LCRI LOW-CARBON RESOURCES INITIATIVE

EPRI

EXECUTIVE SUMMARY

Workshop Proceedings: Advancing Hydrogen Ignition Probabilities: From Risk to Reality

Hydrogen has different ignition behavior than hydrocarbon fuels due to its low minimum ignition energy, wide flammability range, and fast flame speed. As hydrogen infrastructure expands, these risks must be understood and mitigated. However, existing hydrogen ignition probability models, such as the one used in HyRAM+, largely rely on unvalidated data and oversimplify ignition probability by focusing on mass flow rates while neglecting key factors like pressure, geometry, and delay time. The Advancing Hydrogen Ignition Probabilities: From Risk to Reality workshop, held on January 21-22, 2025, in Pleasanton, California, brought together experts from industry, national labs, academia, and regulatory bodies to address gaps in hydrogen ignition probability research. Hosted by EPRI, and organized in collaboration with Sandia National Laboratories, the workshop focused on advancing knowledge of ignition mechanisms, refining predictive models, and developing a clear research agenda. Topics included mechanical, electrical, and spontaneous ignition, limitations of existing models, large-scale experimental approaches, risk assessment frameworks, and mitigation strategies such as ventilation and detection systems. The event emphasized cross-disciplinary collaboration, data standardization, and best practices to enhance hydrogen safety and improve risk assessments.

- **Setting the Stage:** Quantitative risk assessment (QRA) is a systematic approach to evaluating engineering risks by identifying hazards, analyzing consequences (e.g., deflagration, explosion, fire), and assessing failure probabilities through fault tree, event tree, or bowtie analysis. Existing hydrogen ignition probability models, such as the one used in HyRAM+, rely on unvalidated methane-derived data, oversimplifying ignition risks by considering only mass flow rate while neglecting key factors like leak geometry, pressure, and fuel concentration. This approach can lead to misleading risk assessments, overemphasizing jet flames while undervaluing explosion hazards. To improve accuracy, Sandia National Laboratories proposed a fault tree framework that incorporates multiple ignition mechanisms (e.g., external ignition, auto-ignition, diffusion ignition) and uses probability distributions to quantify uncertainties. This flexible model could enable more robust ignition probability estimates, facilitating better risk mitigation strategies for hydrogen applications.

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- **Ignition Mechanisms and Historical Perspective:** The UK Health and Safety Executive (HSE) is focusing on mechanical hydrogen ignition risks (e.g., friction, impact) and spontaneous ignition mechanisms such as diffusion ignition and electrostatic discharge. The MECHEX project found that hydrogen ignites easily from mechanical contact, while the PRESLHY project observed unexplained ignitions in liquefied hydrogen (LH_2) jets. Electrostatic discharges, particularly from small, charged objects, pose a significant ignition risk for hydrogen-air mixtures. Germany's Karlsruhe Institute of Technology (KIT) is conducting experiments and statistical reviews, highlighting gaps in accident reporting and the need for better differentiation between deflagration and detonation events. Weak ignition may not lead to detonation, whereas strong ignition, influenced by parameters such as induction time, CJ velocity, and detonation cell size, can trigger more severe consequences. Studies show that cryogenic hydrogen mixtures lower the minimum detonation cell size, increasing detonability. A better understanding of these ignition mechanisms and their influencing factors may aid in developing effective hydrogen safety strategies.
- **Ignition Modeling:** Hydrogen ignition probability modeling is a key QRA input, with existing approaches relying on fluid-specific, mass release rate, and area-based models. The SAFEN project and its spin-off HICON aim to refine ignition models through experimental work, focusing on diffusion, mechanical, and electrostatic ignition. The SAFEN model builds on the area-based MISOF framework, incorporating factors such as hot surfaces, electrostatic discharges, and shock waves. Key challenges include validating ignition probabilities across different leak sizes, assessing the impact of mitigation measures, and improving scalability from lab-scale tests to real-world conditions. Hydrogen leaks are more likely to ignite than hydrocarbon leaks but remain well below 100%. Testing in refueling stations has shown significantly higher ignition probabilities when non-Ex-rated equipment is present. Ongoing efforts focus on refining ignition probability estimates, addressing uncertainties in hydrogen's lower flammability limit, and improving models to guide safer system designs.
- **Ignition Experiments:** Hydrogen ignition experiments at France's Centre National de la Recherche Scientifique (CNRS) and the US' Sandia National Laboratories focus on fundamental combustion properties, ignition mechanisms, and influencing factors. CNRS investigates chemical kinetics, flammability limits, and ignition delay times using shock tubes and closed vessels, studying the role of turbulence, water vapor, dust particles, and catalytic surfaces. Their studies show that ignition probability varies with temperature, pressure, and the orientation of the ignition source. Sandia's research explores ignition probability in hydrogen jets, mapping light-up boundaries using laser sparks and analyzing the effects of radicals, flow conditions, and mixture composition. Key findings include

the role of electrostatic discharge and spontaneous ignition, particularly in high-pressure releases and LH_2 interactions with water. Both institutions emphasize the need for further study of low-temperature chemistry, real-world ignition conditions, and the interplay between ignition sources and environmental factors.

- **Real-World Considerations and Data:** Hydrogen ignition mitigation strategies focus on ventilation, detection, and component reliability to reduce ignition risk. The US' National Renewable Energy Laboratory (NREL) used computational fluid dynamics (CFD) modeling and HyRAM to analyze hydrogen releases in enclosed environments, evaluating variables such as leak size, direction, ventilation (passive vs. mechanical), and detection thresholds. Mechanical ventilation proved more effective than passive systems in reducing flammable mass accumulation. Early detection significantly improves safety by triggering alarms before dangerous concentrations form. WHA International highlighted the complexity of ignition probability and its dependence on leak dynamics, pressure, contaminants, and nearby ignition sources. They emphasized the need to statistically combine ignition mechanisms, reconsider low-voltage ignition risks, and refine ignition probability models using Monte Carlo simulations. Studies on spontaneous ignition linked geometry, discharge pressure, and vent opening speed to ignition likelihood. Discussions also addressed the impact of environmental conditions, forensic data on Ex-rated equipment failures, and the potential for controlled ignition as a mitigation strategy. Further research is needed on electrostatic discharge probabilities, delayed ignition effects, and ignition risks in various hydrogen release scenarios.
- **Research Prioritization:** During this session, workshop participants identified and ranked both prospective research topics and activities related to hydrogen ignition probabilities. Top research topics included cataloging realistic ignition sources and quantifying their strengths, developing a comprehensive fault tree model, studying the influence of pressure on ignition, distinguishing hazardous from non-hazardous ignition scenarios, and investigating ignition in non-homogeneous hydrogen plumes. Additional topics included data sharing, LH_2 ignition risks, shock diffusion, and time-dependent hazard analysis. The highest-rated activities were establishing an ignition probability consortium with formal data sharing, creating a comprehensive ignition probability landscape review, conducting real-world high-pressure ignition experiments, and mapping certified explosion explosion-proof (Ex) vs. non-explosion proof (non-Ex) components in real systems. Other recommended actions included developing a round robin fault tree framework, drafting a best-practices white paper, defining basic ignition experiments, and aggregating existing models into a more reliable interim metric.

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In conclusion, the workshop highlighted hydrogen's unique properties, including its low ignition energy, wide flammability range, and fast flame speed, making accurate ignition probability modeling essential for risk assessment. Existing models, such as the one used in HyRAM, largely rely on unvalidated data and oversimplify ignition probability by focusing on mass flow rates while neglecting key factors like pressure, geometry, and delay time. A fault tree framework was proposed to improve modeling by incorporating different ignition mechanisms, operational factors, and uncertainty quantification. Key knowledge gaps include understanding hydrogen ignition mechanisms, electrostatic and diffusion ignition, real-world validation of models, overpressure hazards from delayed ignition, and the influence of materials and environmental conditions. Next steps include forming an ignition probability consortium for data sharing, developing comprehensive documentation, conducting real-world ignition experiments, refining mass-based ignition models, and mapping ignition risks across hydrogen applications. Establishing robust models and mitigation strategies may improve hydrogen safety and guide future industry standards.

THE LOW-CARBON RESOURCES INITIATIVE

This report was published under the Low-Carbon Resources Initiative (LCRI), a joint effort of EPRI and GTI Energy addressing the need to accelerate development and deployment of low- and zero-carbon energy technologies. The LCRI is targeting advances in the production, distribution, and application of low-carbon energy carriers and the cross-cutting technologies that enable their integration at scale. These energy carriers, which include hydrogen, ammonia, synthetic fuels, and biofuels, are needed to enable affordable pathways to economy-wide decarbonization by mid-century. For more information, visit www.LowCarbonLCRI.com.

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