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Analysis Methodology for Hydrogen Accident Scenarios in Complex Industrial Environments

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This paper describes a general analysis methodology which was developed for consistent and mechanistic modeling of hydrogen behavior in complex industrial accident scenarios. The methodology includes four steps: 1. Three-dimensional CFD simulation of the time and space dependent hydrogen concentration in the computational domain. 2. Application of experiment-based criteria which allow to estimate the fastest possible combustion regime for the given H2-air-distribution and geometrical constraint. 3. Numerical simulation of the identified combustion regime with a validated 3D combustion code; output from this step are mechanical and thermal loads to surrounding structures. 4. Consequence analysis with respect to a) structural response of the pressure loaded building using 3d-FEM or simpler models and b) health effects on persons. As an example for the analysis procedure the blow-down of 31 kg of hydrogen from a large electrical generator located in a 160,000 cubic meter turbine hall is modeled. Temporal evolution of the H2-distribution, the related hazard potential, the turbulent H2-air deflagration and the resulting loads to the building are calculated. Finally possible mitigation measures are derived for the investigated scenario.

1. Introduction and objectives

Classical explosion protection is based on the definition of hazardous zones (0, 1 or 2) using two criteria: the frequency and duration of the occurrence of an explosive atmosphere and the probability of an ignition source. The applied qualitative formulations lead to large uncertainties in zone dimensions because they do not address important physical effects like source strength, gas buoyancy, or influence of forced convection. To cover such phenomena large unknown correction factors are included in the assessment of the hazardous area (e.g. a factor 10 in IEC 60079-10, Annex B4), which creates a tendency for over-conservative and too expensive safety measures. The classical explosion protection can be improved by a scientific investigation of the actual physical phenomena with modern three-dimensional CFD simulations to predict accident progression and consequences, develop efficient mitigation measures and remove safety related innovation barriers. More knowledge can offer better safety at reduced costs.

This paper presents a self-consistent and mechanistic analysis procedure for large-scale accidents involving unintended release of hydrogen. The procedure, summarized in Figure 1, will be applied to the analysis of a hydrogen blow-down from an electric generator which is cooled with hydrogen gas. Accidental hydrogen release from generators is an important safety issue because in the past turbine vibrations have induced multiple hydrogen leaks at the generator resulting in H2-air flames, and failures to disconnect a generator caused H2-leaks, H2-air combustion and total loss of the generator. Damaged turbo generator sets are an important class of claims to insurers. The scenario investigated in the present paper assumes an earthquake with simultaneous break of the four largest H2-lines to the generator.

2. Mixture Generation during Generator Hydrogen Blow-down

The first step in the analysis is to investigate if formation of a combustible H2-air mixture is possible. To calculate the space and time dependent hydrogen distribution with a three-dimensional code the following input is needed: a) 3d geometry of the plant in the best possible resolution, b) mitigation measures installed in the building, e.g. ventilation, c) definition of the initiating event and accident scenario, d) definition of the gas

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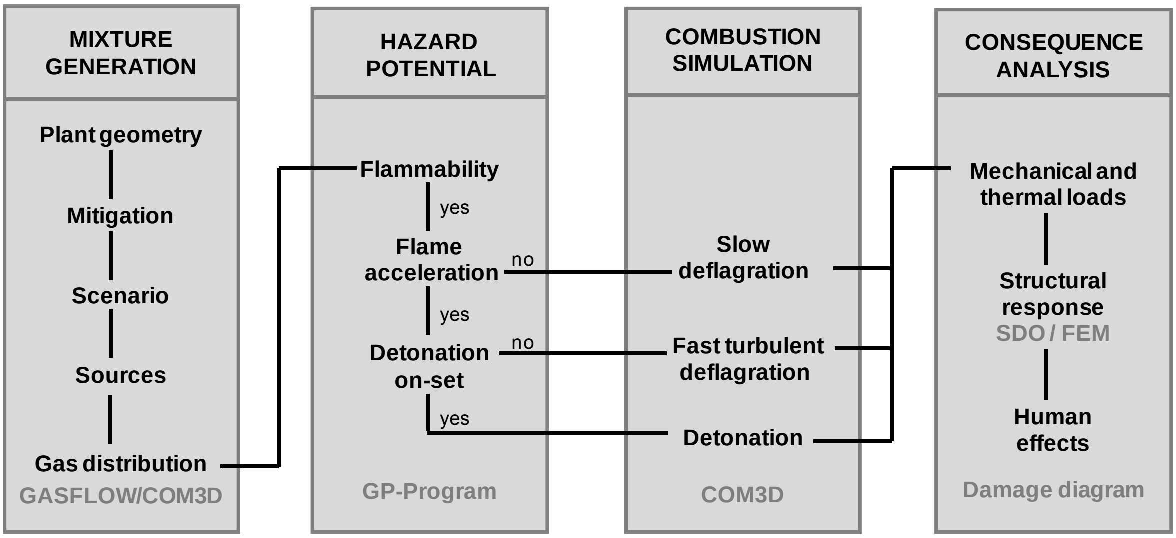

Figure 1   Steps in the mechanistic analysis of accident scenarios with unintended release of hydrogen.

sources flowing into the computational domain with respect to break area, mass flow, velocity and direction for hydrogen as well as other involved gases. In the present work the 3d code COM3D was used to calculate hydrogen transport and mixing (Kotchourko et al., 2015).

The turbine hall had dimensions of 43 m x 45 m x 84 m = 162,000 m^3. The internal structures were modeled with cubic computational cells of 0.5 m side length, resulting in 1.3 million cells. Figure 2 shows a horizontal and a vertical cut through the building with the large turbine in the back and the smaller generator in front.

No active mitigation measures were considered in this accident scenario, hydrogen is released from the generator into quiescent air at normal conditions. The correctness of the numerical geometry model was verified in a special building inspection with personal from the plant.

The selected bounding accident scenario assumed a heavy earthquake causing a simultaneous break of the four largest supply lines to the generator (size DN 80). The break location is directly at the generator bottom, without any residual pipe sections. This assumption provides the largest possible release cross section for the hydrogen inventory in the generator and the fastest release. A fast hydrogen release leaves little time for mixing with air and provides conservative hydrogen concentrations in the turbine hall. The hydrogen release process from the generator, which has a free internal volume of 100 m3, was simulated in a separate series of COM3D calculations using a much finer mesh. The numerical release rate agreed well with other closed analytical correlations for the critical discharge of hydrogen from a pressure reservoir (Figure 3).

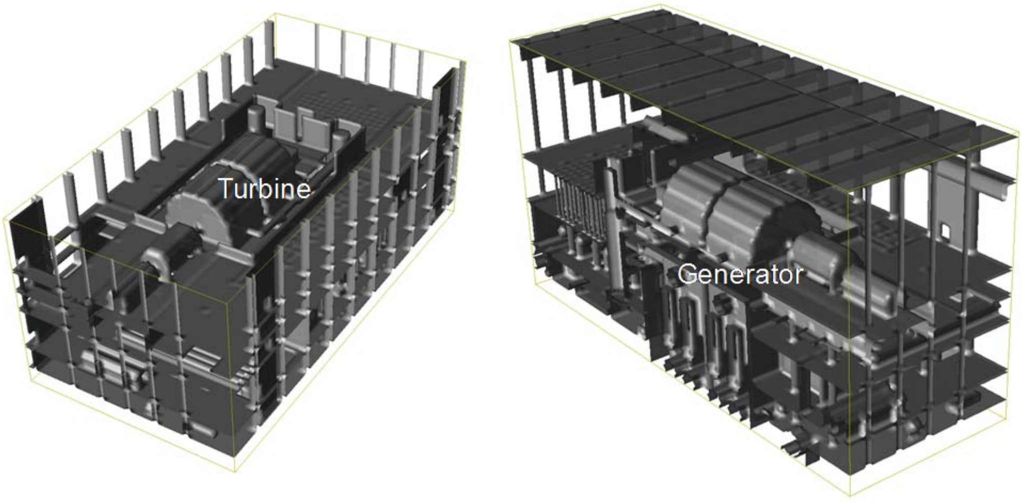

Figure 2 Three-dimensional geometry model for the multi-story turbine hall and the main components.

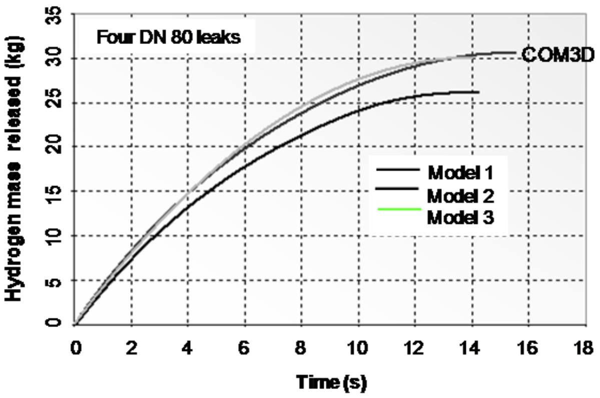

Figure 3 Hydrogen source for the generator blow-down scenario.

According to these results the generator hydrogen depressurizes from 5 to 1 bar in about 15 s, while the release rate drops from about 5 kg/s to zero. A total hydrogen mass of about 31 kg is released downwards into the turbine hall.The use of this hydrogen source term in the COM3D distribution calculation showed that the two floors below the generator are rapidly filled with rich H2-air mixtures during the release period. Figure 4 depicts the calculated isosurface in space for 4 % hydrogen near the end of the blow-down (at 13.7 s). An H2-concentration of 4% in air is often considered as the flammability limit. Although the hydrogen flow is directed downwards from the 19 m level, the existing relatively small openings around the generator (few m^2) also allowed significant flow of hydrogen upwards into the free turbine hall above the 19-m level. With increasing time the envelop of burnable mixtures around the rich H2-air cloud (>75 % H2) grows continuously due to hydrogen diffusion and buoyancy. A standard k-ε model was used to calculate the local turbulent viscosity and turbulent mass diffusivity. Clearly, the applied grid is under-resolved for the free jet emerging at the break, resulting in too low H2 exit velocities, however the jet momentum is lost anyhow after impinging on the floor below the break. In this problem the flow is mainly driven by pressure gradients between adjacent rooms.

Figures of the flow lines show that the main flow direction is downwards from the breaks and then through a large opening in the 19-m floor upwards to the roof. The flow velocities in the interconnecting area decays from initially 35 m/s down to 2 m/s at the end of the release phase. Generally, the hydrogen transport in this multi-story building with interconnected room chains is controlled by the different hydraulic resistances along the available flow paths. The numerous walls and the low "porosity" of the structure cause low mixing with air and high local hydrogen concentrations. During the first 30 s the released 31 kg H2 remain near the generator, and are not transported far into the building (see Figure 4). At this time the space region with more than 4% hydrogen has approximately 20 m length, 16 m width, and 12 m heigth. Explosion protection measures in this zone would reduce the risk from a subsequent hydrogen combustion significantly.

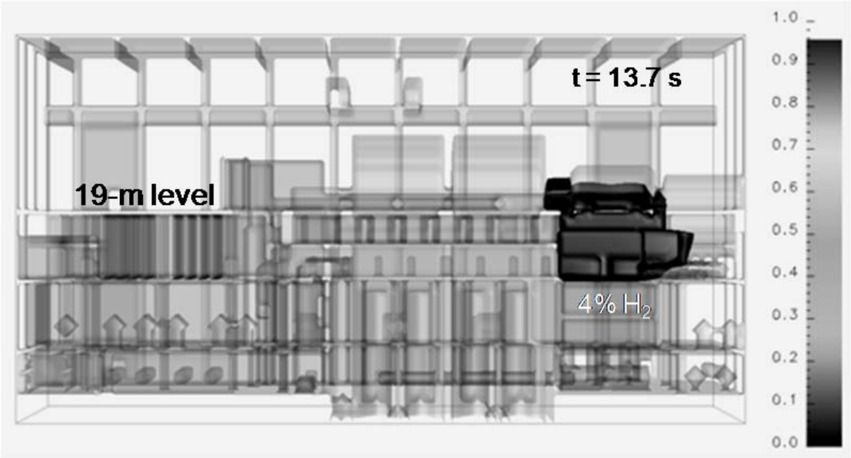

Figure 4 Calculated isosurface for 4% hydrogen in air near the end of the blow-down phase.

3. Hazard Potential of Hydrogen - Air Mixtures

The second step in the hydrogen safety analysis is to evaluate the hazard potential which is connected with the calculated combustible cloud . The hazard is mainly determined by the fastest possible combustion regime for the given mixture composition, scale, and degree of confinement. Three questions need to be answered: 1) is the mixture flammable, 2) is spontaneous flame acceleration from slow to fast (sonic) deflagration possible, and 3) can a transition to detonation occur? The larger the flame speed, the higher the resulting overpressure and potential damage. Since the transition processes cannot be resolved numerically on large industrial scales, empirical transition criteria were developed from a large body of experimental data which allow to estimate the fastest possible flame speed and combustion regime (Dorofeev et al. 2000, Dorofeev et al. 2001, summary in Chapter 3 of Breitung et al. 2000). These publications refer to fully confined mixtures. Criteria for partly confined H2-air mixtures were presented by Kuznetsov et al. 2011.

Due to space limitations only the main results can be summarized here. In the present case of a hydrogen blow-down into the room below the generator, sufficiently high H2 concentrations for flame acceleration were observed (≥ 10.5 % H2). An important prerequisite for DDT is flame acceleration to sonic flame velocities of about 500 - 700 m/s. A detailed analysis showed that there is not sufficient flow obstruction and travel path for the flame front to reach such high velocities, so that the potential for detonation transition was judged low. Therefore a turbulent deflagration was simulated with COM3D.

4. Combustion Simulation

A combustion simulation first requires the definition of location and time of the ignition event. Since no mechanistic arguments can be made in the present scenario, conservative ignition parameters were selected which should result in the highest possible flame velocities. This are a) ignition at the time of the maximum amount of burnable mixture in the building, which are 28 kg H2 at t=14 s, and b) ignition on the floor below the generator (circle in Figure 5 left) leading to intense mixing of the rich H2-cloud with air.

The grey scale in Figure 5 (left) depicts the oxygen concentration at the time of ignition (white = 21 % O2, black = 0 % O2). The dark region below the generator contains mainly hydrogen and less than 5% oxygen, this mixture is not burnable at this time. The turbulent deflagration was simulated with COM3D. The applied KYLCOM combustion model is described in Yanez et al., 2010. Due to the strongly inhomogeneous initial H2 distribution and the complex building geometry the combustion process is very complicated. During the first 0.1 s hydrogen below the generator burns until the available oxygen is consumed. The remaining hydrogen is then driven by the expanding hot H2-steam mixture from the compartment below the generator through a transport opening into the large free open space above the 19-m level, where it mixes with air and burns out rapidly. The flame propagates with 29 m/s at 0.081 s and reaches up to 293 m/s at 0.311 s. Figure 5 (right) shows calculated flow stream lines and velocities 0.311 s after ignition, the transport opening is located at the right corner of Figure 5, right. After 0.7 s only 5 kg of hydrogen remain in a burnable composition (≥ 4%).

During the calculation the maximum pressure occurring at any given location (x,y,z) during the simulation time is stored in a special array (pmax= MAX [p (x,y,z,t)]. The largest pressures occur on the floor and the walls below the generator. The black regions in Figure 6 represent solid structures like generator and turbine. Two representative examples for local pressure histories are shown in Figure 7. The left plot corresponds to a location above the generator in the free open space of the turbine hall. The pressure maximum reaches only

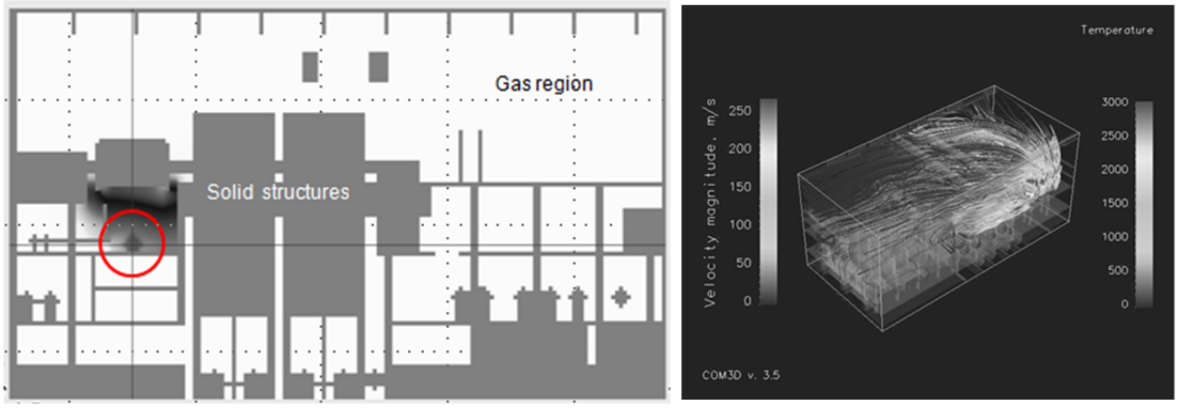

Figure 5 Selected ignition location for the turbulent deflagration simulation in the turbine hall (left) and flow paths in the turbine hall (right). The burned gas velocities reach up to 293 m/s (1050 km/h).

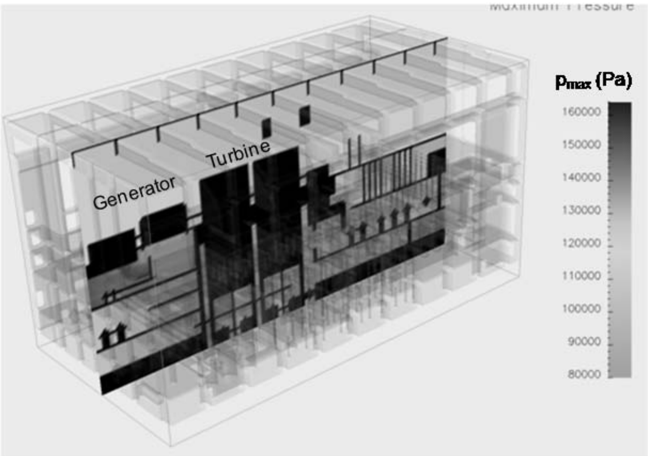

Figure 6 Distribution of the maximum pressures obtained on walls during the combustion process.

5. Consequence Analysis

The consequences of the calculated pressure loads were evaluated with respect to structural damage and human health effects. The main variables are the peak overpressure and the duration of the positive pressure pulse. Comparison of the blow-down data to damage classes given in Baker et al.,1983, shows that the capacity of masonry walls would be exceeded near the generator. Stronger floors and walls with a static load capacity of about 0.5 bar would be needed for load confinement. The upper-most point in Figure 8 (left) corresponds to the pressure signal of Figure 7 (right). A more detailed analysis of structural response is possible, taking into account actual material properties, geometry of the structure, and support conditions (see contribution to this conference by Ramin and Stolz, 2016).

The two most pressure sensitive human organs are the ear and the lung. Comparison of the calculated peak overpressures to data given by Richmond et al., 1989, show that the lung rupture threshold is not reached but that a high probability for ear drum rupture would exist for persons present in the hall in the event of a generator blow-down accident involving a hydrogen combustion.

6. Mitigation Options

The described analysis procedure allows systematic identification of effective mitigation measures for risk reduction along the whole chain of events. In general the following priorities could be investigated to impede accident progression and limit potential consequences: 1) exclude severe accident scenarios by design changes, 2) limit hydrogen sources in total mass and release rate, 3) support hydrogen dispersion and mixing processes, 4) exclude ignition sources or prevent late ignition, 5) suppress flame acceleration by small confinement and low turbulence generation, 6) avoid detonation transition by promoting lean mixtures and small scales for DDT, 7) confine, weaken or direct pressure waves by strong enclosure or venting.

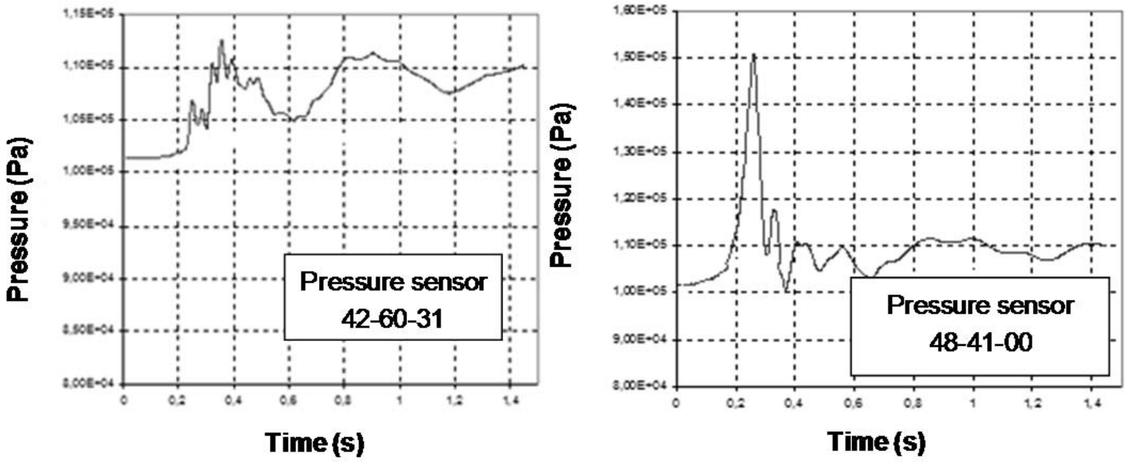

Figure 7 Examples for calculated local pressure histories during the turbulent hydrogen deflagration.

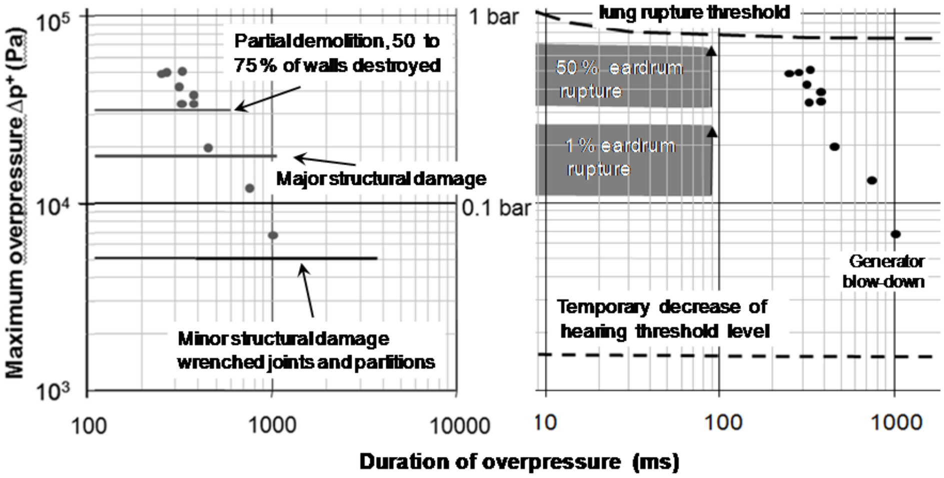

Figure 8 Consequence evaluation for the calculated combustion pressures with respect to structural damage to brick walls (left) and human health effects (right).

For the investigated generator blow-down scenario these guidelines suggest the following mitigation options: a) installation of fast venting lines for hydrogen from the generator to outside of the turbine hall, b) reduction of critical flow rates by flow restriction (e.g. orifices) in potential blow-down lines, c) more openings in walls and floors near the generator, d) modification of the generally also existing nitrogen system for fast inertization of the generator environment, e) less flame confinement by more openings in walls and floors, f) less reactive mixtures from N2 injection, g) reinforced walls. Explosion protection measures in the zone depicted in Figure 4 for > 4% H2 would reduce the risk from a hydrogen combustion significantly.

7. Conclusions

A systematic procedure was developed for scientific analysis of hydrogen accidents in complex industrial environments. The methodology was applied to a conservative generator hydrogen blow-down accident scenario, involving simultaneous break of the four largest lines and subsequent release of 31 kg H2 in 15 s. Numerical 3d simulations of hydrogen distribution and turbulent combustion processes offer new insights into the chain of events, provide deeper understanding of existing safety risks as well as possible mitigation measures, and allow a better safety and cost optimization than the classical explosion protection approach, which is based on very uncertain zone definitions.

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