

Review

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# Large-scale hydrogen storage-transportation equipment safety and accident chain interruption keys for petrochemical industry

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**How to cite this article:** Wang, J.; Zhao, Y. Large-scale hydrogen storage-transportation equipment safety and accident chain interruption keys for petrochemical industry. *Energy Mater.* **2025**, *5*, 500124. <https://dx.doi.org/10.20517/energymater.2025.27>

**Received:** 29 Jan 2025 **First Decision:** 6 Mar 2025 **Revised:** 17 Mar 2025 **Accepted:** 27 Mar 2025 **Published:** 25 Jun 2025

**Academic Editor:** Ho Won Jang **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

## Abstract

As global energy demands escalate, hydrogen has gained increasing recognition as a viable alternative fuel and critical energy carrier for future industrial systems. This review examines unique safety challenges associated with industrial-scale hydrogen storage and transportation infrastructure within petroleum and chemical processing sectors. Systematic analysis of hydrogen storage and transportation equipment failure mechanisms reveals three primary risk dimensions: material degradation from hydrogen embrittlement, gas leakage in high-pressure configurations, and combustion/detonation hazards in complex industrial settings. A targeted accident prevention framework emerges through three synergistic strategies: (1) High-performance material engineering for pressure vessels and pipeline networks, (2) Smart monitoring architectures for leak detection in large-scale installations, and (3) Customized deflagration suppression systems for chemical plant applications. By synthesizing cutting-edge hydrogen safety technologies with industrial case analyses, the study proposes an integrated safety management paradigm combining material innovation, predictive monitoring, and explosion mitigation. These technical countermeasures address operational requirements of petrochemical enterprises in hydrogen infrastructure development while establishing comprehensive safety protocols for industrial hydrogen utilization. The insights offer implementable strategies for enabling secure, large-scale hydrogen deployment in energy-intensive petroleum refining and chemical production environments.

**Keywords:** Hydrogen energy safety, storage and transportation, accident chains, situational awareness, risk management and control



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## INTRODUCTION

Hydrogen is widely regarded as a clean secondary energy source, prized for its high calorific value, abundant availability, and potential to serve as a transformative energy carrier in the 21st century. Rapid advancements in hydrogen production, storage, and fuel cell technologies have propelled its adoption as a critical component of global decarbonization strategies<sup>[1]</sup>. China's Medium and Long-term Development Plan for the Hydrogen Energy Industry (2021-2035) underscores hydrogen's pivotal role in future energy systems, framing it as both a catalyst for green energy transitions and a cornerstone of strategic industrial development. However, the very properties that make hydrogen attractive - its odorless, colorless nature and high energy density - also introduce significant safety risks. Its wide flammability range (4-75 vol% in air), exceptionally low ignition energy (as little as 0.017 millijoules), and rapid flame propagation speeds (exceeding 970 meters/second under certain concentrations) create inherent hazards<sup>[2]</sup>. Moreover, hydrogen's reactivity with materials during storage and transport can induce structural failures, such as hydrogen embrittlement, compromising containment systems and increasing leakage risks - a precursor to catastrophic fires or explosions.

Historical incidents starkly illustrate these dangers [Figure 1]<sup>[3-7]</sup>. In 2007, a hydrogen transfer accident in Muskingum, Ohio, involving a ruptured disk, corroded ventilation, and flawed infrastructure design led to fatal gas accumulation and ignition. Similarly, the 2019 KJØRBO Uno-X station explosion in Norway was traced to undertorqued bolts on high-pressure tanks, where gradual leaks overwhelmed venting capacity, halting regional fuel-cell vehicle deployments. At Tsinghua University (2015), improper chemical storage near hydrogen systems triggered a fire and cylinder rupture, exposing deficiencies in hazard zoning. The 2019 AB Specialty Silicones disaster in Illinois, caused by uncontrolled hydrogen release during chemical production, highlighted failures in gas detection and ventilation, claiming four lives. South Korea's 2019 tank explosion, driven by oxygen-hydrogen mixing during electrolysis and defective safety systems, unleashed energy equivalent to 50 kg of TNT. These cases collectively reveal systemic vulnerabilities - material degradation, procedural noncompliance, and inadequate risk mitigation - that span design, operation, and emergency response.

Current hydrogen storage equipment in petrochemical installations inherits and amplifies the systemic flaws demonstrated in historical disasters. The operational triad of high-pressure containments, extended pipeline networks, and multimodal transfer nodes creates uniquely magnified risks that demand industry-specific safety frameworks. These systems concentrate hydrogen's intrinsic hazards through three synergistic pathways: penetrative molecular behavior accelerating material degradation beyond conventional gas service, hyper-diffusive leak dynamics modulated by industrial infrastructure configurations, and cascading combustion risks inherent to large-scale hydrogen deployment. This complexity challenges conventional safety paradigms, as demonstrated by persistent gaps between laboratory prototypes and operational realities - where theoretical models inadequately predict degradation kinetics under industrial service conditions, while detection systems struggle with hydrogen's unique dispersion characteristics. Our analysis confronts this challenge through a threefold lens: first, deconstructing hydrogen's failure mechanisms across material, leak, and combustion systems; second, evaluating emerging mitigation technologies against industrial scalability criteria; third, proposing a risk-cascade management framework that integrates advanced metallurgy with predictive monitoring and active suppression systems. By bridging materials science, fluid dynamics, and safety engineering, this review establishes a paradigm for transforming petroleum industry's hydrogen infrastructure from vulnerability concentration points into resilient energy arteries.



**Figure 1.** Typical hydrogen incidents. (A) A fatal hydrogen explosion at a power plant in Muskingum, Ohio. (B) A hydrogen explosion occurred at KJØRBO Uno-X hydrogenation station in Sandvika, Norway. (C) Laboratory hydrogen explosion in Tsinghua University. (D) An explosion at AB Specialty Silicones in Waukegan, Illinois. (E) Damage to nearby buildings after the explosion of a hydrogen storage tank in South Korea.

## SAFETY ISSUES OF HSTE

The petroleum industry grapples with hydrogen's tripartite menace: material degradation (embrittlement, blistering) under high-pressure cyclic loads, unpredictable leak dynamics (under-expanded jets, stratified flammability in confined spaces), and cascading combustion risks (spontaneous ignition, detonation transitions). Hydrogen's ultralow ignition thresholds, synergized with residual hydrocarbons and turbulent dispersion in refinery networks, create hypergolic hotspots. Legacy infrastructure's incompatibility with hydrogen permeation and shockwave-driven pressure spikes further exacerbates latent risks inherent to petrochemical ecosystems.

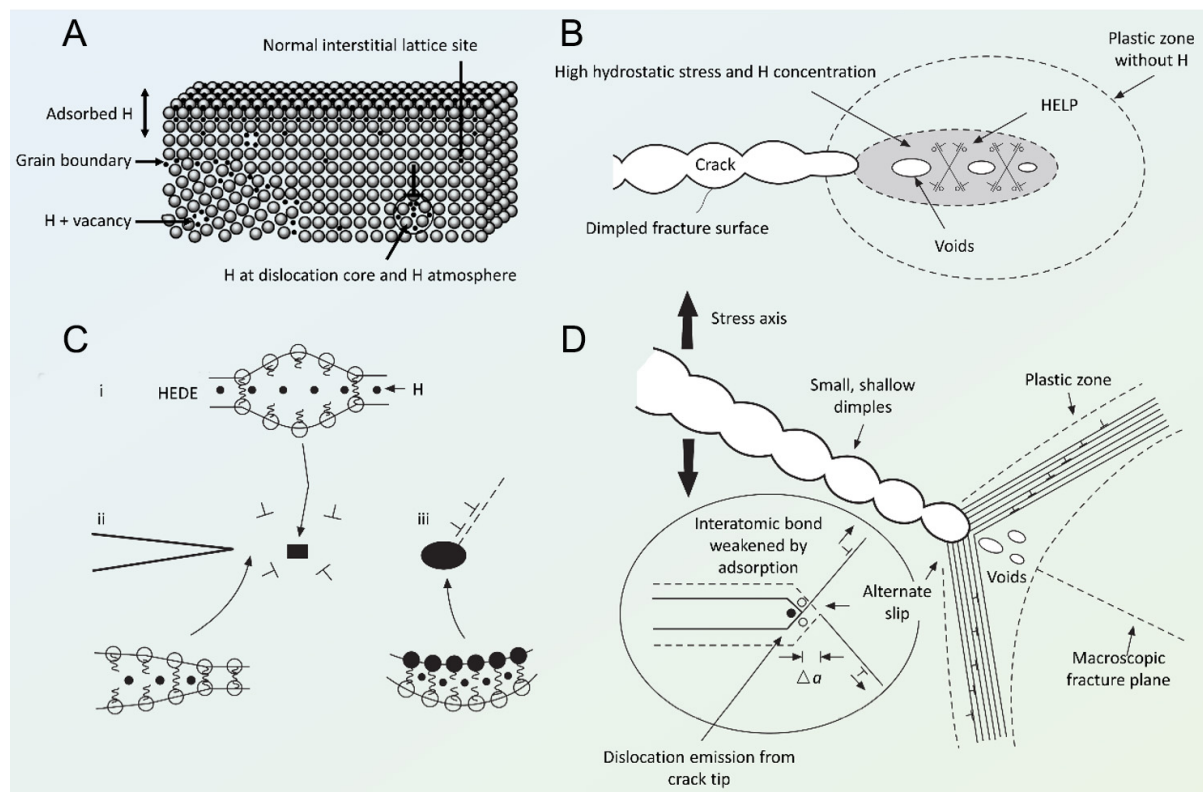
### Hydrogen-induced material failure

Currently, hydrogen storage and transportation primarily utilize four methods: high-pressure gas storage, cryogenic liquid storage, liquid organic hydrogen carriers, and solid-state storage<sup>[8-11]</sup>. High-pressure gaseous hydrogen storage technology is relatively mature but offers lower energy density, while liquid hydrogen storage provides higher energy density but requires an energy-intensive liquefaction process. Liquid organic

and solid-state storage and transportation are safer; however, due to limitations in technological maturity, they have not yet been widely applied in large-scale production. From a cost-benefit perspective, pipeline transportation and high-pressure storage are currently the preferred options. Therefore, austenitic stainless steels (such as AISI 316, 304, 316L, 304L, and other 300 series)<sup>[12,13]</sup>, carbon steels (including Cr-Mo, Cr-Mo-Ni, Cr-Mo-V, etc.)<sup>[14-16]</sup>, and aluminum alloys (such as 5000 series Al-Mg, 3000 series Al-Mn, 7000 series Al-Zn-Mg, etc.)<sup>[17-19]</sup> are widely used materials in the manufacturing of hydrogen storage and transportation equipment (HSTE) and infrastructure.

Hydrogen storage and transportation pose significant risks due to the potential for material failure, which can severely damage pipelines and storage tanks. When exposed to high pressure, hydrogen atoms have the ability to penetrate metal structures, compromising their internal integrity and increasing the risk of catastrophic failures. The detrimental effects of hydrogen on materials manifest in several forms, including hydrogen embrittlement, permeation, blistering, and high-temperature hydrogen attack. Among these, hydrogen embrittlement is notably the most prevalent type of damage. This phenomenon typically arises when hydrogen atoms dissolve in metals and subsequently recombine into hydrogen molecules. This recombination produces localized stress concentrations that can surpass the mechanical strength of the metal, thereby initiating microcracks within the structure [Figure 2A]<sup>[20]</sup>. In pipelines and storage tanks, the embrittlement process is intricate, involving the formation of solid solutions, hydrides, and gaseous byproducts with the metals or their additives. This interaction significantly weakens the bonds at the grain boundaries of the metal, diminishes ductility, and enhances brittleness, which ultimately leads to microcracking and pitting<sup>[21]</sup>. The process of hydrogen-induced cracking comprises six critical steps: the production of hydrogen atoms, their adsorption on the material's surface, absorption into the bulk material, diffusion through the metal lattice, local accumulation of hydrogen atoms, and the eventual initiation of cracks induced by hydrogen<sup>[22]</sup>. This sequence of events underscores the complex challenges faced in preventing hydrogen-related damage in infrastructures intended for hydrogen handling.

Hydrogen diffusion can be expressed through thermodynamic factors, quantified by Sievert's law which states that the dissolved hydrogen concentration  $(C_H)_{dis}$  is proportional to the square root of the hydrogen gas's partial pressure  $(P_{H_2})_{gas}$ ,  $\kappa \times \sqrt{(P_{H_2})_{gas}}$ <sup>[23]</sup>. The principal force driving diffusion is the concentration gradient, as articulated by Fick's first law, which defines the steady-state flow of hydrogen  $J_\infty$  as inversely proportional to the gradient across the diffusion path:  $J_\infty = -D_H \frac{dc}{dx}$ , where  $D_H$  denotes the hydrogen diffusion coefficient<sup>[24]</sup>. This coefficient, dependent on temperature, typically increases as temperatures rise, suggesting that hydrogen diffusion is less pronounced in liquid states due to reduced diffusion coefficients at cryogenic temperatures. The permeation rate of hydrogen, representing the flow rate of dissociated hydrogen atoms across a material, integrates the effects of Sievert's law and Fick's first law into a single expression:  $J_\infty = \frac{D_H \kappa}{d} (\sqrt{P_{high}} - \sqrt{P_{low}}) = \frac{P}{d} \Delta \sqrt{P_{H_2}}$ , where  $P_{high}$  and  $P_{low}$  indicate the higher and lower hydrogen pressures respectively, and  $\Delta \sqrt{P_{H_2}}$  denotes the pressure differential across the material thickness  $d$ <sup>[25]</sup>. Both the diffusion coefficient  $D_H$  and material permeability  $P$  are influenced significantly by temperature variations. Research, including studies by Ishikawa on materials such as aluminum, illustrates that diffusion rates increase significantly with temperature, leading to higher material permeability at elevated temperatures<sup>[26]</sup>. This pattern is also evident in hydrogen diffusion coefficients for materials such as steel, nickel alloys, and various refractories<sup>[27]</sup>. In the context of hydrogen energy applications, certain alloys exhibit exceptionally high permeability, particularly those containing elements such as vanadium (V), niobium (Nb), and tantalum (Ta) due to their body-centered cubic (bcc) structure, which facilitates both hydrogen solubility and diffusion. Earlier studies highlight several high-permeability alloys with dominant bcc phases that significantly influence their hydrogen permeation properties, such as Ta-Ni<sup>[28]</sup>, Nb-Hf-Co<sup>[29]</sup>, Nb-Ti-Ni<sup>[30]</sup>,



**Figure 2.** Hydrogen embrittlement phenomena and mechanisms. (A) Schematic illustration of hydrogen trapping sites within materials at the atomic level. (B) Diagram outlining the HEDE mechanism, highlighting the tensile separation of atoms due to weakened interatomic bonds influenced by hydrogen in the lattice, adsorbed on surfaces, and present at interfaces between particles and the matrix. (C) Diagram depicting the HELP mechanism, characterized by localized plastic deformation and microvoid coalescence in areas of high hydrogen concentration. (D) Diagram illustrating the AIDE mechanism, which facilitates crack propagation via alternate-slip movements from crack tips, enhancing crack and void merging in the plastic zone. Reproduced with permission<sup>[20]</sup>, Copyright 2022 Hydrogen Energy Publications LLC. Published by Elsevier Ltd.

and V-Fe-Al<sup>[31]</sup>. These materials are crucial for advancing hydrogen energy technologies, given their enhanced hydrogen handling capacities.

Three primary physical models elucidate the processes through which hydrogen diffusion precipitates material degradation, as depicted in Figure 2B-D. These models include the hydrogen-enhanced decohesion (HEDE), hydrogen-enhanced local plasticity (HELP), and adsorption-induced dislocation emission (AIDE) mechanisms. Initially posited by Pfeil in 1926, the HEDE model suggests that hydrogen diffusion weakens the cohesive strength among metal atoms<sup>[32,33]</sup>. Conversely, the HELP model argues that hydrogen presence increases the mobility of dislocations, which in turn causes plastic deformation within the metal lattice<sup>[34,35]</sup>. Integrating elements of both HEDE and HELP, the AIDE model proposes that hydrogen atoms, once adsorbed at stress concentration sites such as crack tips, promote either intergranular or transgranular crack propagation, thereby diminishing the material's strength<sup>[36]</sup>. Given the diverse interactions between hydrogen and metals, the mechanisms leading to hydrogen embrittlement and their combined effects are complex and variable, necessitating precise theoretical approaches for their analysis. In pioneering work, Nagumo<sup>[37]</sup> identified hydrogen-vacancy synergies *via* thermal desorption analysis, later formalizing the hydrogen-enhanced strain-induced vacancy (HESIV) theory to explain hydrogen-aggravated fracture<sup>[38]</sup>. The mechanism attributes failure to hydrogen-enhanced vacancy formation and stabilization, evidenced by positron annihilation spectroscopy<sup>[39]</sup> and molecular dynamics simulations<sup>[40]</sup>. These vacancy clusters

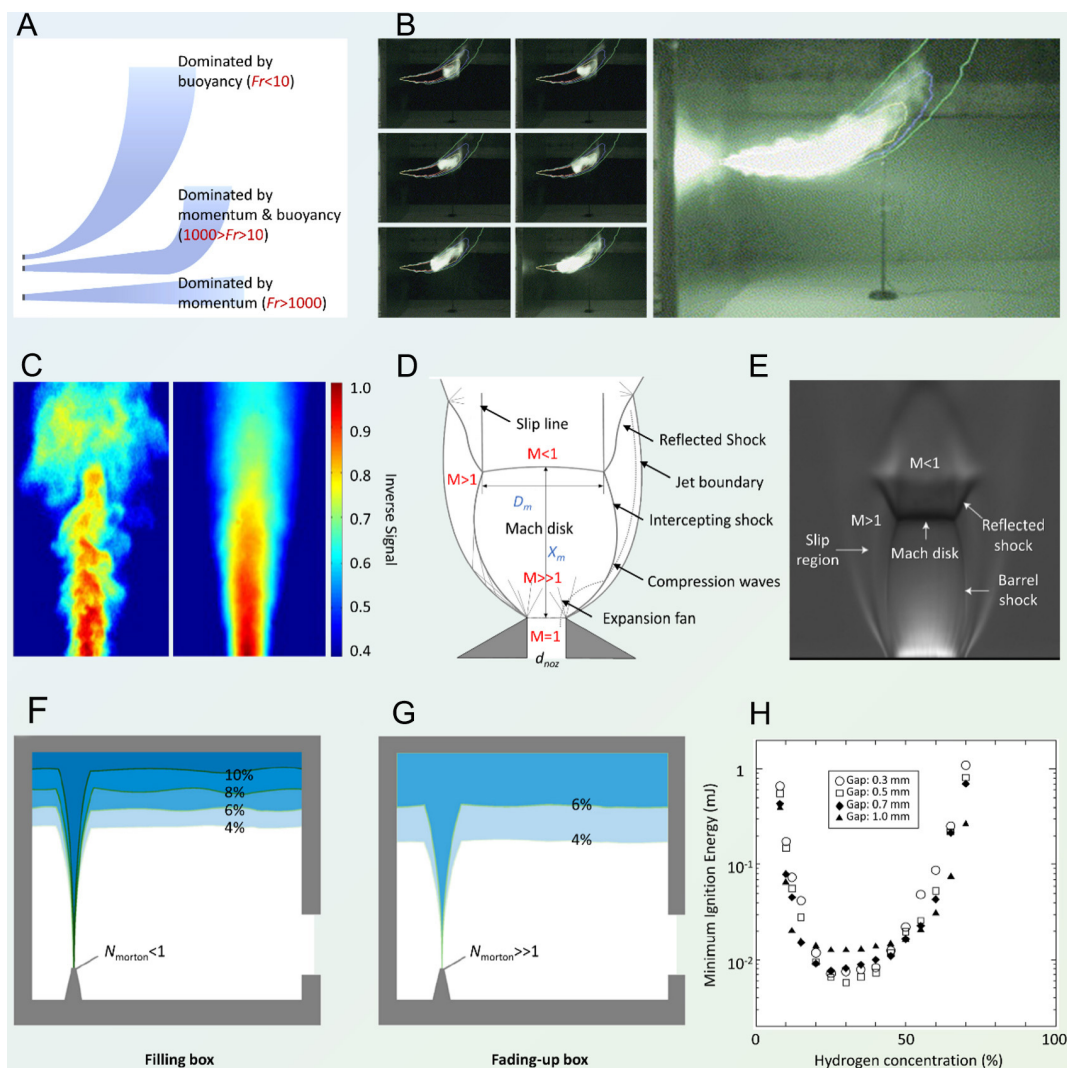
nucleate nanovoids that coalesce into micropores, reducing ductile crack resistance - a phenomenon corroborated by elevated pore density in hydrogen-exposed steels and analogous results in cast iron/alloys. Subsequent studies, such as the hydrogen adatom model by Hou *et al.*<sup>[41]</sup> and the energy calculations by Hickel *et al.*,<sup>[42]</sup> further validated thermodynamic feasibility of HESIV. However, HESIV's reliance on preexisting crack-tip plasticity prompted its integration with complementary mechanisms. For instance, the nanovoid coalescence (NVC) model<sup>[43]</sup> unifies HESIV with HEDE and HELP, reflecting observations of mixed brittle/ductile fracture modes. While HESIV clarifies vacancy-mediated failure, its inability to fully explain plasticity origins underscores the necessity of multi-mechanistic frameworks for comprehensive hydrogen degradation models<sup>[44]</sup>.

Hydrogen permeation and blistering are the main causes of aging in composite material-lined pressure vessels<sup>[45]</sup>. As the smallest diatomic molecules, with a covalent radius of only  $37 \times 10^{-12}$  m, hydrogen molecules can easily penetrate materials such as polymers, with their permeation rate increasing with temperature and storage pressure. Under high pressure, hydrogen gas is readily adsorbed onto plastic liners; if the depressurization rate exceeds the gas diffusion escape rate, blistering of the plastic liner can occur, leading to cracks and failure events in the load-bearing composite material. High-temperature hydrogen attack primarily occurs when system temperatures exceed 200 °C, at which point hydrogen molecules or atoms can rapidly penetrate metals. The interaction of penetrating hydrogen molecules or atoms with impurity elements in the metal (such as carbon) often forms gaseous products (such as methane), causing significant internal pressure<sup>[46]</sup>. Due to the small size of hydrogen atoms and their high mobility when dissolved in metals, rapid formation of bulges, cracks, or elongated pores within the metal can occur.

### Hydrogen gas leak and diffusion

Hydrogen safety incidents often stem from leaks followed by rapid diffusion. When hydrogen gas under high pressure is released into the air, it forms a jet which, based on the pressure differential between the source and the ambient environment, can manifest in one of three distinct states as illustrated in Figure 3A<sup>[47]</sup>: (i) Subsonic jet, where the gas is fully expanded at the outlet; (ii) Critical state jet, characterized by outlet speeds reaching sonic levels; (iii) Under-expanded jet, which occurs when the gas continues to expand and accelerate after being ejected into the atmosphere. For hydrogen systems, a critical pressure threshold of 0.2 MPa is necessary to transition from a subsonic to an under-expanded jet. In the context of fuel cell vehicles, pipeline pressures prior to the initial pressure reduction often exceed this threshold. Additionally, at hydrogen refueling stations and on transport vehicles, pipeline pressures can surpass 20 MPa, which typically results in the immediate development of an under-expanded jet in the event of a leak<sup>[48]</sup>.

The exit densimetric Froude number ( $F_r$ ), a crucial metric in the study of subsonic free jets, quantifies the balance between momentum and buoyancy forces. It is defined as the ratio of the exit velocity of the gas to the square root of the product of gravitational acceleration, nozzle diameter, and the relative density difference between the ambient air and the exiting hydrogen:  $F_r = \frac{U_{exit}}{\sqrt{g d_{noz} (\rho_{\infty} - \rho_{exit}) / \rho_{exit}}}$ <sup>[49]</sup>. This number dictates the behavior of the jet: when  $F_r$  is below 10, buoyancy primarily influences the jet's behavior; for values between 10 and 1,000, both buoyancy and momentum significantly affect the jet; and at values exceeding 1,000, the jet's dynamics are dominated by momentum. To analyze the morphology of hydrogen jets, various techniques are employed, including the transmission schlieren method and planar laser Rayleigh scattering (PLRS)<sup>[50,51]</sup>. The schlieren method utilizes variations in light intensity to detect changes in refractive index caused by density variations, though it simplifies the three-dimensional fluid dynamics into two-dimensional images, which can lead to a loss of information. In contrast, PLRS employs a laser light sheet to capture the characteristics of gas flow. Rayleigh scattering, the physical principle underlying



**Figure 3.** Hydrogen leakage and diffusion process. (A) Schematic diagram depicting hydrogen jets influenced by various mechanisms. (B) Illustration of successful ignition in an environment with a hydrogen concentration exceeding 10%, using a flow rate of 566 L/min through a 9.45 mm orifice. Reproduced with permission<sup>[52]</sup>, Copyright 2006, Elsevier Ltd. (C) Rayleigh scattering images of an unignited hydrogen leak from a tube with a diameter of 1.905 mm, at a flow rate of 10 slm. Reproduced with permission<sup>[53]</sup>, Copyright 2008, Elsevier Ltd. (D) The dynamics of gas flow, showing compression and expansion. Reproduced with permission<sup>[56]</sup>, Copyright 2024 The Authors. (E) Visualization of a hydrogen jet under a pressure of 0.98 MPa viewed vertically. Reproduced with permission<sup>[57]</sup>, Copyright 2012, Elsevier Ltd. (F and G) Two patterns demonstrating the mixing of hydrogen and air. Reproduced with permission<sup>[47]</sup>, Copyright 2023, American Chemical Society. (H) MIE for a  $H_2-O_2-N_2$  mixture, maintaining a constant oxygen ratio of  $O_2/(O_2 + N_2) = 0.35$ , across various hydrogen and oxygen concentrations and four gap distances. Reproduced with permission<sup>[64]</sup>, Copyright 2011 The Authors.

PLRS, occurs when light interacts with particles or molecules smaller than its wavelength, scattering photons elastically. The scattered light intensity is proportional to the gas density and the inverse fourth power of the wavelength, making short-wavelength lasers (e.g., ultraviolet or visible light) ideal for enhancing signal strength. In hydrogen jet studies, Rayleigh scattering is particularly effective because hydrogen's low molecular weight and distinct density contrast with ambient air generate measurable scattering signals, enabling precise, non-intrusive mapping of concentration gradients. This approach overcomes key limitations of the schlieren method, such as 3D-to-2D simplification, while providing high-resolution spatial data. However, PLRS faces challenges when solid objects obstruct the laser sheet or when

background particulates introduce noise.

In practical applications, Swain *et al.* carried out experiments on a horizontal hydrogen jet flowing at 556 standard liters per minute (SLPM), using concentration sensors to create a concentration contour map depicted in Figure 3B<sup>[52]</sup>. Conversely, Houf *et al.* studied a vertical axisymmetric hydrogen leak through a 1.905-mm orifice at a constant mass flow rate, using Rayleigh scattering to map the concentration distribution shown in Figure 3C<sup>[53]</sup>. Accurately calibrating these concentration contours remains challenging, with fixed-point sampling methods predominantly used<sup>[54]</sup>. Nonetheless, further research is necessary to improve sampling accuracy and to understand how the measurement apparatus influences the morphology of the jet.

When the storage-to-ambient pressure ratio surpasses the critical value (approximately 1.9 for hydrogen), an under-expanded jet forms, exhibiting a complex impact structure, uneven velocity distribution, and a Mach disk at its terminus, which separates the supersonic and subsonic regions [Figure 3D]. The characteristics of a Mach disk, such as its formation, position, and diameter, are shaped by several factors including the pressure ratio, the nozzle diameter, and the nozzle's geometric design<sup>[55,56]</sup>. Ruggles *et al.* employed a schlieren system to visually document the shock wave structure in an under-expanded jet formed under a 10:1 pressure ratio with a nozzle outlet diameter of 0.75 mm. Their images distinctly show a barrel-shaped core, the boundary layer of the jet, a prominent Mach disk, and a reflected wave downstream of the Mach disk, as depicted in Figure 3E<sup>[57]</sup>. Crist *et al.* discovered a correlation between the pressure ratio and the spatial placement of the Mach disk. This relationship indicates that the disk's position is proportionate to the square root of the ratio of the critical or stagnation pressure to the ambient pressure, modified by a function of the specific heat ratio, which ranges from 0.65 to 0.67<sup>[58]</sup>. They also found that the dimensionless diameter of the Mach disk and its position from the nozzle share a direct, linear relationship, suggesting that as the pressure conditions within the jet change, so does the scale and location of the Mach disk in a predictable manner<sup>[59]</sup>. This relationship underscores the complexity of the interactions within the jet, driven by both thermodynamic and geometric factors.

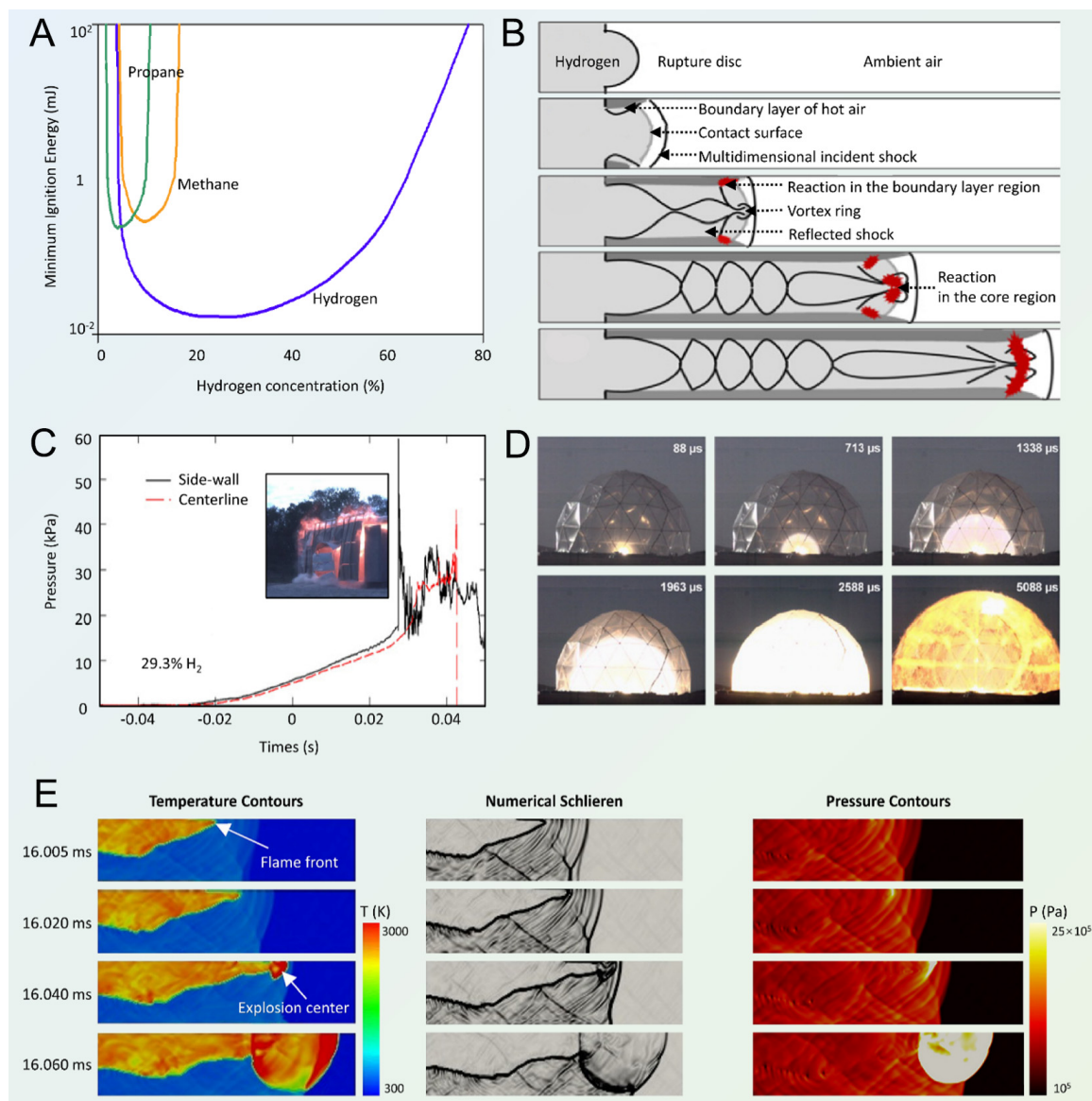
Hydrogen leakage into confined spaces significantly affects the formation, evolution, and kinetics of hydrogen-air mixtures<sup>[60]</sup>. Two leakage modes can be identified based on the leak flow rate [Figure 3F and G]. The "Fading-up box" mode involves a high-pressure, high-initial-momentum leak that completely mixes with air by the time it reaches the ceiling<sup>[61]</sup>. In contrast, the "Filling box" mode, characterized by a low-pressure, low-momentum leak, results in uneven mixing and concentration stratification upon reaching the ceiling<sup>[62]</sup>. To quantify these modes, the Morton number  $N_{Morton} = L_j/Z_r$  is utilized, where  $L_j$  represents the plume formation distance and  $Z_r$  denotes the distance from the release point to the ceiling<sup>[63]</sup>. A Morton number below 1 is indicative of the "filling box" model, whereas a considerably higher value points to the "fading up box" model. In the "filling box" model, the hydrogen plume attains higher concentrations near the ceiling and subsequently spreads downward, forming a distinct concentration gradient. This model facilitates quicker access to both flammable (4%-75% H<sub>2</sub>) and explosive (18%-59% H<sub>2</sub>) zones, and it features a smaller surface volume of the envelope for the same mass flow rate. This results in a higher concentration profile that more readily reaches flammable and explosive conditions. Conversely, the "fading-up box" model does not produce a concentrated plume at the ceiling. Instead, the hydrogen-air mixture becomes more uniformly distributed throughout the space, with minimal vertical gradient, resulting in a larger envelope surface volume. This uniformity supports premixed characteristics, enhancing the volume of combustible mixture.

The Kumamoto group conducted research to compare the ease of ignition and explosion risks between these models, discovering that the minimum ignition energy (MIE) is lowest in environments where the hydrogen concentration is between 20% and 30%, as shown in Figure 3H<sup>[64]</sup>. This phenomenon arises from the interplay of chemical reactivity near stoichiometry, flame thickness stability, and preferential diffusion effects. Specifically, hydrogen-air mixtures in this range balance optimal fuel-oxygen ratios for rapid chain-branching reactions while minimizing heat losses through reduced flame thickness and enhanced laminar burning velocity. Additionally, hydrogen's high diffusivity amplifies flame stretch effects, locally enriching fuel concentration at flame fronts and further lowering ignition energy thresholds. Consequently, the "filling box" model, with its enriched hydrogen concentrations, ignites more readily due to these synergistic factors. In contrast, Nikolaev noted that the "fading up box" model, despite its premixed nature, exhibits an approximately 8% higher combustible volume compared to the "filling box" model for identical leak volumes<sup>[65]</sup>. This disparity highlights how differences in dispersion dynamics - such as localized fuel enrichment versus premixed homogeneity - directly influence combustion risks, underscoring the need for model-specific safety strategies.

### Hydrogen gas combustion and explosion

Hydrogen combustion and explosion can lead to greatly elevated temperatures and pressures, thereby heightening the risks associated. Hydrogen's MIE in air is merely 4% of that for methane, indicating its greater propensity for ignition. When ignited with a low energy source, hydrogen ignites in a laminar phase, achieving a calorific value as high as 143 kJ/g, double that of natural gas, which intensifies the combustion chain reaction<sup>[66]</sup>. As displayed in Figure 4A, in oxygen-enriched settings, hydrogen's MIE can plummet to as low as 0.0056 mJ<sup>[67,68]</sup>, enhancing its susceptibility to ignition. Following this phase, the flame's inherent instability, coupled with the interaction of diverse pressure waves, leads to turbulent combustion. This shift not only accelerates the flame speed but may also escalate to detonation. Particularly critical is hydrogen's extremely low MIE, which makes high-pressure hydrogen leaks susceptible to auto-ignition, resulting in jet fires. These jet fires are marked by high-speed turbulent flames that exert considerable momentum in a specific direction, as shown in Figure 4B<sup>[69]</sup>. In scenarios where gaseous hydrogen is stored in pressurized vessels, the significant pressure differential between the interior of the vessel and the external environment propels the fuel out with high momentum.

The rapid expulsion of high-pressure hydrogen facilitates turbulent mixing with ambient air, creating conditions where ignition risks emerge through interconnected mechanisms. While the reverse Joule-Thomson effect generates a modest temperature rise during expansion (e.g., 9~18 K at 50 MPa), this alone is insufficient to reach hydrogen's autoignition threshold (858 K). However, such heating reduces the MIE, amplifying risks when combined with electrostatic sparks - a hazard driven not by pure hydrogen but by impurities (e.g., particulates or droplets) accelerated in supersonic jets, where friction or impact can generate sparks exceeding hydrogen's ultralow MIE. Dominating spontaneous combustion scenarios, diffusion ignition occurs when shock waves from rapid release compress and heat air to critical temperatures, as demonstrated in confined tubes by Wolanski and Wojcicki<sup>[70]</sup>, where shock reflections at structural discontinuities enhance turbulent mixing and localized heating. These mechanisms synergize dynamically: turbulent mixing (e.g., in complex pipe geometries) accelerates hydrogen-air diffusion, while Joule-Thomson heating lowers MIE, creating conditions where even weak electrostatic discharges or residual shock wave energy can trigger ignition. Experimental studies, such as the work of Grune *et al.*<sup>[71]</sup> with impurity-free systems and the visualization of flame formation in mixing layers by Kim *et al.*,<sup>[72]</sup> underscore the need for holistic safety protocols that address these coupled risks in both confined and open environments.



**Figure 4.** Hydrogen ignition and explosion. (A) MIE of  $H_2$ ,  $CH_4$  and  $C_3H_8$  in air. Reproduced with permission<sup>[67]</sup>, Copyright 2023, Springer Fachmedien Wiesbaden GmbH. (B) Schematic of hydrogen self-ignition within a tube, depicted from top to bottom: the setup prior to rupture; the initial formation of a shockwave; the creation of vortex rings and reactions in both the core and boundary layer regions, triggered by interactions between shockwaves and the boundary layer; reactions occurring primarily in the core region; and the eventual merging of the two reactive zones. Reproduced with permission<sup>[69]</sup>, Copyright 2010, The Combustion Institute. Published by Elsevier Inc. (C) Time histories of overpressure from ignition experiments with 29.3% hydrogen concentrations. Reproduced with permission<sup>[95]</sup>, Copyright 2012, Elsevier Ltd. (D) High-speed images from hydrogen-air cloud detonation test. Reproduced with permission<sup>[98]</sup>, Copyright 2007, Elsevier Ltd. (E) Temperature contours, Schlieren images, and pressure contours capture the final stage of DDT in an uneven  $H_2$ /Air mixture with a 20% concentration. Reproduced with permission<sup>[100]</sup>, Copyright 2022, Elsevier Ltd.

The Joule-Thomson effect, which is pivotal in adiabatic gas flow dynamics through conduits, manifests when gas traverses a throttling device such as a pressure-reducing valve, porous plug, or orifice, inducing both a drop in pressure and a change in temperature. Specifically for hydrogen, the Joule-Thomson cooling effect can lower the temperature to  $-80^\circ C$ . However, when hydrogen gas at high pressure is released into ambient conditions, it experiences the inverse Joule-Thomson effect - a thermodynamic phenomenon governed by hydrogen's negative Joule-Thomson coefficient above its inversion temperature. This unique

property causes temperature to rise during free expansion, contrary to most gases. While this alone does not reach the self-ignition temperature of hydrogen, it does contribute to conditions that favor self-ignition<sup>[73]</sup>. In high-pressure hydrogen leaks, electrostatic ignition may occur due to hydrogen's low MIE and wide ignition range<sup>[74]</sup>. Charged particles, especially when not properly grounded, can accumulate significant electrical potential; for instance, one investigation observed static voltages reaching up to 9 kV at a ventilation outlet, attributed to iron oxide particles mobilized after a leak<sup>[75]</sup>. Additionally, diffusion ignition occurs primarily through the interaction of shock waves with the hydrogen-air mix, where the intensity of the shock wave raises the gas temperature and increases the probability of spontaneous combustion. Research has investigated these mechanisms in tubes or shock tubes following high-pressure hydrogen releases<sup>[76-78]</sup>. Variations in pipeline structure significantly impact self-ignition risks<sup>[79,80]</sup>, as changes in cross-sectional area induce complex flow patterns that enhance ignition probabilities. In pipes with variable interiors, vertical walls generate stronger shock waves and turbulence compared to expansion tubes, which can substantially lower critical relief pressures<sup>[81]</sup>. Other ignition mechanisms include hot surface ignition, where localized high-temperature surfaces ignite hydrogen-oxygen mixtures<sup>[82]</sup>, and mechanical ignition caused by friction and impact<sup>[83]</sup>.

The classification of hydrogen explosions into four categories - expansion deflagration, mixture deflagration, detonation, and deflagration-to-detonation (DDT) - is intrinsically linked to the chain-branching reactions governing hydrogen/oxygen combustion dynamics. These phenomena arise from the competition between chain-branching and chain-termination mechanisms in hydrogen oxidation. For instance, when a hydrogen leak forms a combustible cloud, ignition triggers deflagration driven by radical proliferation (e.g., H, O, OH). This process aligns with the first and second explosion limits of the hydrogen/oxygen mixture, where chain-branching reactions ( $\text{H} + \text{O}_2 \rightarrow \text{OH} + \text{O}$ ) dominate at low-to-intermediate pressures, enabling rapid heat release and flame acceleration<sup>[84]</sup>. However, if the mixture transitions to high-pressure conditions near the third explosion limit, three-body termination reactions ( $\text{H} + \text{O}_2 + \text{M} \rightarrow \text{HO}_2 + \text{M}$ ) and  $\text{HO}_2$ - $\text{H}_2\text{O}_2$  chemistry become critical. Here, the accumulation and subsequent consumption of  $\text{HO}_2$  radicals ( $\text{HO}_2 + \text{HO}_2 \rightarrow \text{H}_2\text{O}_2 + \text{O}_2$ ) introduce nonlinearity into the reaction kinetics, potentially driving the system toward detonation through intensified radical interactions and pressure waves<sup>[85,86]</sup>. The Z-shaped explosion limit curve reflects these competing mechanisms: at low temperatures, wall destruction of radicals suppresses explosions; at intermediate pressures, gas-phase termination ( $\text{HO}_2$  formation) temporarily stabilizes the system; while at high pressures, renewed chain branching *via*  $\text{H}_2\text{O}_2$  decomposition ( $\text{H}_2\text{O}_2 + \text{M} \rightarrow 2\text{OH} + \text{M}$ ) reignites explosivity<sup>[87]</sup>. This interplay explains why violent leaks from high-pressure tanks - where  $\text{HO}_2$ - $\text{H}_2\text{O}_2$  chemistry dominates - often lead to deflagration with large overpressure, while delayed ignition of premixed clouds may escalate to detonation as radical densities surpass critical thresholds. Recent analytical advances, such as eigenvalue analyses of chain-carrier dynamics and homotopy perturbation methods for nonlinear systems, further clarify how perturbations in radical concentrations (e.g., H,  $\text{HO}_2$ ) govern transitions between explosion categories<sup>[88]</sup>. By integrating the  $\text{HO}_2$ - $\text{H}_2\text{O}_2$  subsystem and relaxing steady-state assumptions, modern models now capture the full Z-curve non-monotonicity, bridging microscale chain reactions to macroscale explosion behaviors. Thus, hydrogen explosions are not merely mechanical outcomes of mixing and ignition but manifestations of the underlying chain-reaction criticality, where radical proliferation and thermal-chemical feedback dictate the transition from controlled burning to catastrophic detonation.

Pressure vessel burst (PVB) and boiling liquid expanding vapor explosion (BLEVE) are two major catastrophic outcomes. PVB occurs when a high-pressure gas tank bursts due to factors such as malfunctioning safety devices, increased internal pressure from external heat sources such as fires, or tank failure from hydrogen embrittlement and material damage<sup>[89,90]</sup>. A small crack might only cause a jet fire,

whereas a larger one could lead to a fireball and deflagration. BLEVE happens when a liquid hydrogen container fails due to collision or when hydrogen leaks into the vacuum layer from an internally fatigued wall<sup>[91,92]</sup>. Damage to the insulation layer causes a rapid temperature increase, overheating the liquid hydrogen. Upon reaching the overheating threshold, rapid boiling and evaporation escalate internal pressure until the container bursts. A significant crack or fracture can cause spontaneous combustion of escaping hydrogen, heating the remaining liquid hydrogen and further increasing pressure, resulting in a physical explosion and a large fireball with intense thermal radiation. At ambient conditions, the density of coexisting gas-liquid hydrogen (20.37 K) exceeds that of air, causing leaked hydrogen to hover near the ground, where it absorbs heat and gradually mixes with air to form a flammable hydrogen-air cloud<sup>[93]</sup>.

Hydrogen-air cloud deflagrations are common in hydrogen explosions. When hydrogen fully mixes with air to form a large cloud, a vapor cloud explosion (VCE) occurs if it reaches the flammable limit. Compared to other gases such as methane, unconfined hydrogen-air clouds can generate significant overpressure, and confined clouds are even more dangerous, producing higher blast overpressure [Figure 4C]<sup>[94-96]</sup>. Hydrogen-air clouds can also detonate, resulting in much greater blast loading<sup>[97]</sup>. Detonation, unlike deflagration, involves the adiabatic compression of the leading shock wave, inducing faster ignition and heat release, with much lower reaction times and higher overpressures. Groethe *et al.* conducted field tests, detonating a 30% hydrogen-air cloud with C-4 explosive, reaching flame speeds of about 1,980 m/s and peak overpressures five times higher than deflagration at the same concentration [Figure 4D]<sup>[98]</sup>. Under certain conditions, commonly in confined space or blocked environment, a laminar flame accelerates, generating compression waves that merge into shock waves, leading to deflagration-to-detonation transition (DDT). DDT occurs as the flame accelerates continuously before suddenly transitioning to detonation<sup>[99,100]</sup>, typically within microseconds to tens of microseconds [Figure 4E]. Boundary layer effects increase the flame surface area, enhancing the reaction rate, heat release, and flame stretching. As flame surface speeds increase, pressure waves coalesce into a leading shock wave. Once sufficiently accelerated, the flame surface and shock wave couple, creating a feedback loop that increases temperature and pressure, culminating in detonation<sup>[101,102]</sup>.

Predicting DDT remains challenging due to its microsecond-scale dynamics, which often restrict experimental analysis to qualitative observations. Optical methods such as schlieren imaging and shadowgraphy exploit density gradients to resolve detonation structures (e.g., Mach stems, incident shocks) in confined geometries, though such confinement introduces artifacts such as velocity deficits and amplified transverse waves<sup>[103-105]</sup>. Advanced laser diagnostics, including hydroxyl radical planar laser-induced fluorescence (OH-PLIF) and nitric oxide PLIF (NO-PLIF), provide deeper insights: OH-PLIF maps reaction zones *via* intermediate OH radicals, while NO-PLIF tracks shock-heated regions using seeded NO (2,000 ppm), enabling precise induction zone length measurements. Recent advancements in simultaneous OH/NO-PLIF further discriminate unburned pockets from quenching events in non-confined detonations. While numerical simulations are critical for DDT studies<sup>[106-108]</sup>, accurately modeling the interplay of turbulent combustion, shock waves, and confinement-induced artifacts remains computationally prohibitive.

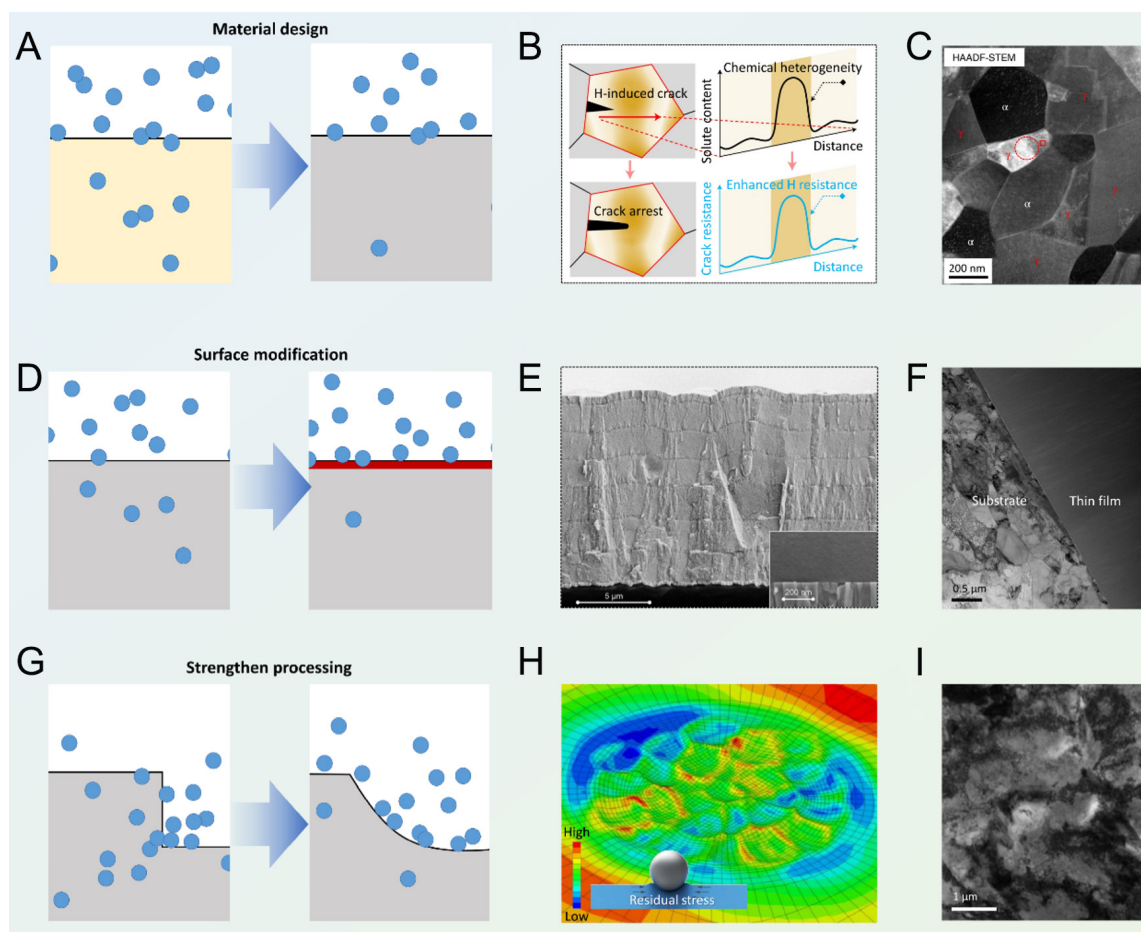
## HYDROGEN INCIDENT CHAIN INTERRUPTION STRATEGY

The disaster incidents during the hydrogen storage and transportation process are diverse and occur abruptly, making emergency warnings challenging. Interrupting the chain of accidents is crucial in preventing such incidents, focusing on three key aspects: first, the safety design of hydrogen storage containers and transportation pipeline materials; second, high spatiotemporal resolution and rapid response hydrogen leak detection; and third, the construction of explosion and detonation isolation mechanisms.

### Material safety design for HSTE

In designing safe hydrogen storage and transportation facilities, a critical step involves selecting and engineering materials with tailored resistance to hydrogen permeation and embrittlement. As illustrated in Figure 5A, this selection process must balance physical and chemical properties, including chemical composition, microstructure, yield/tensile strength, weldability, thermal stability, and manufacturability. Material suitability depends on hydrogen state (liquid, gas, or solid), operational conditions (temperature, pressure, cyclic loading), and design criteria such as hydrogen permeability, HE sensitivity, and mechanical robustness. For instance, austenitic steels with > 7% Ni are widely used for hydrogen containers due to their low hydrogen diffusivity ( $D_{\text{eff}}$ ) and high solubility, attributed to their fcc structure. However, their stability under cryogenic conditions must be carefully assessed, as stress-induced martensitic transformation at subzero temperatures can exacerbate HE susceptibility<sup>[109,110]</sup>. To mitigate this, advanced alloying strategies incorporate nitrogen (N) and manganese (Mn) to stabilize austenite while introducing nano-sized precipitates (e.g., TiC, NbC) as hydrogen traps. These carbides, with binding energies of 40-70 kJ/mol, drastically reduce  $D_{\text{eff}}$  by immobilizing hydrogen at interfaces or within precipitates<sup>[111,112]</sup>. Grain boundary (GB) engineering further optimizes performance:  $\Sigma 5$  and  $\Sigma 9$  boundaries act as preferential trapping sites, while high-angle GBs in nickel alloys are tailored to balance short-circuit diffusion and trapping<sup>[113,114]</sup>. Aluminum alloys, favored for their lightweight properties, require microstructural modifications to offset their inherent strength limitations. For example, 7xxx series alloys leverage coherent T-phase precipitates (superior to  $\eta$ -phase) to redistribute hydrogen from GBs to grain interiors, reducing interfacial decohesion<sup>[115,116]</sup>. Additions of zirconium (Zr) form  $\text{Al}_3\text{Zr}$  dispersoids, which act as high-capacity hydrogen traps, enhancing HE resistance without compromising ductility<sup>[117]</sup>. Innovative material designs exploit solute heterogeneity to achieve synergistic properties. As shown in Figure 5B and C, Mn-Al-Si steels engineered with Mn-rich buffer zones suppress strain-induced martensite formation, maintaining austenite stability under deformation while resisting hydrogen-assisted cracking<sup>[118]</sup>. Similarly, high-entropy alloys such as CoCrFeMnNi utilize atomic-scale disorder and nanotwinning to limit hydrogen enrichment and dislocation impingement at GBs, achieving exceptional HE resistance<sup>[119,120]</sup>. Advanced coatings and surface treatments (e.g., laser melting, ultrasonic nanocrystallizing) on metallic components further reduce hydrogen uptake by altering surface energy barriers or introducing compressive residual stresses<sup>[121]</sup>. Ultimately, hydrogen-resistant materials demand a holistic approach integrating alloy chemistry, phase stability, defect engineering, and processing techniques. These strategies collectively ensure compliance with operational demands while addressing the trilemma of strength, permeability, and embrittlement resistance.

Polymers such as polyethylene (PE) and polyvinyl chloride (PVC) are widely employed in structural components of hydrogen storage and transportation systems (e.g., piping, tanks) due to their low cost and chemical inertness<sup>[122]</sup>. However, for sealing applications in high-pressure hydrogen environments - particularly in dynamic systems such as compressors, valves, and fuel cell connectors - advanced elastomers such as fluorinated elastomers (FKM), acrylonitrile-butadiene rubber (NBR), and brominated butyl rubber (BIIR) are prioritized<sup>[123-125]</sup>. These materials uniquely address the dual challenges of hydrogen permeation resistance and mechanical reliability. FKM, for instance, leverages its highly polar C-F bonds to minimize hydrogen diffusion by stiffening the polymer matrix and reducing free volume, while its inherent thermal stability ensures performance under cyclic pressure fluctuations. NBR, enriched with nitrile groups, provides a polar backbone that impedes hydrogen solubility; when compounded with high-surface-area fillers (e.g., carbon black), it further reduces permeability by adsorbing hydrogen at filler-matrix interfaces and elongating diffusion paths. BIIR, modified with bromine, enhances intermolecular cohesion through halogen-induced polarity, effectively lowering both hydrogen solubility and diffusion rates. In contrast, while PE and PVC may suffice for static, low-pressure components, their susceptibility to hydrogen embrittlement, higher permeability, and limited elasticity under repetitive stress render them unsuitable for sealing roles. For example, PVC's rigidity and PE's semi-crystalline structure can lead to microcrack



**Figure 5.** Hydrogen embrittlement prevention strategies. (A) Schematic representation of configurations designed to prevent hydrogen embrittlement through the selection of appropriate materials. (B) Conceptual diagram depicting the propagation of a hydrogen-induced crack traversing a specifically designed, solute-rich buffer region; the solute concentration profile and associated crack resistance are illustrated schematically on the right. (C) High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) reveals Mn-rich zones in austenite clusters/grains. Reproduced with permission<sup>[118]</sup>, Copyright 2021, The Author(s). (D) Application of a surface treatment. (E) Hydrogen permeation through disordered nanostructured tungsten films. Reproduced with permission<sup>[129]</sup>, Copyright 2012 Elsevier B.V. (F) Cross-sectional bright-field TEM image of  $\text{Al}_{45}\text{Ti}_{38}\text{W}_{17}$  thin film revealing non-columnar growth from 100C6 steel substrate with robust interfacial adhesion. Reproduced with permission<sup>[130]</sup>, Copyright 2021 Elsevier B.V. (G) Selection of an appropriate design by avoiding sharp variations. (H) The distribution of residual stress after multi-impact SP treatment. (I) TEM image of SP (0.50 MPa) specimen surface layer showing dense dislocation networks at martensite boundaries, with lath structure elimination, confirming SP-induced dislocation density enhancement. Reproduced with permission<sup>[149]</sup>, Copyright 2016 Elsevier Ltd.

formation under high-pressure hydrogen exposure, accelerating failure. Recent advancements in nanocomposites (e.g., graphene oxide-reinforced NBR)<sup>[126]</sup> and multilayer barrier coatings<sup>[127]</sup> further optimize these elastomers by introducing nanoscale tortuosity and interfacial blocking effects. Notably, even these advanced elastomers cannot fully reconcile the trade-offs between hydrogen impermeability, mechanical durability, and processability - a trilemma that fundamentally constrains monolithic material solutions for hydrogen storage and transportation systems.

As an alternative solution, developing innovative surface modification techniques to create composites that integrate the advantageous characteristics of various materials is the most viable option [Figure 5D]. Metal plating composites are a widely utilized surface treatment technique, with their effectiveness in resisting hydrogen largely depending on the metallurgical interactions between the plating material and the base

metal. In cases where there is no interaction, such as with silver or copper platings on stainless steel, the plating may offer little to no reduction in hydrogen permeability. Conversely, significant interactions can result in the formation of a continuous intermetallic layer, such as when aluminum is plated onto a cobalt-nickel alloy, which markedly decreases hydrogen permeability. Research has also explored several ternary metal alloys as potential hydrogen permeation barriers. For instance, Zn-Ni-Cd alloy coatings have demonstrated superior permeation blocking capabilities compared to pure Cd and Zn-Ni coatings<sup>[128]</sup>. This enhanced performance is attributed to the inclusion of Cd, which not only reduces hydrogen evolution but also increases the composite reaction constant, thereby effectively slowing hydrogen diffusion kinetics. Lakdhar and colleagues have applied Al-Ti-W coatings to 100C6 steel substrates utilizing magnetron sputtering technology, as shown in Figure 5E and F<sup>[129]</sup>. With an increase in the tungsten content within the coating, both mechanical properties and resistance to hydrogen absorption improve. Notably, the  $\text{Al}_{45}\text{Ti}_{38}\text{W}_{17}$  film sample has shown the most effective results in blocking hydrogen<sup>[130]</sup>.

Compared to metals, polymers used as protective coatings have very limited mechanical strength, but their low hydrogen permeability is attractive. Table 1 lists the hydrogen permeation characteristics of some typical commercial thermoplastic plastics and elastomers in high-pressure hydrogen environments, where FKM and high-density PE (HDPE) exhibit relatively lower hydrogen permeation rates<sup>[131-134]</sup>. Due to the presence of semi-crystalline, ordered, and amorphous regions in the microstructure of thermoplastic plastics, their response to exposure to high-pressure hydrogen is not as pronounced. Copolymer-based coatings are another potential approach to control hydrogen diffusion through molecular-scale architectural design. By strategically arranging polar/nonpolar segments, these systems suppress hydrogen solubility while ensuring mechanical robustness. Ethylene vinyl alcohol (EVOH) copolymers exemplify this strategy, where hydroxyl groups form interlocking hydrogen-bonding networks to immobilize hydrogen molecules, with barrier efficiency governed by crystallinity modulation through ethylene/vinyl alcohol ratio optimization<sup>[135]</sup>. Complementary fluorinated systems such as polyvinylidene fluoride (PVDF) exploit fluorine's low polarizability to inhibit hydrogen adsorption at polymer interfaces<sup>[136]</sup>. Hybrid architectures further integrate lamellar nanofillers (e.g., h-boron nitride) to synergize chemical resistance with physical barrier effects - the nanofillers extend gas diffusion pathways through tortuous geometric blocking while preserving the copolymer's structural integrity<sup>[137]</sup>. This dual mechanism couples polarity-driven solubility reduction with steric hindrance, addressing both hydrogen permeation and environmental durability. Such molecular-to-microstructural engineering enables multifunctional coatings compatible with pipeline service conditions, including humidity and mechanical stress, without requiring explicit layer separation for corrosion protection.

Recent advancements in deposition technologies have led to the development of ceramic materials that exhibit high strength, thermal resistance, and low thermal expansion, making them ideal candidates for hydrogen permeation barriers. Among these, oxide ceramics are among the most recognized coatings for this purpose. According to recent research by Levchuk *et al.*, a 1-micron-thick  $\alpha$ -alumina coating, applied *via* filtered arc discharge technology, can reduce the hydrogen permeability of a stainless-steel substrate by a factor of 1,000<sup>[138]</sup>. Other similar materials include alumina ( $\text{Al}_2\text{O}_3$ )<sup>[139]</sup>, zirconia ( $\text{ZrO}_2$ )<sup>[140]</sup>, erbium oxide ( $\text{Er}_2\text{O}_3$ )<sup>[141]</sup>, yttria ( $\text{Y}_2\text{O}_3$ )<sup>[142]</sup>, and chromia ( $\text{Cr}_2\text{O}_3$ )<sup>[143]</sup>. While nitride ceramics may not excel in coating adhesion, residual strain, or thermal expansion compatibility, they still represent a promising option for hydrogen permeation barriers. For instance, a silicon nitride ( $\text{Si}_3\text{N}_4$ ) coating enhanced the permeation resistance of Eurofer stainless steel by 2,000 times<sup>[144]</sup>, whereas zirconium nitride (ZrN) improved this capability by as much as 4,600 times<sup>[145]</sup>. Various studies have elucidated the mechanisms underlying the barrier effect<sup>[146]</sup>. Upon absorbing hydrogen atoms, the ceramic coating experiences ionic bond dissociation, leading to the formation of covalent bonds between hydrogen and nitrogen or oxygen. The establishment of

**Table 1. Hydrogen permeability comparison between typical metals and polymers**

| Metals <sup>[132]</sup> | Permeability         | Polymer <sup>[133-136]</sup>            | Permeability                                |
|-------------------------|----------------------|-----------------------------------------|---------------------------------------------|
| Ferritic steels         | 0.3                  | Polytetrafluoroethylene (PTFE)          | 0.032                                       |
| Austenitic steels       | 0.09-0.12            | Fluoroelastomer (FKM)                   | 0.035                                       |
| Vanadium                | 290                  | High-density polyethylene (HDPE)        | 0.0082                                      |
| Titanium                | 75                   | Ethylene propylene diene monomer (EPDM) | 0.079                                       |
| Tungsten                | $4.3 \times 10^{-5}$ | Nitrile butadiene (NBR)                 | 0.05                                        |
| Molybdenum              | 0.12                 | Polyvinylidene fluoride (PVDF)          | 0.015                                       |
| Nickel                  | 1.2                  | Ethylene vinyl alcohol (EVOH)           | $1.2 \times 10^{-5}$ - $2.3 \times 10^{-4}$ |
| Iron                    | 1.8                  | Brominated butyl rubber (BIIR)          | 0.0023-0.0087                               |

Permeability:  $P \times 10^{-10}$  (mol H<sub>2</sub> m<sup>-1</sup> s<sup>-1</sup> Pa<sup>-0.5</sup>).

robust bonds, such as O-H and N-H, significantly hinders the diffusion of hydrogen atoms, thereby safeguarding the bulk material from hydrogen-induced degradation.

Shot peening (SP) is another effective and commonly employed technique for enhancing the surface properties of industrial components, complementing traditional coating processes [Figure 5G]. This method leverages the cold working hardening effect, wherein spherical shots strike the target surface, resulting in surface deformation and the induction of residual compressive stress. These changes enhance the mechanical strength and ductility of the surface while simultaneously inhibiting the diffusion of hydrogen atoms. SP is frequently used to improve hardness, fatigue strength, and crack resistance, particularly against wear and corrosion-induced damage<sup>[147,148]</sup>. Numerous studies have confirmed that SP treatment provides substantial protection against hydrogen degradation for materials such as X80 pipeline steel, low carbon steel, and pearlitic steel. Samples subjected to SP exhibited superior mechanical properties after hydrogen exposure compared to untreated specimens. Additionally, earlier research underscored the importance of mechanisms such as grain refinement, increased GB and dislocation density, and the establishment of compressive residual stress in limiting hydrogen ingress into the metal, as illustrated in Figure 5H and I<sup>[149]</sup>.

In practical engineering applications, the storage and transportation of natural gas blended with hydrogen have emerged as the preferred industrial solution for ensuring operability and safety, attracting significant global research interest. Investigative teams across various countries have examined the compatibility of conventional pipeline steels in high-pressure hydrogen environments. Meng's analysis of the mechanical properties of X70 and X80 pipeline steels mixed with natural gas revealed that while both steels retained their yield and tensile strengths, their notched tensile strength diminished, and the rate of fatigue crack growth markedly increased. His findings indicated that increasing the hydrogen content to 50% in natural gas at a pressure of 12 MPa significantly reduced the plasticity and fracture toughness of X80 steel, accelerating fatigue crack growth<sup>[150]</sup>. The European Union's NATURALHY project determined that hydrogen concentrations of up to 50% in natural gas do not critically compromise the safety or durability of pipeline steel<sup>[151]</sup>. Additionally, Li *et al.*<sup>[152]</sup> and Lei *et al.*<sup>[153]</sup> investigated the use of polymer pipes, such as PE and PVC, for hydrogen transport. They acknowledged these materials' high compatibility while expressing concerns regarding their aging and greater hydrogen permeability compared to metal pipes. Further research by Hardie *et al.*,<sup>[154]</sup> Slifka *et al.*,<sup>[155]</sup> and Drexler *et al.*<sup>[156]</sup> suggested that lower-grade steels could be suitable for hydrogen pipelines. Before hydrogen can be blended into natural gas pipelines, thorough validation of the pipelines' adaptability is essential. This process includes assessing and testing steel grade, pressure, chemical composition, and toughness at various hydrogen ratios through compatibility tests and practical blending trials.

Current studies have yet to fully clarify the detailed mechanisms of hydrogen damage or the synergistic effects involved. Advanced techniques such as Transmission Electron Microscopy (TEM) and Atom Probe Tomography (APT) have provided insights into hydrogen embrittlement. Recent advancements in molecular simulations have also filled gaps in experimental research and helped validate findings. However, most investigations have concentrated on pure hydrogen or mixtures with nitrogen, often neglecting the potential interactions with contaminants such as sulfides and carbon oxides. In situ tensile tests under hydrogen conditions are vital for assessing the integrity of high-pressure hydrogen pipelines and storage. Unfortunately, research aimed at quantifying hydrogen damage, predicting its occurrence, and developing prevention strategies remains insufficient.

### **Leakage awareness for HSTE**

The awareness of leakage situations in hydrogen storage and transportation is a complex task involving multiple management activities, aimed at preventing emergencies, controlling social damage, and reducing public impact. With the rapid advancement of technologies such as sensors, the Internet of Things (IoT), machine learning, 3D simulation, digital twins, drones, navigation, and satellite communication, adopting proactive awareness strategies through smart technology has become a trend. This approach plays a crucial role in enhancing the timeliness, effectiveness, and comprehensiveness of chemical disaster management and emergency response. The strategy primarily consists of four key components: intelligent sensing technology and devices, dynamic IoT systems, precise disaster situation deduction, and an emergency command platform.

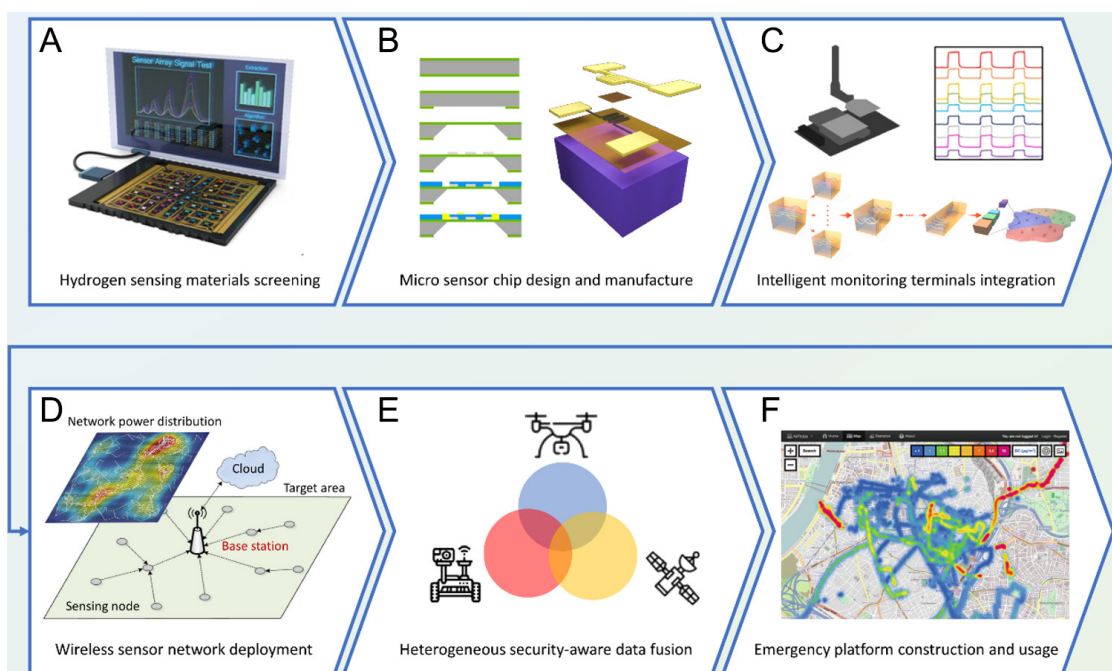
In the realm of hydrogen gas sensing terminal equipment, current hydrogen sensors, based on their working principles and testing methods, can be classified into optical, acoustic, thermal conductivity, catalytic, work function, resistive, and electrochemical types. These sensors mainly rely on changes in refractive index, spectral absorption, temperature, mass structure, and electrical properties caused by the interaction between sensitive material elements and hydrogen gas. They generate optical or electrical sensing signals through digital-analog conversion<sup>[157]</sup>. Each type has its advantages and disadvantages. For example, optical sensors have strong specificity and fast signal transmission but are limited by equipment size and investment cost, affecting their deployment density and the refinement of monitoring spatiotemporal scales. Acoustic, thermal conductivity, and work function sensors are small in size and low in power consumption but are troubled by long-term stability, target selectivity, and hysteresis issues, respectively. Traditional catalytic, electrochemical, and resistive hydrogen sensors generally offer relatively high sensitivity and sampling frequency, simpler component structures, and convenient signal processing. However, they consume more power, are often restricted by power supply line installation standards, and lack flexibility in expanding monitoring points and inspection routes. Moreover, their performance in detection range, response rate, anti-interference capability, and environmental adaptability often leaves much to be desired in complex environments or when dealing with multi-component mixed target atmospheres. In fact, no specific type of hydrogen sensor currently meets all application needs, providing ample room for the development of novel hydrogen sensor technologies.

Compared to conventional sensors, MEMS (micro-electromechanical systems) gas sensors offer advantages such as low power consumption, high selectivity, easy scalability, high integration, and a wide dynamic measuring range. They effectively overcome the monopolization, high consumption, and inefficiency of traditional detection methods, representing an optimal balance of "cost-market-comprehensive characteristics"<sup>[158]</sup>. The introduction of novel nanosensitive materials and advanced microstructured chips, along with cross-scale integration, can significantly enhance the adaptability of monitoring elements, expand the detection spatiotemporal coverage, and improve the accuracy of monitoring results and risk event identification in complex operational environments. At the present stage, the development

bottlenecks for MEMS gas sensors applied in hydrogen storage and transportation primarily focus on the rational screening of sensitive materials [Figure 6A]<sup>[159]</sup>; the design and optimization of new principle chip structures [Figure 6B]<sup>[160]</sup>; on-chip array integration and precise loading technology for sensitive film layers<sup>[161]</sup>; the unification of comprehensive characteristics of sensing devices, process compatibility, and mass production capability; multi-component gas edge algorithm with low resource consumption [Figure 6C]<sup>[162]</sup>; the standardization and customization of interfaces for transmission layer technologies such as 4G, 5G, LTE-Cat1, NB-IoT, and satellite communication<sup>[163]</sup>.

Dynamic sensing in IoT systems, based on wireless sensor network (WSN) architecture, typically features characteristics such as large-scale deployment, self-organization, random placement, and frequent changes in network topology in the context of hazardous gas leak monitoring applications. The widespread distribution of sensor nodes, limited energy supply, and communication bandwidth pose challenges to the design and management of WSNs [Figure 6D]. Particularly in harsh outdoor environments or emergency situations, the network's dynamism, reliability, and resilience are problematic, and accurate environmental monitoring is compromised as the network scales. Therefore, designing network protocols requires considering energy-saving and damage-resistant topology control strategies to enhance network robustness and adaptability, ensuring network connectivity and coverage, thereby extending the network's lifespan. Early topology control primarily focused on energy saving and balancing energy consumption through power control, hierarchical structuring, and sleep strategies<sup>[164,165]</sup>. However, these methods, based on static models, overlook the uncertainties in practical applications and lack effective fault tolerance mechanisms. To address network damage and node failures, researchers have proposed strategies such as increasing node redundancy in recent years, but this may reduce the network's energy efficiency and lifespan. Recently, to adapt to dynamic changes in network environments, researchers have explored dynamic model methods including node regeneration technology and data link reconstruction, improving the network's self-healing capabilities and cost-effectiveness<sup>[166,167]</sup>. The introduction of dynamic models, especially combined with low-power MEMS microsensors and modern technologies such as drones and tracked robots, significantly enhances the feasibility of implementing dynamic topology control. With the unique demands of high-risk industries such as oil and petrochemicals on industrial IoT, current research focuses on constructing logical links, node configuration, reducing path lengths, and improving network clustering coefficients, with relatively less study on network robustness and vulnerability. Therefore, there is an urgent need to integrate WSNs with complex network dynamics, considering the impact of node mobility, wake/sleep states, and changes in communication range on topology changes<sup>[168]</sup>. By applying new network theories to study topology structures under unstable and uncertain environments, such as power optimization, clustering, network deployment, and scale-free topology evolution, WSN topology control can be achieved from a perspective of overall performance optimization.

The analysis of hydrogen leak disasters necessitates the integration and fusion of diverse safety perception data from multiple sources. Given the notable differences in spatiotemporal distribution, accuracy, and data consistency across fixed and mobile sensor networks, employing efficient fusion techniques to filter out erroneous or abnormal data is essential [Figure 6E]. This step enhances data usability and reduces the volume of data transmission<sup>[169]</sup>. Moreover, it is crucial to account for the spatiotemporal variability of these data sources, structured disaster scenario representations, and factors such as regional characteristics, system operations, maintenance, and historical accident data. This comprehensive approach allows for an in-depth analysis of environments prone to disasters, the factors causing these disasters, and the entities affected<sup>[170]</sup>. Utilizing tools such as event trees and interpretive structural models facilitates the analysis of transmissibility between nodes in disaster scenarios. By focusing on the causal, derivative, and coupling relationships among disaster risk factors, it is possible to construct network models for typical disaster



**Figure 6.** Intelligent emergency command strategy for hydrogen leakage disaster management. (A) On-demand artificial hydrogen olfaction achieved through the use of combinatorial high-throughput screening approaches. Reproduced with permission: Copyright 2020, The Authors<sup>[159]</sup>. (B) Design and schematic of the fabrication process for a low-power micro-sensing chip. Reproduced with permission: Copyright 2016, IOP Publishing Ltd.<sup>[160]</sup>. (C) Smart monitoring terminals integration for real-time gas identification by deep learning algorithm. Reproduced with permission: Copyright 2019, The Authors<sup>[162]</sup>, and permission: Copyright 2019, The Authors<sup>[170]</sup>. (D) A dynamic wireless sensing network, created by integrating both fixed and mobile safety sensing devices, where optimizing the network's matrix topology significantly enhances system robustness. Reproduced with permission: Copyright 2020, Elsevier B.V.<sup>[167]</sup>. (E) Integrating and merging information from multi-source heterogeneous data, including collection, analysis, processing, and dissemination. (F) The dynamic IoT system, equipped with an early warning safety strategy, consolidates monitoring from hydrogen disaster sources and potential risk areas. It offers an intuitive interface for seamless human-computer interaction, facilitating emergency management and supporting decision-making processes. Reproduced with permission: Copyright 2017, Springer International Publishing Switzerland<sup>[177]</sup>.

scenarios. These models cover individual disasters, coupled disasters, and secondary disasters<sup>[171,172]</sup>. Techniques such as principal component analysis and cluster analysis aid in identifying the characteristics of factors causing hazardous chemical disasters. A thorough deduction of disaster scenario evolution enables the dynamic analysis of disaster propagation paths under various emergency rescue scenarios. This analysis can predict the initial outbreak points, secondary derivative points, and the spatiotemporal evolution of disasters.

Additionally, integrating probabilistic quantitative models of disaster scenarios with system dynamics and dynamic Bayesian networks (DBNs) - and incorporating sensor-driven real-time data - enables precise simulation, prediction, and mitigation of hydrogen storage and transportation risks<sup>[173,174]</sup>. For instance, in a high-pressure storage facility, sensor networks continuously monitor parameters such as pressure, temperature, and hydrogen concentration. When a pressure anomaly is detected (e.g., a valve malfunction), probabilistic models simulate potential failure pathways (e.g., leakage → dispersion → ignition), while system dynamics models predict hydrogen plume behavior under ambient conditions. Concurrently, DBNs update risk probabilities in real time by assimilating sensor data, enabling adaptive decision-making. This framework was validated in a case study at a hydrogen refueling station, where it reduced false alarms by 30% and prevented a critical incident by triggering automated valve closure and ventilation within 5 s of detecting a 10% pressure deviation. Such integration not only enhances predictive accuracy but also enables

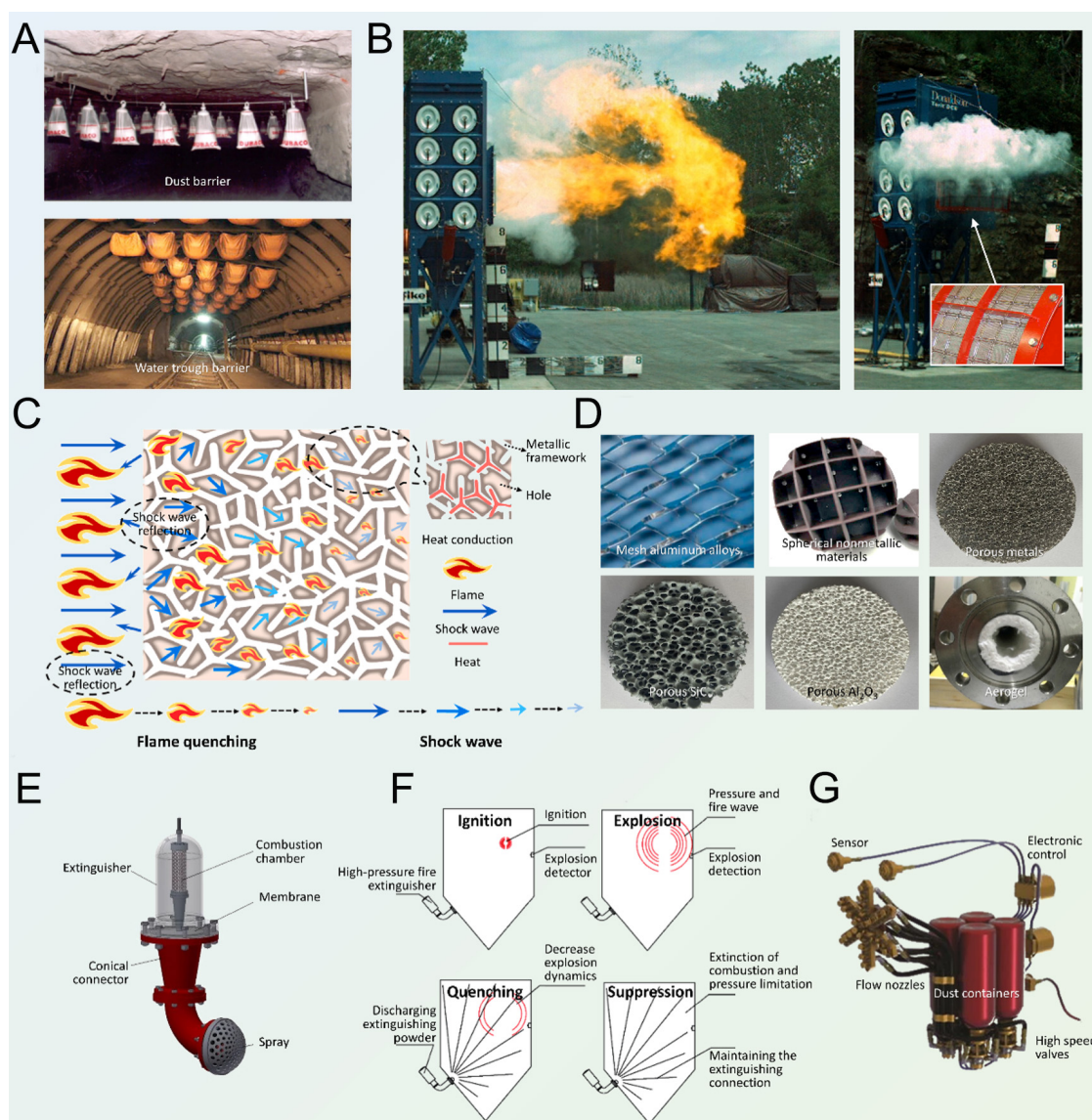
proactive risk mitigation, as demonstrated by Patel *et al.*, where AI-CFD hybrid models cut computational costs by 50% while maintaining 95% precision in leak localization<sup>[175,176]</sup>.

The development of an emergency command platform unites monitoring systems for diverse disaster sources and hazard points, creating a Dynamic Real-Time Digital Map (DRDM, Figure 6F). Utilizing 3D geographic information systems, oblique photography, and other 3D visualization technologies, this platform vividly displays the sources and scenarios of hazardous chemical disasters on a map<sup>[177]</sup>. Linked to IoT real-time data, the DRDM showcases the precise locations and safety conditions of various sensing devices (including both fixed and mobile detection equipment), mobile disaster sources (such as transport vehicles), and rescue equipment<sup>[178]</sup>. By leveraging data from multi-sensor terminals across varying environmental conditions, the platform establishes specific thresholds for anomaly information, ensuring coverage of disaster sources and real-time alerts under diverse operational scenarios. Recognizing the nuanced impacts of different disaster risk factors and the intensity of disaster-causing elements on affected carriers is crucial. This necessitates the integration of damage mechanisms, crucial decision-making nodes, and the evolution of states, followed by the implementation of tiered warning systems<sup>[179]</sup>. To facilitate a tiered early warning system for hazardous chemical incidents, based on dynamic, multisource heterogeneous data, the fuzzy comprehensive evaluation method is employed to develop situation assessment and early warning models<sup>[180]</sup>. Furthermore, utilizing pair analysis, probabilistic neural networks, and disaster safety assessment techniques, the platform constructs a disaster early warning database and an emergency management response paradigm, integrating warning extents and secondary/derivative characteristics<sup>[181]</sup>. This ensures that the early warning information disseminated to governments, enterprises, and individuals, among other disaster-prepared entities, is timely, accessible, and distinctly categorized.

### Deflagration and detonation mitigation for HSTE

Mitigating deflagration and detonation serves as the final line of defense for the safety of hydrogen storage and transportation equipment. As in conventional gas or dust explosion scenarios, the strategies for mitigation can be broadly classified into passive and active methods. Passive methods function autonomously without requiring additional control units, activating solely based on the physical effects of an explosion, DDT, or detonation itself. In contrast, active methods rely on detectors and control units to implement targeted preventive measures prior to the occurrence of an explosion.

Passive explosion suppression technology was initially implemented in the coal mining industry, where passive barriers are widely utilized. This method leverages the kinetic energy of the pressure wave generated by an explosion. Upon detonation, a pre-installed barrier is displaced by the pressure wave, releasing inert materials that create a flame-retardant mist. Passive barriers can be categorized into different types, such as dust barriers and water barriers [Figure 7A], depending on the inert material employed<sup>[182,183]</sup>. From an installation perspective, they are divided into centralized and distributed systems. Stone dust barriers have been widely used to prevent coal dust explosions since the 1920s, but they have limitations: high wind speeds can reduce their effectiveness, and they are prone to clogging due to moisture over long exposures. In contrast, water barriers are easy to maintain, cost less, and can effectively extinguish flames by dispersing water mist into the path of the explosion flames, as well as moistening nearby dust and airflow, thereby effectively suppressing flame propagation. Beyond passive barriers, ventilation systems are also a common means of preventing explosions, functioning by releasing explosive pressure that may accumulate in enclosed spaces<sup>[184]</sup>. Flame arresters in flameless venting devices allow gas to be vented while preventing flame spread<sup>[185]</sup>. Since Humphry Davy first used fine metal mesh as a flame arrester in 1815, porous materials have been widely studied for their excellent flame-suppressing performance. Studies show that the pore size, material, and thickness of porous materials significantly impact the speed of flame propagation



**Figure 7.** Passive and active methods for hydrogen explosion and detonation suppression. (A) Distributed bagged dust barrier (top) and multi-layered water trough barrier (bottom). Reproduced with permission<sup>[182]</sup>, Copyright 2022, Elsevier B.V. (B) Test of explosion venting without (left) and with a flameless venting device (right). Reproduced with permission<sup>[185]</sup>, Copyright 2008, The Authors. (C) Porous materials hinder explosion spread through several physical mechanisms, including energy dissipation, acoustic damping, heat absorption, flame quenching, and thermal expansion and deformation. Reproduced with permission<sup>[186]</sup>, Copyright 2023, Elsevier Ltd. (D) Morphology and structure of various typical porous materials: expanded aluminum mesh, spherical non-metallic substances, metallic foams, ceramic foams and aerogels. Reproduced with permission<sup>[187]</sup>, Copyright 2020 Hydrogen Energy Publications LLC., permission<sup>[193]</sup>, Copyright 2021, Taylor & Francis and permission<sup>[195]</sup>, Copyright 2017, Elsevier Ltd. (E) Active explosion suppression system built on the high-pressure fire extinguisher. Reproduced with permission<sup>[196]</sup>, Copyright 2021, The Author(s). (F) The principle of the active explosion suppression system. Reproduced with permission<sup>[198]</sup>, Copyright 2021, The Author(s). (G) Graphical overview of the components in an active barrier system. Reproduced with permission<sup>[197]</sup>, Copyright 2015, The Author(s).

and the suppression of combustion pressure waves [Figure 7B and C]. In microchannels (planar gaps, annular gaps, capillaries, etc.), flame propagation and DDT can accelerate due to wall constraints and boundary layer effects; however, in subsequent detonation propagation, there is insufficient detonation, inversely proportional to the narrow gap height and initial pressure<sup>[186,187]</sup>. Overall, when the pore size is small, porous materials act as damping permeation media; when the pore size is larger, porous materials

transform into turbulent elements, leading to increased combustion area and intensified combustion.

Currently, mesh aluminum alloys (MAAs) and polyurethane foam are commonly utilized as explosion-proof materials<sup>[188,189]</sup>. In the early 1980s, the U.S. established a military standard (MIL-B-87162) for employing expanded aluminum mesh to mitigate aircraft fuel tank explosions. This standard was later revised to MIL-B-87162A in 1994 to enhance the evaluation methods for mesh MAAs. However, the U.S. military discontinued MIL-B-87162A in 2004 due to challenges related to the loading and unloading processes, high maintenance costs, and metal fragments obstructing fuel inlets, leading to a shift away from metal-based explosion suppression materials<sup>[190]</sup>. Today, such materials are predominantly found in civilian applications. In contrast to MAAs, foam copper, with its three-dimensional porous structure, offers exceptional sound absorption and thermal conductivity. Additionally, its superior ductility minimizes cracking under shock wave impacts, allowing for a degree of deformation that effectively cushions shock waves and enhances reusability. Some pioneering research indicates that just 3 cm of foam copper can significantly suppress explosions during the DDT<sup>[191-193]</sup>. Recently, new non-metallic materials, particularly silica/nitride ceramic aerogels, have gained substantial research interest [Figure 7D]. The unique network structure of aerogels provides low thermal conductivity, lightweight density, high flexibility, and excellent compressive performance, positioning them as optimal candidates for shock absorption and explosion suppression<sup>[194,195]</sup>. Nonetheless, limited production capacity restricts their commercial availability, keeping them in the developmental phase.

Passive explosion suppression technologies typically cannot guarantee optimal deployment timing, and active suppression methods equipped with triggering devices can effectively compensate for this deficiency [Figure 7E-G]<sup>[196-198]</sup>. Active (trigger-based) barriers generally consist of sensors, dispensers, and suppressants. Sensing devices can detect an imminent explosion by monitoring sudden changes in pressure, temperature, or (ultraviolet, infrared) radiation, activating the dispenser. The dispenser then triggers the release of inert suppressants using pressurized gas, springs, or detonating cords as igniters [Figure 7F]<sup>[198]</sup>. Common suppressants include Halon 1301, water, stone powder (such as limestone), sodium bicarbonate, diammonium phosphate, potassium chloride, potassium bicarbonate, and sodium chloride<sup>[199]</sup>. However, due to the high reactivity of hydrogen and oxygen, traditional materials often fall short in suppression effectiveness. Strategies to reduce peak explosion pressures of hydrogen by diluting oxygen concentration with inert gases are usually inefficient, for example, the minimum effective inert concentration for carbon dioxide needs to reach 88%, and for nitrogen, 93%, which are far higher than the minimum suppression concentrations required for hydrocarbons (such as methane)<sup>[200]</sup>. Although the combination of high-density water mist and inert gases can more effectively slow down the combustion speed of hydrogen flames, it is still difficult to completely suppress explosions at extremely high mist densities unless the oxygen content is reduced to below 10%<sup>[201,202]</sup>.

In contrast, the fluorine found in hydrofluorocarbons is effective at scavenging active free radicals such as H, O, and OH, thereby interrupting chain reactions and demonstrating superior suppression capabilities for hydrogen explosions<sup>[203,204]</sup>. However, the high-pressure storage and release requirements for hydrofluorocarbons limit their broader application. Recently, researchers have introduced modified perfluorohexanone dry water, a technique that integrates water mist with perfluorohexanone to mitigate the storage challenges associated with fluorocarbon compounds such as  $\text{CHF}_3$ ,  $\text{C}_2\text{HF}_5$ ,  $\text{CF}_3\text{CHFCF}_3$ <sup>[205]</sup>. When modified perfluorohexanone dry water is used at a mass fraction of 16.70 wt% and a concentration of  $700 \text{ g/m}^3$ , the maximum explosion pressure is reduced by 54.37%, while the rate of increase in maximum explosion pressure decreases by 98.80%. Moreover, to inhibit the propagation of explosions between containers, the implementation of active isolation systems can be considered. These systems utilize

independent flame and pressure detectors to trigger mechanical barriers or chemical isolation measures. Upon detecting a signal, the system controller activates the gas cylinder actuator to promptly engage shut-off valves or discharge suppressants along the path of the advancing flame. It is important to note that neither passive nor active explosion suppression methods can guarantee complete safety. The dependability and efficacy of different systems should be assessed using probabilistic modeling or risk analysis methods. When determining whether to implement passive, active, or hybrid systems for deflagration and detonation isolation, considerations should include their effectiveness, associated costs for system maintenance, and their compatibility with current installations.

## CONCLUSION AND OUTLOOK

This review delves into the crucial aspects of operational safety and security for storage and transportation equipment, showcasing a variety of effective technical innovations and safety management strategies. Advancements in material safety design, leakage detection, and mitigation technologies for deflagration and detonation can markedly diminish the safety risks in hydrogen storage and transport. However, the impending surge in green hydrogen demand - projected by IEA to reach 150 million tons by 2030 - necessitates balancing technical innovation with evolving policy frameworks and cost-benefit dynamics. Four priority research directions emerge:

- (i) Coupled damage mechanisms and safety design for large-volume hydrogen storage containers, including studies on hydrogen-induced material degradation under complex loads, extreme environments, and with heterogeneous materials, strategies to prevent brittle fracture, and overpressure protection in extreme conditions;
- (ii) Damage failure mechanisms and prevention of hydrogen embrittlement in long-distance hydrogen pipelines, uncovering deterioration mechanisms in pipeline materials and welds within hydrogen environments, developing a compatibility assessment system, and establishing safety thresholds and damage control methods;
- (iii) Quick detection of hydrogen gas leaks and diffusion in large-scale green hydrogen facilities, understanding leak and diffusion patterns in large containers and across regional pipelines, and developing rapid response leak detection methods with high spatiotemporal resolution;
- (iv) Evolution of hydrogen gas combustion and explosion in complex settings and deflagration and detonation mitigation mechanisms, creating models to predict behaviors and outcomes of hydrogen gas deflagration and detonation, investigating porous materials' suppression effects and flame quenching mechanisms, and elucidating mitigation mechanisms in typical scenarios.

The global policy landscape presents both drivers and challenges for implementing these solutions. Major economies have escalated hydrogen ambitions, with the US targeting 50 million tons of green hydrogen by 2050 and China's 2021-2035 plan allocating \$20B+ for hydrogen infrastructure. Paradoxically, 78% of surveyed nations lack unified hydrogen safety regulations, creating fragmented compliance landscapes. Urgent standardization efforts should integrate three dimensions: Aligning material testing protocols with ISO/TC 197 guidelines; Establishing cross-border certification for hydrogen-compatible welding technologies; Developing risk-based zoning frameworks for large-scale storage facilities.

Cost-benefit analyses reveal critical leverage points: While PEM electrolyzer costs have fallen 60% since 2015 to \$800/kW, green hydrogen production remains 2-3× more expensive than gray hydrogen. Techno-economic modeling shows that combining advanced leakage detection (reducing losses by 15%-20%) with optimized composite pipelines (cutting transport costs to \$0.3-0.5/kg/100 km) could achieve grid parity in heavy transport by 2035. Notably, China's "West-East Hydrogen Transmission" megaproject demonstrates that scaling 50 MPa pipelines to 3,000 km lengths lowers LCOH by 38% compared to trucking.

To accelerate commercialization, three synergistic strategies prove essential: First, integrating hydrogen safety R&D with national carbon markets through tradable risk mitigation credits. Second, establishing "Hydrogen Valleys" that co-locate offshore wind farms, underground pipelines, and industrial users to validate circular economy models. Third, implementing tiered subsidy schemes that prioritize technologies with dual safety-cost benefits, such as self-sealing composite tanks showing 25% lower lifecycle costs than conventional designs.

## DECLARATIONS

### Acknowledgments

The authors acknowledge funding from the Key Research and Development Plan of Shaanxi Province.

### Authors' contributions

Investigation, validation, formal analysis, writing, and visualization: Wang, J.

Conceptualization, methodology, investigation, writing, visualization, supervision, project administration, and funding acquisition: Zhao, Y.

### Availability of data and materials

All discussed data originate from previously published studies properly cited throughout the text. For access to original datasets, readers should refer to the corresponding references provided in the bibliography.

### Financial support and sponsorship

This work was financially supported by the Key Research and Development Plan of Shaanxi Province (No. 2024GX-ZDCYL-01-06).

### Conflicts of interest

Both authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

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