SAFETY DISTANCES: COMPARISON OF THE METODOLOGIES FOR THEIR DETERMINATION

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ABSTRACT

In this paper, a study on the comparison between the different methodologies for the determination of the safety distances proposed by Standard Organizations and national Regulations is presented. The application of the risk-informed approach is one of the methodologies used for the determination of safety distances together with the risk-based approach. One of the main differences between the various methodologies is the risk criterion chosen. In fact a critical point is which level of risk should be used and then which are the harm events that must be considered. The harm distances are evaluated for a specified leak diameter that is a consequence of some parameters used in the various methodologies. The values of the safety distances proposed by Standard Organizations and national Regulations are a demonstration of the different approaches of the various methodologies, especially in the choice of the leak diameter considered.

1.0 INTRODUCTION

In order to reduce the consequences of a possible accident that can take place in a plant of hydrogen in a storage, in a pipeline or in a hydrogen refuelling station, it is important to assure suitable distances between the source of the risk and the targets. These distances are generically called safety distances or separation distances in the case of NFPA. To have a clear understanding of the concept of safety distance, it is necessary to give a specific definition as the one used by EIGA IGC Doc 75/07/E [1]: "the safety distance is the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident".

In the same way, in the NFPA codes, the separation distance is used for reducing the risk of incident escalation and for avoiding the increase of the consequences. The ultimate standards that consider new safety distances for hydrogen applications are the ISO/DIS 20100 [2], specific for fuelling stations, and the NFPA2 "Hydrogen Technical Code" [3]. The latter introduces a new methodology, the risk-informed process. The definition of "risk-informed" is presented in the Sandia's report [4]: "this approach is opposed to a risk-based process because utilizes risk insights obtained from quantitative risk assessments (QRAs) combined with other considerations like the results of deterministic analyses of selected accidents scenarios, the frequency of leakage events at hydrogen facilities, and the use of safety margins to account for uncertainties, to establish code requirements".

The same approach is used in the ISO/DIS 20100 [2] for the determination of the safety distances. On this point there is not a lot of clarity: in the paper [5] the ISO's approach is defined as risk based but the procedure for the determination of the safety distances is analogous to the risk informed process. In the next paragraphs the two methodologies for the determination of the safety distances, used by ISO and NFPA will be compared.

In Italy the lack of a Regulation that contemplates the distribution and the transport of hydrogen in pipelines has created the basis for a Draft of technical rules in this field [6]. One of the considered safety elements inside the Draft are the safety distances, that have been determined through the experimental tests [7], with the purpose to obtain public data that can be used in a future Regulation.

The Italian Regulation for hydrogen filling station [8] is the only one that considers the application of hydrogen safety distances. In the next paragraph these distances will be compared with the above exposed of the draft ISO/CD 20100 [2] regarding the same application, while the experimental safety distances of the Italian Draft on technical rules on distribution and transport of hydrogen will be compared with the separation distances of the NFPA2 [3].

2.0 DETERMINATION OF SEPARATION DISTANCES BY NFPA

A risk-informed approach for selecting the leak diameters was utilized to establish the separation distances in NFPA2 [3] and NFPA55 [9]. The risk-informed approach included three considerations: the frequency of leakage for typical hydrogen facilities, the cumulative frequency of system leakage, and the risk from leakage events for the example facilities. All three considerations are dependent upon the choice of example facilities and hydrogen-specific component leakage frequencies.

The NFPA's approach for selecting the distances utilizes harm criteria evaluated from deterministic analyses of hydrogen jets based on a selected leak diameter. The leak diameter is selected based on the expected frequency of different size leaks in typical gaseous hydrogen storage facilities and the associated risk from all leaks. Hydrogen-specific component leak frequencies were generated as a function of leak size for several hydrogen components using Bayesian analysis. When data are limited, such as for hydrogen facilities, Bayesian techniques are the most proper in comparison to the traditional statistic analysis because they evaluate the probability of a hypothesis, based on some prior probability (values from the compressed gas, chemical processing, hydrocarbon industry, and nuclear sources), which is then updated in the light of new relevant data (hydrogen-specific failure data). The cumulative probability for different leak sizes was then calculated to determine which range of leaks represents the most likely leak sizes. The risk resulting from different leaks size was also evaluated for four standard gas storage configurations.

Harm Criteria	Harm Distance (Leak Area)			
	>0.10 to 1.72 MPa (>15 to 250 psig)	>1.72 to 20.68 MPa (>250 to 3000 psig)	>20.68 to 51.71 MPa (>3000 to 7500 psig)	>51.71 to 103.43 MPa (>7500 to 15000 psig)
Un-ignited jet concentration – 4% mole fraction of hydrogen	31.2 m (20% Area) 22.1 m (10% Area) 15.7 m (5% Area) 12.1 m (3% Area) 7.0 m (1% Area)	36.1m (20% Area) 25.6 m (10%Area) 18.1 m (5% Area) 14.0 m (3% Area) 8.1 m (1% Area)	22.6 m (20% Area) 16.0 m (10% Area) 11.3 m (5% Area) 8.8m (3% Area) 5.0 m (1% Area)	26.8 m (20% Area) 19.0 m (10% Area) 13.4 m (5% Area) 10.4 m (3% Area) 6.0 m (1% Area)
Radiation heat flux level of 1577 W/m^2 (500 Btu/hr-ft^2)	23.4 m (20% Area) 15.9 m (10% Area) 10.7 m (5% Area) 7.9m (3% Area) 4.1 m (1% Area)	28.1 m (20% Area) 19.0 m (10% Area) 12.8m (5% Area) 9.5 m (3% Area) 4.8 m (1% Area)	16.6 m (20% Area) 11.2 m (10% Area) 7.8 m (5% Area) 5.5 m (3% Area) 2.6 m (1% Area)	20.5 m (20% Area) 13.8 m (10% Area) 9.6 m (5% Area) 6.8 m (3% Area) 3.3 m (1% Area)
Radiation heat flux level of 4.7 kW/m^2 (1500 Btu/hr-ft^2)	17.0 m (20% Area) 11.6 m (10% Area) 7.9 m (5% Area) 5.9 m (3% Area) 3.1 m (1% Area)	20.2m (20% Area) 13.8m (10% Area) 9.4m (5% Area) 7.0 m (3% Area) 3.7m (1% Area)	12.2 m (20% Area) 8.2 m (10% Area) 5.5 m (5% Area) 4.1 m (3% Area) 2.1 m (1% Area)	14.9 m (20% Area) 10.0 m (10% Area) 6.7 m (5% Area) 5.1 m (3% Area) 2.6 m (1% Area)
Greater of radiation heat flux level of 25237 W/m^2 (8000 Btu/hr-ft^2) or visible flame length[1]	13.0 m (20% Area) 9.2 m (10% Area) 6.5 m (5% Area) 5.0 m (3% Area) 2.9 m (1% Area)	15.0 m (20% Area) 10.6 m (10% Area) 7.5m (5% Area) 5.8 m (3% Area) 3.4 m (1% Area)	9.4 m (20% Area) 6.7 m (10% Area) 4.7 m (5% Area) 3.6m (3% Area) 2.1 m (1% Area)	11.1 m (20% Area) 7.9 m (10% Area) 5.6 m (5% Area) 4.3m (3% Area) 2.5 m (1% Area)
Greater of radiation heat flux level of 20000 W/m^2 (6340 Btu/hr-ft^2) or visible flame length[1]	13.0 m (20% Area) 9.2 m (10% Area) 6.5 m (5% Area) 5.0 m (3% Area) 2.9 m (1% Area)	15.0 m (20% Area) 10.6 m (10% Area) 7.5m (5% Area) 5.8 m (3% Area) 3.4 m (1% Area)	9.4 m (20% Area) 6.7 m (10% Area) 4.7 m (5% Area) 3.6m (3% Area) 2.1 m (1% Area)	11.1 m (20% Area) 7.9 m (10% Area) 5.6 m (5% Area) 4.3m (3% Area) 2.5 m (1% Area)

[1]The largest harm distances are predicted for the visible flame length.

Figure 1 Harm distances for different leak areas, harm criteria, and pressures (Table taken from Sandia's Report [4]).

The risk evaluation indicates that the use of 0.1% of the component flow area, as the basis for determining separation distances, determines a risk that is significantly smaller than 2 x 10^{-5}/yr risk guideline selected by the NFPA2 [3] TG6 for both 20.7 MPa and 103.4 MPa example systems. On the other hand, the use of a leak size that goes from a 1% to 10% of the component flow area determines risk estimates that are slightly above, but reasonably close to the risk guideline. Based on this input, the separation distances specified in NFPA2 [3] and NFPA 55 [7] would be based on a leak size equal to 3% of the largest flow area downstream of a gaseous storage system greater than 11.3 m^3. The separation distances are illustrated in Fig. 1.

3.0 DETERMINATION OF SAFETY DISTANCES BY ISO

The method used by ISO for determining safety distances is based on the single component leak frequency model. A model for prediction of dangerous effects like Flash fire (4% concentration in free jet), thermal effects (two times flame length) and overpressure effects is considered along with the estimation of risk from leakage events.

Three harm criteria were evaluated in the deterministic analysis and used to determine the safety distances for the different exposures or targets:

• Members of public and other customers 10^{-5}/year.

• Critical exposures (e.g. involving people or very critical equipment) x 10^{-6}/year (to be developed).

• Customers refuelling their vehicle 10^{-4}/year.

The safety distances are defined for different types of hydrogen systems forming a well identifiable physical module.

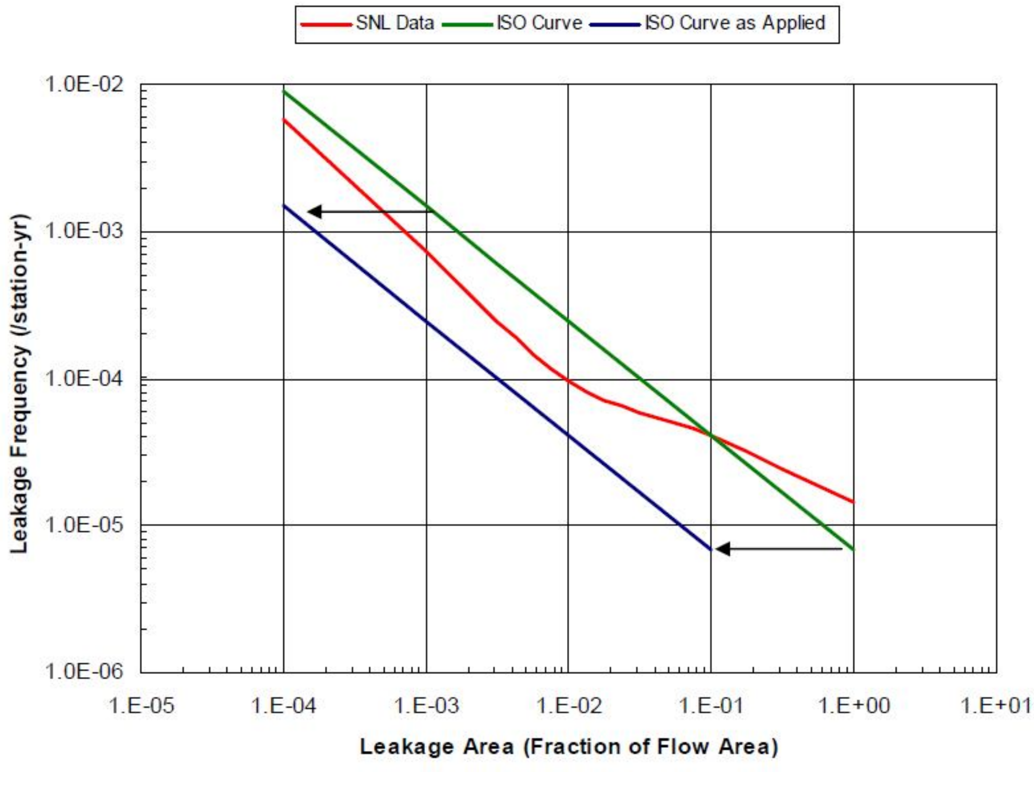

Figure 2 Comparison of valve leak frequency distribution used in NFPA and ISO analyses [5].

Passive systems are defined as systems used to store or transfer hydrogen which do not include hydrogen compression or hydrogen generation devices. They may or not include controls and instruments. Three categories are defined for passive hydrogen systems according to water volume, service pressure and stored quantity. For systems of Categories 1 and 2, sub-categories are defined considering different levels of likelihood of leak in these systems. This level of leak likelihood is assumed to be reflected by the value of the Leak Probability Indicator (LPI) for that system. On the other hand active systems are defined as process systems performing a hydrogen generation or compression function. These may include a storage function.

In the method used by ISO, the QRA study is not clear, especially in the determination of the component release frequencies. Quantitative risk assessment is needed to quantify the risks of hydrogen facilities and this methodology is often considered as a valuable tool to support the communication with authorities during the permitting process. For this reason statistic analysis and data source must be clearly illustrated, but it is also true that the ISO/DIS 20100 [2] is under development. The only information about the statistic analysis and the data source are given in the paper [5]: "the component leakage distribution utilized in the ISO analysis is illustrated in Fig. 2 as a linear versions (on a log-log plot) of the values generated by Sandia National Laboratories. The linearization of the SNL data distributions was performed to simplify the ISO analysis and allow for a method to generate alternate separation distances for facilities that are substantially different than the example facility used to establish the ISO separation distance table. However, the ISO linear leak frequency distributions actually used in the risk analysis were shifted an order of magnitude when used in the ISO risk analysis (Fig. 2)". In the paper [5] we underline that the reason for shifting the frequencies of one order of magnitude is not explained.

4.0 COMPARISON OF NFPA AND ISO METHODOLOGIES

The differences are listed below:

1-Determination of components release frequencies. While in the NFPA's code [3] a Bayesian analysis is used, the ISO's code [2] uses a different statistic analysis that only in case of valves and compressors, produces similar release frequencies in comparison to those used by Bayesian analysis. For the other components, the frequencies of release obtained by the ISO's team result to be greater for holes smaller the 1% of the flow area considered. The comparison of the release frequencies is illustrated in a Report [10]. However as before indicated statistic analysis and data source of ISO are not clearly illustrated.

2-Probability of ignition. ISO's code [2] considered only the event of a jet fire (with probability of ignition equal to 0.04), while NFPA's code [3] considered both the jet fire (with probability of 0.008) and flash fire (with probability 0.004).

3-Different adaptability of application. While in the NFPA's code [3] the cumulative release frequencies of the various components are calculated for the determination of the leak diameter of an example storage facility, the ISO's code [2] considers the release frequencies of single components. NFPA takes in account a generic plant. Instead ISO's methodology take in account systems constituted by different numbers and different kinds of components.

4-Acceptance criterion of the select risk. The choice of the acceptable risk criterion used by the NFPA is 2 10^{-5}/year, while in the ISO's code [2] it is 10^{-5}/year for the public, 10^{-4}/year for customers refueling their vehicle and it's under development the risk for critical exposures. Risk is evaluated for each target in ISO [2] (people, components, and structures), this choice is in agreement with EIHP2 that suggested different risk acceptance criteria for occupational risk, than risk to costumers and people outside the station. NFPA [3] only evaluated risk of fatality to person at the lot line.

5-Different leak sizes considered. The most important difference in comparison to the NFPA is in the choice of the hole's area dimension because while in NFPA's codes [3] is considered always the 3% of the flow area, in the ISO's code [2] it is always not only smaller, but it varies according to the type of system that is considered, arriving to a maximum of 1.81% of the flow area for active systems.

The values of the separation distances (NFPA [3]) and the safety distances (ISO [2]) are different for the reasons exposed above and also because targets and facility pressure ranges are different between the two, but the method for their determination is the same. If we consider the definition of risk-informed process given by Sandia's report [4], we can say that the ISO's approach is risk-informed and not risk-based.

5.0 COMPARISON OF ISO AND ITALIAN REGULATION SAFETY DISTANCES FOR HYDROGEN FUELING STATION

In the Italian Regulation for hydrogen filling station [8], the safety distances that must be respected inside the hydrogen fuelling stations are defined. Having above exposed the method used for determining such distances according to the draft ISO/CD 20100 "Gaseous Hydrogen Fuelling Station", it is interesting to compare the values of the distances referred to the same application established by ISO with the Italian Regulation [8]. The mentioned safety distances have been applied to a hydrogen fueling station considered in the project Hysafe [11] . The safety distances concerning a compressor (active system) and a dispenser (passive system) are illustrated in Table 1 and Table 2.

Table 1. Italian Regulation's safety distances [8] and ISO's safety distance [2] comparison for a compressor of a fueling station considered in the project Hysafe [11].

Targets	Italian Regulation's safety distances (m)	ISO's safety distances (m)
Occupied buildings – openable openings and air intakes	30	7
Occupied buildings – bay, windows	30	9
Unoccupied buildings – openable openings and air intakes	30	4
Pedestrian and vehicle low- speed passage ways	15	4
High voltage lines	22,5	5
Roadways	> di 15	5

Table 2. Italian Regulation's safety distances [8] and ISO's safety distance [2] comparison for a dispenser of a fueling station considered in the project Hysafe [11].

Targets	Italian Regulation's safety distances (m)	ISO's safety distances (m)
Occupied buildings – openable openings and air intakes	30	6
Occupied buildings – bay, windows	30	8
Unoccupied buildings – openable openings and air intakes	30	3
Buildings of combustible materials	30	5
Flammable liquids above ground < 4000L	30	3
Flammable liquids above ground > 4000L	30	5
Stocks of combustible materials	30	3
Flammable gas storage above ground > 500 Nm3	30	3
Pedestrian and vehicle low- speed passage ways	15	3
High voltage lines	12	3
Roadways	22.5	5

The Tables 1 and 2 above show that the two safety distances are notably different: ISO's safety distances are always smaller in comparison to those of the Italian Regulation [8]. One of the reasons of this difference of values is that the safety distances used in the Italian Regulation [8] are the same used for methane. To consider the two gases equivalent involves excessive safety distances for hydrogen, because as it is experimentally illustrated, the necessary safety distances for hydrogen, at the same pressure and leak diameter of release, are smaller to those of methane by around 20%.

Another reason for the difference among the considered safety distances is that the maximum allowable filling pressure in Italy is 220 bar. If the filling pressure is higher all the safety distances are increased by 50%. This point results to be very conservative because an increase of the pressure like double doesn't correspond to an increase equal to 50% in the safety distances to apply.

The safety distances of the Italian Regulation are evaluated with a methodology based on historical numbers given by pratical applications. A future approach for determining hydrogen safety distances in refuelling station must take in account the risk-informed process.

6.0 COMPARISON OF NFPA AND UNIVERSITY OF PISA METHODOLOGIES

The deterministic model [12] used for determining separation distances used by the NFPA, is similar to the deterministic model of EFFECT 7.6 [13] used in experimental analysis by University of Pisa for the determination of safety distances included in the Italian Draft of technical rules for the distribution and transport of hydrogen in pipelines. Furthermore both methodologies apply the following conservative hypotheses:

• Safety and separation distances result independent from the volume of gas storage. The two methodologies consider constant in time the radiation produced by jet fires.

• pressure loss are not considered between the storage and the leak.

• The releases are valued in absence of ventilation.

• A reduction of pressure is not considered in consequence of the loss.

• The hole is considered circular.

• Horizontal releases are considered.

The 2.5% of the pipeline's nominal diameter was the dimension used during an experimental analysis effectuated at the University of Pisa. This choice is in agreement with the most probable release holes in a standard hydrogen storage plant determined by the bayesian statistic analysis of NFPA (leak diameter smaller than 0.1% pipe's flow area that correspond to a leak diameter smaller than 3% of the pipe's inside diameter).

As illustrated above, the choice of the leak diameter considered by the NFPA [3] is conditioned by the risk analysis and by the selected values of the risk criterion. In fact the leak diameter considered for the determination of the separation distances is 3% of the pipe's flow area which correspond to a leak diameter between 10 and the 20% of the inside diameter of the pipeline, while in the experimental analysis is about 2.5%.

Using the EFFECTS code [13] we compared the NFPA's method with our application (distribution of hydrogen in pipeline). We took a characteristic pipe diameter considering the NFPA's range of compatible pressure (0.10-1.72 MPa in Table 3), and then the correlated leak diameter of 9.1 mm calculated with the NFPA's correlation (1), considering the 3% of the pipe's flow area (x).

$$d_{leak} = (x)^{\frac{1}{2}} d_{pipe} \tag{1}$$

where d_{leak} , d_{pipe} – length, m.

Table 3. Pressure ranges for NFPA2 [3] and NFPA55 [9] separation distances tables and associated system characteristic pipe diameter (take from Sandia's Report [4]).

Storage Pressure Range (MPa)	Characteristic Pipe Diameter (mm)
> 0.103 to ≤ 1.72	52.50
> 1.72 to ≤ 20.68	18.97
> 20.68 to ≤ 51.71	7.92
> 51.71 to ≤ 103.42	7.16

The results obtained with EFFECT [13] considering the same leak diameter, pressure range and thermal radiation considered by NFPA [3] are represented in Table 4.

Table 4. Harm distances comparison.

Harm criteria (kW/m^2)	EFFECT 7.6's harm distance (m)	NFPA's harm distance (m)
1.577	8.5	7.9
4.7	7.1	5.9
20	6.4	5
25	6.3	5

The Safety distances calculated in the experimental analysis by University of Pisa result slightly greater than those calculated by NFPA [3] of about 6% for low values of thermal radiation, and up to almost 20% for thermal radiation between 20 and 25 kW/m^2. Such differences are surely imputable to the parameters of the simulation code.

7.0 QUANTITATIVE RISK ASSESSMENT STUDY ON GASEOUS HYDROGEN REFUELING STATION IN CHINA

The paper "Quantitative risk assessment on 2010 Expo hydrogen station"[14] presents a study on a gaseous hydrogen refueling station. QRA is an important tool to determine safety distances as mentioned in the previous paragraphs.

In this study the scenarios and input data chosen are based on a previous HAZOP study on the Expo station. The initial failure frequencies are taken from Purple Book [15] and UK Offshore Release Statistics [16]. All continuous releases are assumed to be horizontal and heat radiation, overpressure effects, the probability of an explosion event, of a flash fire, or an immediate ignition, are taken from Purple Book [15]. The risk acceptance criteria are adopted from EIHP2 document which suggests different risk acceptance criteria: occupational risk (10^{-4}/year), risk for costumers (10^{-4}/year) and people outside the station for which both individual (10^{-6}/year) and societal risk measures must be considered.

The results in Table 5 show that the leaks from compressors and dispensers are the main risk contributors to the risks of the station. The values of the corresponding safety distances are higher than the safety distances calculated by ISO [2] and EIGA IGC 15/06E [17] reported in Table 6 because the release hole sizes are always assumed to be the maximum size of the pipe, hose or connection part. The justification of this choice is the possibility of effectively reducing the uncertainties caused by analysts' assumptions. Anyhow this is a very conservative assumption.

Table 5. Probability of a major accident causing one or more fatalities among customers (take from "Quantitative risk assessment on 2010 Expo hydrogen station"[14]).

	Without additional safety barrier systems	With additional safety barrier systems
Leak from compressors	1.20×10^{-3}	< 1 x 10-[6]
Leak from dispensers	1.17×10^{-3}	$< 1 \times 10^{-6}$
Pipe work rupture	1.76×10^{-6}	1.76×10^{-6}
Leak from vehicles fittings	9.52×10^{-6}	9.56×10^{-6}
Others	$< 1 \times 10^{-6}$	$< 1 \times 10^{-6}$
Total	2.38×10^{-3}	1.19×10^{-5}

Table 6. Comparison of calculated safety distance in Chinese QRA with values in some safety codes for hydrogen refueling station.

Vulnerable target	Safety distance in Chinese QRA [14] (m)	IGC 15/06E [17] (m)	ISO/DIS 20100 [2] (m)	Italian Regulation [8] (m)
Concentration of people	9	8	6[a]	20

a The value is referred to active systems with pressure system between 55 and 110 MPa.

The use of risk mitigation measures like barriers is very important for safety and for the determination of the safety distances, since it should significantly reduce any risk as illustrated in Table 5. In fact if safety distances can prevent more probable releases from small leaks, barriers are suitable for the mitigation of greater releases.

8.0 CONCLUSIONS

The development of the Italian Draft of technical rules [6] for hydrogen distribution and transport must consider some safety aspects, especially the safety distances. Many countries as Italy choose to use methane's safety distances for hydrogen activities and applications. This practice results to be inadequate because it sets conditions to respect, inherent to the safety distances, more severe than those necessary for hydrogen.

The experimental tests for the determination of hydrogen safety distances, used in the Italian Draft of technical rules [6], performed by the University of Pisa have been validated by the international methodology. In fact the choice of the leak diameter is related to the more probable holes of release determined by statistic analysis, which are based on available data given by worldwide studies on chemical processes. Moreover the hypotheses of release and the deterministic models used for determining safety distances are analogous and more conservative than NFPA [3].

The substantial difference between NFPA, ISO and University of Pisa, in determining safety distances, is the choice of the leak diameter's dimension. NFPA selects release holes equal to about 17% of the chosen pipeline's inside diameter, while ISO's method follows the same procedure of NFPA [3] for the determination of the distances, but considers smaller release holes and, for pipelines (very simple gas systems), equal to a 3% of the reference pipeline's inside diameter. A similar value is considered by University of Pisa.

The purpose of NFPA [3] is to protect persons situated at the lot line of the plant. Particularly the acceptable risk along with a statistic analysis that considers the release frequencies of a whole plant and not of a single component, is the reason for a release hole equal to 3% of the flow area.

Unlike what NFPA [3] prescribes, ISO [2] and University of Pisa determine safety distances which are used to prevent the evolution of accidental sceneries and to mitigate the consequences produced by the release of “small dimensions” in accordance with the definition previously quoted by EIGA [1]. In literature “small dimension” indicates holes smaller than 1% of the pipeline’s flow area which produces smaller and medium releases. For greater releases, University of Pisa considers other safety measures like barriers.

Taking in account the methodologies above exposed, The values of the safety distances proposed by Standard Organizations and national Regulations are a consequence of the leak diameter choice. For this reason is important to clearly define for which purpose the safety distances should be used. In particular is important to define if safety distances should be used to prevent and protect targets from great releases or to prevent great releases and protect from more probable small releases. Once established the safety distances purpose, it will be possible to compare the various methodologies and , for example, to understand if considering leak frequencies of the whole plant would it be more conservative to considering leak frequencies of single components and their related subsystems.

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