3D RISK MANAGEMENT FOR HYDROGEN INSTALLATIONS (Hy3DRM)

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ABSTRACT

This paper introduces the 3D Risk Management (3DRM) concept for hydrogen installations (Hy3DRM). The 3DRM framework entails an integrated solution for risk management that combines a detailed site-specific 3D geometry model for a system, a computational fluid dynamics (CFD) tool for simulating accident scenarios involving dispersion, fire and explosions, and a methodology for frequency analysis and quantitative risk assessment (QRA). In order to reduce calculation time, and to cover escalating accident scenarios such as structural collapse and projectiles, the CFD-based consequence analysis can be complemented with 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. This first 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 possibilities and prospects for future development.

1. INTRODUCTION

1.1 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 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 fuels: a tendency to cause embrittlement in metals, very low boiling point and density, very low ignition energy, wide flammability range, high rate of combustion, and a propensity to undergo deflagration-to-detonation-transition (DDT). Hence, fires and explosions represent a significant hazard for hydrogen installations, and special 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, and significant changes to safety standards and legislation for industry [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.

1.2 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. The ALARP principle emphasizes the obligation to reduce the risk to a level 'as low as reasonably practicable', even if the risk evaluation comply with 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)[1] can nevertheless be a valuable tool for detecting deficiencies and improving safety performance in complex technical systems [7-8], provided qualified personnel conduct and document the analysis in a consistent manner, and the organization implement and communicate the recommended safety measures.

A significant fraction of the incidents listed in the Hydrogen Lessons Learned (H_2LL) database at the Hydrogen Tools Portal [9] 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.

1.3 Hydrogen Risk Assessment Models (HyRAM)

HyRAM is a methodology and accompanying software toolkit that provides a platform for integration of state-of-the-art engineering models and data relevant to hydrogen safety [10-11]. The HyRAM software toolkit from SANDIA establishes a standard methodology for conducting QRAs and stand-alone consequence analysis relevant to assessing the safety of hydrogen fuelling and storage infrastructure. The toolkit integrates fast-running deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing the impact of hydrogen hazards on

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[1] 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).

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. The user may extend the scope of HyRAM with additional models and data. Users of HyRAM may extend the QRA analysis to development of codes and standards, code compliance and facility safety planning.

2. 3D RISK MANAGEMENT

This section summarizes the principles and ideas that inspire the development of the 3DRM concept.

2.1 Communication and culture

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 are unaware of the hazards, as well as 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”* — Wartenberg & Chess [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 mass-production by self-organizing teams and automated processes, accompanied by an increasing fraction of knowledge workers in the overall work force. There is significant potential for improving safety by taking advantage of the continued increase in computational power and storage capacity, as well as the introduction of increasingly advanced control systems, detectors, portable devices, simulation tools, geographic information systems (GIS), communication technology, etc.

> *“In an economy where the only certainty is uncertainty, the one sure source of lasting competitive advantage is knowledge.”* — Nonaka [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 companies adopt for handling safety and security. DeMarco & Lister [14] defines risk management as *“the business of believing only what you have the right to believe”*. This applies to technical and organizational aspects of how the management of a company chooses to implement safety measures, the services provided by safety consultants, and the validation and marketing of tools for consequence and risk assessments.

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 [15].

2.2 Consequence analysis

Many accidents involve fluid flow in complex geometries, with or without chemical reactions: loss-of-containment (release) and dispersion of flammable, asphyxiating, malodorous, toxic and/or radioactive material in gaseous, liquid and/or solid form; gas, mist, spray, dust or hybrid explosions; propagation of blast waves; jet and pool fires; etc. 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 the consequence models relate to scaling and complexity. Although limited accuracy in the estimates for event frequencies 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 Reynolds-averaged Navier-Stokes (RANS) equations, such as the k-ε model [16], complemented with sub-grid models to account for the influence of objects and phenomena that cannot be resolved on the computational grid [17]. The steady increase in computational resources (speed, memory, etc.), accompanied by parallelization of numerical solvers, allows for faster calculations on larger 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 solution 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 to reproduce results from specific sets of 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 [18]. Gexcon has validated the CFD tool FLACS-Hydrogen for a wide range of dispersion and explosion scenarios [19].

2.3 Overview of 3D Risk Management

Figure 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 3D Risk Management (3DRM) framework. The primary motivation for introducing 3DRM is to prevent major losses in industry and society by facilitating the combined use of advanced modelling and visualization techniques for risk communication, and thereby contribute towards improved risk awareness and safety culture in organizations, all within a framework adapted for the era of knowledge workers [20]. The 3DRM concept entails the use of dedicated software system, and incorporates significant aspects of the philosophy behind the methodology used for developing the system itself. Hence, the use of 3DRM for a complex industrial plant represents a kind of Agile risk management [15], with the traditional user 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.

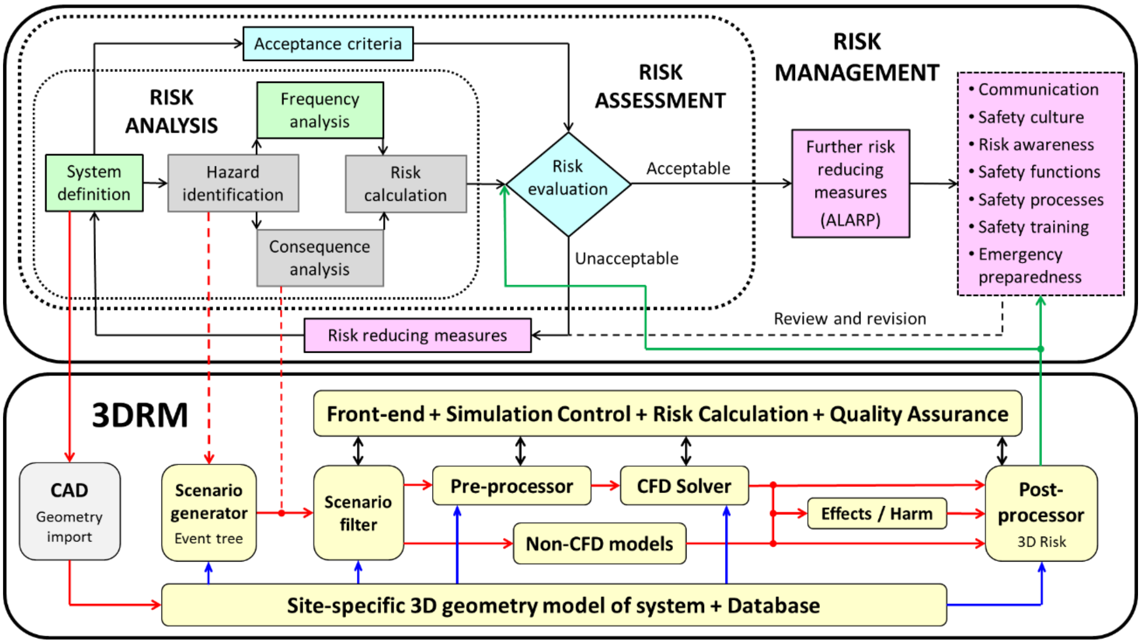

Figure 1. Schematic representation of risk analysis, risk assessment, risk management and 3DRM.

The workflow involved in establishing the 3DRM framework for a specific system could typically entail the following steps:

- 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.

The dispersion simulations may generate explosion simulations automatically based on stepwise accumulated probability of ignition within the flammable volume. For certain facilities it may be relevant to extend the analysis to include optimization of gas detector layout based on specific criteria, such as maximum probability of detecting the dispersed clouds in general, or maximum probability of detecting the clouds that result in the most severe consequences. It is also possible to extend the analysis to include structural response of selected parts of the geometry, such as blast and fire walls.

The hazard identification process and the frequency/consequence estimates proceed according to established methods, but whenever possible the analyses make use of relevant metadata from databases and CAD formats, and all 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 a valuable resource in this process [5, 21].

Within the 3DRM framework, the QRA can become a continuous process that evolves throughout the lifetime of the facility. The most complex part of the system is the CFD code and the infrastructure required to maintain, develop and validate this part of the software. In order to support complete QRA studies, the system includes various seamlessly integrated utility programs and libraries: scenario generator, scenario filter, source term models for leaks, a project-based front-end for supporting project databases, a module for simulation control and quality assurance (advanced run manager), 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 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 functionalities of detection and mitigation systems, as well as escalating accident scenarios. In this way, the virtual model may serve as a database for safety-related information, including relevant case histories, thereby preserving corporate knowledge over time and improving the general 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 the 3D geometry model for the CFD tool. It is necessary to perform regular revisions and updates to the geometry model throughout the lifetime of the plant. Within the 3DRM framework, an outdated geometry model represents technical debt – it is important to use the ‘as is’ model, not the ‘as built’ version. In addition, ‘what if’ versions can be useful for planning, design optimization, and to account for temporary structures such as scaffolding and barracks used during modification or maintenance work. A built-in ‘version control system’ keeps track of all changes, and authorized personnel approve the final inclusion in the official 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 to 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 simpler consequence models with results obtained with an advanced CFD tool. 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. The virtual 3D geometry may contain links to relevant documents and pre-simulated accident scenarios, as outlined above, 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 (e.g. learning 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.

2.4 Hy3DRM

The main goal of the project 3D Risk Management for Hydrogen Installations (Hy3DRM) is to develop the 3DRM concept for hydrogen installations, including a prototype for 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.

3. CASE STUDY

This section presents an early prototype of Hy3DRM that combines event frequencies estimated with HyRAM and consequences estimated with the CFD tool FLACS-Hydrogen (FLACS v10.4) to analyse the risk associated with fire and explosion for a hypothetical hydrogen filling station.

3.1 System definition

Figure 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 [22]. 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.

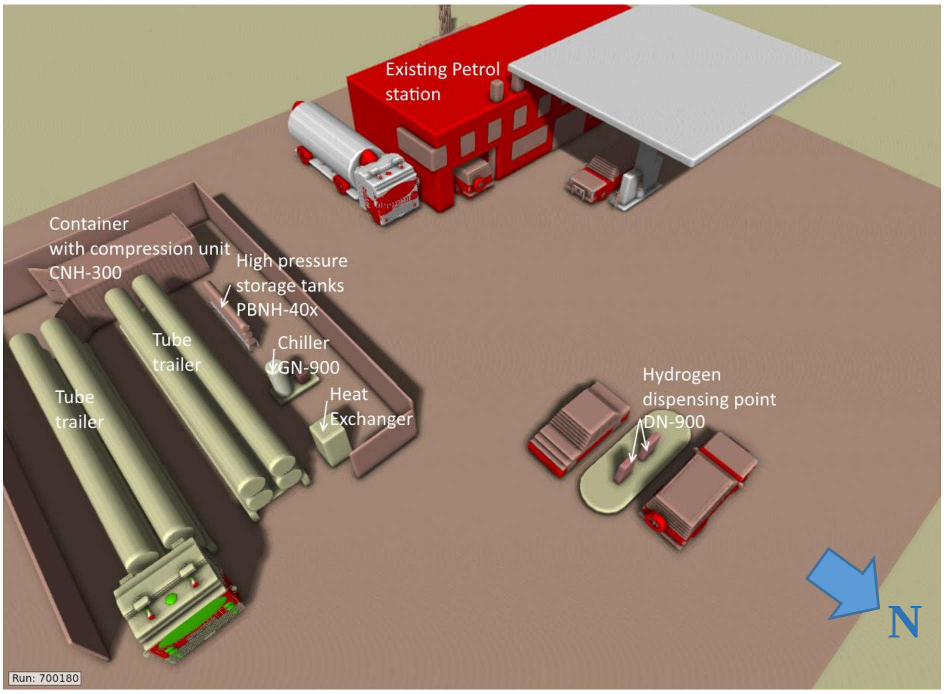

Figure 2. Layout of hypothetical filling station.

3.2 Fault and event trees

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

3.3 Dispersion simulations

Six representative release location were chosen based on the layout of the installation and release frequency data: the container with the compressor unit, both sides of the high pressure storage tanks, two locations in the tube trailers, and the dispensing point. Seven leak scenarios were modelled for each of the six locations: the six Cartesian directions plus 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 Figure 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.

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	1 034	7.16	2.00
Tube trailer	207	12.60	1.59
Dispenser	700	7.16	1.50

3.4 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. Figure 3 illustrates a jet fire near the high-pressure storage tanks.

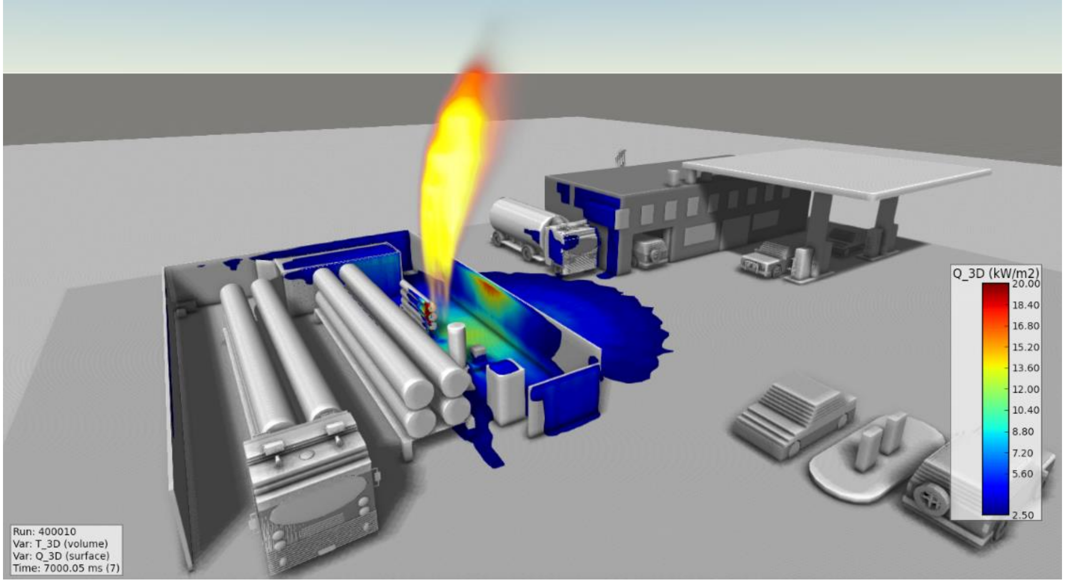

Figure 3: Jet fire and radiation contours.

3.5 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 energy required for successful ignition is also lower for the stoichiometric mixture, compared to lean and rich 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 ‘explosion’ scenarios. The simulation results are most likely on the conservative side, but it should be noted that the analysis does not account for DDT and detonations.

3.6 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 (explosion) ignition, and ignition location. Table 2 summarizes the event frequencies used for risk calculations [11, 23-24], and figures 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.

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

3.7 Human vulnerability model

The location-based potential risk of fatality from the heat radiation emitted from jet fires was determined from the following [25]: $\text{Probit} = 38.48 + 2.56\, ln\,(t\, q^{4/3})$, where the exposure time t was assumed to be 20 s, and q is the heat flux [W m^{-2}] from the CFD simulations. The frequency of fatality for a given scenario is the product of the event frequency and the probability of fatality. Figure 8 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.

3.8 Future work

The feasibility study for the hypothetical filling station will be extended to include a larger number of scenarios. 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.

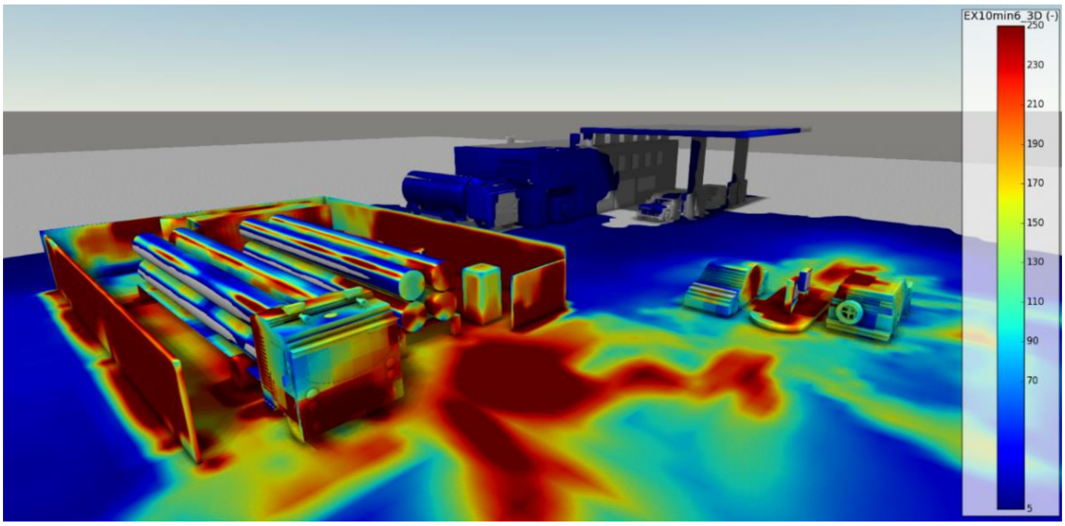

Figure 5. Heat radiation contours with frequency exceeding 10^{-6} yr^{-1}.

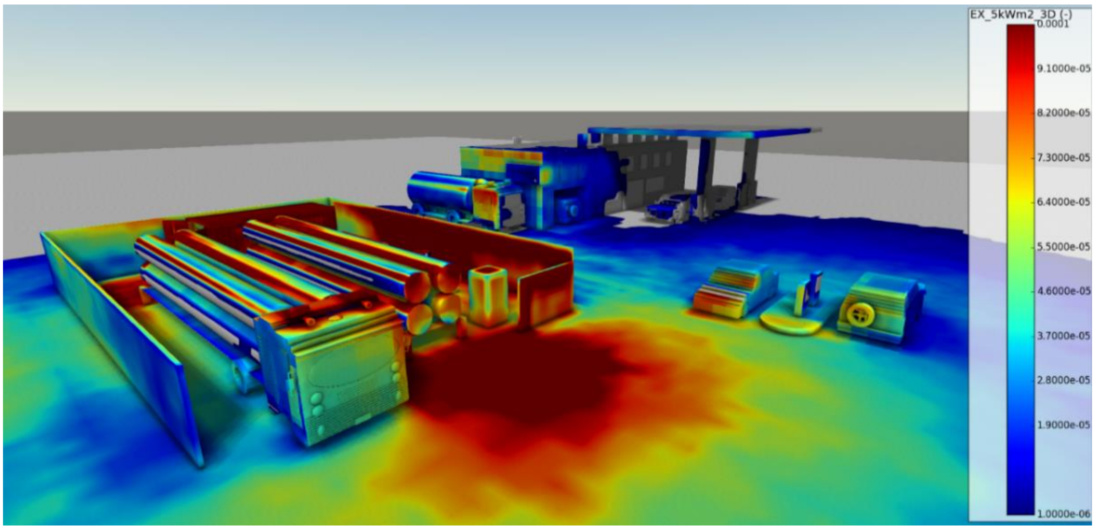

Figure 6. Frequency contours, from 10^{-06} to 10^{-04} yr^{-1}, for 5 kW m^{-2} radiation load.

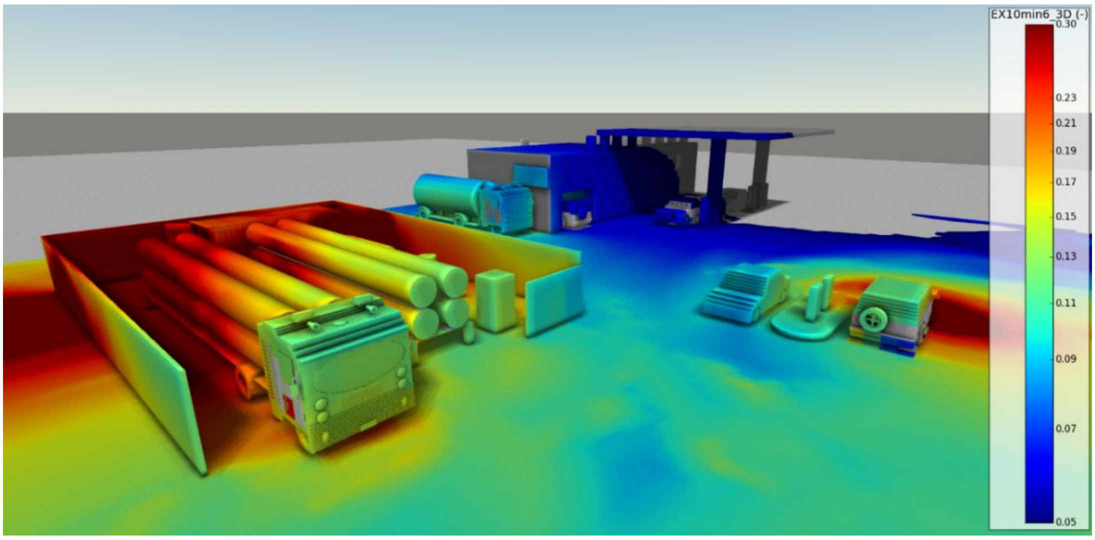

Figure 7. Explosion overpressure contours (up to 300 mbar) for frequency exceeding 10^{-6} yr^{-1}.

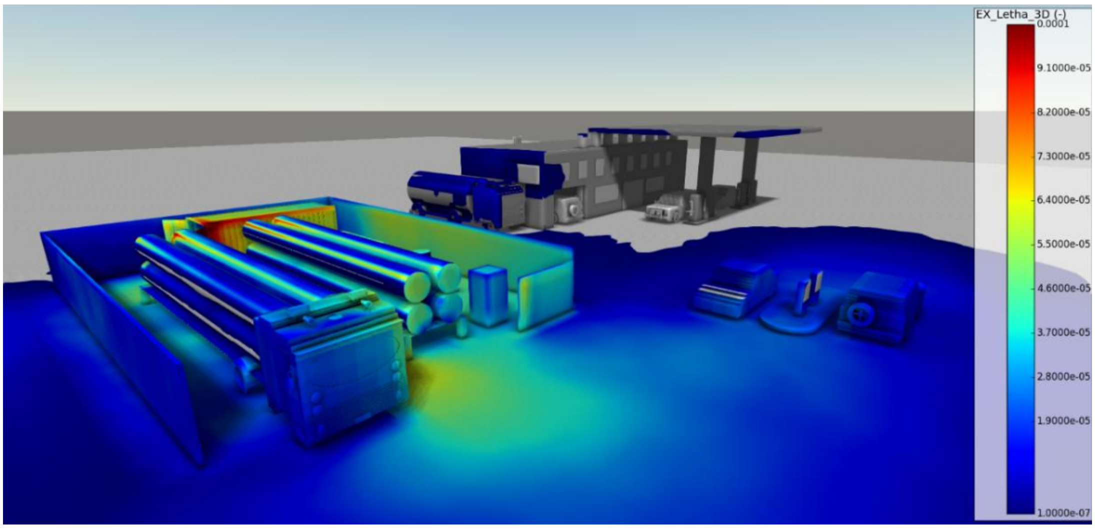

Figure 8. Fire radiation location based lethality frequencies, from 10^{-06} to 10^{-04} yr^{-1}.

4. 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 designing accidental loads 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 CFD-based consequence analyses. The primary advantages of 3DRM over classical approaches to risk management are the modelling of physical phenomena, the visual format for communication, and the 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 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 this prototype to a full 3D QRA for the hypothetical filling station, as well as real systems. The complete set of simulated events from a QRA represents valuable input to design and optimization of safety measures (e.g. detector optimization), quantification of the uncertainty in risk estimates (e.g. optimizing the number of scenarios), and training material for employees and contractors.

The main limitation of the 3DRM concept is that complete implementation requires dedicated commitment from the end-user. 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.

5. 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, 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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