PERFORMANCE-BASED REQUIREMENTS FOR HYDROGEN DETECTION ALLOCATION AND ACTUATION

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ABSTRACT

The hydrogen detection system is a key component of the hydrogen safety systems (HSS). Any HSS forms a second layer of protection for the assets under accidental conditions, when a first layer of protection - passive protection systems (separation at "safe" distance, natural ventilation) are in-operable or failed. In this report a performance-based, risk-informed methodology for establishing of the explicit, quantitative requirements for hydrogen detectors allocation and actuation is proposed. The main steps of the proposed methodology are described. It is suggested (as a first approximation) to use in a process of quantification of a hydrogen detection system performance (from safety viewpoint) a five-tiered hierarchy, namely 1) safety goals, 2) risk-informed safety objectives, 3) performance goal and metrics, 4) rational safety criteria, 5) safety factors. Unresolved issues of the proposed methodology of Safety Performance Analysis for development of the risk-informed and performance-based standards on the hydrogen detection systems are synopsized.

1.0 INTRODUCTION

1.1 Active Protection Layers and Passive Protection Layers

The hydrogen detection system (hereafter - HDS) is a key component of the hydrogen safety systems (HSS). Any HSS forms a second layer of protection for the assets under accidental conditions, when a first layer of protection - passive protection systems (separation at "safe" distance, natural ventilation) are in-operable or failed.

Importance of the HSS (as an additional protection layer) will, certainly, increase with gradual penetration of hydrogen (as a commercial product) into different niches of consumer market (hydrogen-fueled vehicles, home heating, energy supply). Scarcity of a free space in modern cities forced already to revise a "separation (or safety) distances" doctrine, which has been extensively and successfully validated during a previous half–century in the aero-space and nuclear applications, chemical, petrochemical and gas industries. Engineering justification and regulatory support of a "separation distances" reduction were in a focus of activity during the last decade worldwide. However, reduction of the separation distances is not an infinite. Sooner or later this resource of safety provision will be exhausted. As soon as the key safety issues, related with outdoor hydrogen storage and distribution, will be removed, potential resources of the active protection layers, in general, and the HSS in particular, will be a foremost task.

1.2 Safety Performance of Hydrogen Detection System (HDS) as Engineering Problem

Success in application of the detector-based HSS with the aim of safety level enhancement depends heavily on performance characteristics of hydrogen detection system just as a spatially distributed mesh of detectors, networked electronically and worked according to accepted safety criteria.

Performance characteristics of a stand-alone sensor are well elaborated and documented. The detailed and explicit requirements on accuracy of response, measuring range, response time, sensitivity to hydrogen, ambient temperature, pressures, relative humidity, cross sensitivity to CO, durability, life time, calibration, maintenance can be found in various technical specifications of vendors, testing and calibration protocols of the standardisation bodies, guidelines of professional societies, national and international standards.

Situation with performance characteristics (from viewpoint of guaranteed safety provision) of HDS as a system of multiple detectors, which are spatially distributed and should work coherently according to some safety criteria, is much more modest. Now, the technical requirements for allocation of the hydrogen sensors are based on purely empirical experience and are described in a so-called prescriptive manner. Below, the real problems of (dominating now) prescriptive paradigm are illustrated on two topical practical issues. These issues, formulated as paradoxes, are not presented to point out on a wrong or right solution but rather to illustrate that setting up a really working safety performance requirements is not a simple matter and instead requires substantial forethought and systematic work. Effective development of rigorously substantiated technical requirements for HDS requires a traceable, transparent framework of analysis (like requirement engineering in IT applications [1]). From our viewpoint, this framework will include with necessity an application-tailored glossary; reflecting notions and terms, which are specific for area under consideration; facility-specific risk assessment technique and last but not least – methodology of analysis of safety performance of hydrogen detection systems. This methodology can be named as Safety Performance Analysis.

1.2.1 Limitations of Prescriptive Approach

Detectors Allocation. "100 cars – 100 detectors" Paradox.

In currently available technical guidelines, normative and regulatory documents, the technical requirements (in fact - wishes) for allocation of the hydrogen detectors are formulated in a too general form and do not have a clear substantiation, supported by any quantitative physics-based or engineering methodology. For example, in respected and authoritative technical report [2] it is suggested to arrange sensors in "location where hydrogen leaks or spills are possible". In a representative underground garage in Moscow, approximately one hundreds of hydrogen-fueled cars can be parked. Before invention and practical implementation of a 100% leak-free hydrogen on-board storage systems, each car can be a potential source of hydrogen leak. Does it means that it will be necessary to allocate one hundred of hydrogen detectors (one detector per each parking slot)? Unfortunately, in a prescriptive approach the specific methods or procedures of attaining of the proclaimed objectives are absent.

Another example of in-operability (more specifically – inability to apply an empirical rule to a similar system) of the prescriptive requirements and standards is the following. During preparation of the HYPER project [3] deliverable – WP1. HYPER Database of Regulatory Codes and Standards – around three hundreds of codes, standards and other normative documents from EU, US, Australia and Russia (SU) were found. Only in two documents [4, 5] there were explicitly described the procedures on - how to define a minimal number of flammable gas detection per a given confined area ? and how to allocate detectors inside of enclosure under protection ? However, both documents were prepared for specific use in oil and gas industry. All procedural and quantitative information in the mentioned documents was focused on the gaseous hydrocarbons only. Due to absence of description of any underlying principles, their usefulness for hydrogen safety application is questionable. Again, a prescriptive document states a goal, but does not show a principle or method – how to attain the goal.

Detection Limit. "100ppm – 1000ppm" Paradox.

Recommendations for a lower level of the hydrogen leak warning alarms, articulated in terms of fraction of LEL (Lower Explosive Limit) and documented in a lot of the international and national standards and pre-normative studies reports, are also prescriptive. Prescriptive nature of the currently available requirements both for sensor allocation and alarm activation have the following limitations - they do not 1) establish a clear expectation for sensor system, based on foreseeable use, 2) ensure explicit connection to requirements for the expected sensor system applications, 3) provide confidence that accepted requirements for sensor system will be enough to attain an acceptable (or tolerable) protection level. For example, recent discussion [6] on "how early should" hydrogen detection "be implemented to effectively improve safety and not become an operational nuisance at the same time?" revealed two different view-points. According to one viewpoint, "detection limit" shall be "as low as possible" ("100 ppm detection limit"). According to another viewpoint, "it was recommended" (on the base of CFD calculations of tailpipe emissions and a few reasonable assumptions on possible scenario of refuelling) "to establish the lower detection limit for hydrogen refuelling at 1,000 ppm". But why not just preserve a widespread limit – 2 vol.% or to propose an "extended" limit - 3 vol. % ? From our viewpoint, a vulnerability of abovementioned reasoning is related with absence of a direct and transparent relationship between values under discussion (100 ppm, 1000 ppm, 2 vol.%, 3 vol.%, or else) and real hazardous potential of tailpipe emissions. In a prescriptive approach (even containing risk-informed data), there are no a clear hierarchies – what is more important from safety viewpoint ?

1.2.2 Necessity of performance-based, risk-informed design of Hydrogen Detection Systems

In order to resolve the deadlock, associated with both a clash of different opinions ("100 – 1000 ppm") on lower detection limit and with absence of practically operative procedures ('100 cars – 100 detectors") on detector allocation, it will be worthwhile to try to find and articulate a mutually agreed framework, which can be used as a basis for selection of the acceptable solutions in hydrogen safety. Ideally, if this framework would be based not on prescriptive "rule-of-thumb", applicable to a specific and limited in scope area, but have been based on a set of the rational (scientific or engineering) principles or methods, which can equally be applicable to different situations. Similar problem was already encountered in safety provision and technical regulation of the large, high-consequence systems – nuclear power [7] and civil construction industry [8]. In both cases, a development of performance-based, risk-informed approach has been selected as a most suitable and effective measure in a long-term perspective.

In this report a first version (in fact – sketch, scheme) of a performance-based, risk-informed (PBRI) methodology for establishing of the explicit, quantitative requirements for hydrogen detectors allocation and alarm activation is described. At first, an overall procedure of PBRI design of hydrogen detection systems, details of proposed "Safety Performance Analysis" (SPA) and its relations with facility-specific "Risk Assessment" (RA) are described. After that, the un-resolved issues of SPA, which is necessary for development of the risk-informed and performance-based standards on the Hydrogen Detection Systems, are discussed.

2.0 METHODOLOGY OF PERFORMANCE-BASED, RISK-INFORMED DESIGN OF HYDROGEN DETECTION SYSTEMS

A methodology for conceptual and detailed design of the Hydrogen Detection Systems is proposed and explained below. The proposed methodology can be named as performance-based or physics-based approach. Main goal of this approach is a development of the quantitative, traceable requirements for sensor allocation (minimal number per area under protection, minimal distance between two adjacent detectors) and actuation (lower detection limit).

2.1 Term and Notions

In this report for safety performance analysis purposes, the following terms and notions will be used:

Assets - any valuable entity (humans, business continuity, built environment, property, natural environment), which can be subjected to hydrogen hazard exposure and, as a consequence, can be undergone an appropriate loss (injury or loss of life for humans, loss of mission for business, structural damage for property, etc.). Risk of harmful consequences of hazard exposure can be reduced by using of an alarm system (AS), a protection (PS) or a mitigation system (MS).

Actuator – any technical device responsible for actuating the alarm, protection, mitigation systems of HSS.

Critically important assets (CIA) – assets, which shall be protected by HSS in first turn. CIA are defined during a facility-specific Risk Assessment (RA). It can be an entity with a lowest tolerability to a leading hazardous factor, or most risky ones. Specific risk-informed criterion for definition of CIA shall be defined within RA.

Explosive cloud (EC) – a part of hydrogen-air gas mixture with concentration between Lower (LFL) and Upper (UFL) Flammability Limits, where a real consumption of hydrogen can proceed during combustion process (either in deflagration or detonation form). EC is a direct, realistic hazard for assets.

Hazard – any physical or chemical process, which can provide a loss for assets. Hazard is characterized by a hazardous factor and a harmful potential. Each hazardous factor can by scaled by its performance metric. For example, hydrogen deflagrative explosion is a hazard. Blast wave is a hazardous effect (factor). Blast wave overpressure (or impulse) is a hazard performance metric. Harmful potential of deflagrative explosion can be measured (scaled) using mass of hydrogen, which can be consumed during the combustion inside of the explosive cloud envelope.

Hydrogen safety system (HSS) is a set of the engineered sub-systems, aimed to protect assets, allocated within facility, against direct, relevant and realistic hazards, associated with un-intended (accidental) hydrogen leaks at performance level, established by stakeholders. HSS can include – hydrogen detection system (HDS), management unit (MU), alarm system (AS), prevention, protection (PS) or mitigation systems (MS).

Hydrogen detection systems (HDS) is a "sensing" part of a hydrogen safety system (HSS). HDS is a set of the hydrogen detectors, allocated either inside of enclosures, which shall be protected from harmful consequences of hydrogen leaks, or around of a potential hydrogen release point at outdoor sites under accident conditions. HDS is aimed to detect the appearance of hydrogen-air mixture (not necessary an explosive cloud) and activate in time a hydrogen prevention or mitigation systems. An HDS includes 1) hardware for physical detection of presence of flammable hydrogen-air mixture and determination of hydrogen concentration, 2) technical means for transmission of signals from detection to management unit, 3) management unit for processing of the signals according to accepted safety criteria.

Prevention and protection systems - sets of technical means, targeted to exclude formation of explosive cloud (forced ventilation, cutoff valve, inertization, retardation) within facility.

Mitigation system - set of technical means, targeted to restrict the intensity or scale of the harmful consequences (igniters, catalytic recombiners, sprinklers).

2.2 Performance-Based, Risk-Informed Requirements Development. Procedure Description

In order to develop the performance-based requirements (see background details in [7, 8]) for hydrogen detection systems the following five-tiered hierarchy is proposed (top-bottom approach):

1) establish safety goals for detector-based hydrogen safety system

2) define risk-based safety objectives (functional requirements)

3) establish safety-related performance metrics and goal (operative requirements)

4) define rational safety criteria

5) define safety factors

Each step in an overall process of performance-based, risk-informed requirements elaboration is described below in more details. It is necessary to stress, that proposed methodology includes two equally important, but distinctive parts - facility-specific Risk Assessment (steps 1, 2, 5) and Safety Performance Analysis (steps 3 and 4). Their interaction is shown at Figure 1 below.

2.3 Step 1: Qualitative Safety Goal (Tier 1: Hydrogen Safety)

In general, safety goals reflect the interests both of the community at large and of specific stakeholders, such as owners, tenants, facility managers, residents and personnel [8]. In order to facilitate an obtaining a consensus of all stakeholders with different background, it is reasonable to formulate safety goal in a qualitative form. For model hydrogen detection system (HDS) an overall safety goal can be stated as following:

SG: The primary goal for HDS is to provide a timely, relevant and complete enough information for the actuators of the HSS on really hazardous hydrogen-air mixture appearance inside of a space under protection of HSS, which permit to reasonably avoid intolerable (or un-acceptable) losses to assets, associated with potential harmful direct effects (suffocation, burn) or in-direct (explosion, fire, missile) consequences of hydrogen leaks.

Safety goal shall be established at initial stage of Risk Assessment.

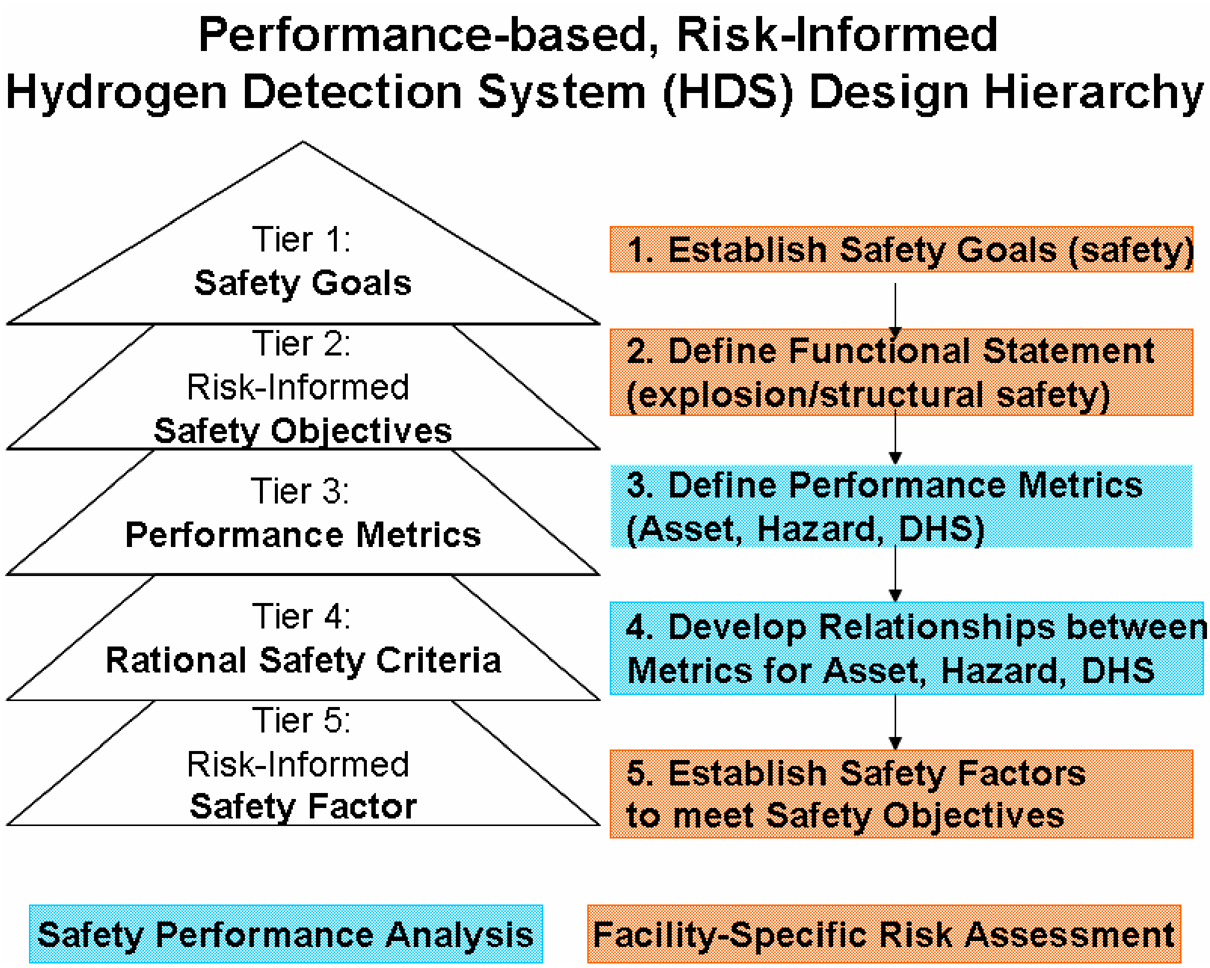

Figure 1. Interaction of risk-informed goals, objectives, safety factors (facility-specific Risk Assessment) and performance metrics and criteria (Safety Performance Analysis) in Hydrogen Detection System design.

2.4 Step 2: Qualitative Safety Objectives (Tier 2: Functional Requirements – life/fire/explosion safety and business continuity)

The abovementioned overall goal is, in first turn, intended to reach a consensus between stakeholders with different background, and speaks to the issues of human safety, business continuity, property damage, etc. but gives no specific guidance on functional expectations in respect to different assets, which should be protected by HSS under accident conditions. So, associated functional statements are needed. They should be used, mainly, by experts with engineering background as a technical problem statement. Any functional requirement shall explicitly specify at least three topics – 1) assets (what shall be protected ?), 2) hazards (what is a relevant hazard for the given assets ?) and 3) level of protection of assets against appropriate relevant hazard (what is a level of protective system performance that is tolerable or acceptable to stakeholders from safety view-point, in other words – what is a safety performance of HSS ?). Detailing of safety goal can be made by defining a set (in fact a multi-level tree) of particular safety objectives, which focus on specific assets.

Potential safety objectives (as an example) for a model HDS can be the following:

SO1: Life safety and injury prevention (explosion safety). HDS shall be designed and installed so as to detect a really hazardous explosive cloud formation and to actuate the appropriate prevention or mitigation systems in proper time and thereby to prevent or mitigate harm to human (occupants or personnel) health and life due to either the primary hazardous consequences of hydrogen-air explosion (blast wave-induced eardrum or lung failure, etc.) or the secondary ones (missile wound or contusion, burn, etc.) to levels determined by a facility-specific risk assessment.

SO2: Property and infrastructure protection (structural and engineering systems safety). HDS shall be designed and constructed so as to reasonably protect structural elements of building or its interior (windows, doors, ceiling) from the effects of hydrogen-air explosion and associated blast-induced losses to levels (damage, failure, collapse), which are determined by a facility-specific risk assessment and assumed as tolerable (acceptable) for a set of the design basis accident scenarios (diameter, flowrate of hydrogen leaks, etc.).

SO3: Mission protection (business continuity safety). HDS shall be designed and constructed so as to prevent a loss of mission (for example, business) continuity, and/or damage of the engineering systems due to either the primary hazardous consequences of hydrogen-air deflagrative explosion (blast effects) or the secondary ones (missile effects) to levels determined by a facility-specific risk assessment.

Mentioning of the “really hazardous explosive cloud formation” is essential. It is a means to orient designers on searching and discussion of a trade-of between safety level and reasonable sufficiency (“100 ppm – 1000 ppm paradox”). Detection of vanishingly small amounts of hydrogen, which do not possess real threat (capability to provide a visible or sensible damage), will result in false alarms and wasting of resources.

For any facility (refuelling station, underground parking, etc.), which shall be protected by HSS, it is possible to formulate a lot of the safety objectives. Ranking of the potential functional requirements and selection of the relevant ones shall be made via facility-specific risk assessment and communication.

Let’s admit, that after risk assessment and communications with the stakeholders it was found, that the SO2 is a main safety objective. For designers of the HDS, it means, that facility-specific risk assessment selected the deflagrative explosion as a most risky scenario, i.e. risk (probability times consequences) of explosion has a highest rank and it is necessary to find technical or other means, which provide engineering solution for a given problem. In summary, for our model case the critically important assets are the following - structural elements of building or its interior (windows, doors, ceiling). Dominating hazard is hydrogen explosion. Level of protection is scaled by minor damages of interior.

2.5 Step 3: Safety Performance Metrics and Goal (Tier 3: Operative requirements)

To satisfy the safety objective (functional requirement) selected at the previous step and make them to be operative, it is necessary to carry out a Safety Performance Analysis, i.e. to define safety-related metrics and establish a safety performance goal of the HDS under development. In other words, it is necessary to define explicitly – what is a main hazardous factor (physical or chemical effect), which governs a potential loss scale or damage extent ? How to scale (via measurement or estimation) a hazard level for the given assets ? What kind of physical parameter (or parameters) should be timely detected in order to prevent losses, stated in functional requirements ? Safety performance goal statement is a means to answer on a key question – how to restrict extent (or intensity) of hazardous effect, if hydrogen release will occur ?

Operationally it can be made by defining two performance metrics (measures or scales).

2.5.1 Hazard-related Metrics (Cause-Effect Relation)

Damage Metric (Effect)

In our model case, hydrogen explosion (hazard) can damage windows (assets) via *hazardous effect (factor)* – blast wave. At engineering level of accuracy, which permits to retain the key features of effect and is sufficient for practically reasonable quantitative estimations, a blast wave overpressure - ΔP_{bw} - can be regarded as an approximate *Performance Characteristics* of hazardous effect or *Damage Metric* (DM). The higher the value of blast wave overpressure is, the higher the damages of structural elements can be. Numerical value of performance characteristics of hazardous effect defines a criticality (extent) of damage or loss. In other word, the overpressure ΔP_{bw} can be used as a rough[1] metric or scale of hazardous effect of blast wave on structural element or interior of building, since its numerical value is proportional to resulting damage.

Metric of Harmful Potential of Explosive Cloud (Cause)

Blast wave was generated during ignition of explosive cloud, so its performance characteristic depends on harmful potential of explosive cloud. How it is possible to measure (or to scale) a harmful potential of explosive cloud ? In a first approximation, an answer is the following: total mass of hydrogen m_{total}, allocated inside of explosive cloud envelope (constrained by two concentration boundaries – low and upper flammability limits) and consumed during combustion, can be used as a metrics of a *Harmful Potential of Explosive Cloud* (HPEC).

In fact, the main performance parameters of blast wave (overpressure, positive phase duration) depends on a complex set of the physico-chemical and geometrical conditions, which are present during blast wave formation and propagation via explosive cloud. These circumstances can include – spatial distribution of the hydrogen concentration and turbulence level fields inside of explosive cloud, shape and size of explosive cloud, ignition point location, etc. Accurate estimation of history of evolution of the blast wave performance characteristics requires an advanced physico-chemical models and computational tools. In this paper, in order not to overcomplicate the description of the proposed methodology, the simplest metrics of harmful potential of hazard is selected.

Summing up, the destructive impact of hazardous effect (blast wave with damage metric - ΔP_{bw}) depends on harmful potential of explosive cloud (m_{total}). If we would like to control intensity of blast wave, we shall control a harmful potential of explosive cloud. This is an important (from our viewpoint) statement for resolution of the abovementioned “100 ppm – 1000 ppm” paradox. During discussion of the safety level, which shall be provided by HDS, it will be reasonable to focus on those aspects of dominant hazardous effect, which govern the accident evolution and define damage scale. In our model case, it will certainly be a harmful potential of an explosive cloud, but not a detection

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[1] an impulse (peak overpressure times pulse duration) of blast wave is a more precise parameter, which governs the damage extent (see details in [11]).

limit for hydrogen sensor, whose position and relevance to characterize a real threat is questionable. Local concentrations of hydrogen-air mixture, which is 1/10 or 1/1000 of flammability limits, are certainly necessary but not a sufficient characteristics of harmful (in case of explosion - explosive) potential under consideration. However, today only the local concentrations are subjected to technical regulation – but not the harmful potential of hydrogen release. Detection limit (value of concentration of hydrogen, which will launch the alarm and emergency ventilation system) shall be derived from value of harmful potential of explosion cloud, but not vice versa.

After definition of the key (from safety performance analysis viewpoint) notions – harmful potential and performance metric of hazardous effect, a preliminary statement of safety performance goal for HDS can be proposed - HDS shall be designed with adequate capacity and sensitivity to detect formation of an explosive cloud with hydrogen total mass m_{total} , which is less than critical ones.

Up to now, the safety-related performance characteristics of dominant hazard and critically important assets were discussed. To complete a scope of Safety Performance Analysis, it is necessary to define in more details the safety-related performance characteristics of HDS.

2.5.2 HDS-related Metrics (Detector Impact Distance, Detection Limit, Leak Response Time)

Characterization of safety performance of HDS can be made within the following framework:

1. Overall volume of facility (in- or out-door) can be divided into separate *Protected* (by HSS) *Zones* (areas or units).

2. Each *Protected Zone* (safety zone) is served by one hydrogen detector only. Distance from centre of *Protected Zone* (where detector is allocated) to its boundary is a *Detector Impact Radius*.

3. Each detector is responsible for disclosure of any potential leaks of hydrogen, which can occur within a specific *Protected Zone* (of its responsibility). Leak disclosure shall be made within *Response-to-Leak Time*. Specific value of RtLT is defined according to Safety Criteria, accepted for a given HDS during facility-specific Risk Assessment. *Safety Criteria* shall relate a *Detection Limit* of a given detector with *Detector Impact Radius* on the base of critical value of harmful potential of explosive cloud and *Acceptable Level of Hazard* (for assets under protection), defined at facility-related Risk Assessment.

2.5.2 Safety Performance Goal for HDS

On the base of the metrics, defined earlier for hazard, asset and HDS, a safety performance goal can be proposed for our model hydrogen detection system:

SPG: HDS shall be designed and installed so as to detect a potential explosive cloud, which can appear during a design basis scenario of hydrogen leak inside of specific Protected Zone, at time moment, which permit to activate actuators of HSS (alarm, prevention, protection, mitigation systems) before a *Harmful Potential of Explosive Cloud* will pose a real threat for assets.

List of the design basis hydrogen leaks shall be defined during facility-specific Risk Assessment. A critical level of harmful potential (what is a real threat ?) shall be specified during Step 4. Rational Safety Criteria of Safety Performance Analysis (see below).

2.6 Step 4: Rational Safety Criteria (Tier 4: Relations between safety-related metrics)

In order to attain the safety performance goal, proposed to our model HDS, a set of quantitative criteria (relations between performance metric for hazard, assets and HDS) shall be defined explicitly. In order to avoid “traps” of prescriptive approach it is necessary to describe specific methods (or procedures), which will permit to demonstrate a conformance with the safety criteria.

Safety Criterion 1: Detector Impact Radius (Hazard level restriction)

SC1: *Harmful Potential of Explosive Cloud* for a time period, limited by *Response-to Leak Time* and *Detector Impact Radius*, is less then *Acceptable Level of Hazard* for assets under protections.

For an *Acceptable Level of Hazard* can be taken a critical (for damage of interior of building) value of blast wave overpressure $ALH \equiv \Delta P_{bw} = 5kPa$ as it is used now in Russian fire safety rules for buildings [12]. In order to meet the requirement of Safety Criterion 1, it is necessary to link a value of performance characteristics of hazardous effect (blast wave overpressure) at boundary of protected zone (most conservative case) with harmful potential of explosive cloud. If total mass of hydrogen inside of explosive cloud will be accepted as a metric of its harmful potential, then requested link can be written as

$$ALH \equiv \Delta P_{bw}\Big|_{critical} = 5kPa = P_{AICC}\Big|_{DIR} = 717(kPa) \cdot \frac{m_{total}(kg)}{V_{DIR}(m^3) \cdot \rho_{H_2}(kg/m^3)} \qquad (1)$$

$$protection\ \ level \equiv crit.value\ of\ \ damage\ metric = f(harmful\ \ potential, DHS\ metrics)$$

Right side of formula (1) is an analytical expression (see details in [12]) for pressure value of Adiabatic Isochoric Complete Combustion (AICC) of hydrogen with total mass m_{total} and density ρ_{H_2} within protected zone of volume V_{DIR}. Physical meaning of proposed Safety Criterion 1 is the following – DHS shall activate the actuators of HSS before Harmful Potential of Explosive Cloud attain a critical value. In this case, an expected value of blast wave overpressure at boundary of protected zone will be less then the critical ones (5 kPa). This safety criterion establishes a direct link between safety-related performance characteristics of hazard m_{total} and spatial performance characteristics of DHS – Detector Impact Radius (via V_{DIR}).

Safety Criterion 2: Minimal number of detectors

Minimal number of detectors, which is necessary to protect a whole volume V_{PF} of facility, will be defined as

$$N_{\min} = \frac{V_{PF}}{V_{DIR}} \qquad (2)$$

Explicit formulations of the other necessary safety criteria – for response time and detection limit – require a more detailed analysis of the two physico-chemical aspects – mechanisms of explosive cloud formation (shape, size) and kinetics features of evolution of concentration field within cloud.

Today, quantitative information on these aspects of explosive cloud behaviour is known only for two representative cases – 1) steady (or instant) free jet in open space [13] and 2) foreseeable leaks into confined space with compatible spatial scales [14].

Development of the performance-based requirements for other practically important cases – underground parking ("slab" geometry), car repair workshops ("canyon" or "channel" geometry) – requires an additional information (either experimental or computational) on the basic gas-dynamic patterns of explosive cloud formation and their quantitative spatial and temporal characteristics.

2.7 Step 5: Safety Factor (Tier 5: Treatment of uncertainties)

All data, used in Safety Performance Analysis, posses a certain degree of uncertainty. Uncertainties can be related with a large number of reasons – experimental data uncertainties, model uncertainties, limits in our understanding of hazardous phenomena, etc. In order to reach a guaranteed protection it is reasonable to introduce an appropriate safety factor.

For our model case, safety factor (SF) can be introduced in the following way: in all calculations of Safety Criteria during Safety Performance Analysis to use for harmful potential of explosive cloud a numerical value m_{total}/SF instead of m_{total}. It will guarantee, that during activation of the preventive or protective systems of HSS inside of protected zone a residual amount of flammable hydrogen-air mixture will be with harmful potential SF-times less that real hazard.

Selection and substantiation of a specific value of safety factor will require a more detailed analysis of uncertainties and quantification of their sources and propagation.

3.0 CONCLUSIONS

1. Prescriptive approach to formulation of the technical requirements for hydrogen safety system in general and for hydrogen detection system in particular possess a lot of shortcomings. Two representative examples, formulated as paradoxes, show that prescriptive approach is a real barrier for development of rational-based detection systems for hydrogen safety applications.

2. In order to overcome the problems, associated with prescriptive approach, a baseline five-tiered procedure for development of the performance-based, risk-informed technical requirement is proposed. The proposed approach is compatible with performance-based, risk-informed regulation systems under development worldwide for nuclear energy or civil construction applications.

3. Roles and interaction of the facility-specific Risk Assessment and the proposed Safety Performance Analysis during development of technical requirements for hydrogen detection systems are described.

4. Content and depth of the proposed Safety Performance Analysis can be extended with availability of new quantitative information on explosive clouds formation for different accident scenarios.

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