QUANTITATIVE RISK ANALYSIS OF GASEOUS HYDROGEN STORAGE UNIT

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ABSTRACT

A quantitative risk analysis to a central pressurized storage tank for gaseous hydrogen has been performed to attend requirements of licensing procedures established by the State Environment Agency of São Paulo State, Brazil. Gaseous hydrogen is used to feed the reactor to promote hydrogenation at the surfactant unit. HAZOP was the hazard identification technique selected. System components failures were defined by event and fault tree analysis. Quantitative risk analysis was complied to define the acceptability concepts on societal and individual risks required by the State Environmental Agency to approve the installation operation license. Acceptable levels to public society from the analysis were reached. Safety recommendations to the gaseous hydrogen central were proposed to assure minimization of risk to the near-by community, operators, environment and property.

INTRODUCTION

Hydrogen is a very important gas as source of energy. The wide use of hydrogen favors the technology development and the improvements on safety aspects. Hydrogen storage can be performed by mobile or stationary systems. Today, hydrogen is being used as vehicular source of energy in countries as USA, Germany and Canada. The general public access in vehicular systems, to the hydrogen turns to be a problem. Hydrogen flame is invisible. It is known by the scientific community that hydrogen release can form a flammable/explosion cloud in air mixtures. The lower and upper flammable limits for hydrogen in air are 4% and 75%, respectively. Hydrogen is a lower density gas compared to air and has a buoyancy velocity in air of 1.2 to 1.9 m/s at normal conditions of pressure and temperature. BREWER [1] refers to the explosion limits to be between 18.3% and 59% v/v but, other authors refer to as low as 9% to the lower explosion limit. The theoretical hydrogen explosion energy release is equivalent to 2.02 kg TNT/Nm3. The minimal ignition energy is 0.02 mJ. At ambient pressure and temperature, hydrogen heats up while expanding, presenting an inverse phenomena than the majority of gases. Hydrogen ignition can result in deflagration or detonation, depending on the gas concentration, the cloud size and the local system geometry. This risk in unconfined hydrogen installations is much lower than in confined space installations. Hydrogen is normally stored in ASME designed pressurized vessels or steel bottles or cylinders. Hydrogen storage systems can store hydrogen as compressed gas, cryogenic liquid or hydrocarbon reformed. These systems normally operate at ambient temperatures with a working pressure between 150 to 400 bar.
In Brazil, any type of industrial installations requires Federal or State Environment Agency license. To apply to the plant operating license, the industry has to prepare a quantitative risk analysis (QRA). Normally, the industry contracts a third party consultant for the sake of job transparency and expertise. QRA was based on State Environment Agency norm [2] to evaluate the societal and individual risks. F-N curves were adopted to estimate the societal risk and the tolerable risk limits established by the Agency were 1×10^{-5} /year as the maximum tolerable individual risk and less than 1×10^{-6} /year for the acceptable risk. The individual risk calculation was based on the criterion proposed by the Dutch TNO in the Purple Book [3]. Results confirmed the risk social risk was negligible and individual risk was $< 1 \times 10^{-6}$ /year at the plant fence for the potential events of UVCE and or Fireball formed after gaseous hydrogen release from the catastrophic rupture of the hydrogen storage tank.

HAZARD QUANTIFICATION

HAZOP was used to hazard identification in the hydrogen storage plant. To continue the risk analysis, it was selected storage tank rupture as the worst possible event identified to QRA, according to the event severity classification. To define the probable events that contribute to loss containment of gaseous hydrogen, the fault tree analysis (FTA) was used. FTA was tied-in to the event tree analysis (ETA) to determine the ignition probabilities. With this methodology, it was possible to obtain the gaseous hydrogen release occurrence frequency. ETA shows graphically the sequence of accidents starting from an initiating event [5, 6] and includes the responses of safety systems and operators to the initiating events. ETA requires a knowledge of the potential initiating failures or system upsets (that can potentially cause a non desired event), as well as the safety system operation or the emergency procedures, which can potentially mitigate the consequences of an initiating event. ETA depends of the initiating events complexity and safety systems. Delphi technique is sometimes used to solve ETA's [5]. FTA was built on possible events that can cause gaseous hydrogen loss of containment at the storage tank. The protection barriers were associated to the results and the QRA evaluation performed. Fig. 1 shows the tie-in trees for the gaseous hydrogen loss of containment. The failure rates used in Fig. 1 were obtained from data banks [7, 8], TISEC and the Hydrogen Research Institute [9]. The resulted frequency occurrence to UVCE was 1.0 x 10^{-7}/year and for the fireball was 1.0 x 10^{-6}/year.

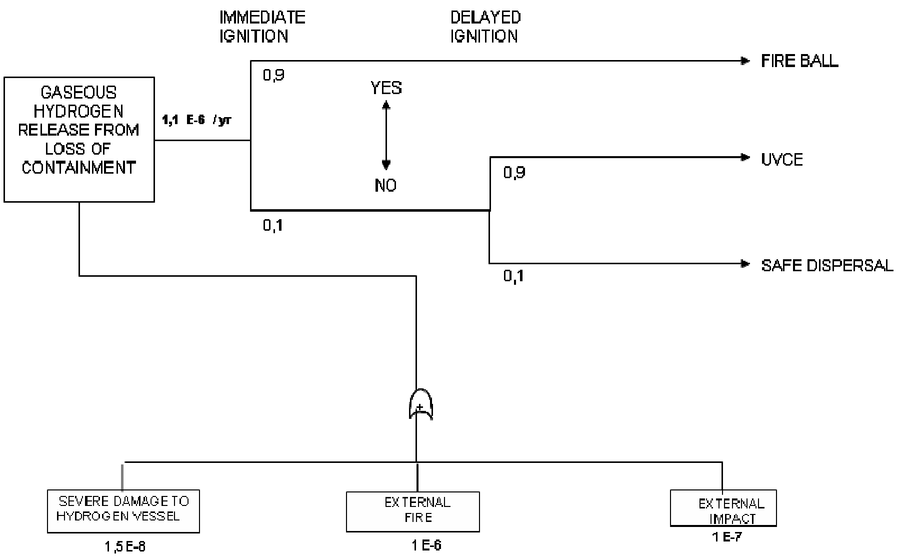

Figure 1. Fault and event trees tie-in to loss of containment of gaseous hydrogen

RISK EVALUATION

The Societal Risk is the population risk present at the incident area and indicates the catastrophic damage level. Normally, it is presented as F x N diagrams on which likelihood-consequence curves are compared with criterion lines for assessing tolerability, where: F is the accumulated frequency and N, the fatality number. Fatality probability associated to the physical effects and public present during working hours at daylight and night at the incident occurrence was determined. Physical effects considered in the risk evaluation are UVCE (unconfined vapor cloud explosion) and Fireball. Near-by the hydrogen storage area, there is petrochemical plant. At this plant there are 105 workers during the administrative period and 25 workers at night period.

TNO [3] recommends the use of protection factors for thermal flux and overpressure incident to the workers that depends the existing local protection. The values for the probability of fatality at the region at risk were based on the Environmental Agency norm [2] and shown in Fig. 2. The protection factors used to estimate the societal risk are presented in Tab. 1. The societal and individual risks evaluation worksheet was prepared by NUNES and TERUYA [4]. The societal risk results are presented in Tab. 2.

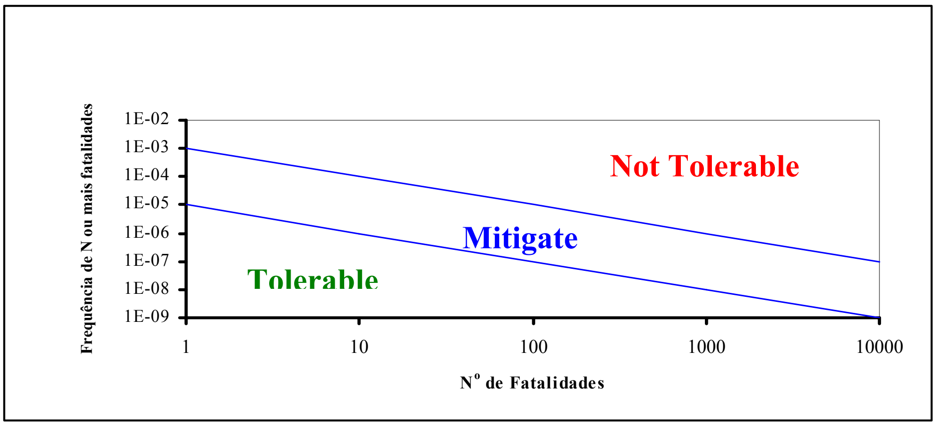

Figure 2. F x N Diagram for Societal Risk

Table 1. Protection Factors and the Criterion of Probability of Fatality [2, 3]

Physical Effects	Protection Factor
Thermal Flux	-
< 35 kW/m^2 (at day period)	0.93
< 35 kW/m^2 (at night period)	0.99
>35 kW/m^2	0
Overpressure	-
0.3 – 0.1 bar	0.90 (note 2)
> 0.3 bar	0
Probability of Fatality	
75% for exposed personnel and the probability of fatality curve of 50%	-
25% for exposed personnel and the probability of fatality curve of 50%	-
100% for the exposed personnel inside the gas cloud up to the curve limit (LFL= 4%)	-

Notes: (1) 100% of fatality to the events of UVCE and fireball, for both working periods and wind 360º.

(2) TNO recommends the protection factor of 0.90 but, the State Agency considers no protection factor to explosion effects.

Table 2. Societal Risk Results

Incident Event	Accumulate Frequency (F)	Fatalities (N)
Loss of Containment of gaseous hydrogen	1.15 x 10^{-7} /yr	10

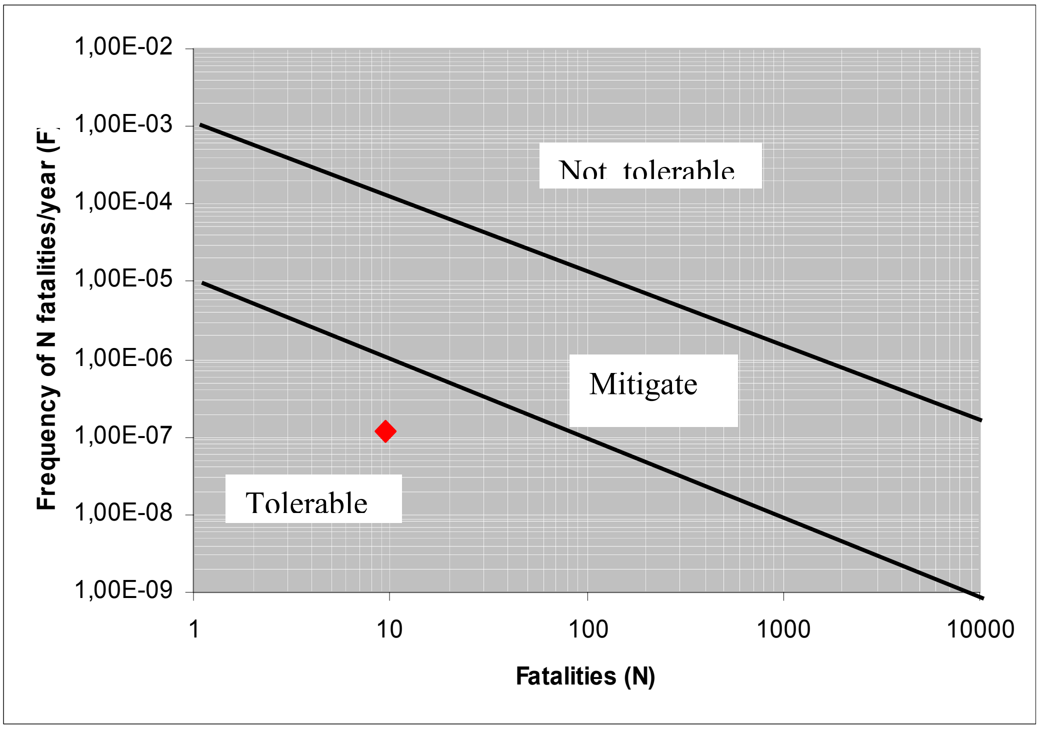

Figure 3. Societal Risk Diagram

Individual risk is the incremental probability of fatality that the hazard imposes on some particular person.
It was defined a matrix with cells of 25 x 25 meters to the individual risk calculation to a maximum distance from the incident center of 300 meters. The individual risk was calculated to each cell separately with Eq. (1), considering cell event frequency, ignition and fatality probabilities and wind frequency. The iso-risk curves are designed on the plant aerial photo, with frequencies of 10^{-4} /yr up to 10^{-8} /yr. The iso-risk curve was at the frequency level of 1 x 10^{-6} /yr as shown in Fig. 4.

$$Individual\ Risk = \sum \left[frequency \times P_{class} \times P_{wind\ direction} \times P_{ignition} \times P_{fatalities} \right] \quad (1)$$

where P - probability.

CONCLUSION

The resulting events from the loss of containment of the gaseous hydrogen storage tank are jet fire, flash fire, UVCE, fireball and safe dispersion. QRA showed that UVCE and fireball are the most impacting ones to the near-by industrial plants, besides its lower likelihood occurrence. The consequences and people vulnerability concerning thermal flux remain within the storage unit premises and will not impact the near-by industrial plants. The F x N diagram showed that the calculated societal risk for the event of gaseous hydrogen loss of containment, resulted in a likelihood of 1.15 x 10^{-7} /yr and presented a possible fatality of ten persons at the neighboring plant, has remained in the tolerable region. The designed iso-risk curve for the studied event presented a likelihood level of 1 x 10^{-6} /yr, that is considered tolerable according to the acceptability criterion of the State Environmental Agency.

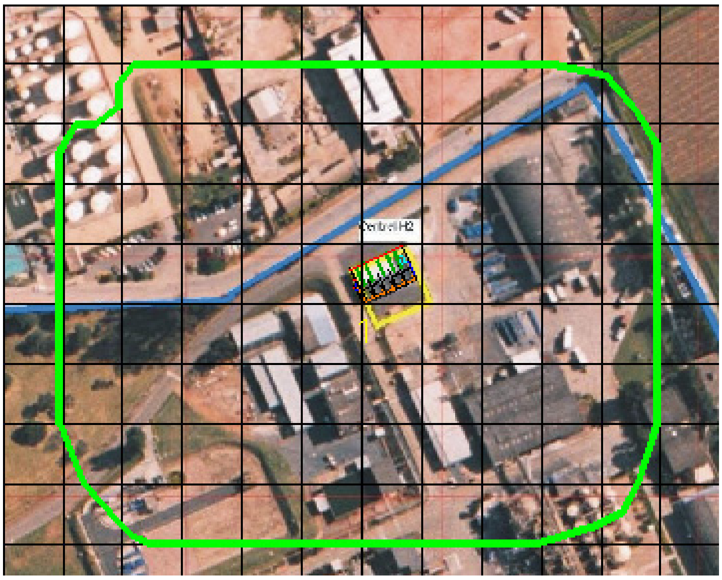

Figure 4. Iso-risk Curve of the Calculated Individual Risk

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