FOR A SUCCESSFUL ARRIVAL OF THE HYDROGEN ECONOMY IMPROVE NOW THE CONFIDENCE LEVEL OF RISK ASSESSMENTS!

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ABSTRACT

For large-scale distribution and use of energy carriers classified as hazardous material in many countries as a method to assist land use planning, to grant licenses, to design a safe installation and to operate it safely some form of risk analysis and assessment is applied. Despite many years of experience the methods have still their weaknesses even the most elaborated ones as e.g. shown by the large spread in results when different teams perform an analysis on a same plant as was done in EU projects. Because a fuel as hydrogen with its different properties will come new in the daily use of many people incidents may happen and risks will be discussed. HySafe and other groups take good preparatory action in this respect and work in the right direction as appears from various documents produced. However, already a superficial examination of the results so far tells that further cooperative work is indispensable. To avoid criticism, skepticism and frustration not only the positive findings should be described and general features of the methods but the community has also to give strong guidance with regard to the uncertainties. Scenario development appears to be very dependent on insight and experience of an individual analyst, leak and ignition probability may vary over a wide range of values, Computational Fluid Dynamics, or CFD models may lead to very different result. The Standard Benchmark Exercise Problems, SBEPs, are a good start but shall produce guidelines or recommendations for CFD use or even perhaps certification of models. Where feasible narrowing of possible details of scenarios to the more probable ones taking into account historical incident data and schematizing in bowties, more explicit use of confidence intervals on e.g. failure rates and ignition probability estimates will help. Further knowledge gaps should be defined.

1. INTRODUCTION

The perspectives for hydrogen as an energy carrier look great. The world feels a real need to reduce carbon dioxide emissions and to become less dependent on oil. There will be however a transition period of considerable duration, already because new investments require capital, much newly built coal, oil and natural gas facilities have to be written off, hydrogen fuel cells and cars have to be produced on large scale and find their way to the market and a new supply and distribution network has to be established.

Hydrogen is not toxic, but its eagerness to combine with oxygen is a concern. Safety records of hydrogen processing in present petrochemical industry however are good. On the other hand, introduction of production, storage, transportation and use on the widespread scale required to replace present hydrocarbons will undoubtedly bring incidents. The large scale introduction will unavoidably bring many people in touch with the technology and standards of engineering are not everywhere at the high level of present day petrochemical complexes. The energy carrier is needed not only in industrial concentrations but also in densely populated areas. So, in incidents people may become hurt. Experience shows that one large scale incident with fatalities can throw a new technology backwards for years. The psychological impact of risk, once shown somewhere to occur and witnessed by TV is difficult to erase. Old misunderstood stories like the one on the Hindenburg will be remembered by the media after an accident happened and will add to the fear. Such situation will be worsened if 'experts' contradict each other or express uncertainty.

Apart from preventing possible confusion after an accident, it already pays to have the methods and data ready to be able to estimate risks on the forehand and to perform studies comparing risks of hydrogen and present-day hydrocarbon fuels in large-scale processing, storage, distribution and use. Risk analysis in some form is giving guidance to improve operational safety by designing and installing preventive and protective measures where appropriate and economical. Even before realization of a project, in quite a number of countries it has become common practice in land use planning to carry out a risk assessment of the activities planned. In many places for licensing decision, competent authority will require an assessment of the risk of installations if depending on properties the quantity of hazardous material involved surpasses a certain threshold. Further developments are going toward a larger role of emergency response services in the planning stage. For planning sufficient means for self rescue and effective deployment of emergency response units a time resolved scenario analysis is becoming desirable. The foregoing is because a major change and certainly a large incident with impact in the public domain can have political repercussions.

All this may be an ‘open door’ and the HySafe community has wisely taken initiatives for many activities in drafting standards, educating and training people, performing risk studies and organizing these ICHS conferences. The recent reports on risk assessment methods (DNV Research & Innovation, 2008 [1]) and on re-fuelling station risk studies (IEA [2]) are certainly a good step, but not sufficient. The reasons will be explained below supported by various literature references.

2. RISK ANALYSIS: STRENGTHS AND WEAKNESSES IN GENERAL

In many countries but in particular in Europe because of the Seveso I and II Directives risk assessments of process installations and hazardous material stores have become common. Also, some countries brought activities with smaller quantities under the same regime. Established procedures have developed. Public safety acceptance criteria based on individual risk and societal risk are commonplace qualitatively but differ still considerably when it comes to quantitative figures. In general the methodology has widely found acceptance.

Risk analysis of process and storage installations can be considered as a system analysis focused on defining failure scenarios with release of hazardous material. Each release will have consequences while there will also be a certain probability. Hence the product of both provides for each scenario a risk figure. The release probability follows from failure rates of equipment resulting in spill and their estimation follows reliability engineering approach, the consequences are split into physical effects (severity) and damage to exposed ‘receptors’. For hydrogen the effects will be in first instance heat radiation, and overpressure and the receptors are people, structures and further environment with their own vulnerabilities and surface area densities. It requires many models and data. By domino effects in a plant area with involvement of other substances also toxic effects may occur. Strength of risk analysis is undoubtedly that an overall measure of potential hazard of an operation is derived. The aggregation of the risk of the different possible scenarios to one figure, to geographical risk contours or to a plot of the exceedance frequency of a number of fatalities as a function of that number provides overview and a basis for control of the situation. Weakness is the confusion arising by a large spread in results by different views on starting points, models, data as we shall see below.

Because of the important decisions to be based on risk analysis, the European Commission has funded twice a comparative risk assessment trial with teams from different countries, the first by 11 teams reported by Amendola et al., 1992 [3], the second, project ASSURANCE, with participation of 7 teams by Lauridsen et al., 2002 [4]. Both studies have been on an ammonia storage plant. The results of the first study in terms of individual risk figures for a given scenario scatter over 5 orders of magnitude. In the second study teams have been more experienced but also selection of scenarios has now been part of the exercise. Figures 1A and B show the spread in results of the latter while Table 1 borrowed from the Lauridsen report is providing an overview of the sources of scatter and uncertainty.

More or less in parallel efforts have been undertaken also funded in part by the EC to certify dispersion models according to a protocol prepared in the SMEDIS project (Duijm et al., 1997 - Scientific Model Evaluation of Dense Gas Dispersion Models [5]). In addition some years ago the

European Working Group on Land Use Planning announced it would take action with respect to scatter in failure rate data. However to date no concrete results are found.

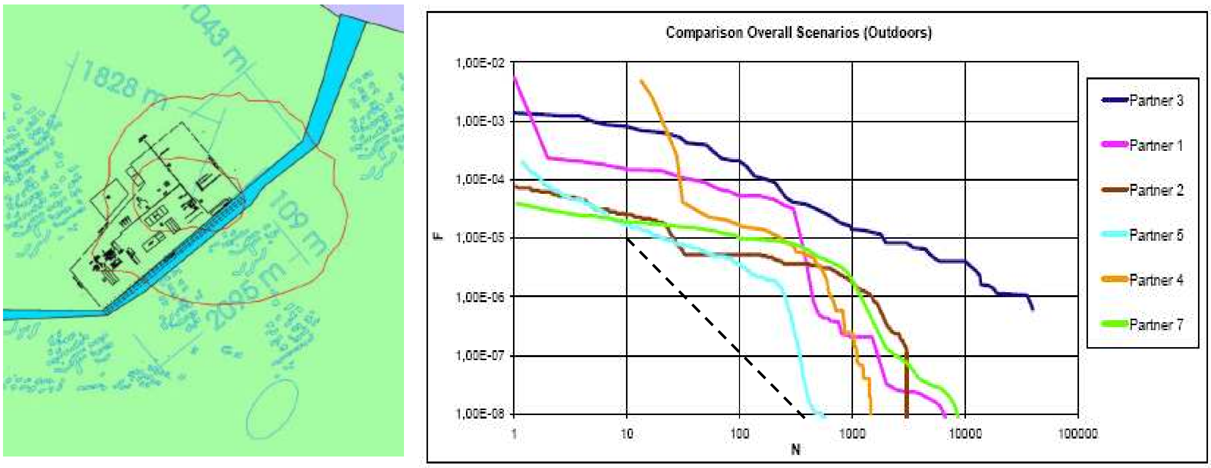

Figure 1a and b. Results of EU Benchmark exercise ASSURANCE 2002 by Lauridsen et al. [4]. *Left:* Maximum and minimum 10^{-5} /yr individual risk contour found in the analysis: because the large maximum contour lies for a major part outside the plant's premises crossing even inhabitation, this result will present a dilemma to decision makers. The minimum contour is limited to the plant premises except for a part overlapping the river. *Right:* Societal or group risk results on assumed population density expressed in F,-N curves differing by two orders of magnitude. Dutch societal risk acceptability guideline $F \leq 10^{-3} \times N^{-2}$ (F frequency /yr of N or more fatalities, $N \geq 10$) is represented by a dotted straight line piece; none of the curves meets the criterion. (At $N = 100$ the order is at the top partner 3, followed by partners 1, 4, 7, 2, 5).

Table 1. Qualitative assessment of the importance of various factors to the uncertainty in the calculated risk (the more stars the more important) in EU project ASSURANCE [4]

Uncertainty Factor	**Importance**
Differences in the qualitative analysis	**
Factors relating to frequency assessment:	
Frequency assessments of pipeline failures	***
Frequency assessments of loading arm failures	****
Frequency assessments of pressurized tank failures	****
Frequency assessments of cryogenic tank failures	***
Factors relating to consequence assessment:	
Definition of the scenario	*****
Modeling of release rate from long pipeline	***
Modeling of release rate from short pipeline	*
Release time (i.e. operator or shut-down system reaction time)	***
Choice of light, neutral or heavy gas model for dispersion	****
Differences in dispersion calculation codes	***
"Analyst conservatism" or judgment	***

From Table 1 it is clear that defining scenarios is the largest source of spread in final result. Yet it is essential to make a reliable overview of all different possibilities of an unwanted release first. Methods to obtain completeness with a guarantee are not existent. Experience in what can go wrong is a strong source of information. This experience is sometimes condensed in check-lists. Trying to obtain inspiration by reviewing accidents of which information can be retrieved from data bases is certainly a good possibility but is usually considered time consuming and not very fertile. Usually approaches such as What, if, FMEA Failure Mode and Effect Analysis) or even better HAZOP

(Hazard & Operability study) are followed. The latter on the basis of design drawings tracks systematically the course of the hazardous material through a system with a team questioning and brainstorming at each section what occurs at deviation of the normal course of the process. However, even when along this way mechanisms leading to possible releases are identified, then still the precise conditions of a release offer a large variety of possibilities [4]. What will be the release rate, will the containment fail catastrophically or not, which direction will point a jet, will it hit another component and become a spray etc.?

Dispersion, explosion and fire models are based on physics with a limited number of condition and state parameters and material properties. The models can be experimentally tested and validated in a simple geometrical situation (spherical, cylindrical or plane symmetry) in which results given conditions are identical, and shall be reasonably reproducible. Problem in application of these models usually is the complexity of the geographical environment with variable atmospheric conditions (wind, temperature distribution), terrain topology (hills, dykes, ditches), location, type and size of structures, vehicles, vegetation (rows of trees, shrubs) etc. It requires advanced Computational Fluid Dynamic models to get a realistic simulation of what can happen in practice. Given sufficient effort within bounds a reasonable picture of reality can be obtained of e.g. the distance to which a toxic or explosive concentration of gas can extend given a source, the overpressure and impulse an explosion of a gas cloud can generate or the radiation intensity, smoke cloud generated by a fire. Despite the 30 years or more of work on CFD-models there can be still considerable spread in outcomes and differences with field tests. For dispersion this may range over roughly a factor of 2 in concentration [7], for explosion models it will be a kind of same [8], whereas for fire models the situation is slightly better (e.g. [9]). If beside threshold values also a time development of the dispersion of cloud or an evolving fire is asked, simulation becomes again more difficult, but certainly not impossible, albeit that the models do not allow a fine time resolution. Concentration fluctuations on a certain point, for example, can usually not be produced.

In case of failure rates uncertainty is even more serious. There are many factors playing a role: design of the piping, vessel or other component, materials used, assembling, use of the equipment with fluctuations in pressure temperature and mechanical loading by vibration, pumping, corrosion, maintenance frequency, quality etc. Apart from the material and technical factors these are influenced by risk management quality which sets safety culture and determines human factor. On top of that, data in the literature in general just quote point values without specifying a confidence interval, although a certain range of hole size at a certain frequency may be given, as e.g. in the recent review paper by Spouge, 2005 [10]. Moreover a large variety of sources is found quoting quite different values.

For determining impact of effects on people, structures and the environment given heat radiation intensity time profile or an overpressure time history at a given location or a toxic concentration a limited number of data in the form of probit relations of the probability of being killed is available e.g. Green Book [9]. These relations are developed for normal, healthy persons and contain themselves still uncertainty. Data on sustaining injury and their effect on functioning of people are scarce or non-existent. Effect on structures relies again on models e.g. based on Finite Element Models.

Beside the full fledged risk analysis also more limited approaches are made. A very successful one is Layer of Protection Analysis, LOPA [12] which on the basis of a scenario of an initiating event in team sessions quantitatively the need, effectiveness and reliability of successive, independent protective layers (detection, decision, action e.g. shutdown, emergency measures) analyzes and forms a basis for application of IEC 61511 [13]. Yet even less detailed are semi-quantitative methods of risk ranking usually just in orders of magnitude.

As a conclusion it can be stated that risk analysis is in demand because it provides overview of a complex situation with many hazards on the basis of which assessment and decision making can occur. On the other hand there is quite a reservation to make with respect to the accuracy of the results. Risk estimates contain considerable uncertainty by lack of knowledge, limited computer time and randomness in data, although this is not shown by the figures. Usually only point values are given. Some are inclined to take the conservative side; others have an interest to intrude into the area under risk just up to the allowed limit. The variability in outcomes can lead to much debate in case of land use planning or licensing. Disagreement in model outcomes will cause friction among planners from both private and public parties with different interests. This is providing fertile ground for lawyers, while competent authorities under pressure will be uncertain and will try to delay decision or eliminate the risk source and with that delay or eliminate the activity. Therefore improvements and clarity in the community are needed. The above did not include differences between various countries in risk evaluation and acceptance criteria.

3 WISH-LIST FOR HYDROGEN RISK ANALYSIS

HySafe report by DNV *Survey of Hydrogen Risk Assessment methods*, 2008 [1] describes methods, discusses the above mentioned problems in broad sense and makes a number of suggestions where further work shall focus on. Further an IEA report composed by Tchouvelev [2] provides some example QRAs on re-fuelling stations. However a more rigid format and a program listing problems, indicating the way to solution and clearly proposing action, will be more convincing and will show the way forward. Below various aspects will be addressed. We shall start with scenario definition because scenarios constitute the building stones of risk analysis.

Scenarios

1). A list of representative sample installations both static and mobile will be helpful. Realistic standard scenarios can be based on such installations as e.g. hydrogen production plant (various types?); hydrogen main storage and distribution centre close to a city; hydrogen tank car involved in collision in a tunnel; hydrogen distribution pipeline; compressed gas/liquefied gas hydrogen fuelling station with and without LPG and other fuels; hydrogen storage and fuel cell room in a dwelling.

2). Hydrogen incident database with its Hydrogen Incident reporting Tool [14] will be a source of inspiration for scenarios, but historical data are not are not sufficient even if these are abstracted from the case and written in a hazard-barrier-target format because history for hydrogen in these applications is too short. As already mentioned also systematic HAZOP, FMEA shall be applied. Information so gained will be used in point 3).

3). For each of these installations bowtie diagrams (fault tree-critical event-event tree) should be built including the preventive and protective safety systems (barriers). In principle each pathway from a basic event of the fault tree to a branch endpoint in the event tree forms a scenario. The way it is done in EU project ARAMIS [15, 16] can be followed. ARAMIS has been designed to get a better, more reproducible handle on scenario development. From the various scenarios obtained a selection has to be made of those which on the basis of estimated consequences and frequencies surpass a certain threshold. This can be performed with the aid of a semi-quantitative risk matrix. The selected ones are called in ARAMIS language reference accident scenarios or RAS. From the selected ones the severity of effects will be elaborated in more depth.

4). If the above sketched track is followed a provisional list of standard scenarios can be drawn up which contain small but crucial details and which structure the thinking. In fact from the papers presented in the 1st and 2nd ICHS conferences already quite a few scenarios come forward. For example the inside space dispersion and explosion type of problems is worth studying, also jet impinging on a wall outside because a wall near a hydrogen store will be frequently used as protection, and the impinging jet will more rapidly mix with air, e.g. [17]. Another scenario which should be sorted out is a large compressed hydrogen pressure vessel becoming pinched through. If the jet ignites immediately it will be a fire problem. In case it not immediately ignites but delayed, explosion may occur and the conditions at which transition to detonation becomes probable are worth finding out (size of tank, pressure, degree of confinement). Finally there will be the liquefied hydrogen release problems.

Frequency of a leak

The above mentioned HySafe report [1] pays considerable attention to the fact that hydrogen leaks cannot be taken similar to hydrocarbon ones. In usual risk studies three release levels are taken: relatively small and continuous, emptying a vessel in 10 minutes and a catastrophic failure, each with its own frequency. The IEA report on QRA of re-fuelling stations [2] presents the HyTrec study, which specifies frequencies for two leak hole sizes: 1 and 10 mm borrowed from the UK HSE leak frequency database, which is mostly for hydrocarbon leaks. LaChance, 2007 [18] distinguishes three leak rates for hydrogen but takes frequencies partly from the same hydrocarbon sources [10].

HYPER, 2008 [19] emphasizes that hydrogen due to its low viscosity is much more prone to leakages from piping connections than hydrocarbons. In particular in confined space this will present a hazard, because a leaking hydrogen connection near the floor will fill up a space from the ceiling downward with an explosive mixture as e.g. shown by Lowesmith et al., 2007 [20]. Detection, ventilation and recombination can form protective barrier systems, but prevention of the leakage remains first priority. The above stresses too the uncertainty when it comes to data on leak frequencies as hydrocarbon experience cannot be trusted. When special hydrogen proof connections are being introduced and leak tests build up experience it is strongly recommended not only to report mean frequency values but by applying classical statistics (chi-squared test) also the two-sided confidence limits. Unfortunately, there is little that can be done here in simulation; all knowledge on leak frequency and magnitude depends on empirically obtained information. Finally, barriers get much more value if their reliability can be established and even more so if standard IEC 61511 [13] SIL levels can be certified.

Probability of ignition

Given a leak and hence a critical event, next question to be answered for an event tree is the probability of ignition. Ignition shall be distinguished in immediate and delayed ignition because of the different consequence this may have. The probability will depend on the environment which can have many different features (open, semi-open, confined but ventilated, confined). A special feature of hydrogen is that in case of a very high pressure store even a small leak may ignite spontaneously because the hydrogen jet from the leak is causing a shock in the surrounding air which heats up the gas and mixes oxygen with hydrogen in its wake. Moreover, compared to hydrocarbons the ignition energy of hydrogen is even lower and so the probability of ignition is estimated higher than of hydrocarbons, although most ignition sources provide much more energy than is required even for near explosion limit mixtures. This all makes it not easy to specify values. The IEA report [2] examines in the Discussion inputs on leak sizes, frequencies and results in terms of safe distances (to 2 vol.% H_2) of three studies: HyTrec by DNV in Norway, one by Sandia Nat'l Lab, and the Canadian study on CNG and compressed hydrogen. It noticed large differences of more than an order of magnitude in both in- and outputs. Even more the IEA report on Knowledge Gaps [21] explains clearly the differences between hydrogen and hydrocarbons in this respect because of cloud size and explosion limits and less because of ignition energy, stresses the lack of hydrogen historical data and recommends an estimation approach. Since this figure together with the leak frequency determines much the overall incident frequency it deserves much research attention. An approach may be to take historical events for a particular hydrocarbon in a given scenario, model with CFD as much as is possible the situation and investigate why the ignition probability is as reported and transpose then the whole to a case with hydrogen. Later evidence can then update the probability figure by applying Bayesian update. A special case is spontaneous ignition of a jet. Reactive CFD models will be able to help out. Also DNV report [1] pays much attention to the ignition probability aspect and states in a conclusion that HySafe WP9 will propose a best practice for answering the question. Hopefully then WP9 will also quantify uncertainty by specifying confidence intervals.

Probability of fire or explosion

Given ignition next question is what type of combustion will take place: again a difficult question to answer. A jet in the open will result in a cloud which is completely different also with respect to confinement from one of a spill of cryogenic liquid hydrogen of from a slow leak in a room. Also a cloud originating from a similar type of source can differ in its effects at ignition depending on scale of release, presence of congestion for a flame, power of ignition source, degree of mixing with air etc. Effects can range from jet fire, flash fire, deflagration with moderate blast, rapid accelerating flame with medium blast and detonation. So, it will be very difficult to give generally applicable probability figures. Each situation has to be judged on its own and the most evident way to proceed is doing a CFD simulation and producing a deterministic answer. This way in principle the extent of dispersion, global concentration gradients (less the spatial and temporal higher frequency fluctuations), and once the cloud ignites, flame propagation can be simulated and blast derived. By varying details in geometry of release, location, time after release and strength of ignition, wind direction and such like a range of answers can be derived and probability values can be assigned on the basis of likelihood of situations.

Computational Fluid Dynamics models

To avoid confusion and to obtain a quality aura CFD models with a “stamp” are needed as the SMEDIS protocol [3] had as objective. For reliable and reproducible answers programs must be transparent, verifiable, and robust. To that end codes have to be examined. Reliability of software forms a sector of science in itself. The requirements are simple, but not easily satisfied. ‘Transparent’ means it shall be more than just a black-box. Insight in model assumptions and limitations, which inputs and equations are used at each step and other information shall be easily obtained. ‘Verifiable’ means sources of input values (references) shall be traceable, as also the choices that were made and the reasons for those choices. ‘Robustness’ has to do with reproducibility. The outcome shall not be dependent on the team performing the calculation. The SMEDIS protocol distinguishes a number of steps of which the first is: assessment of the model with respect to the physics describing the phenomena including terrain features – slopes, valleys - and obstacles, and aerosols when relevant. Then verification of translation into algorithms in the software code occurs, and finally validation of the results against test data sets tested on first comparisons has to be performed. Hanna et al. [7] developed statistical performance measures. Variability in outcomes makes application of the requirements even more compelling.

In 1st and 2nd ICHS conferences four inter-comparison studies have been reported of which results were quite encouraging. These Standard Benchmarks Exercise Problems carried out by 6 - 14 teams depending on the type of test with different models to predict with CFD the outcome of dispersion tests in confined space (SBEP V1 subsonic vertical release in a vessel [22], SBEP V3 subsonic vertical release in a garage [23], SBEP V4 horizontal under-expanded jet, SBEP V5 subsonic horizontal jet release in a multi-compartment room [24]) or a deflagration blast overpressure in the open (SBEP V2 deflagration of H_2-air [25]) did show in repeated trials a convergence of results. However although good progress was made further research should result in a limited number of models with some sort of certified trustworthiness. The use of a SMEDIS type protocol approach seems the way to go.

Risk presentation

Both from a public and private point of view hydrogen risks will be judged against the benefits. In the *public domain* risk is usually expressed as the probability of being killed when exposed in unprotected standing position at a certain location with respect to the risk source during one year: individual risk. Points of the same value can be presented as a contour. A risk source can produce different scenarios with different contours. A plant area can contain different risk sources. The contours from the Lauridsen report [4] shown in Figure 1a are of the worst scenario. All scenario information can be accumulated in a second, from the point of view of aversion more important measure, namely the frequency $f(N)$ of getting exactly N fatalities per year in the area as a function of the number N. It can be calculated when all individual risk points of various scenarios are combined with a population density chart and summed. Integration over N yields a third measure: Expected Value of lives lost per year or Probability of Loss of Life, PLL [25]. A third, even more renowned measure is societal or group risk which is the frequency of exceedance, $F(\geq N)$ of having N or more fatalities in the area per year. This measure is derived by summing $f(N)$ starting from the scenario with the largest N-value. The graphs in Figure 1b show examples of societal risk plots. However, beside the wish to express risk from a source in one figure, there is also the requirement for spatial resolution applying Geographical Information System, GIS. Risk contours can be depicted on a map but these do not reflect exposure and hence resulting fatalities. TNO and RIVM in the Netherlands recently developed a method to show *F*,-*N* information on a map as shown in Figure 2a and b. The hydrogen community can benefit from using this new method.

Figure 2a and b. Representation of societal risk as developed by TNO and RIVM in the Netherlands, not as the usual *F*,-*N* curve of all possible scenarios a risk source or cluster of sources can produce (*F* = Frequency of exceedance of *N* fatalities versus the number *N*), but as a location-specific value in a 50×50 m^2 area indicated by color (or here grayscale). Population density data are embedded in each cell. A *F*,-*N* curve is calculated for each cell taking into account only risk sources that affect the cell but fatalities due to it in the whole area, **left**, and **right** of only the fatalities in the 50 m square cell. Subsequently, the position of the *F*,-*N* curve versus the norm is translated into color e.g. figure **left:** (red) – dark area middle top with dot **-** = above the norm; orange **-** not present **-** a factor 10 below, yellow – outlined diagonally dashed area center left – a factor 100 below, light green – periphery lightly vertically dashed **-** safe, and green – periphery dark **-** very safe). The **right** figure serves to find more easily the hazard 'hot spots'. This example concerns a railway shift yard and a stationary risk source [24]. The small circles represent risk contours around a static risk source.

For a *business case* other measures matter such as a *F*,-€ curve, which is analogue to *F*,-*N* but with monetized losses instead of fatalities; another one is Expected Annual Loss, *EAL* which is the loss at a certain scenario multiplied with the expected frequency of that scenario. *EAL* can be applied in answering the question how safe is safe enough when considering an additional protection layer. In fact, the contribution of each Independent Protection Layer (IPL, preventive barrier or escalation control) can be expressed in risk reduction, hence in saving *EAL* but also in Cost of Ownership including investment, maintenance, cost of false alarms and spurious trips. For a set of scenarios possible for an installation an *EAL* spectrum can be shown which will indicate clearly the worst scenarios with respect to losses. Value at Risk, a measure quite popular in financial risk analysis, is yet another way to characterize risk of an installation. It is the maximum loss to be expected at e.g. 99% confidence level.

The measures form together a system of metrics. Few examples have been seen yet in which these measures have been elaborated well.

Uncertainties

Uncertainties are either caused by lack of knowledge of effect and damage mechanisms and possible scenarios leading to incompleteness and wrong use of models, or by inaccurate and unreliable data. As we have seen in EU project ASSURANCE [4] choice of details in scenarios may lead to a large spread in outcomes of a multi-team exercise. From probability point of view no objection is seen to average the logarithms of results and to construct a mean *F,-N* curve unless one of the teams is given a higher trustworthiness than others. In that case the values can first be weighted. Beside a mean, a value for variance can be calculated and applied as a safety factor. This will certainly increase confidence level.

Evaluation/appreciation of risk

A Risk Matrix consisting of a plot of logarithm of scenario consequences versus logarithm of their frequencies is in risk analysis rather common. Also *F,-N* plots are logarithmic in both variables. Many people have no feel though for the difference between e.g. 10^{-5} and 10^{-6} or 10^{5} and 10^{6}, but know better the difference between 5 and 6. Jaynes [27] in his standard work on Probability Theory quotes repeatedly the law of Weber-Fechner which says that intuitive human sensations tend to be logarithmic functions of the stimulus. The logarithm can best be expressed in decibels (10*10-based logarithm; in sound this was a natural choice for expressing signal strength). Taking this into account it turns out that comparing risk figures on the basis of their logarithms is justified. Some LOPA teams focusing on acceptable frequency for a catastrophic event already years ago took a value of 7 as a target for sufficient layers to protect against potentially the highest risk. In other words with the layers credit points have to be accumulated to achieve a target value of 7 meaning the event frequency is lowered till 10^{-7} per year. Also differences shall then be judged on their logarithmic values.

Decision making

Decision making is not an absolute process. There is always weighing involved of risks against benefits, although in land use planning, LUP and licensing of plant with sometimes huge consequences for contracts legal certainty is important and one tries to be as objective as possible. In some countries therefore decision is made on the basis of a legal risk criterion, in others on safe distance e.g. a 1% lethality borderline. In again other countries one has opted for more explicitly weighing cost versus benefit by considering worst case scenarios, installing protections and awaiting public acceptance. QRA and a risk criterion enable optimum use of space by taking account directional effects of the risk consequences and trading off severity against frequency while accepting a certain threat for workers and inhabitants. However, even in the Netherlands where risk analysis for licensing as a method (SAFETI.nl) including the data to be used is standardized, the analysts trained and the individual risk criterion is rigidly maintained, a weighing process is left open for societal risk. Here, the criterion is seen as guidance. According to the newest regulation emergency responders (regional fire brigade) have to give advice to competent authority on the basis of the information collected in a QRA. However various other aspects will come into the picture than just numbers of fatalities. It is also selection of a representative scenario from the many in a QRA, level of preparation for getting such disaster under control, self-rescue possibilities and evacuation, number of injured persons and nature/ seriousness of injuries, emergency vehicles access routes, possible measures of mitigation of effects at the risk source, and estimating remaining risk to be weighed by the responsible mayor/council. Fire brigades are struggling with these new tasks. When dealing with hydrogen refuelling stations it would be good to prepare for such analysis and have suggestions for scenarios ready, in particular when it concerns mixed stations with e.g. LPG.

For a business case one could do a straightforward cost–benefit analysis, trade-off insurance premium and expected annual loss against investment and maintenance in more protection versus residual risk and determine the optimum. However, occupational fatalities and injuries have to be weighed. Willingness to pay for preventing a fatality and injury is also subjective. In economic risk analysis one uses utility functions (utility between 0 and 1). In such function a decision maker or body of decision making is ‘calibrated’ by determining his/their indifference of obtaining a certain sum now instead of a potentially larger uncertain profit in the future. Such curve has a concave, exponential shape. It remains subjective but one could formalize the decision process to determine such a curve in the negative as a disutility curve for risk. In comparison with hydrocarbon fuels prepared cases for convincing a future owner of a station or other hydrogen installation could help to make the conversion to hydrogen easier.

4. CONCLUSION OF WHAT CAN BE DONE TO ASSIST LARGE SCALE CONVERSION TO HYDROGEN

For a successful introduction of hydrogen it is crucial to control the hazards and to be able to determine the risks at a acceptable level of confidence. Reports as the recent D113 [28] are important to gain trust. However, clear and transparent measures of risk together forming a system of risk metrics in comparison with hydrocarbon values can be rather convincing. This has still to be worked out.

Uncertainty can strongly be reduced by agreeing on a number of standard scenarios, use of validated consequence models which are certified on the basis of a protocol, and expressing spread of data such as on failure rates in confidence intervals. The first two ICHS conferences have shown a rapid improvement of consequence models and knowledge about phenomena. It is now the time to start agreeing on unavoidable spread in extent of dispersion after a leak, ensuing explosion blast strength and fire intensities, and also on expected failure rates and their variance of vessels, piping, connections etc. The latter require for its uncertainty margins also taking account of quality of installation, reliability of maintenance with its human factor, ageing of equipment etc. So that when risk gets quantified for a particular site the experts shall not be publicly divided over the issues and will be able to indicate the range in which the risk value falls. Decision making under uncertainty coping with variance deserves special attention. How far should one stay at the safe side while knowing the extent results can vary? A suggestion for a safety factor can be made. Decision making for public safety and for business strategy is different but both can be facilitated by having examples ready and comparison with traditional fuels at hand.

Although the efforts up to now have been very useful, the work is by far not completed. Why not organising some working groups to tackle the various aspects and to contribute to a final risk review?

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