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3D risk management for hydrogen installations

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ABSTRACT

This paper introduces the 3D risk management (3DRM) concept, with particular emphasis on hydrogen installations (Hy3DRM). The 3DRM framework entails an integrated solution for risk management that combines a detailed site-specific 3D geometry model, a computational fluid dynamics (CFD) tool for simulating flow-related accident scenarios, methodology for frequency analysis and quantitative risk assessment (QRA), and state-of-the-art visualization techniques for risk communication and decision support. In order to reduce calculation time, and to cover escalating accident scenarios involving structural collapse and projectiles, the CFD-based consequence analysis can be complemented with empirical engineering models, reduced order models, or finite element analysis (FEA). The paper outlines the background for 3DRM and presents a proof-of-concept risk assessment for a hypothetical hydrogen filling station. The prototype focuses on dispersion, fire and explosion scenarios resulting from loss of containment of gaseous hydrogen. The approach adopted here combines consequence assessments obtained with the CFD tool FLACS-Hydrogen from Gexcon, and event frequencies estimated with the Hydrogen Risk Assessment Models (HyRAM) tool from Sandia, to generate 3D risk contours for explosion pressure and radiation loads. For a given population density and set of harm criteria, it is straightforward to extend the analysis to include personnel risk, as well as risk-based design such as detector optimization. The discussion outlines main challenges and inherent limitations of the 3DRM concept, as well as prospects for further development towards a fully integrated framework for risk management in organizations.

Introduction

Hazards and safety

Extraction, conversion, storage and use of energy play a fundamental role for the advancement of modern societies, and will continue to do so in the foreseeable future. Humankind will consume energy commodities at a growing rate due to population growth and improvements in the standard of living. While the global reserves of fossil fuels diminish, continued release of carbon dioxide on a massive scale is likely to influence the global climate. Hence, the energy infrastructure needs a shift towards increased use of renewable energy sources, such as wind, hydroelectric and solar, as well as more sustainable use of conventional hydrocarbons (e.g. carbon capture and storage). In this perspective, the International Energy Agency (IEA) [1] and the

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European Commission (EC) [2] foresee that hydrogen will play an increasingly important role as energy carrier, providing environment-friendly energy to end-users. However, widespread acceptance and use of hydrogen in society will require significant progress in the field of hydrogen safety – the discipline of science and engineering that deals with safe production, handling and use of hydrogen in industry and society in general [3]. Several characteristic properties of hydrogen differ significantly from conventional hydrocarbon fuels, such as gasoline, diesel and natural gas: a tendency to cause embrittlement in metals, very low boiling point and density, very low ignition energy, relatively wide flammability range, high laminar burning velocity, and a propensity to undergo deflagration-to-detonation-transition (DDT) under certain conditions. Hence, fires and explosions represent a significant hazard for hydrogen installations, and specific measures are required for reducing the risk to an acceptable level. This applies to relatively simple systems, such as fuel cells, vehicles and filling stations, as well as complex industrial facilities, such as nuclear power plants. The recurrence of low-probability high-consequence events in complex systems is well documented and possibly 'normal' [4]. Common features of many industrial disasters include a relatively limited understanding of the actual hazard prior to the event, an escalating chain of sub-events, severe losses, often resulting in significant changes to safety standards and legislation [5].

Numerous factors influence the level of safety an organization can achieve for a given system: potential for loss, maturity of technology, environmental concerns, risk perception, safety culture and awareness, safety functions and processes, safety training and emergency preparedness, relevant standards and legislation, etc. Many organizations adopt a hierarchy of principles for risk reduction: inherent safety > prevention > passive mitigation > active mitigation > procedural safety. The most expensive safety measure may not be the most efficient, and investments in additional measures, beyond a certain level of safety, will not necessarily reduce the overall risk (e.g. due to increased complexity of the overall system). Statistical records from accidents and near misses demonstrate that engineered safety and administrative procedures cannot replace risk awareness, competence and a healthy safety culture at all levels of the organization: human errors account for about 80 percent of all events – only 20 percent involve equipment failure [6]. From the events caused by human error, about 70 percent stem from latent organizational weaknesses, and only 30 percent are due to mistakes by individuals.

Risk

The aim and purpose of risk assessments include 1) to systemize knowledge and uncertainties about phenomena, processes and activities in systems such as chemical plants, power plants and offshore installations, 2) to describe and discuss the results of the analysis in order to provide a basis for evaluating what is tolerable and acceptable, and 3) to compare and optimize different design options and risk reducing measures [7,8]. The ALARP principle emphasizes the obligation to reduce the risk to a level 'as low as reasonably practicable', even if the risk evaluation indicates a level of safety within stated acceptance criteria.

There are inherent uncertainties associated with most risk analyses, especially for complex systems and emerging technologies. The hazard identification process is challenging, especially for industries where there is no framework in place for systematic reporting of accidents and near misses. There is generally insufficient data available for estimating precise and up-to-date expectation values for event frequencies. Finally, there is often significant uncertainty associated with the estimated consequences. Hence, the outcome depends not only on the choice of methodology, data, and tools, but also on the experience and competence of the personnel involved. Quantitative risk assessment (QRA) can nevertheless be a valuable tool for detecting deficiencies and improving safety performance in complex technical systems [7–9], provided qualified personnel conduct and document the analysis in a consistent manner, and the organization implements and communicates the recommended safety measures. In the literature, the abbreviation 'QRA' may refer to either 'quantitative risk analysis' or 'quantitative risk assessment' (i.e. risk analysis as well as evaluation of the results). For all practical purposes, the use of the term QRA in this paper includes techniques and concepts such as probabilistic risk assessment (PRA), probabilistic safety assessment (PSA), concept safety evaluation (CSE) and total risk analysis (TRA).

A significant fraction of the incidents listed in the Hydrogen Lessons Learned (H_2LL) database at the Hydrogen Tools Portal [10] lists human errors and missing, misleading or neglected procedures as plausible causes. To this end, it is essential not only to understand the physical phenomena and the technological challenges associated with increased use of hydrogen as an energy carrier, but also to assess and manage risk. Risk management refers to a coordinated set of activities and methods used to direct an organization and to control the many risks that can affect its ability to achieve its objectives [6,7]. Management of operational risk should take into account risk analysis, previous events and near misses, safety barriers, modifications, the age of the installation, technological developments, the likelihood of natural disasters or malicious attacks, etc. It is important to include representative worst case scenarios in the analysis – such events can have strong implications for the choice of risk-reducing measures, and they represent important cases for safety training in organizations.

Hydrogen Risk Assessment Models (HyRAM)

The HyRAM software toolkit from SANDIA establishes a standard methodology for conducting QRAs and stand-alone consequence analysis relevant for assessing the safety of hydrogen fuelling and storage infrastructure [11]. HyRAM comprises a methodology and an accompanying software toolkit that provides a platform for integration of state-of-the-art engineering models and data relevant to hydrogen safety. The toolkit integrates fast-running deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing the impact of hydrogen hazards on people and structures. HyRAM incorporates generic probabilities for equipment failures for nine types of