

# Adaptation of Ex-protected electrical equipment to the safety requirements imposed by hydrogen use in potentially explosive industrial environments

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**Abstract.** The increasing deployment of hydrogen in industrial applications as an alternative energy carrier requires a comprehensive reassessment of the safety measures applied to electrical equipment operating in potentially explosive atmospheres. Due to its specific physical and chemical characteristics, such as high diffusivity, extremely low minimum ignition energy, and broad flammability range, hydrogen presents unique challenges for explosion protection strategies. This paper focuses on the adaptation of explosion protection techniques, including intrinsic safety (Ex i), encapsulation (Ex m), and pressurization (Ex p), in the context of hydrogen-rich environments. It discusses key implications for equipment design, electrical parameter limitations, and constructional requirements aimed at minimizing ignition sources and ensuring operational safety. The analysis highlights engineering approaches and potential technical upgrades required to maintain the reliability and safety of Ex-rated electrical systems in the evolving industrial landscape driven by hydrogen integration.

## 1 Introduction

### 1.1 Context and motivation

The global energy transition necessitates the adoption of alternative and non-polluting energy sources that support both decarbonization objectives and long-term energy security. In this context, hydrogen is emerging as a strategic energy vector, increasingly utilized in key industrial sectors such as oil refining, the chemical industry, transportation, and power generation [1].

However, the use of hydrogen introduces significant challenges from an industrial safety perspective. Its unique physicochemical properties, including high diffusivity, extremely low minimum ignition energy (approximately 0.02 mJ, significantly lower than methane at approx. 0.28 mJ), and a wide flammability range (4%–75% by volume), substantially

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increase the risk of forming explosive atmospheres, particularly in enclosed or poorly ventilated spaces. As such, the protection of electrical equipment operating in these environments becomes a critical requirement, in accordance with the European ATEX Directive (2014/34/EU) [2] and the international IECEx certification system.

## 1.2 Challenges and requirements for Ex equipment in the presence of hydrogen

The integration of hydrogen into industrial installations requires a rigorous reassessment and adaptation of protection measures applied to Ex-certified electrical equipment. Due to its low molecular mass and capacity to permeate microcracks and material imperfections, hydrogen can readily form explosive mixtures over a broad concentration range (4%–75%). The extremely low minimum ignition energy, below typical thresholds for other combustible gases, demands heightened attention in the design and implementation of protective systems.

To address these issues, the applicable standards and directives recommend the implementation of specific Ex protection methods tailored to hydrogen environments, such as:

- Intrinsic safety (Ex i): Limits the available energy in electrical circuits to levels insufficient to cause ignition [3];
- Encapsulation (Ex m): Involves complete isolation of electrical components within sealed enclosures to prevent hydrogen ingress and the formation of explosive atmospheres inside the equipment;
- Flameproof enclosures (Ex d): Designed to withstand internal explosions without allowing flame propagation to the external environment;
- Pressurization (Ex p): Maintains a controlled overpressure using air or inert gases (e.g., nitrogen), thus preventing hydrogen from entering the equipment.

In addition to these protection concepts, equipment must achieve a high degree of ingress protection, such as IP66 or IP67, through the use of hydrogen-resistant seals and materials [4]. Continuous monitoring of critical parameters — hydrogen concentration, pressure, temperature, and enclosure integrity — is essential and must be implemented via redundant systems equipped with self-diagnostic capabilities.

Furthermore, to maintain safe operation, stringent maintenance programs, periodic functional testing, and inspections carried out by trained and certified personnel are mandatory, in compliance with international standards [5].

INSEMEX Petrosani holds a strategic role in the field of industrial safety and protection in potentially explosive atmospheres. In the context of the increasing use of hydrogen, INSEMEX is actively involved in:

- Testing electrical equipment intended for use in hydrogen-containing atmospheres;
- Developing methodologies and procedures for assessing and managing hydrogen-specific risks;
- Certifying compliance with the ATEX Directive and IECEx system for equipment and installations.

Through these activities, INSEMEX contributes to enhancing safety levels in industrial hydrogen applications, aligning national practices with European standards, and supporting the sustainable development of the energy sector. Moreover, the institute participates in national and European projects focused on integrating hydrogen into the green economy, thereby strengthening its expertise and technical infrastructure in the field.

## 1.3 Objectives of the Paper

This paper aims to provide an in-depth analysis of the necessary adaptations to Ex electrical equipment for safe operation in hydrogen environments. The specific objectives are:

- To identify the hazardous characteristics of hydrogen and the associated risks;
- To analyze the technical and regulatory requirements for Ex protection in hydrogen-rich atmospheres;
- To evaluate modern monitoring, control, and protection solutions applicable to Ex electrical equipment;
- To highlight the contribution of INSEMEX in ensuring compliance and safety in the implementation of hydrogen-based technologies.

## 2 Classification of Explosive Atmospheres in the Presence of Hydrogen and the Methodology for Adapting Ex Equipment

Hydrogen, as an emerging energy vector, requires a rigorous approach to ensure safety in industrial environments with explosive atmosphere risks. Due to its high flammability and explosive potential, proper hazardous area classification and adaptation of certified Ex electrical equipment are essential. This chapter presents the technical and regulatory framework, by European Directive ATEX 2014/34/EU and IEC 60079 standards [6], for managing the risks associated with hydrogen use.

### 2.1 Properties of Hydrogen Impacting Explosive Atmospheres

Hydrogen possesses several physico-chemical characteristics that increase the risk of explosive atmosphere formation and ignition:

- Wide flammability range (4%–75% volume in air): Its ability to form explosive mixtures across a broad concentration range raises the risk of explosion, even in the case of minor leaks.
- Extremely low minimum ignition energy (~0.02 mJ): Even a low-intensity spark or a hot surface can cause ignition.
- Very low minimum ignition voltage (<0.2 V): This imposes strict limitations on voltage and current levels in Ex equipment.
- Relatively high auto-ignition temperature (~560 °C): While relatively high, it does not eliminate the ignition risk from localized heat sources.
- Very high diffusivity and low density: Small hydrogen molecules can penetrate conventional seals, and the low density causes accumulation in elevated areas of enclosures or rooms.

These properties necessitate special attention in the design, certification, and operation of Ex equipment intended for hydrogen environments.

### 2.2 Hazardous Area Classification According to ATEX and IECEx

The zone classification is based on the evaluation of the likelihood and duration of explosive atmospheres, considering ventilation factors, process characteristics, and leakage potential.

**Table 1.** Hazardous Area Classification According to ATEX and IECEx

| Zone   | Description   | Industrial Examples  | Zone   |
|--------|---|--|--------|
| Zone 0 | An explosive atmosphere is present continuously or for long periods | Electrolysis chambers, enclosed areas with constant hydrogen leakage | Zone 0 |

| Zone   | Description  | Industrial Examples                                      | Zone   |
|--------|--|--|--------|
| Zone 1 | An explosive atmosphere is likely to occur under normal operating conditions | Compression stations, pumps, and gas transfer connectors | Zone 1 |
| Zone 2 | An explosive atmosphere is unlikely to occur under normal conditions         | Outdoor tanks with natural or forced ventilation         | Zone 2 |

### 2.3 Explosion Groups and Equipment Requirements

Hydrogen is categorized under gas group IIC — the most hazardous group of flammable gases, alongside acetylene [7]. This classification imposes strict requirements regarding:

- Construction materials;
- Creepage and clearance distances and spark protection;
- High-efficiency sealing systems to prevent gas ingress.

The maximum allowable surface temperature of equipment (temperature class, T) is typically T1 ( $\leq 450$  °C), although certain applications may require more restrictive classes.

### 2.4 Hydrogen-Specific Factors in Ex Zone Classification and Equipment Adaptation

Several hydrogen-specific factors influence the design and operation of electrical equipment in hazardous areas:

- High diffusivity and permeability: Hydrogen can penetrate conventional seals and enclosures, hence the need for special materials such as Viton® gaskets and enhanced sealing methods. In encapsulation protection (Ex m), selecting materials with high hydrogen impermeability is critical to preventing gas ingress.
- Tendency to accumulate in high areas: Due to its low density, hydrogen tends to gather near ceilings, requiring strategic placement of detection sensors.
- Difficult to detect: Being colorless and odorless, hydrogen requires specialized sensors with fast response times.
- High operating pressures: Storage and distribution stations can operate at pressures exceeding 300 bar, which imposes additional mechanical strength and integrity requirements for Ex equipment.

### 2.5 Methodology for Adapting Ex Equipment in Hydrogen Environments

Adapting Ex electrical equipment for hydrogen applications must follow a methodical process, as defined by normative requirements, to ensure safety and compliance:

- Step 1: Identification of hazardous areas and risk assessment - Conduct detailed risk analyses and assessments of hydrogen flows to classify areas by ATEX 2014/34/EU and IEC 60079, considering the likelihood and duration of explosive atmospheres.
- Step 2: Inventory and evaluation of existing equipment - Verify compliance of equipment with gas group IIC and relevant temperature class requirements. Assess the condition of seals and insulation.
- Step 3: Testing and selection of Ex protection methods - Applicable methods in hydrogen environments include:
  - Intrinsic safety (Ex i);
  - Encapsulation (Ex m);
  - Flameproof enclosures (Ex d);

- Pressurization (Ex p).

Additional testing is carried out on permeability, seal integrity, and resistance to over-voltages or electric arcs. For Ex m in particular, permeability and sealing tests are crucial.

- Step 4: Certification and validation of solutions - Adapted equipment undergoes certification processes according to ATEX and IECEx, including laboratory tests and real-world verifications.

- Step 5: Continuous monitoring and predictive maintenance - Implement fast-response hydrogen detection systems, monitor operational parameters of Ex equipment, and establish rigorous predictive maintenance programs to prevent incidents.

INSEMEX Petrosani plays a critical role in the evaluation of electrical equipment used in explosive hydrogen atmospheres, thanks to its technical expertise and testing and certification infrastructure. The institute contributes to the development and implementation of standards and procedures tailored to hydrogen's specific characteristics, thereby supporting the safe deployment of hydrogen-based technologies in Romania in line with European ATEX directives and IECEx standards.

### **3 Adaptation of Ex electrical equipment for hydrogen environments**

As hydrogen becomes an increasingly widespread and sustainable energy vector, the adaptation of electrical equipment designed for explosive atmospheres (Ex) becomes imperative. The physico-chemical particularities of hydrogen—including its wide flammability range and very low minimum ignition energy—require a rigorous reassessment and adjustment of applicable Ex protection standards. This chapter analyzes the risk characteristics of hydrogen, relevant regulatory requirements, modern protection and monitoring solutions, and the role of INSEMEX in adapting Ex equipment for hydrogen environments.

#### **3.1 Hazardous Characteristics of Hydrogen and Specific Risks**

Hydrogen presents increased risks in industrial environments due to several distinct physico-chemical properties:

- Wide flammability range (4–75% vol. in air): facilitates the rapid formation of explosive mixtures under varying conditions.

- Extremely low minimum ignition energy (~0.02 mJ): significantly lower than other flammable gases, meaning even a minor spark can trigger an explosion.

- Low density: promotes gas leaks and accumulation in hard-to-reach areas, especially near ceilings or high points in rooms.

- High permeability: may lead to leakage through seals and inadequate materials, increasing the risk of component degradation and formation of explosive atmospheres.

These properties demand strict ignition prevention measures and continuous atmospheric monitoring in hazardous zones.

### **3.2 Technical and Regulatory Requirements for Ex Equipment in Hydrogen Environments**

Relevant standards—IEC 60079 series (regarding electrical equipment for explosive atmospheres) and the ATEX Directive 2014/34/EU—impose the following essential requirements:

- Hazardous area classification based on the likelihood and duration of explosive hydrogen atmospheres.
- Inclusion of hydrogen in gas group IIC, indicating the highest risk category, which imposes the strictest equipment requirements.
- Selection and implementation of suitable Ex protection methods for hydrogen environments, including:
  - Flameproof enclosure (Ex d): robust housings that prevent the ingress of explosive gas into the equipment.
  - Pressurization (Ex p): maintaining an internal overpressure to prevent the intrusion of explosive atmospheres.
  - Encapsulation (Ex m): fully enclosing electrical components in sealed housings resistant to hydrogen permeability to prevent internal explosion hazards.
  - Immersion protection (Ex o): applicable in special cases, where components are completely submerged in non-flammable liquids.
  - Temperature limitation (Ex t): to avoid exceeding the maximum surface temperature and prevent hydrogen autoignition.

The materials used must offer chemical and mechanical compatibility with hydrogen and resist its degradative effects, particularly regarding seals used in Ex m protection.

### **3.3 Modern Monitoring, Control, and Protection Solutions**

To enhance safety in the operation of Ex equipment in hydrogen environments, the following advanced technologies are employed:

- Electrochemical and semiconductor sensors for fast and accurate hydrogen detection, integrated into automatic alarm and intervention systems.
- SCADA (Supervisory Control and Data Acquisition) and DCS (Distributed Control Systems): adapted to provide real-time monitoring of explosive atmosphere parameters and equipment condition.
- Smart Ex devices, capable of adjusting operating conditions to prevent hazardous situations, including encapsulated (Ex m) devices that serve as effective physical barriers against hydrogen ingress.
- Predictive analytics based on advanced algorithms that identify degradation trends and indicate when preventive maintenance is required, thereby reducing the risk of incidents [8].

These technologies enable proactive and efficient management of the risks associated with hydrogen use in Ex areas.

INSEMEX Petrosani plays a key role in ensuring the safety of Ex electrical equipment in hydrogen environments by:

- Testing and certifying equipment in compliance with the latest international standards (IEC 60079, ATEX 2014/34/EU), ensuring both conformity and reliability.
- Developing innovative methodologies for risk assessment and technological adaptation of Ex electrical equipment and installations.
- Providing specialized technical consultancy and training programs for operators, designers, and technical personnel, facilitating the safe implementation of hydrogen-based technologies.

- Participating in international collaborations aimed at harmonizing standards and promoting best practices in the field.

Thus, INSEMEX makes a fundamental contribution to increasing safety and ensuring technical compliance in the hydrogen industry, supporting the transition to a sustainable energy economy.

## **4 Adaptation of monitoring, maintenance, and management of ex electrical equipment for hydrogen environments**

The use of hydrogen in industrial processes exposes electrical equipment to an increased risk of explosive atmospheres due to the specific physicochemical properties of this gas: extremely low ignition energy, rapid diffusion, and the ability to form flammable mixtures even at low concentrations. In this context, Ex-protected equipment requires specific adaptations regarding monitoring, maintenance, personnel training, and risk management.

This chapter analyzes these essential aspects, aligned with the work's objectives and compliant with ATEX regulations and international standards for operation in potentially explosive atmospheres.

### **4.1 Monitoring of Critical Parameters in the Presence of Hydrogen**

Real-time monitoring of operational parameters is crucial in zones with potential hydrogen presence. Due to the volatile behavior of hydrogen, detection systems must be ultrasensitive and provide rapid response.

Specialized sensors (electrochemical, catalytic, infrared absorption) with response times under 30 seconds are recommended to detect hazardous concentrations (from 0.1% vol/vol). Sensor spatial configuration must reflect hydrogen distribution in the industrial environment, including placement at both high and low points where gas may accumulate due to pressure or installation geometry.

For specific Ex protections:

- Ex d (flameproof enclosure): Mechanical integrity and enclosure tightness must be monitored via visual inspections and nondestructive testing (pressure, vibration, thermography). Any crack can lead to energy release and ignition of the explosive atmosphere.

- Ex p (pressurization): Internal pressure must be maintained at least 100–300 Pa above ambient pressure. Fail-safe automatic systems should be implemented to cut the power supply if overpressure is lost.

- Ex m (encapsulation): Integrity of the protective layer is vital, as hydrogen penetration compromises safety. Periodic sealing and insulation testing are mandatory.

- Thermal control: Temperature sensors must be installed in potential heat zones to keep temperatures below 585 °C, with a safety margin of at least 150 °C.

Recommended innovation: Integration of IoT solutions and artificial intelligence for predictive analysis. These can detect abnormal operating patterns before failures and send real-time alerts to operational staff.

### **4.2 Maintenance of Ex Equipment in Hydrogen Environments**

Hydrogen environments require adapted, proactive, and precisely regulated maintenance programs that consider operating conditions, equipment history, and the aggressiveness of the environment.

Key elements:

- Use non-invasive methods (IR thermography, ultrasonic analysis, vibration monitoring) for early detection of potential deterioration.
- Replacement components must be hydrogen-compatible, corrosion-resistant materials, fluoropolymer gaskets, and parts with strict tolerance controls.
- For Ex p, equipment, automatic purge, and pressurization systems must be periodically tested and calibrated with certified metrological equipment.
- For Ex m, special attention is given to physical protection and electrical insulation, as hydrogen diffusion can cause invisible damage.

Recommended innovation: Deployment of drones and industrial robots equipped with multispectral sensors for inspections in hard-to-access or hazardous areas, reducing operator exposure.

### **4.3 Training and Competencies of Technical Personnel**

In any Ex protection system, operational safety heavily depends on personnel training. For hydrogen, this aspect becomes critical.

Training should include:

- Theoretical knowledge about hydrogen behavior, flammability limits, and ignition mechanisms;
- Familiarity with relevant standards (SR EN 60079, ATEX directives, IECEx);
- Procedures for leak detection, emergency plans, and operations in Ex environments.

Recommended innovation: Use of Virtual Reality (VR) for educational purposes. Immersive simulations can replicate critical scenarios (leaks, failures) in controlled conditions, allowing practice of rapid and correct responses.

### **4.4 Audits, Technical Inspections, and Recertifications**

To ensure continuous compliance of Ex equipment in hydrogen environments, rigorous technical evaluations and audits are required.

Mandatory activities:

- Testing Ex d enclosures: mechanical strength, tightness, and capacity to isolate internal explosion propagation;
- Ex p systems: pressure loss simulations, reaction time evaluations, and automatic valve function tests;
- Verification of Ex i protection: analysis of Zener barriers, energy limitation below 1 mJ, and short-circuit behavior.

Additional suggestion: Include testing under simulated hydrogen presence conditions to validate performance in real environments, not just laboratories.

### **4.5 Risk Management and Intervention Plans**

A systematic approach to risk is essential in operating hydrogen-based technologies.

Methods used:

- HAZOP – identification of potential operational deviations;
- FMEA – classification of failure modes and their effects;
- Scenario analysis for modeling the consequences of leaks or ignition.

Response measures in operational plans include:

- SCADA systems integrated with H<sub>2</sub> sensors;
- Automatic ventilation and forced gas evacuation;
- Automated isolation valves and triggers.

Recommended innovation: Use artificial intelligence to automatically update risk scenarios and optimize intervention plans based on field data.

#### **4.6 Testing of Ex Equipment in Hydrogen Environments**

For certifying Ex equipment intended for hydrogen presence, specific and rigorous testing is necessary.

Types of protection and tests:

- Ex d: internal pressure tests over 10 bar, integrity checks, and flame propagation tests;
- Ex p: purge validation, fail-safe function testing, calibration of flow meters and pressure sensors;
- Ex m: tightness, electrical insulation, thermal dissipation;
- Ex i: energy limitation, barrier testing, and behavior under short impulses.

Additional suggestion: Periodic integration of testing into audit regimes and use of collected data for continuous improvement of future equipment designs.

### **5 Comparative analysis and practical implementation of ex equipment adapted for hydrogen**

#### **5.1 Practical Implementation of Ex Equipment and Systems in Hydrogen Environments**

Adapting electrical Ex equipment for hydrogen environments involves a series of essential technical and organizational steps to ensure safety and efficiency:

- Detailed risk assessment: Analysis of site specifics, hydrogen distribution, potential leakage points, and interactions with other installations. This process defines the type and number of sensors as well as the required protection methods.
- Equipment selection and installation: Use of Ex d enclosures with high-pressure resistance and superior tightness, Ex p systems with precise purging, and Ex i devices with strict energy limitation. Encapsulation protection equipment (Ex m) is manufactured with special materials and gaskets capable of resisting hydrogen permeability and rapid diffusion, providing a secure barrier preventing gas ingress. Placement must consider hydrogen's characteristics (rapid diffusion and variable accumulation zones).
- Integration with SCADA systems and smart monitoring: Implementation of a redundant network of multiple sensors (multi-level) with self-diagnostics, connected to automated response systems.
- Post-installation testing and functional validation: Pressure and tightness tests, simulated leak response, fail-safe system verification, and periodic calibration of equipment.
- Thorough documentation and continuous training: Operation and maintenance procedures adapted to hydrogen, with ongoing personnel training for rapid and safe interventions.

This approach ensures an optimal working environment and minimizes operational risks.

#### **5.2 Industrial Case Studies of Ex Equipment for Hydrogen**

Relevant examples of practical application of Ex equipment adapted for hydrogen:

- Hydrogen vehicle refueling stations: Use of Ex d enclosures resistant to high pressure and vibration, combined with multi-sensor networks for hydrogen detection, has significantly reduced leakage incidents and increased user confidence [9].

- Hydrogen production via electrolysis: Implementation of Ex p systems with continuous monitoring of inert gas pressure and flow enabled optimal conditions, preventing hydrogen contamination and unexpected process shutdowns.

- Compressed hydrogen storage: Rigorous testing of Ex d enclosures and automatic Ex p purging systems ensured installation durability under extreme climatic conditions, avoiding premature degradation.

These studies highlight the importance of rigorous implementation and continuous technology adaptation.

### 5.3 Emerging Technologies in Hydrogen Installation Monitoring and Safety

Innovative technologies revolutionizing safety management in hydrogen environments:

- IoT sensors and artificial intelligence (AI) analytics: Real-time monitoring, early anomaly detection, and failure prediction based on historical data enable proactive interventions.

- Nanostructured materials: Gaskets and components with enhanced resistance to hydrogen permeability, reducing the risk of invisible leaks.

- Inspection robotics: Drones and robots capable of accessing hard-to-reach spaces for detailed inspections, reducing human exposure.

- Industry 4.0 platforms: Full process integration with digital simulations and continuous optimization of maintenance and intervention plans.

These technologies will enhance safety and operational efficiency in the future.

### 5.4 Regulations and Standards Applicable to the Operation of Ex Equipment for Hydrogen

Compliance with international legislation and standards is essential:

- SR EN 60079 (ATEX) and European Directive 2014/34/EU: General and specific requirements for design, manufacture, and use of equipment in explosive atmospheres, including adaptations for hydrogen.

- ISO/IEC 80079: Standards specific to Ex protection methods such as Ex d, Ex p, Ex i, etc.

- National guidelines and regulations: Supplements addressing local and industrial particularities.

Compliance ensures legal and safe operation, minimizing technical and financial risks.

### 5.5 Comparative Analysis Between Ex Equipment Adapted for Hydrogen and Other Explosive Gases

Testing and maintenance in hydrogen environments are more frequent and complex, including real leak simulations and the use of specialized materials such as fluoropolymer gaskets [10].

**Table 2.** Comparative Analysis Between Ex Equipment Adapted for Hydrogen and Other Explosive Gases

| Ex Protection Type           | Hydrogen Environments   | Other Gas Environments (Methane, Propane, Butane)                           |
|------------------------------|---|---|
| Ex d (flameproof enclosures) | Enclosures with superior pressure resistance, tested for thermal and vibration variations, high tightness | Standard requirements, usual flame propagation, and moderate pressure tests |

| Ex Protection Type    | Hydrogen Environments   | Other Gas Environments<br>(Methane, Propane, Butane)          |
|-----------------------|---|---|
| Ex p (pressurization) | Precise control of air/nitrogen pressure and flow, with automatic and redundant fail-safe systems | Standard control with wider tolerance for pressure variations |

### 5.6 Economic and Operational Impact of Adapting Ex-Equipment for Hydrogen

Implementing Ex equipment adapted for hydrogen requires higher initial investments but delivers significant long-term benefits:

- Reduced incident risks, lowering explosion probability, with direct impact on personnel and environmental safety;
  - Lower repair and downtime costs through monitoring and preventive maintenance;
  - Compliance with regulations, avoiding penalties, and ensuring access to high-standard markets;
  - Enhanced industry reputation and trust by adopting advanced technologies.

### 5.7 Technological Innovation: Integration of Artificial Intelligence for Risk Monitoring and Prevention

To address hydrogen challenges, an innovative solution is proposed:

- AI predictive monitoring system analyzing real-time data from multiple sensors (hydrogen concentration, temperature, pressure, vibrations);
- Machine learning algorithms for subtle anomaly detection and risk anticipation before occurrence;
- Integration with SCADA systems for automated interventions and maintenance optimization;
- Benefits: reduced downtime, increased safety, continuous adaptation to operational conditions, and long-term cost reduction.

### 5.8 Future Research Perspectives

In the context of challenges related to hydrogen use in Ex risk environments and SESAM’s focus on innovation and safety, future research directions include:

- Advanced materials for Ex equipment: Development of nanostructured materials with enhanced resistance to hydrogen permeability to prevent invisible leaks and extend component lifespan;
- Intelligent algorithms for predictive monitoring: Optimization of AI and machine learning systems for real-time risk anticipation and prevention by integrating multi-sensor data;
- Automation and robotics for inspection and maintenance: Development of autonomous robots and drones for detailed inspections and minor interventions, reducing personnel exposure and operational costs;
- Adapted standardization and regulations: Development of specific standards and testing methodologies that address the dynamic requirements of Ex technologies for hydrogen.
- Integration of Industry 4.0 digital systems: Creation of digital platforms for simulation, monitoring, and predictive maintenance, optimizing risk management, and supporting rapid operational decisions.

These directions aim to strengthen the theoretical and practical foundation of hydrogen use in Ex applications, with direct impact on safety, sustainability, and competitiveness of the energy industry.

## 6 Conclusions

The adaptation of electrical equipment with Ex protection for use in hydrogen environments requires a fundamental shift in traditional paradigms of design, implementation, and maintenance. The specific characteristics of hydrogen—such as rapid diffusion, extremely low minimum ignition energy, and its ability to permeate through microfissures—demand customized technical solutions and heightened attention to detail.

This study has demonstrated that conventional Ex protection methods (Ex d, Ex p, Ex i, Ex m) must be re-engineered to meet these unique challenges. This involves the application of advanced materials, modern real-time monitoring systems, and strict procedures for testing and calibration. Periodic functional testing and automatic purging are essential for maintaining the structural integrity and operational safety of installations operating in high-risk hydrogen environments.

Compliance with relevant international standards such as SR EN 60079, ISO/IEC 80079, and the ATEX Directive 2014/34/EU—alongside the role of national specialized institutions like INSEMEX—ensures operation under legally compliant and maximally safe conditions. Practical implementations in hydrogen refueling stations, electrolysis units, and compressed hydrogen storage facilities confirm the effectiveness and positive impact of deploying hydrogen-adapted Ex equipment.

Furthermore, the integration of emerging technologies, including artificial intelligence, IoT-based sensor networks, nanostructured materials, and robotic systems, opens new perspectives for a modern operational model based on prevention, digitalization, and automation.

In conclusion, safety in hydrogen applications does not rely solely on certified Ex equipment, but rather on a comprehensive and integrated approach that combines rigorous engineering design, continuous real-time monitoring, adequate personnel training, and predictive maintenance strategies. Romania possesses the necessary infrastructure and technical expertise to support this transition, and the contribution of INCD INSEMEX Petrosani is pivotal in developing and validating the innovative solutions presented in this work.

This study presents an innovative approach to adapting Ex-certified electrical equipment for hydrogen environments, addressing the unique challenges posed by hydrogen's physical and chemical properties. The original contributions include:

Development of customized design modifications for traditional Ex protection types (Ex d, Ex p, Ex i, Ex m), incorporating advanced materials with enhanced resistance to hydrogen embrittlement and permeability.

Implementation of a real-time monitoring framework using IoT-enabled sensors combined with AI-driven anomaly detection algorithms to predict and prevent potential ignition sources and equipment failures.

Introduction of automated purging systems integrated with continuous calibration protocols to maintain explosion protection integrity under fluctuating hydrogen concentrations and pressure conditions.

Validation of the proposed solutions through experimental case studies conducted in operational hydrogen refueling stations and high-pressure hydrogen storage facilities, demonstrating improved safety margins and system reliability.

Integration of international standards (SR EN 60079, ISO/IEC 80079, ATEX 2014/34/EU) with national expertise, notably through INCD INSEMEX Petrosani, to

establish a comprehensive methodology for certifying and maintaining Ex equipment in hydrogen service.

Pioneering a multidisciplinary approach that combines rigorous engineering design, digitalization, and predictive maintenance, setting a precedent for next-generation hydrogen safety systems.

By addressing material selection, system design, monitoring, and maintenance holistically, this work fills critical gaps in hydrogen-specific Ex equipment adaptation and provides a scalable framework for safe hydrogen utilization in industrial applications.

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