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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 hydrogen system components, generic probabilities for hydrogen ignition, and probabilistic models for the impact of heat flux on humans and structures, combined with fast-running, computationally and experimentally validated models of hydrogen release and flame behaviour. Users may extend the scope of HyRAM with additional models and data, and extend the QRA analysis to development of codes and standards, code compliance and facility safety planning.

3D risk management

This section summarizes the ideas that inspired the development of the 3D risk management (3DRM) concept and describes how 3DRM can be implemented and used in organizations.

Communication and culture in organizations

Even the most elaborate QRA is of limited value if the analysis and the results reside in reports only, and users/operators of the facility have limited understanding of the system, including the hazards and the recommended and implemented safety measures. Conducting a risk assessment for a complex system is an inherently multi-disciplinary undertaking that should involve personnel with intimate knowledge of the systems, as well as safety experts. Effective communication of the outcome and recommendations from QRAs to all relevant stakeholders represents a fundamental challenge: *"True progress in managing risk [ ] can be made only if the people affected by the problem are part of the solution"* [12].

Technological progress creates both challenges and opportunities with respect to safety and risk management. A general trend in many branches of industry is the replacement of labour intensive mass-production with automated processes and self-organizing teams, typically accompanied by an increasing fraction of knowledge workers in the overall work force. Whereas procedures and check-lists will remain important parts of the approach to safety in many organizations, it is not obvious that the classical approach of implementing risk management as a top-down process is optimal for the type of 'non-routine' problem solving that characterizes knowledge workers. To this end, there can be significant potential for achieving risk reduction and improvements to safety culture and resilience in organizations by taking advantage of the steady development in technology within areas such as computational power, storage capacity, high-performance computing (HPC), cloud solutions, control systems, detectors, portable devices, simulation tools, optimization schemes, geographic information systems (GIS), communication technology and virtual reality (VR):*"In an economy where the only certainty is uncertainty, the one sure source of lasting competitive advantage is knowledge"* [13].

The importance of creating and sharing knowledge within an organization, and continuously converting tacit knowledge into explicit knowledge [13], is not limited to the productivity and innovation in a company – it applies equally well to safety. Whereas it is important to implement a corporate strategy for risk management, it is essential to create a culture for knowledge sharing, and to establish arenas and incentives for effective and transparent communication of risk within organizations that operate complex facilities where there is significant potential for loss. The challenge of establishing positive attitudes, beliefs, perceptions and values in relation to safety should not be underestimated: *"Culture eats strategy for breakfast"* — Peter Drucker (1909–2005).

There are obvious ethical aspects to the approach organizations adopt for handling safety and security. Inspired by the essay *"The ethics of belief"* by William K. Clifford [14], DeMarco & Lister [15] defines risk management as *"the business of believing only what you have the right to believe"*. The same definition can be applied to technical and organizational aspects of how the management of a company chooses to implement safety measures and grow safety culture, the services provided by safety consultants, and the validation and marketing of tools for consequence and risk assessments. There is increasing focus on the importance of dealing with the uncertainty in risk assessments: *"When considering risk, the knowledge and uncertainty aspects always need to be reflected, and ignoring these dimensions introduces an arbitrariness in the management process that is unacceptable."* [8].

Best practice for safe and profitable operation of modern industrial facilities has many features in common with the development of complex software systems. In order to achieve long-term success, it is important to respond to change, track changes, report and address issues, automate repeated tasks, limit the extent of technical debt, involve the users of the system, energize people and empower teams, align constraints, develop competence, grow structure, practice transparency towards impediments, and continuously improve everything [16]. To this end, it is not a coincidence that the 3DRM concept emerged from a team of knowledge workers in an organization that develops a complex software system.

Consequence analysis

Many accidents involve fluid flow in complex geometries, with or without chemical reactions: loss of containment and dispersion of hazardous material, fires, explosions and runaway reactions. Hazardous materials may include flammable, asphyxiating, malodorous, toxic, radioactive and/or cryogenic materials, in gaseous, liquid and/or solid form. In accordance with common practice, the term *explosion* refers to a sudden release of energy, resulting in an increase in pressure that may cause losses. This definition includes, but is not limited to, phenomena such as chemical explosions (i.e. gas, mist, dust and hybrid explosions, propagating in either deflagration or detonation mode, as well as detonation of condensed explosives) and physical explosions (e.g. bursting pressure vessels and vapour explosions). Under certain conditions, such as low degree of confinement and congestion relative to the reactivity of the mixture, premixed combustion of fuel-air mixtures may not result in damaging overpressures (sometimes referred to as 'flash fire'). However, the propagating flame and combustion products may still represent a hazard. The term *fire* refers to non-premixed combustion, and includes phenomena such as jet and pool fires. Fires may trigger explosions and vice versa, and both may result in structural collapse.

The types of models used for assessing the consequences of flow-related accident scenarios range from simple empirical correlations, via phenomenological models of varying complexity, to computational fluid dynamics (CFD) tools that account for initial and boundary conditions, and solve the governing equations for conservation of mass, momentum and energy. The main uncertainties associated with most consequence models relate to scaling and complexity. Although limited accuracy in the estimates for event frequencies to some extent may justify the use of simpler consequence models, the spatial scale and complexity of most low-probability-high-consequence events significantly exceed the range of scenarios that constitute the empirical foundation for such models. Regardless of the complexity of the consequence model, it is essential that safety engineers understand the underlying assumptions and inherent limitations of the tools they use, as well as the level of accuracy they can expect in the results.

The governing equations for turbulent fluid flow are well established. However, analytical solutions are primarily of academic interest, and discrete solutions by direct numerical simulation (DNS) can only be realized for idealized systems. Models based on large eddy simulations (LES) have gained increasing popularity in recent years. However, within the context of simulating industrial accident scenarios, most commercial CFD tools still rely on turbulence models based on the Reynolds-averaged Navier–Stokes (RANS) equations, such as the $k - \varepsilon$ model [17], complemented with sub-grid models that account for the influence of objects and phenomena that cannot be resolved on the computational grid [18]. The steady increase in computational resources (speed, memory, number of processors, etc.), accompanied by parallelization of numerical solvers, allows for faster calculations on large computational domains. However, there is still a need for further speed-up, improved accuracy, and reduced sensitivity of the results with respect to the spatial resolution used in the simulations. Technology based on adaptive mesh refinement (AMR) represents a promising approach for achieving this goal.

The validation and documentation process represents a fundamental challenge for developers of any model system that aspire to describe a wider range of physical phenomena, or other initial and boundary conditions, than the ones that can be mapped out by a finite number of experiments. Both government bodies and industry show increasing awareness of the need to qualify models for particular applications, for instance by requiring modellers to demonstrate the capabilities of their models by reproducing results from specific experiments. The current trend in software development for application-specific CFD tools entails an integrated framework for model validation, implemented as a natural extension of the continuous integration and life-cycle management system for the software [19]. Gexcon has validated the CFD tool FLACS-Hydrogen for a wide range of dispersion and explosion scenarios [20].

Overview of 3D risk management

The primary motivation for introducing 3DRM is to prevent major losses in industry and society by combining state-of-the-art modelling tools and advanced visualization techniques in an integrated framework for risk assessment and various aspects of risk management, and thereby facilitating improved risk awareness and safety culture in organizations, all within a framework adapted for the era of knowledge workers [21]. Fig. 1 shows a schematic representation of the classical concepts of risk analysis, risk assessment and risk management (upper part), and how these processes relate to the 3DRM framework. The approach entails the use of a dedicated

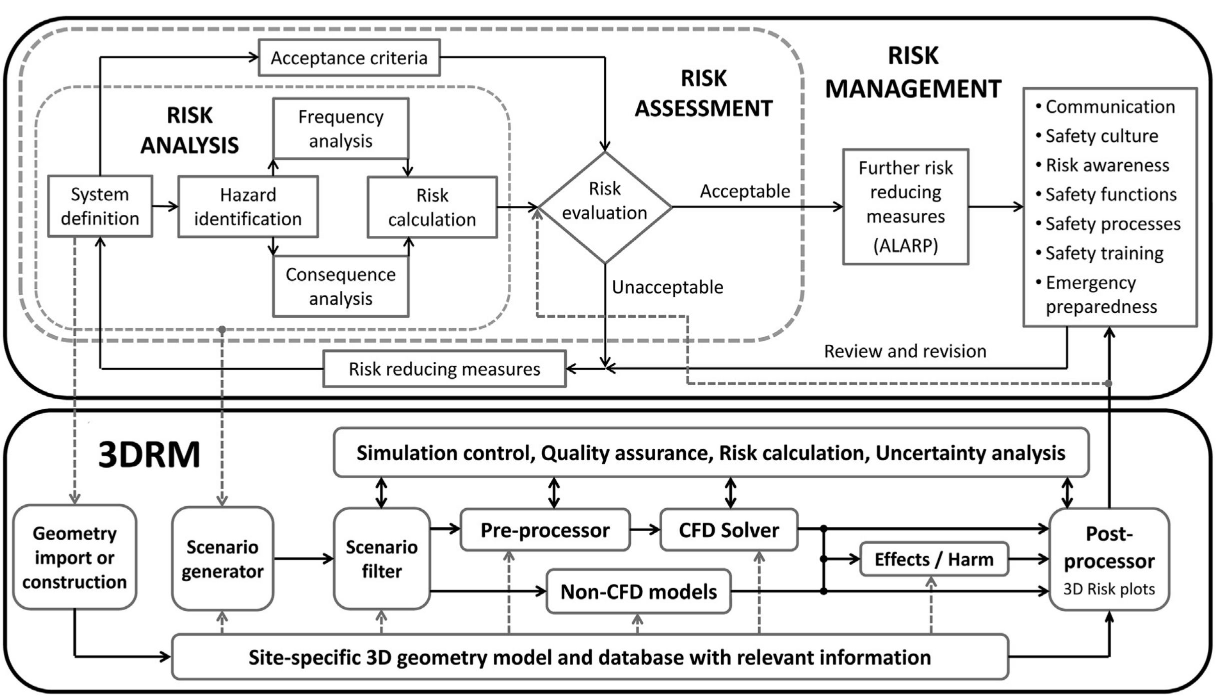

Fig. 1 – Schematic representation of risk analysis, risk assessment, risk management and 3DRM.

software system, and incorporates significant aspects of the philosophy behind the methodology used for developing the same system. Hence, the use of 3DRM for a complex industrial plant represents a kind of 'Agile risk management' [16], with the traditional users of the software replaced by the people operating the facility and other stakeholders. In its complete implementation, 3DRM becomes an integrated risk management framework for a specific facility, characterized by extensive use of a detailed site-specific 3D geometry model. The 3D model facilitates interactive communication between stakeholders, as well as the use of state-of-the-art tools for consequence modelling and visualization.

The workflow involved in establishing a 3DRM framework for a specific installation could typically entail initial steps such as:

- Importing or constructing the 3D geometry model, in sufficient detail to support CFD simulations.
- Identifying and registering the inventory of hazardous materials in the 3D geometry model.
- Identifying and registering the main safety functions in the 3D geometry (escape routes etc.).
- For flammable materials: identifying and registering potential ignition sources in the 3D geometry.
- For personnel risk: registering personnel densities in the 3D geometry.
- Simulating representative wind conditions according to the wind rose for the facility.
- From the wind simulations, simulating a representative set of release and dispersion scenarios.
- From the release scenarios, simulating a representative set of jet and pool (liquid) fire scenarios.
- From the dispersion scenarios, simulating a representative set of explosion scenarios.
- For personnel risk: estimating the effect (harm) on personnel caused by physical parameters such as radiative or convective heat flux, pressure loads, drag loads, etc.
- Calculating and visualizing risk contours in the 3D geometry model.

As many as possible of these tasks can and should be automated. For instance, the software can identify potential leak points, such as flanges, fittings and valves, from a detailed computer aided design (CAD) model, and the dispersion simulations may generate explosion simulations automatically based on stepwise accumulated probability of ignition within the flammable volume. However, it is of critical importance that the QRA is not reduced to a ritual aimed at documenting compliance. The risk analysis represents the starting point for further analysis and optimization of risk-reducing measures.

For certain facilities it is relevant to extend the analysis to include optimization of risk-reducing measures, such as identifying the gas detector layout that maximises the probability of detecting dispersed clouds in general or the clouds that result in the most severe consequences. An alternative approach can be to focus on an acceptable threshold for the consequences resulting from undetected clouds. It is also possible to extend the analysis to include structural response of selected parts of the geometry, such as blast and fire walls. From CFD simulations of explosion events, it is possible to identify the parts of the geometry that cause the most severe flame acceleration, and hence pressure loads, and use this information to optimize the design.

The hazard identification process and the frequency/consequence estimates may proceed according to established methods, but whenever possible the analyses should make use of relevant metadata from databases and CAD formats, and all relevant hazards should be registered in the 3D geometry model. The calculations can run automatically on a server and/or in the cloud, and it is straightforward to track changes in the overall risk and the relative contribution from specific units or modules. By distinguishing between locations for primary (initiating) events (e.g. loss of containment), secondary events (e.g. ignition of a flammable cloud), and possible escalation to tertiary, quaternary, etc., events, and by correlating this information with the corresponding consequences predicted in various target locations, it is possible to analyse dependencies and scenarios that entail complex chains of events. Case histories from previous events in similar facilities represent valuable information in this process [5,22].

Within the 3DRM framework, the QRA may develop towards a more or less continuous process that evolves throughout the lifetime of the facility. In addition to the CFD tool, the 3DRM framework includes various seamlessly integrated utility programs and libraries, such as a scenario generator, a scenario filter, source term models for leaks, a front-end for supporting project databases, a module for simulation control and quality assurance (QA), and libraries of consequence models, event frequencies, personnel densities, site-specific boundary conditions, etc. As such, 3DRM complements the classical risk assessment by introducing interactive tools for safety and design reviews, safety training, operational safety, emergency response training, and other aspects of risk communication and decision support in organizations.

For operational use it is possible to extend the use of the 3D model to various aspects of risk management and risk communication: interactive training of employees and contractors, work permits, hazardous area classification, interactive learning, emergency preparedness and emergency response. In principle, it is possible to track and visualize the movement of personnel and vehicles within industrial facilities in the 3D geometry, for instance during exercises. Realistic accident scenarios can be simulated and animated, and it is straightforward to take into account the functionality of detection and mitigation systems, as well as escalating accident scenarios. In this way, the virtual 3D model serves as a user interface for a database for safety-related information, including relevant case histories. This preserves corporate knowledge over time and improves the ability of the organization to learn from previous accidents.

One of the main advantages of the 3DRM approach is the possibility to implement the system stepwise, starting from early design versions of the 3D geometry model. It is necessary to perform regular revisions and updates to the geometry model throughout the lifetime of the installation. Within the 3DRM framework, an outdated geometry model represents technical debt – during operation, the vision is to use the 'as is' model, not the 'as built' version. During the design phase, it is necessary to estimate the layout of the 'as built' geometry, for instance through statistical analysis of realized geometries for similar installations. For planning, design optimization, and to account for temporary structures such as scaffolding and barracks used during modification or maintenance work, it is straightforward to use 'what if' versions of the geometry. A built-in 'version control system' keeps track of all changes, and authorized personnel approve the final inclusion in the official 3D model. The cost of implementing gradual and temporary modifications in the virtual 3D model represents a marginal fraction of the overall costs associated with the actual physical modifications to the plant.

It is of paramount importance for safety and security that people continue to challenge and question the tools they use for making engineering predictions. An inherent feature of the 3DRM concept is the competence building that results from comparing predictions from empirical consequence models with results obtained with more advanced CFD tools. It should be straightforward to visualize the results from different models side-by-side in the same 3D model, and thereby gain experience and knowledge about the application range and the suitability of the various models. For specific scenarios, it will also be possible to compare model predictions with results from relevant experiments.

Effective communication requires technology that can be adapted to the target audience. The safety training may involve own personnel or contractors, it may be conducted on-site or remotely, and it may include the use of virtual reality (VR) and game technology [23]. The virtual 3D geometry may contain links to relevant documents and pre-simulated accident scenarios, and it should be straightforward to toggle the visualization of various classes of objects: structure, piping, process units, main safety functions, gas detectors, safety barriers, warning symbols, case histories, P&IDs, Smart P&IDs, etc. By adopting suitable visualization techniques, from schematic illustrations to photo-realistic rendering, it is possible to optimize the system for different forms of communication, such as classroom lectures, web-based learning and virtual/mobile augmented reality.

The 3DRM framework allows, to various degrees, for the continuous integration of new knowledge and information in the risk management system. Revisions and reviews should nevertheless take place at scheduled intervals, to secure that the system is used to its full potential, to include modifications, and to facilitate input from external expertise. It is essential to learn from accidents and near misses in other plants or industries. The field of process safety technology develops steadily, and it is essential to update the information stored in the database, as well as the competence of the people involved.

The main limitation of the 3DRM concept is that complete implementation requires a dedicated end-user. It is nevertheless possible to develop proof-of-concept prototypes for artificial systems.

Hy3DRM

The main goal of the project 3D risk management for hydrogen installations (Hy3DRM) is to demonstrate the use of 3DRM on a prototype of a hypothetical hydrogen filling station. The project also addresses critical knowledge gaps in the understanding of turbulent flame propagation in congested regions, including the possibility of realizing DDT. Finally, the project incorporates a strong element of collaborative research on hydrogen safety through the International Energy Agency (IEA) Hydrogen Implementation Agreement (HIA) Task 37 on Hydrogen Safety [1].

Case study

This section presents the QRA part of the 3DRM concept for a hypothetical filling station. The analysis combines event frequencies estimated with HyRAM with consequences from fire and explosion scenarios simulated with the CFD tool FLACS-Hydrogen (FLACS v10.5). The fire scenarios are limited to jet fires, and the explosion scenarios are limited to deflagrations.

System definition

Fig. 2 illustrates the hypothetical filling station used in the case study. This is a slightly modified version of a 100 kg day^{-1} reference station [24]. Hydrogen from the tube trailer is compressed and stored in the high-pressure storage tanks. The storage and process area is partly enclosed by a firewall.

Fault and event trees

The event tree includes non-ignited releases, immediate ignition (fire scenarios), and delayed ignition (gas explosions). The study does not include structural response and secondary fires (i.e. fires triggered by an explosion), rupture of high-pressure vessels and damage resulting from projectiles, DDT and detonations.

Dispersion simulations

Six representative release location were chosen based on the layout of the installation and data for representative release frequencies: the container with the compressor unit, both sides of the high pressure storage tanks, two locations near the tube trailers, and the dispensing point. Seven leak scenarios

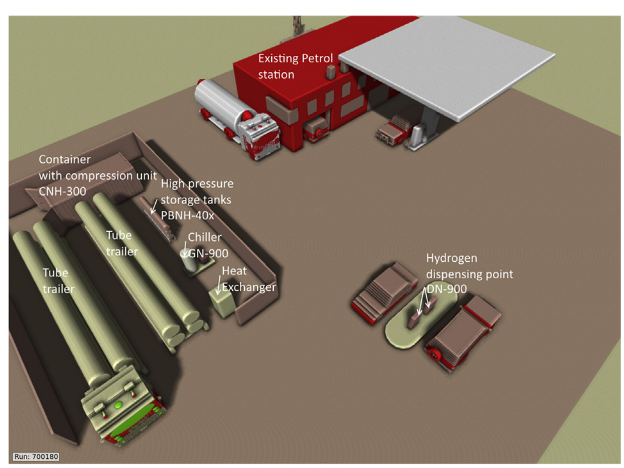

Fig. 2 – Layout of the hypothetical filling station.

were modelled for each of the six locations: jet releases in the six Cartesian directions and a diffuse leak. Since the normal JET utility in FLACS assumes ideal gas law, the release calculations were done with an in-house version developed for high-pressure hydrogen releases. Table 1 summarizes the inventory and release properties for the various release locations. For simplicity, only full bore ruptures were modelled, and all releases are assumed to be steady state. Four arbitrarily chosen wind conditions were used with the following directions relative to plant north (see Fig. 2): 1.0 m s^{-1} 0°; 5.0 m s^{-1} 0°, 5.0 m s^{-1} 180° and 5.0 m s^{-1} 270°. A total of 168 dispersion scenarios were simulated, and the dispersed clouds were used as input to the explosion simulations.

Fire simulations

The initial and boundary conditions for the jet fire simulations were identical to the dispersion simulations, but with immediate ignition after onset of the release. A total of 168 jet fire scenarios were simulated. Fig. 3 illustrates a jet fire near the high-pressure storage tanks.

Explosion simulations

The flammable clouds from the dispersion simulations were used as initial conditions for the explosion simulations. Four ignition locations were selected for each cloud, positioned in regions where the gas concentration was close to stoichiometric. This approach saves simulation time, since ignition in other parts of the cloud would result in a lower rate of combustion, at least during the initial phase of flame propagation. The ignition energy is also lowest for near stoichiometric mixtures. The study included a total of 672 gas explosion simulations. Since the CFD code takes into account the effect of congestion and confinement, it is not necessary to distinguish between ‘flash fire’ and ‘deflagration’ scenarios. The simulation results are most likely on the conservative side, with the notable exception that the analysis does not account for DDT and detonations. Transition to detonation would produce even higher pressures for some of the scenarios that include strong deflagrations, for instance inside the container with the compressor.

Risk calculations

The frequency of occurrence for each scenario was calculated by multiplying the relevant leak frequency with the probabilities for the specific leak direction, wind condition, immediate (fire) vs. delayed (deflagration) ignition, and ignition location. Table 2 summarizes the event frequencies used for risk calculations [11,25,26], and Figs. 4–6 show selected contour plots. The analysis assumes an even distribution of the event frequencies between the various wind conditions, leak direction and ignition location in the selected scenarios.

Human vulnerability model

The location-based potential risk of fatality from the heat radiation emitted from jet fires was determined from the

Table 1 – Summary of release locations and release rates.

Process units and scenarios	Pressure [bar *g*]	Representative internal diameter [m]	Release rate [kg s^{-1}]
Container with compressor unit	207	19.00	3.55
High pressure storage tanks	1034	7.16	2.00
Tube trailer	207	12.60	1.59
Dispenser	700	7.16	1.50

Table 2 – Summary of frequencies [yr^{-1}] for the risk analysis.

Process units and scenarios	Number	Releases	Jet fires	Explosion
Container with compressor unit	1	2.3E-03	5.1E-05	2.6E-05
High pressure storage tanks	2	1.1E-03	2.5E-05	1.3E-05
Tube trailer	2	2.2E-03	5.2E-05	2.6E-05
Dispenser	1	7.1E-04	3.8E-05	1.9E-05
Total	6	2.3E-03	5.1E-05	2.6E-05

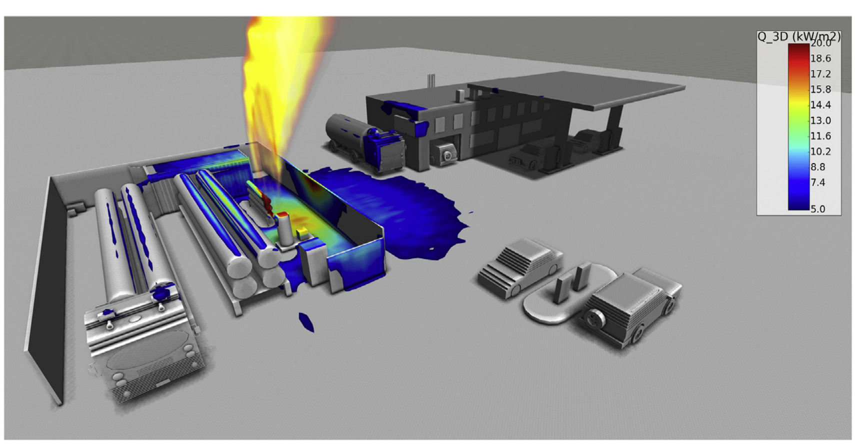

Fig. 3 – Jet fire and radiation contours.

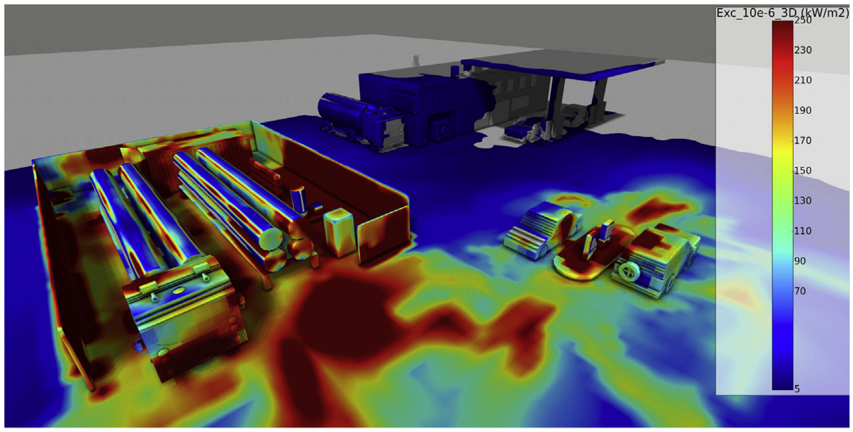

Fig. 4 – Heat radiation contours with frequency exceeding 10^{-6} yr^{-1}.

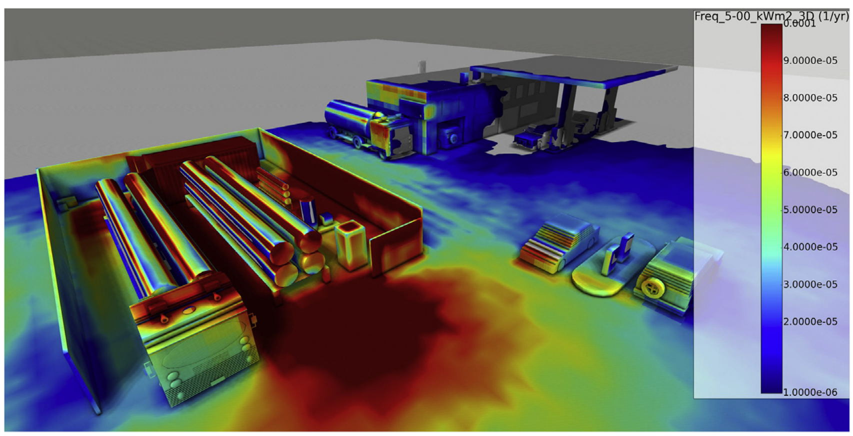

Fig. 5 – Frequency contours, from 10^{-06} to 10^{-04} yr^{-1}, for 5 kW m^{-2} radiation load.

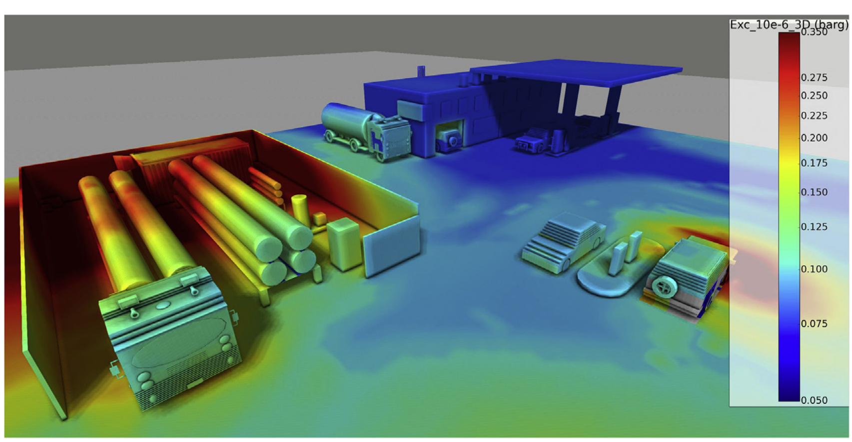

Fig. 6 – Explosion overpressure contours (up to 300 mbar) for frequency exceeding 10^{-6} yr^{-1}.

following [27]: Probit = 38.48 + 2.56 ln (t $q^{4/3}$), where the exposure time t was assumed to be 20 s, and q is the heat flux [W m^{-2}] estimated from the CFD simulations. The frequency of fatality for a given scenario is the product of the event frequency and the probability of fatality. Fig. 7 shows the annual location-based fatality risk contours calculated from all the fire scenarios. Similar plots can be made for fatalities resulting from explosion pressure or other physical effects.

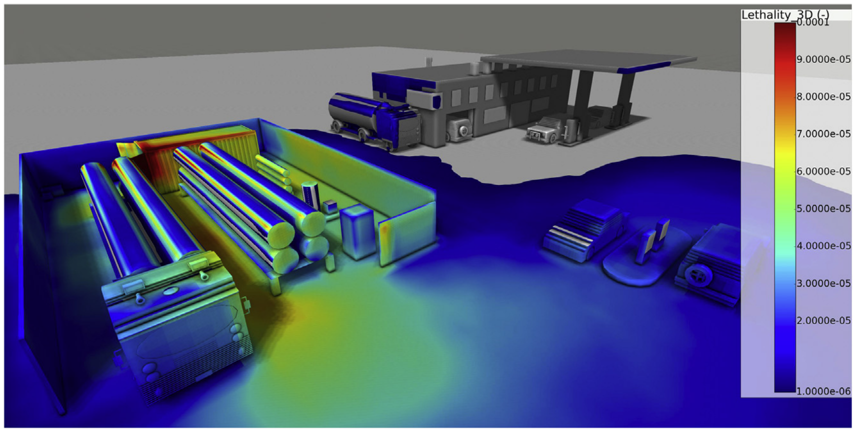

Fig. 7 – Fire radiation location based lethality frequencies, from 10^{-06} to 10^{-04} yr^{-1}.

Future work

The feasibility study for the hypothetical filling station will be extended to include a larger number of scenarios. The description of the system can be extended with realistic piping, instrumentation, etc., allowing for automated identification of potential leak and ignition points. It is also straightforward to expand the scope to include probability of fatality for explosions, by using appropriate damage criteria and personal densities. It will also be interesting to explore closer integration between HyRAM and FLACS, and to compare risk estimates obtained with CFD simulations and the reduced order models in HyRAM. In a longer perspective, Hy3DRM should be implemented for real hydrogen applications, preferably in cooperation with the operator and users of the facilities.

Discussion

Realistic simulation of flow-related accident scenarios requires extrapolation to spatial scales and degrees of complexity that extend significantly beyond the range of scenarios that can be covered by controlled experiments. This limits the application range for consequence models based on empirical correlations, and CFD is arguably the best available option. Accurate CFD calculations require detailed geometry models, and the cost and time required for implementing such models for the sole purpose of estimating risk metrics and design accidental loads (DAL) cannot always be justified from a cost-benefit point of view. However, the potential use of a detailed 3D model of an industrial facility extends significantly beyond the CFD-based consequence analyses. The primary advantages of the 3DRM concept, over classical approaches to risk management, include the strong coupling between the QRA and risk management, the realistic modelling of physical phenomena, the visual format for communication, and the inherent focus on safety culture, transparency and learning in organizations.

There are several inherent limitations of the 3DRM approach. It is essential to differentiate between 3DRM and so-called ‘expert systems’ – in 3DRM it is up to the users and stakeholders to define the system and to analyse, discuss, understand and manage the risk in their facility. Furthermore, 3DRM is a virtual system that provides a framework for risk management, whereas actual control of hazards requires risk awareness at all levels of the organization, focus on safety culture and continuous improvements, physical implementation of safety measures, preventive maintenance, etc.

In spite of the significant simplifications in the analysis, the case study for the hypothetical filling station demonstrates the potential for improving safety in hydrogen installations by means of Hy3DRM. It is straightforward to extend the prototype to a full 3D QRA for a more detailed version of the hypothetical filling station, as well as for real systems. The set of simulated events from the QRA represents valuable input to the process of designing and optimizing safety measures (e.g. detector layout), quantifying and discussion the uncertainty in risk estimates (e.g. optimizing the number of scenarios, visualizing individual events and their associated uncertainty intervals in a risk matrix, etc.), and developing training material for employees and contractors.

The main limitation of the 3DRM concept is that complete implementation requires dedicated commitment from end-users. It is nevertheless possible to develop proof-of-concept prototypes for artificial systems, and to take advantage of selected aspects of 3DRM, such as 3D risk assessment.

Conclusions

The 3DRM concept extends the use of detailed geometry models to all aspects of risk management, with particular focus on risk communication, safety culture and continuous improvements. The technology required for implementing 3DRM is available today. However, it is foreseen that the development of computers, sensors, portable devices, etc. will create numerous possibilities for extending the functionality in the future. Significant work remains with respect to establishing a robust framework for the interaction between the various components in the system. Seamless integration between software packages from various vendors can speed up the process significantly: geometry and metadata from CAD models, state-of-the-art risk analysis tools, such as HyRAM, simulation results from CFD codes and simpler models, 3D risk calculations and advanced optimization routines.

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