrical resistivity

The moisture content of a powder is one of the most influential factors determining its electrical resistivity. Even small variations in moisture can cause orders-of-magnitude changes in both bulk (volume) resistivity and surface resistivity, which directly impacts the risk of electrostatic ignition in dust-handling operations and hybrid explosive atmospheres.

• **Mechanism of Influence**

Moisture affects resistivity through several interrelated physical and chemical mechanisms:

- Water Adsorption: Water molecules adhere to the surface of powder particles, especially in hygroscopic materials (e.g., starch, cellulose, flour),

- Surface Conduction Pathways: Adsorbed water forms thin, weakly conductive films that bridge particle surfaces and create new paths for charge dissipation,

- Increased Ionic Mobility: Moisture enhances the mobility of ions, allowing charges to be neutralized more rapidly.

The net effect is a reduction in resistivity, particularly for insulating powders.

• **Quantitative Influence**

The relationship between moisture content and resistivity is non-linear and highly material-dependent. However, general trends are well established (Table 3).

Table 3. The relationship between moisture content and resistivity.

Moisture Content	Resistivity Trend	Typical Effect
0–1% (dry)	Very high (10^{12}–10^{14} Ω·m)	Electrostatic hazard is severe; charge persists
2–4%	Moderate (10^{9}–10^{11} Ω·m)	Partial dissipation; moderate hazard
>5%	Low (10^{6}–10^{8} Ω·m)	Charges dissipate quickly; reduced hazard

For instance, dry wheat flour may have a resistivity >10^{13} Ω·m, while at 6% moisture it may drop below 10^{8} Ω·m.

• **Material-Specific Sensitivities**

- Organic dusts (e.g., cocoa powder, sugar, wood flour) are highly sensitive to moisture and show strong resistivity reduction with even small increases.

- Inorganic powders (e.g., alumina, cement, silica) often require higher moisture levels to show a comparable resistivity drop.

- Conductive additive-enhanced powders (e.g., with carbon black) may become too conductive when moisture is present, requiring careful design for process control.

• **Explosion Risk Implications**

- Dry powders with high resistivity can accumulate charge during handling (e.g., pneumatic transport, mixing, sieving), creating conditions for electrostatic discharges.

- Increased moisture helps reduce the minimum ignition energy (MIE) risk from electrostatics - but may increase the risk of other ignition sources (e.g., microbial activity, clumping).

Moisture content critically influences the resistivity of powders and, by extension, their electrostatic ignition hazard. Proper control of moisture - through drying, humidification, or conditioning - is essential in explosion safety strategies for dust-handling facilities. Safety assessments must consider both the minimum and maximum expected moisture levels in the process to ensure robust ATEX compliance.

5 Electrostatic risk factor (ERF) framework

The Electrostatic Risk Factor (ERF) Framework is a structured methodology designed to quantify and qualify the electrostatic ignition hazard associated with powder handling, gas-powder mixtures (hybrid atmospheres), and potentially explosive environments. It integrates material properties, process conditions, and environmental variables into a risk-based model suitable for use in ATEX zone classification, HAZOP analysis, and explosion protection design.

The ERF Framework aims to:

- Identify electrostatic ignition potential in complex industrial scenarios,
- Rank materials or processes based on relative electrostatic risk,
- Support design of preventive and protective measures (e.g., grounding, humidification, inerting),
- Complement dust explosivity testing with a charge-generation perspective.

It is applicable in industries such as:

- Powder coating,
- Additive manufacturing (metal and polymer),
- Food and pharmaceutical processing,

- Hydrogen co-processing with solids (hybrid ATEX zones).

Table 4. Electrostatic Risk Factor (ERF) Framework.

Dust Resistivity	Hydrogen Present	Risk Level	Recommended Controls
$>10^8$ Ω·m	Yes	Very High	Ex d IIC / Ex t IIIC, RH >60%, dual sensors
10^4–10^8 Ω·m	Yes	High	Zone 21, gas detection, bonding
$<10^4$ Ω·m	No	Low	Zone 22, ESD controls as needed

The ERF Framework provides a repeatable, transparent, and adaptable method for assessing electrostatic hazards in both traditional and hybrid explosive atmospheres. It supports evidence-based decision-making, ensuring that explosion safety strategies are both proactive and proportionate to real-world risks.

6 Electrostatic discharge as an ignition source for hydrogen in dusty environments

Yes - electrostatic discharge (ESD) can ignite hydrogen-air mixtures, and in the presence of combustible dust, the risk is further amplified due to the formation of hybrid explosive atmospheres. These environments combine the worst-case characteristics of gas-phase flammability (hydrogen) and solid-phase combustion (dust), resulting in lower minimum ignition energies (MIEs) and a broader ignition probability spectrum.

• **Hydrogen's Exceptional Sensitivity to ESD**

Hydrogen is among the most ESD-sensitive gases, due to:

- Extremely low MIE: ~0.02 mJ in air (as per IEC 60079-20-1),
- High diffusivity: promoting rapid and uniform distribution,
- Wide flammability range: 4–75% vol. in air.

Even very weak electrostatic discharges, including brush discharges and propagating brush discharges, can ignite hydrogen under normal atmospheric conditions.

• **Role of Dust in Ignition Enhancement**

While dust may not always ignite directly via ESD (especially at low charge levels), it plays several key roles in increasing overall ignition susceptibility:

- Suspended dust can act as a heat sink, extending flame duration and favoring hydrogen ignition.
- Charged dust particles can generate localized fields that enhance discharge formation.
- Triboelectric charging in pneumatic transport lines, mixers, and silos can produce discharges sufficient to ignite hydrogen–air mixtures even when the dust itself has high MIE.
- Hybrid atmospheres often exhibit MIEs lower than either component alone.

• **Experimental Evidence**

According to EN 1127-1 and research cited in [2]:

- Hydrogen-air mixtures can be ignited by discharges as low as 0.015 mJ,
- In laboratory setups simulating hybrid atmospheres (e.g., flour + 8% H_2 in air), ignition was observed at significantly lower energy levels than either dust or gas alone,
- Dry, non-conductive powders (e.g., polymer dusts) increase the probability of ESD by inhibiting charge dissipation.

• **Industrial Relevance and Examples**

- Additive manufacturing: Metal dust in enclosed chambers, cooled with hydrogen — critical ignition risk.

- Food and pharma: Hydrogen used in hydrogenation processes near dust-generating units.
- Battery production: Dry powder handling in the presence of hydrogen outgassing from testing cells.

In these applications, poor grounding, low humidity, and insulating materials can lead to invisible, spontaneous ESD events that ignite H_2.

• **Mitigation Strategies**

To reduce ESD ignition risk in dusty hydrogen environments:

- Ensure effective grounding and bonding of all conductive equipment (resistance < 10 Ω),
- Use conductive or dissipative materials for containers, ducting, and flexible IBCs,
- Maintain relative humidity > 50% to promote charge dissipation,
- Continuously monitor hydrogen concentration and electrostatic fields,
- Avoid simultaneous dust cloud formation and hydrogen accumulation in the same zone,
- Apply inerting (e.g., nitrogen flushing) where feasible.

Electrostatic discharges can and do ignite hydrogen in dusty environments, especially in hybrid atmospheres where conditions combine to lower the effective ignition energy threshold. Recognizing this synergistic hazard is crucial for ATEX zone classification, HAZOP studies, and the implementation of effective ignition prevention measures in modern processing industries.

7 Case study - cereal processing plant

A cereal processing facility specializing in the production of oat-based ingredients operates multiple grinding, mixing, and packaging lines. During a process expansion, a hydrogenation unit was introduced to treat certain cereal oils. This introduced a new ignition risk due to the potential leakage of hydrogen gas into areas with airborne oat flour, forming a hybrid explosive atmosphere.

• **Material Characteristics**

- Dust type: Oat flour
- Measured bulk resistivity: 2×10^9 Ω·m
- Moisture content: 4.5%
- MIE of oat flour: ~50–60 mJ (variable with moisture and dispersion)
- Hydrogen ignition threshold: ~0.02 mJ

Despite the moderate resistivity, dry conditions and high-speed powder transfer via pneumatic transport lines resulted in frequent electrostatic charge accumulation, especially near FIBC unloading and silo filling points.

• **Hazard Identification**

- Potential hybrid atmosphere: Fine oat flour suspended in air + possible hydrogen presence.
- Primary hydrogen risk:
  - Chronic leak potential from hydrogenation unit valves,
  - Acute leak scenario from pipeline microcracks or joint failures within the distribution system feeding multiple points in the facility.

Hydrogen leaks from pressurized pipelines - even in small quantities - can result in localized enrichment near ceilings or within enclosures. Combined with suspended dust, this creates a high-sensitivity ignition zone.

- Ignition scenario**:** Electrostatic discharge (e.g., propagating brush discharge in silo) ignites hydrogen-air mix or hybrid cloud.
- Electrostatic Risk Factor (ERF): Calculated as 22 (High) due to resistivity, low RH, and dust concentration near equipment.

• **Implemented Interventions**

- Explosion-Proof Equipment Upgrade
  - All electrical and mechanical equipment in affected zones was upgraded to dual-rated protection:
    - Ex t for combustible dusts (Zone 21),
    - Ex d / Ex i for hydrogen (Zone 1, gas group IIC).
  - Particular attention was given to equipment installed near pipelines and potential leak points.
- Real-Time Monitoring
  - Hydrogen detectors (electrochemical, 0–4% range) were strategically placed:
    - Above hydrogenation skids,
    - Inside false ceilings and above ducting where H_2 accumulation from pipeline leaks was plausible.
  - Electrostatic field sensors installed near filling and transfer points detect high-voltage gradients.
  - Signals routed to a central PLC, triggering ventilation ramp-up, process interlocks, and visual/audible alarms.
- Humidity Stabilization via HVAC Retrofit
  - Relative humidity stabilized at 55% ± 5% to enhance surface conductivity and reduce static buildup.
  - HVAC zoning designed to avoid condensation risk around hydrogen pipes and powder hoppers.
- Conductivity Control through Additive Use
  - A graphite-based conductive additive (1.5% w/w) was introduced into selected oat flour streams.
  - Reduced resistivity to $5 \times 10^7\ \Omega \cdot m$, significantly lowering charge accumulation risk during transfer.
  - The additive was validated to have no negative impact on taste, flowability, or product labeling.
- Revised Explosion Protection Document (EPD)
  - The EPD was updated to incorporate:
    - Risk scenarios involving hydrogen leaks from pipelines,
    - Gas-dust hybrid ignition models, based on [3] et al. (2020) [3],
    - Realignment of zones as hybrid Zone 21/1 with overlap between dust and gas hazards,
    - Clearly defined responsibilities for inspection, leak detection, and shutdown procedures.

• **Outcomes and Impact**

- No ignition events recorded over 18 months of operation,
- ERF Index reduced to 11 (Moderate) post-intervention,
- Improved hydrogen pipeline inspection protocol implemented using leak detection spray and ultrasonic testing,
- Centralized SCADA integration now enables real-time diagnostics and predictive maintenance,
- Enhanced audit compliance with ATEX regulatory frameworks.

This case illustrates that even in food-grade powder processes, the coexistence of hydrogen (especially from pipelines) and airborne dust can lead to a critical ignition hazard. The implementation of a multilayered protection strategy - targeting both electrostatic and hydrogen-related risks- demonstrates the importance of integrating technical, procedural, and environmental controls in hybrid ATEX zones.

8 Best practices for hybrid zone classification

Hybrid explosive atmospheres occur when combustible dusts are present alongside flammable gases or vapors, creating complex ignition risks that cannot be addressed by treating dust and gas separately. Proper hybrid zone classification ensures that all ignition sources are identified and appropriately mitigated. The following best practices are recommended:

• **Combine ATEX Zone Classifications Logically**

- Use the conventional ATEX zoning system to define areas with individual risks:
  - Dust zones: Zone 20 (continuous), Zone 21 (frequent), Zone 22 (occasional).
  - Gas zones: Zone 0 (continuous), Zone 1 (frequent), Zone 2 (occasional).
- For hybrid atmospheres, define overlapping zones that consider both dust and gas presence.

Example: An area with occasional dust clouds and frequent hydrogen presence may be designated as Zone 21/1.

- Equipment used in such areas must meet dual protection (e.g., Ex t for dust and Ex d or Ex i for gas).

• **Use HAZOP / HAZID to Identify Hybrid Interaction Points**

- Perform a Hazard and Operability Study (HAZOP) or Hazard Identification (HAZID) with a hybrid focus:
  - Identify points of potential interaction between gas and dust streams (e.g., powder drying with solvent vapors, hydrogen leaks near silos).
  - Include deviations such as "dust cloud in solvent vapor," "hydrogen in filter housing," or "powder dispersion near leak-prone piping."
- Consider both normal operations and abnormal scenarios (e.g., leaks, ruptures, electrostatic buildup).

• **Incorporate Real-Time Sensor Feedback in Classification**

- Use sensor data to refine the extent and severity of hybrid zones:
  - Hydrogen detectors, VOC sensors, and dust concentration monitors should inform zoning boundaries.
  - Real-time feedback helps adjust zoning dynamically or detect unsafe trends (e.g., simultaneous high dust concentration and gas leak).

- Implement thresholds for automatic intervention (e.g., shutdowns, isolation, inerting) based on sensor correlation.

• Apply [5] and IEC 60079-10-1 as Reference Standards

- [5]: Focuses on dust hazard area classification, including layering, suspension, and source strengths.
- IEC 60079-10-1: Provides guidance for gas hazard area classification, based on leak grading and ventilation.
- While neither standard addresses hybrid zones explicitly, they provide the foundation to:
  - Quantify source strength and frequency for each phase,
  - Define overlapping zones with proper ignition source control,
  - Support development of Explosion Protection Documents (EPD) under Directive 1999/92/EC.

Note: In absence of specific hybrid standards, expert engineering judgment and case-by-case assessment are essential, supported by documented risk analysis.

Hybrid zone classification requires more than a sum of dust and gas risks - it demands a holistic, interaction-aware approach. Best practices include combining ATEX zones, using structured hazard analysis tools (HAZOP/HAZID), integrating sensor data, and grounding decisions in established standards. This layered strategy enhances both technical accuracy and regulatory compliance in facilities facing hybrid explosive atmospheres.

9 Implementation of real-time zoning adjustments

Traditional ATEX zoning relies on static assumptions about flammable atmospheres under "normal" operating conditions. However, in hybrid or dynamic environments, risk levels fluctuate significantly due to process variations, leaks, dust dispersion, and environmental changes. Implementing real-time zoning adjustments enables a risk-responsive strategy, improving safety, uptime, and regulatory alignment.

- Sensor-Driven Zoning Linked to Control Systems
    - Install gas detectors, dust concentration sensors, humidity monitors, and electrostatic field meters at critical points (e.g., silo tops, hydrogen lines, mixing zones).
    - Use a central PLC or DCS to process sensor data and:
        - Flag excursions above preset LEL or dust density thresholds,
        - Trigger interlocks, shutdowns, or ventilation commands,
        - Reclassify zones dynamically in safety logic (e.g., elevate from Zone 22 to Zone 21 during silo filling).
- Define risk-based thresholds calibrated to ignition probability and MIE of local materials.

Example: If H_2 > 10% LEL and dust opacity > 15 mg/m³ → switch to hybrid Zone 21/1 status.

- Adaptive Zone Mapping Through Digital Twins
    - Develop a digital twin of the hazardous process area using real-time process data and CFD models.
    - Simulate:
        - Gas dispersion from valves or pipelines,
        - Dust cloud formation and sedimentation,
        - Hybrid atmosphere evolution under airflow conditions.
    - Overlay sensor data to create a real-time hazard map showing zone boundaries and ignition risk levels.
    - Interface with maintenance systems to prioritize leak-prone or dust-prone areas for intervention.

This enables not just classification, but predictive visualization of zone escalation and decay over time.

- AI/ML Algorithms Predicting Ignition Likelihood
    - Apply machine learning models (e.g., random forest, SVM, neural nets) trained on:
        - Historical ignition incidents,
        - Dust and gas concentration trends,
        - Electrostatic discharge events,
        - Environmental parameters (RH, temperature, flow velocity).
    - Use predictive outputs to:
        - Estimate ignition likelihood in real time,
        - Forecast emerging hybrid zones,
        - Enable proactive zoning decisions and alerts before hazardous thresholds are breached.

Advanced algorithms can even model time-weighted exposure to sub-threshold concentrations, improving risk granularity.

- Regular EPD Updates Reflecting Live Conditions

- Use insights from real-time monitoring to dynamically update the Explosion Protection Document (EPD):
    - Document temporary zone changes due to process conditions,
    - Log sensor-based zoning events as part of incident history,
    - Demonstrate adaptive safety compliance during audits.
- Implement EPD revision workflows that support digital signatures, version control, and real-time data integration from plant SCADA systems.

• Benefits of Real-Time Zoning

- Reduced downtime through targeted interventions,
- Fewer false alarms and more meaningful zoning boundaries,
- Improved worker safety and process transparency,
- Enhanced compliance evidence for ATEX, SEVESO III, and insurance inspections,
- Foundation for Industry 4.0 explosion safety in complex or hybrid-risk facilities.

Real-time zoning shifts the paradigm from design-based assumptions to data-driven decisions. By integrating sensors, digital twins, and predictive AI, operators can dynamically classify zones and adjust protective measures based on actual conditions - ensuring higher accuracy, responsiveness, and safety in hybrid explosive environments.

10 Cost-effective strategies for hybrid explosion mitigation

Mitigating explosion risks in hybrid atmospheres—where combustible dusts and flammable gases (e.g., hydrogen) coexist—often requires advanced equipment and infrastructure. However, many facilities, especially in food, pharma, and materials handling sectors, seek cost-effective solutions that provide adequate safety without excessive capital expenditure. The following strategies offer a high safety-to-cost ratio, supporting both ATEX compliance and practical implementation.

• **Use Conductive Additives in High-Resistivity Dusts**

- Many organic and polymeric powders exhibit volume resistivities $>10^{11}\ \Omega\cdot m$, increasing the risk of electrostatic ignition.
- Incorporating small percentages (0.5–2%) of conductive additives such as:
    - Carbon black,
    - Graphite,
    - Metallic flakes (e.g., aluminum, stainless steel)

can reduce resistivity by several orders of magnitude.

- Additives can be blended during mixing or pre-compounded for consistent distribution.
- Cost is low compared to grounding retrofits or high-end ESD monitoring systems.

Example: Reducing oat flour resistivity from $10^{10}\ \Omega\cdot m$ to $10^{7}\ \Omega\cdot m$ can eliminate the need for zone reclassification and additional barriers.

• **Maintain Optimal Humidity Using Affordable Humidifiers**

- Electrostatic charge accumulation is significantly higher under dry conditions (RH <30%).
- Installing industrial ultrasonic or steam humidifiers to maintain RH between 50–60%:
    - Reduces static generation,
    - Increases surface conductivity of powders,
    - Helps stabilize dust cloud dispersion.
- Mobile or ceiling-mounted humidifiers are low-cost and scalable, especially for silo rooms, FIBC stations, and packaging zones.

A €500 to €1000 investment in humidification can prevent ESD incidents that would otherwise require costly Ex-rated redesigns.

• **Implement Tiered Zoning with Low-Cost Hydrogen Detectors**

- Instead of applying blanket Zone 1 classifications, a tiered zoning approach uses:

- Point-source H_2 detectors (electrochemical or MOS type),
- Localized Zone 1 designation only where leaks may occur,
- Peripheral areas retained as Zone 2 or non-hazardous when H_2 levels are below thresholds.

- Detectors with 4–20 mA output and ATEX approval can be obtained for a few hundred euros and integrated into basic PLCs or even standalone alarms.

This method allows targeted mitigation while keeping overall explosion protection system (EPS) costs low.

• **Reuse Existing Ex-Rated Equipment Across Multiple Zones**

- Where possible, repurpose certified Ex t and Ex d equipment across adjacent or overlapping hybrid zones, avoiding redundant purchases.

- Moveable motors, control panels, or ventilation units already compliant with Zone 21/1 can serve multiple process lines by:

- Implementing interlocked relocation procedures,
- Using modular cable routing and connectors.
- Ensure documentation is updated in the Explosion Protection Document (EPD) to reflect shared use.

Avoids procurement of duplicate ATEX equipment, a major cost driver in expansion projects.

• **Invest in Training and Procedural Controls First**

- Before deploying expensive sensors or automation, invest in:

- Operator training on safe powder handling and leak detection,
- Procedures for bonding, grounding, and inspection,
- Checklists and work permits that control ignition risks operationally.

- Well-trained personnel can prevent ignition scenarios more effectively than underutilized technology.

Example: Preventing spark discharge from an ungrounded FIBC with a grounding checklist costs virtually nothing compared to the consequence of an ignition event.

Hybrid explosion risk can be effectively mitigated without major investment by focusing on material modifications, environmental control, selective detection, and procedural discipline. These cost-effective strategies not only enhance safety and compliance, but also enable scalable safety upgrades aligned with process growth and technological evolution.

11 Alignment of ATEX zones with IECEx classifications

The ATEX Directive (EU) and the IECEx System (international) share a harmonized framework for classifying hazardous areas based on the frequency and duration of the presence of flammable substances—gases, vapors, or combustible dusts. Although developed under different regulatory umbrellas, the zone definitions are directly aligned, ensuring global compatibility in equipment certification and risk assessment.

Table 5. Zone Alignment Table.

ATEX Zone	IECEx Equivalent	Area Description
Zone 0	Zone 0	Continuous presence of flammable gas/vapor (≥1000 h/year)
Zone 1	Zone 1	Frequent presence during normal operation (10–1000 h/year)
Zone 2	Zone 2	Occasional or short-term presence (≤10 h/year)
Zone 20	Zone 20	Continuous or frequent presence of combustible dust clouds

ATEX Zone	IECEx Equivalent	Area Description
Zone 21	Zone 21	Frequent occurrence of dust in suspension during operation
Zone 22	Zone 22	Infrequent or abnormal presence of suspended dust

• **Key Points of Harmonization**

Both systems adopt the same zone numbering and comparable definitions based on likelihood of explosive atmospheres.

Equipment certified under IECEx is generally accepted under ATEX, and vice versa, provided that documentation and marking meet both regulatory requirements.

Ex equipment categories and protection levels (e.g., EPL Ga/Gb/Gc or Da/Db/Dc) also map between the systems, allowing interoperable certification.

• **Hybrid Zone Considerations**

Hybrid explosive atmospheres (dust + gas) are not defined as separate zones in either system.

Instead, simultaneous classification under both gas and dust standards is required:

- Example: A processing area may be classified as Zone 21 (dust) and Zone 1 (gas) if both hazards are expected.

Equipment used in such zones must have dual conformity (e.g., Ex d IIC / Ex t IIIC), and risk assessments must follow both IEC 60079-10-1 (gas) and IEC 60079-10-2 (dust).

ATEX and IECEx use a zone-based hazard classification system that is fundamentally aligned, facilitating global standardization, interoperability of equipment, and harmonized explosion protection strategies. For hybrid zones, parallel application of both gas and dust standards ensures full coverage of ignition risks and proper equipment selection.

12 Practical outlook and recommendations

Effective prevention of ignition in hybrid explosive atmospheres requires a balanced approach—blending material science, process safety, and compliance strategy. Based on current industry practices and research findings, the following recommendations are advised for facilities handling combustible dusts and flammable gases such as hydrogen:

• **Actively manage powder resistivity** through moisture control and conductive blending

- Continuously monitor moisture content of powders to maintain optimal resistivity ranges, especially during seasonal variations.
- Incorporate conductive additives (e.g., graphite, carbon black) for high-resistivity dusts to reduce electrostatic buildup during handling and transfer.

• **Integrate real-time sensing**, HAZOP methodology, and adaptive zoning

- Deploy hydrogen detectors, dust sensors, and electrostatic monitors at critical control points.
- Conduct HAZOP/HAZID studies with a focus on hybrid scenarios—especially leak-dust interaction points.
- Use dynamic zoning based on live sensor feedback to reflect true ignition risk, rather than relying solely on static design assumptions.

• **Prioritize low-cost mitigation** measures before large-scale investment

- Maintain relative humidity >50% using cost-effective humidifiers to prevent electrostatic charge buildup.
- Ensure all equipment and containers are properly grounded and bonded (resistance <10 Ω).

- Apply smart, tiered ATEX zoning using targeted monitoring instead of blanket hazard classification.

• **Leverage ATEX harmonization** for streamlined global compliance

- Select equipment with dual ATEX/IECEx certification (e.g., Ex t / Ex d IIC) to reduce redundancy and ease procurement for international operations.
- Align Explosion Protection Documents (EPDs) with both EN and IEC standards, ensuring unified documentation for audits and inspections.

A risk-informed, resource-efficient approach can significantly enhance safety in hybrid environments—without incurring prohibitive costs. By combining targeted material adjustments, intelligent monitoring, and harmonized compliance tools, organizations can ensure both regulatory conformity and operational resilience in the face of evolving explosion hazards.

13 Conclusions

Hybrid explosive atmospheres—where combustible dusts coexist with flammable gases such as hydrogen—introduce ignition risks that are fundamentally distinct from single-phase hazards. These risks are shaped by the synergistic effects of:

- **Dust resistivity** and its dependency on material composition, moisture, and particle morphology,
- **Hydrogen enrichment**, which lowers minimum ignition energy (MIE) to values as low as 0.02 mJ,
- **Electrostatic phenomena** driven by pneumatic transport, friction, and poor charge dissipation,
- **Environmental parameters** such as relative humidity, which modulate surface conductivity and charge decay.

In this context, relying on traditional static zoning and standard mitigation strategies is no longer sufficient. Instead, an effective prevention strategy must adopt a multi-parameter, standards-aligned approach—rooted in the combined application of:

- [6] (material properties),
- [3] and [14] (zoning),
- [2] (electrostatic hazards),
- And real-time safety instrumentation and monitoring.

This paper presents a comprehensive blueprint that connects **particle-level parameters** (e.g., resistivity, moisture content) with **process-scale interventions** (e.g., real-time hydrogen detection, electrostatic monitoring, adaptive ATEX zoning). Through a case study and data-informed frameworks such as the **Electrostatic Risk Factor** (ERF) model, we demonstrate how explosion prevention can be **scalable, predictive**, and **economically optimized.**

Key conclusions include:

- **Material conditioning** (e.g., humidity control and conductive additives) is a cost-effective first line of defense against electrostatic ignition;
- **Dual-rated equipment** (Ex t + Ex d/i) and hybrid-aware zoning provide robust compliance across ATEX and IECEx frameworks;
- **Real-time sensor integration** - combined with digital twins and machine learning—enables dynamic risk response and continuous improvement;
- **Hybrid atmosphere modeling** must become a core part of HAZOP and EPD methodology to reflect modern processing realities.

Ultimately, transitioning from static protection to adaptive safety engineering is essential to address the evolving ignition risks in powder-handling environments enriched with hydrogen or other flammable gases. The tools, frameworks, and strategies outlined in this study provide a path forward for facilities aiming to align safety, regulatory compliance, and operational efficiency in the age of hybrid explosion hazards.

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