RISK INFORMED SEPARATION DISTANCES FOR HYDROGEN REFUELLING STATIONS

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1 ABSTRACT

The lay-out requirements developed for hydrogen systems operated in industrial environment are not suitable for the operating conditions specific to hydrogen refuelling stations (service pressure of up to 95 MPa, facility for public use). A risk informed rationale has been developed to define and substantiate separation distance requirements in ISO 20100 *Gaseous hydrogen – refuelling stations* [1]. In this approach, priority is given to preventing escalation of small incidents into majors ones, with a focus on critical exposures such as places of occupancy (fuelling station retail shop), while optimizing use of the available space from a risk perspective, a key objective for being able to retrofit hydrogen refuelling in existing stations.

2 INTRODUCTION

The use of Hydrogen as an energy carrier involves novel operating conditions, such as higher operating pressures than previously applied (700 bar), and installation and use in public settings (such as fuelling stations).

The safety distance requirements previously developed for industrial applications are not necessarily adequate for these new conditions. Space constraints in non industrial settings further require that separation be applied according to a well defined criterion, keeping in mind that there are also other measures that can be applied to achieve the desired level of safety.

In this context, separation requirements can therefore be analyzed within the more general framework of risk informed mitigation, where a combination of means to bring the residual risk to (potentially) exposed persons or objects below a specified target is considered. It is to be noted that separation is also a means to protect the system itself from sources of exterior aggression.

Compared to other forms of mitigation, separation is a generic means that can be in principle applied to any facility. *The main objective of separation is to mitigate the effect of a foreseeable incident and prevent a minor incident from escalating into a larger incident* [2]

A rationale was developed along these lines in ISO 20100 for defining separation distance requirements applicable to the hydrogen sub-systems present in a gaseous hydrogen refueling station, which are typically the following:

- Hydrogen supply system (e.g. tube trailer)
- Hydrogen compression skid
- Hydrogen buffer storage
- Hydrogen dispensers

There are two commonly used standardized dispensing pressures: 35 MPa and 70 Mpa. The design pressure of the dispensing systems is greater than these values, as hydrogen flow is achieved as a result of a higher pressure in the dispensing system than in the vehicle fuel tank.

3 FORM OF SPECIFICATION OF SEPARATION REQUIREMENTS – TABLES VS FORMULAS

Separation distance requirements are typically specified by means of a table indicating the separation to be applied between the equipment considered and elements potentially present in its environment.

The table format offers clear benefits in terms of ease of use and compliance verification. Furthermore, tables can be applied at a very early level of system definition.

An alternative approach that has recently been used in codes, such as NFPA 55 [3], to specify separation distance requirements is to provide formulas for application by the user. Apart from being less practical, this has the following disadvantages:

- Requirements resulting from a formula may differ between two systems that are similar enough to be arguably covered by the same requirements - this is an obstacle to standardization
- Providing formulas raises the risk that design parameters will be chosen to minimize safety distance requirements although this choice does not reduce the actual risk level to exposures
- The results are not necessarily checked to provide adequate protection from foreseeable deviations, as can be done with predefined separation distance figures.
- The values of parameters used in the formula may only be known upon completion of detail design (such as maximum internal pipe diameter). This conflicts with the fact that site selection and basic lay-out is performed early on, before initiation of detail design.

In view of the above, and in the absence of clearly identified advantages of specifying requirements by means of formulas, the ISO working group developing separation distance requirement for hydrogen refueling stations chose to specify these by means of tables.

4 STEPS FOR PRODUCING A SEPARATION DISTANCE TABLE

The following basic steps need to be performed to produce a risk informed separation distance table:

1. Select key system characteristics or parameters that fundamentally determine actual risk impact.
2. Based on these characteristics or parameters, divide the full set of systems addressed in categories of systems with a roughly similar risk impact, and to which a single set of safety distance requirements can therefore apply.

   Category limits should be defined considering the different families of equipment actually used (e.g. 35 MPa vs 70 MPa fuelling systems, where pressure is an identified risk factor)
3. Use a risk model – applying a criterion on estimated residual risk - to determine the separation distance requirements for each category, considering the range of parameter values defining the category
4. Populate the distance table and evaluate the result:
   - the separation distances need to achieve their objective with regards to the complete risk integrating all the forms of escalation that should be considered, not only the phenomena covered by the formula selected for application in the risk model
   - the separation distance figures need to evolve consistently and regularly with the complete risk.

   Adjustment to the definition of the categories or to the evaluation of the distance may be required to achieve these objectives through an iterative process.

5 SELECTION OF THE FUNDAMENTAL SYSTEM CHARACTERISTICS DETERMINING RISK IMPACT

For practicality, the selected characteristic needs to reflect a fundamental property resulting from the nature of the system and therefore known already at the stage of general design.

The set of system characteristics to be selected is that which is best correlated with actual risk impact, knowing only these characteristics. For such a set, the risk impact ranking of two different systems that are similar with regards to all the selected characteristics except one, is quite likely to be determined by that characteristic.

For the characterization to be effective, there needs to be a good level of independence between the selected characteristics, i.e. the correlation between the selected characteristics for the range of systems considered needs to be low.

The following three fundamental system characteristics were retained to categorize storage systems:

System size

System size is a fundamental factor to consider because it is related to risk impact in the two following ways:

1. The risk of escalation is strongly determined by leak size, which is strongly related to piping diameter, which is strongly related to system size.
2. The risk of escalation is strongly related to release duration. Indeed, increased release duration increases the likelihood:

   a) that a neighboring piece of critical equipment will be critically damaged by jet fire impingement associated to the release

   b) that hazardous concentrations will develop in a neighboring space where hydrogen could accumulate

Release duration is strongly related to hydrogen inventory, which is strongly related to system size.

Operating pressure - for small systems only

As smaller systems are constructed from components with dimensions (flow sections) falling in a relatively limited range, there is a correlation in such systems between leak sizes and operating pressure.

This is not the case in large systems where the range of component dimensions is very large, and therefore no significant information on risk impact can be drawn simply from the operating pressure: a low pressure storage system can have a greater risk impact as a high pressure system due to much larger piping diameter.

Number of components in the system that are a potential source of a release, reflecting the probability of having accidental release

The risk impact is related to the probability of accidental releases from the system, which is in turn related to the number of components that are a potential source of accidental release (this is further developed in sections 8.3 and 8.5). An equivalent expression of this characteristic used hereafter is the system complexity level.

6 STORAGE SYSTEMS CATEGORIES

On the basis of the system characterization described in section 5, and considering the types of equipment actually in use, levels are defined for each characteristic as follows:

System size

Two levels are defined according to a criterion on water volume and hydrogen quantity

- Small: water volume < 3000 L or hydrogen quantity < 100 kg
- Large: water volume > 3000 L and hydrogen quantity > 100 kg.

Pressure in small systems

Two pressure levels are defined

- Medium to high pressure: up to 55 MPa
- Very high pressure: greater than 55 MPa.

System complexity level as reflected by the number of components that are a potential source of release

Three levels are defined according to a quantification and thresholds detailed in 8.5 and designated as follows: (i) Very simple - only applicable to small systems (ii) Simple (iii) Complex.

Through the application of this categorization scheme, the full set of systems is broken down into categories grouping systems having the same characterization. By construction of the categorization scheme, systems belonging to the same category can be considered to have a roughly similar risk impact, and, therefore, a single set of separation distance requirements can apply to these.

Table 1 provides the three resulting size-pressure categories in relation to size, pressure and eight resulting sub-categories in relation to size, pressure, and complexity level, for hydrogen storage systems.

Table 1 – Categorization scheme

<table>
<tr><td colspan="6">Small systems
< 3000L or < 100 kg</td><td colspan="2" rowspan="2">Large systems
> 3000L and > 100kg</td></tr>
<tr><td colspan="3">Medium to high pressure
<= 55 MPa</td><td colspan="3">Very high pressure
> 55 MPa</td></tr>
<tr><td colspan="3">Size-pressure category 1</td><td colspan="3">Size-pressure category 2</td><td colspan="2">Size-pressure category 3</td></tr>
<tr><td>Very simple</td><td>Simple</td><td>Complex</td><td>Very simple</td><td>Simple</td><td>Complex</td><td>Simple</td><td>Complex</td></tr>
</table>

The size and pressure boundaries of the three size-pressure categories are illustrated in Fig 1.

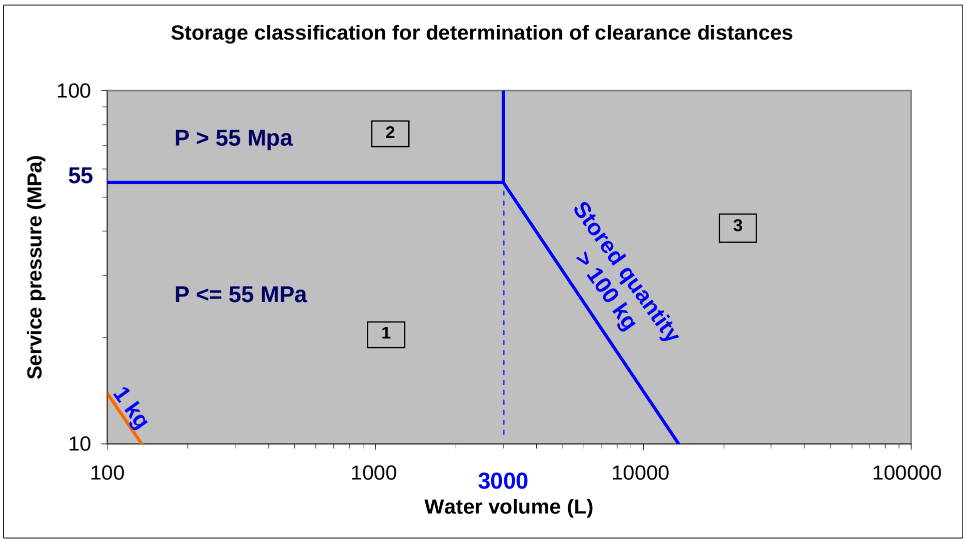

Figure 1. Size-pressure categories for storage systems

7 CHARACTERIZATION OF EXPOSURES

7.1 Consideration of exposure criticality

Some exposures, called critical exposures, justify greater precaution, i.e. application of a more stringent risk criteria, due to the greater aversion to the potential consequences of an escalation scenario involving these exposures.

Locations where there is a risk of affecting many people at once, such as the fuelling station shopping catering area, fall in the category of critical exposures.

A large size storage of flammable fuels is another example of critical exposure.

7.2 Identification of the effect having the worst consequences

Hydrogen releases are a potential hazard as a result of the following possible phenomena:

- flash fire resulting from delayed ignition of the hydrogen-air mixture created by the release
- jet fire resulting from ignition of the release
- overpressure effects resulting from the delayed ignition of the hydrogen-air mixture created by the release

The phenomena that is considered for determining the separation requirement depends of the nature of the exposure:

- Avoiding exposure to flash fire and hence to flammable hydrogen-air mixtures will be the driving concern for protection of persons
- Avoiding potential escalation from jet fire will be the driving concern for protection of process equipment and structures.
- Avoiding exposures to overpressure effects will be the driving concern for the protection of bay-windows

Characterization of the exposures in a fuelling station with regards to criticality and worst consequence effect is provided in section 10.

8 RISK MODEL - DESCRIPTION AND DATA INPUT

8.1 Risk model principle

The separation distance requirements are defined for each category of system by application of the risk model described hereafter.

This risk model integrates the following <u>four key elements</u>:

1. The relationship between the leak frequency and leak size (i.e. initiating event frequency in function of initiating event amplitude).
   This is the function providing the cumulated frequency of having a leak greater than a given size.
   This data can be derived from leak statistics, processed with the aim of defining a leak frequency for each predefined leak class (e.g. very small leaks, small leaks, medium leaks , large leaks, ruptures).
2. An evaluation of the conditional probability that the leak will produce the feared consequences on exposed objects, assuming they are close enough to be impacted. Typical conditions are leak ignition and release direction impacting the exposure.

   The value of the conditional probability applied is discussed in section 8.4.

   Application of this probability to the cumulated leak frequency distribution yields the cumulated frequency of feared effect on exposures in the vicinity of the system in function of leak size, assuming that the exposure is close enough to be impacted by a leak of the considered size.
3. A consequence model enabling the estimation of the distance at which a leak of a given size can produce the feared effects if all the conditions for these effects to materialize are present (e.g. ignition, jet in the right direction…). The physical effect to be taken into account (e.g. engulfment in a flammable cloud, thermal effects of a jet fire, overpressure) as well as the effect intensity threshold for producing the feared effect depend on the type of exposure considered (persons, equipment, buildings).

   The consequence model applied to estimate the distance at which a hydrogen release can produce hazardous effects in function of leak size is described in section 8.9.
4. A residual risk criteria defined for the exposure considered, translated into a frequency limit. This frequency limit is applied to determine the leak size to be considered for defining an

adequate separation distance requirement between the source and the exposure.
The frequency limit will depend on the magnitude of the consequences of the feared event; e.g. the residual risk target is more stringent (reflected by a lower frequency limit) when a leak can generate a flammable atmosphere in a building with high occupation than in an area where only one person is likely to be present.

The residual risk targets applied in function of the type of exposure are discussed in section 8.7.

Fig. 2 illustrates the determination of a separation distance from the elements presented above.

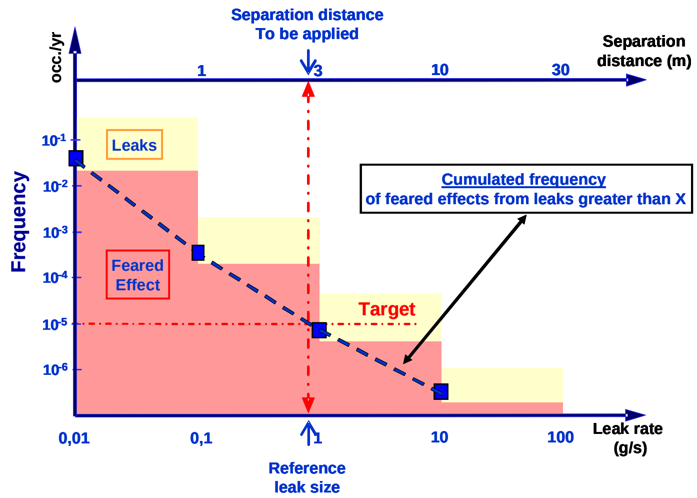

Figure 2. Determination of separation requirement by application
of a frequency criterion on the residual risk of feared effect from the system

It is to be noted that the application of a separation distance is not always the most adequate means to lower the residual risk of harm to exposures to the targeted level. In some situations, such as excessive residual risk from severe initiating events, prevention or other forms of mitigation will be more appropriate.

The separation requirements developed under this approach can be said to be risk informed because the latter takes into account the risk impact of the particular system and involves the application of a risk criteria. These requirements are only risk informed however, because the risk model does not provide an accurate evaluation of actual risk impact. The approach does however allow to provide a good level of consistency between separation requirements and risk impact, considering also the greater sensitivity of some exposures.

8.2 Input to the risk model in relation to system and exposure category definitions

Practical application of the risk model requires the following input:

System feared effect frequency in function of leak size

The system feared effect frequency is estimated by adding up the feared effect frequencies of its main components.

Component feared effect frequencies are the component leak frequencies, multiplied by the probability that a leak will produce hazardous effects, modeled as ignition probability multiplied by the geometric factor of the effect.

Component leak frequencies are derived from published leak statistics, in the format of leak frequencies in function of leak size where leak size is expressed in percentage of the component's internal flow section.

The component leak frequency data applied in the risk model, and the way it is summated to estimate system feared effect frequency is presented in section 8.3.

The system leak frequency distribution is hence determined by (i) the number of components that are a potential source of release (ii) the internal diameter of these components, which is typically a function of the size of the system

Based on the above, by allocating a maximum internal diameter to each system size class (Small systems and Large systems), and a maximum number of components that are a potential source of leak to each system complexity level (Very Simple, Simple, Complex), it is possible to allocate a system leak frequency distribution to each of the categories defined in section 6.

Risk criteria

Two different risk targets are considered depending on whether the exposure is critical or not. The selected target values are presented in section 8.7.

Consequence calculation

The extension of thermal effects and of the flammable hydrogen air mixture are calculated in function of leak diameter and operating pressure using the formulas provided in section 8.9.

Leak size in % of flow area is selected by application of the risk criteria, knowing the system's cumulated feared effect frequency in function of leak size, as described in section 8.1. Leak diameter can then be determined assuming the maximum internal diameter defined for the system size class.

The maximum internal diameter and pressure values selected for each size-pressure category are presented in section 8.8.

8.3 Component leak frequency

Component leak frequencies data input to the risk model is derived from the work of J. Lachance of Sandia National Laboratories (SNL) [4], hereafter referred to as the Sandia Report, which consisted in reviewing various sources of statistical data on component leak frequencies in order to generate reference data for components in hydrogen service.

This work covers the four types of components which are retained by the risk model for estimating the leak frequencies of the systems implemented in hydrogen fuelling systems: joints, valves, compressors, hoses

Compressor data is used as reference to cover all systems where hydrogen is generated and/or compressed; these are referred to as "process systems".

Determination of leak size range frequencies

For each of the selected components the Sandia Report provides leak frequencies for different leak sizes defined as follows:

- Small leaks – Leak area is 1% of total flow area
- Large leaks – Leak area is 10% of total flow area
- Rupture – Leak area is 100% of total flow area

This formulation of leak sizes is not fully adequate from a statistical point of view, as the frequency data needs to refer *to leak size intervals*, rather than to a specific leak size value. The size intervals considered in the risk model presented here are: [0.01% ; 0,1%], [0.1% ; 1%][1% ; 10%][10% ; 100%]. To apply the model it was therefore necessary to review the available information relative to leak size present in the statistical data sources compiled in the Sandia Report, in order to produce the frequency estimates for each size range.

As shown hereafter, this analysis allows to conclude the following:

- The median frequency computed for "small leaks" is an appropriate estimation of the frequency of leaks in the size interval [0.1%-1%]

- The median frequency computed for “large leaks” is an appropriate estimation of the frequency of leaks in the size interval [1%-10%]
- The median frequency computed for “ruptures” is an appropriate estimation of the frequency of leaks in the size interval [10%-100%]

Extrapolation to smaller size ranges is done by assuming an exponential relationship between leak frequency and leak size, as was done in the Sandia Report.

Review of data on valves

Table 2 shows the records relative to valves from generic data bases that include data allowing to estimating leak size as a percentage of flow area.

Table 2 - Leak frequency and leak size data relative to valves

Component	Specific Component Type	Severity	Frequency	Units	Leak Size Description	Source Type	Source
Valve	Manual, 2 inch	Small Leak	1,40E-05	Per Year	>1 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	Manual, 6 inch	Small Leak	4,80E-05	Per Year	>1 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	Manual, 18 inch	Small Leak	2,20E-04	Per Year	>1 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	Actuated, 6 inch diam non-pipeline	Small Leak	2,60E-04	Per Year	>1 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	All Sizes	Small Leak	1,00E-03	Per Year	1% cross sectional area	Chemical Process	Cox, A.W., Lees, F.P., Ang, M.L., "Classifications of Hazardous Locations," Institution of Chemical Engineers, 2003
Valve	All Sizes	Large Leak	1,00E-04	Per Year	10% cross sectional area	Chemical Process	Cox, A.W., Lees, F.P., Ang, M.L., "Classifications of Hazardous Locations," Institution of Chemical Engineers, 2003
Valve	Manual, 6 inch	Rupture	4,80E-07	Per Year	>50 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	Actuated, 6 inch diam non-pipeline	Rupture	1,90E-06	Per Year	>50 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	Manual, 18 inch	Rupture	2,30E-06	Per Year	>50 mm	Hydrocarbon	Spouge, John, "New Generic Leak Frequencies for Process Equipment, "Process Safety Progress, Vol. 24, No. 4, 2005
Valve	All Sizes	Rupture	1,00E-05	Per Year	100% cross sectional area	Chemical Process	Cox, A.W., Lees, F.P., Ang, M.L., "Classifications of Hazardous Locations," Institution of Chemical Engineers, 2003

These data points are plotted in Fig. 3 for “Small leaks” and Fig. 4 for “Ruptures” as follows (not enough points for “Large leaks”).

- The data points labeled “original data” reflect the actual data for valve leaks where leak size data was available
- The points labeled “SNL collected” show the size that was allocated to all the valve leak records in the Sandia Report: 1% of flow section for “Small leaks”, 100% of flow section for “Ruptures”. *This is typically one or two orders of magnitude greater than the size data, where such data is available.*

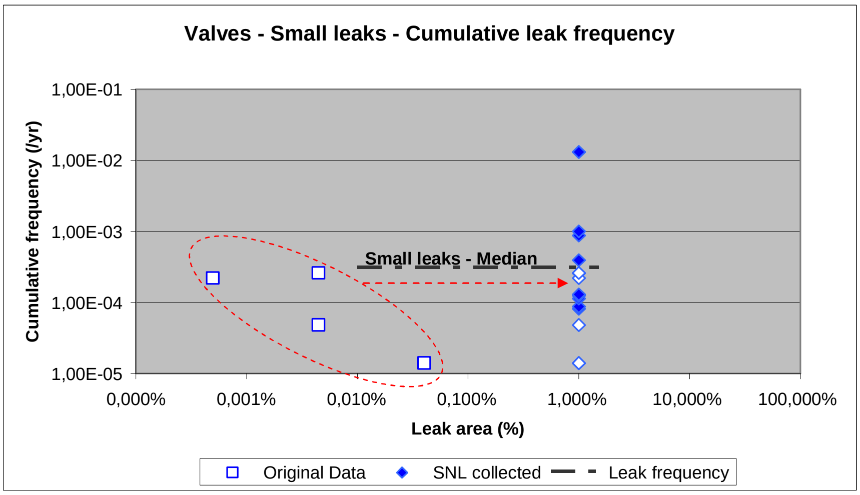

Figure 3. “Small leak” frequency data points for valve

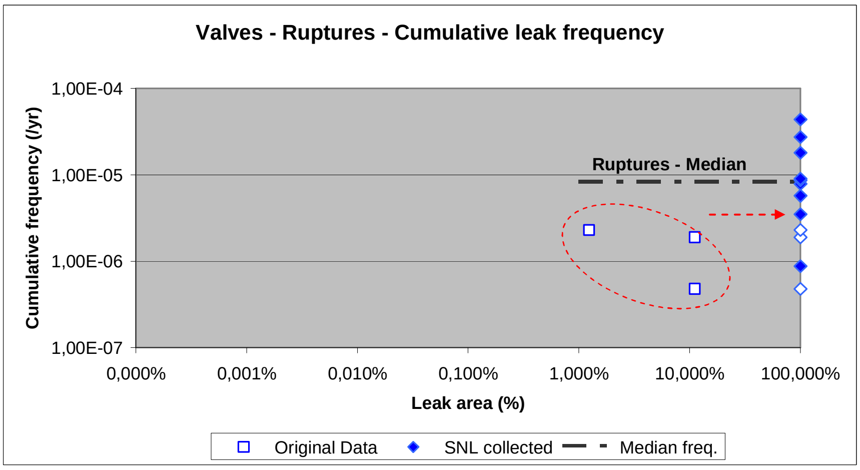

Figure 4. “Rupture” frequency data points for valve

For identifying a relationship between leak size and leak frequency, it is as important to exploit the data relative to leak size as the data relative to frequency.

The fact that size data, when available, points to sizes significantly smaller than the reference size selected in the Sandia Report, shows that the leak size range frequency allocation adopted for the risk model presented in this study is appropriate.

Review of data on other components

A similar analysis was performed for the other components considered, where enough records include data allowing to estimate leak size (100% of the records relative to flanged joints, 67% of the records relative to compressors). As shown in table 3, for these two components where such data is available:

- the logarithmic average of the frequency of “Small leaks” is greater or equal to the logarithmic average of the frequency of 0.1% to 1% size leaks considering the available leak size data
- the logarithmic average of the frequency of “Large leaks” is greater or equal to the logarithmic average of the frequency of 1% to 10% size leaks considering the available leak size data
- the logarithmic average of the frequency of “Ruptures” is greater or equal to the logarithmic average of the frequency of 10% to 100% size leaks considering the available leak size data

Table 3 – Comparison of leak frequencies in function of allocation to leak category or leak range

Component	Logarithmic average of leak frequencies			
	Leak category		Leak range	
Flanged Joints	Small leak Large leak Rupture	5,49E-05 - 3,60E-07	1,20E-04 3,71E-05 - 3,60E-07	[0,01%-0,1%] [0,1%-1%] [1%-10%] [10%-100%]
Compressor	Small leak Large leak Rupture	7,35E-03 - 4,69E-06	7,35E-03 - - 4,69E-06	[0,01%-0,1%] [0,1%-1%] [1%-10%] [10%-100%]

This again confirms that the specified leak size range frequency allocation adopted for the risk model presented in this study is appropriate.

Additional considerations for data input relative to joints and hoses

In the Sandia Report, specific leak frequencies were produced for components in *hydrogen service* as opposed to generic service.

For valves and compressors, the leak frequencies computed considering hydrogen service are not significantly different from those derived only from the generic data.

For joints and hoses, the leak frequencies computed considering hydrogen service are significantly lower than those derived only from the generic data. However the dependency to leak size was also greatly altered, resulting in small leaks having about the same frequency as large leaks. If the dependency of leak frequency to leak size is that small, a risk informed approach leads to either one of the following outcomes: either a separation distance is needed to protect against full bore rupture, or no separation is needed at all. In the former case, the more appropriate protection measure is to increase the means of prevention to bring the residual risk to target.

For application of the risk model, a conservative approach was chosen for joints and hoses: the dependency of leak frequency to leak size found in the *generic data* was kept, with frequency shift applied to the whole curve to coincide with the "large leak" frequency computed for hydrogen service. *The frequencies considered in the risk model for small leaks on joints and hoses are therefore much greater than those computed in the Sandia Report*.

Data fitting to exponential functions

The risk model assumes an exponential relationship between leak size and leak frequency:

CF (LS) = 10^{A} LS ^{B}

With the following notations: CF is the cumulative frequency of leaks greater than LS, LS is the considered leak size, expressed in fraction of flow section, A and B are constant values characteristic of the component considered.

This relationship results in a linear relationship in log-log scale.

Table 4 provides the A and B coefficients adopted for the components considered by the risk model, These provide the best fit with the median component frequencies provided in the Sandia Report, with the adjustments explained above.

Table 4 – Coefficients of component leak frequency functions

Component type	Function coefficients	
	A	B
Joints	-6,75	-0,81
Valves	-5,96	-0,81
Compressors	-5,69	-1,13
Hoses	-5,44	-0,84

These functions are plotted in the Fig. 5

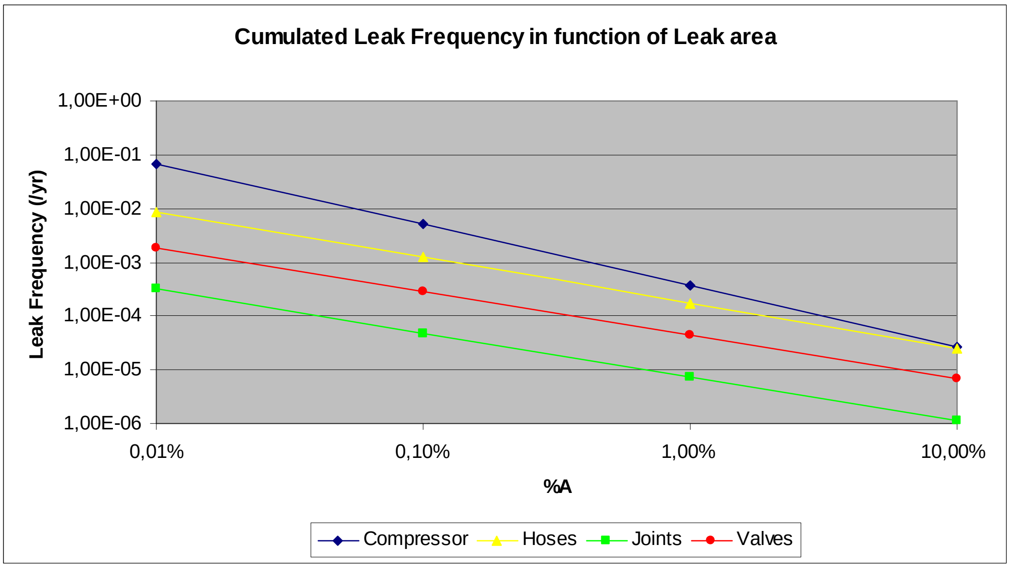

Figure 5. Component leak frequency in function of leak size in % of flow section

8.4 Probability that a leak will produce hazardous effects

Two conditions are considered in the model for estimating the probability that a leak will produce hazardous effects:

Leak ignition

It is observed in the Sandia Report that the ignition probabilities suggested in the literature vary by orders of magnitude, with a general agreement on the fact that this probability increases with release flow rate.

For small systems (as defined in section 6) a conservative value of 0.04 is applied in the model, over the whole leak size range considered (these are leaks smaller than 125 g/s), for both delayed ignition an immediate ignition probability. This corresponds to a total ignition probability of 0.08. This is more conservative that in the Sandia Report where the total ignition probability applied for leaks up to 125 g/s is 0.012.

For large systems (as defined in section 6) a higher ignition probability of 0.1 is applied in the model, to account for the influence of leak size, both for delayed ignition an immediate ignition probability. This corresponds to a total ignition probability of 0.2.

Geometric factor

The geometric factor allows to account for the fact that the effects of the release is directional and therefore do not necessarily affect an exposure within impact range.

The values used in the Sandia Report were applied: for compressors, joints and hoses: 0.125 ; for valves: 0.08.

The probability that a leak will produce hazardous effects is modeled as the product of the ignition probability and the geometric factor.

The application of this factor to the cumulated leak frequency yields the *cumulated feared effect frequency* for each component considered, as shown in Fig 6.

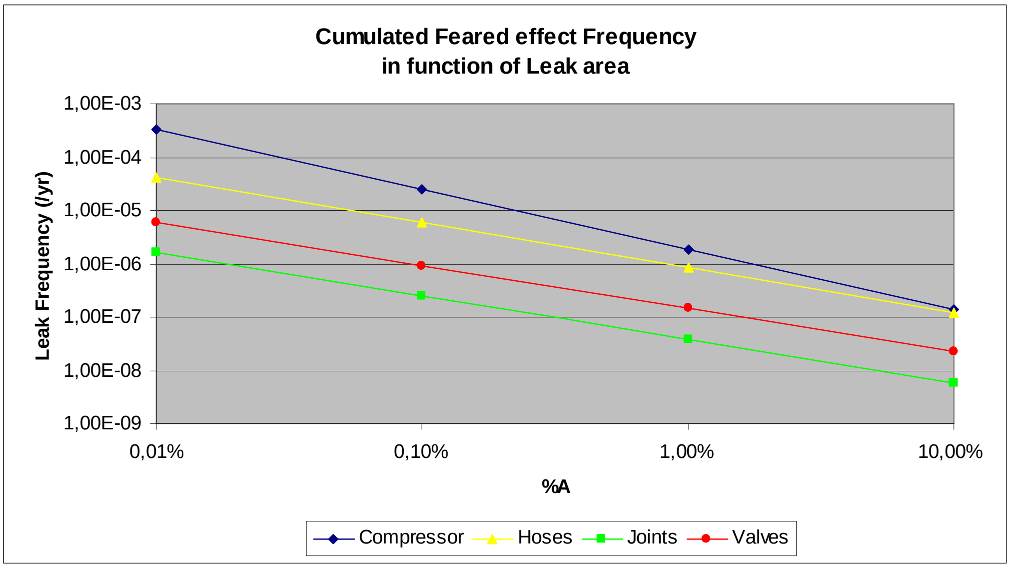

Figure 6. Component feared effect frequency in function of leak size in % of flow area

8.5 System feared effect frequency

The feared effect frequency for a system is obtained by summing the feared effect frequencies of its components considered to be a potential source of leak.

This operation is simplified by the fact that the feared effect frequency considered for joints, valves, and hoses differ by a factor that is constant of the leak size range (as reflected by the fact that the frequency curves are parallel in log-log scale)

This allows to define a “joint equivalent ratio” (JER) for valves and hoses:

Based on the data input:

- a valve has the same contribution to a systems feared effect frequency as four joints of the same internal diameter.
- a hose has the same contribution to a systems feared effect frequency as 24 joints of the same internal diameter.

The probability of having an accidental release, reflected by the number of components in the system that are a potential source of a release – a characteristic identified as key for determining the systems risk impact – can therefore be quantified by a single figure, hereafter called Hazard Probability Indicator (HPI).

The HPI is the JER weighted summation of the number of potentially leak sources i.e. joints, valve, and hoses.

For components of smaller internal diameter than the maximum internal diameter in the system, an equivalence factor equal to the square of the ratio of diameters may be applied to the JER. The validity of this approximation results from the fact that leak frequencies are roughly proportional to the inverse of the leak size expressed in % of flow section, which is itself proportional to the square of flow diameter.

For components operating at a pressure lower than the reference Service Pressure, an equivalence factor equal to the ratio of pressures may be applied to the JER. The validity of this approximation results from the fact that leak rates are proportional to pressure.

For the evaluation of the HPI, piping connections of valves and hoses are considered to be part of the component and are therefore not counted as joints.

EXAMPLE:

For a system including 3 valves (JER = 4), 10 non welded joints (JER = 1) and 1 hose (JER = 24), (all with comparable internal diameter and subject to identical service pressure) :

HPI = 3 x 4 + 10 x 1 + 24 x 1 = 46.

8.6 System complexity level boundaries in relation to the HPI

The HPI is logically a measure of the system complexity level, a key characteristic chosen to categorize systems, reflected by the number of components that are a potential source of release.

For application of the risk model, the boundaries of the three complexity levels defined in section 6 are the following, considering the different types of hydrogen systems that could be present in a fuelling station.

- For small systems (size-pressure categories 1 and 2):
  - Very Simple gas systems (VS type): HPI ≤ 15

    Example: a Pressure regulation panel
  - Simple gas systems (S type): 15 < HPI ≤ 60

    Example: a simple buffer storage system.
  - Complex gas systems (C type): 60 < HPI ≤ 135

    Example: an instrumented hydrogen buffer storage cascade system.
- For large systems (size-pressure category 3)
  - Large simple storage systems (LS type): HPI ≤ 45

    Example: a 100 m3 vessel for stationary storage of compressed hydrogen at 4,5 MPa.
  - Large complex storage systems (LC type): 45 < HPI ≤ 100

    Example: a hydrogen tube trailer

8.7 Risk criteria

Based on the Sandia Report, the residual risk criteria applied in the risk model is 10^{-5} feared events /yr from any given hydrogen systems.

This order of magnitude is in line with the expectation that hydrogen dispensing systems should implement safety approaches allowing to ensure that the risk for people permanently present in a fuelling station is not significantly increased due to the presence of such systems, compared to the currently existing risk in conventional stations.

As explained in section 8.2, with regards to critical exposures, a more stringent criteria is applied for consistency with increased aversion to events with severe consequences. The risk target applied in the risk model for critical exposures is $4\ 10^{-6}$/yr.

8.8 Maximum internal diameter and pressure boundaries of size-pressure categories

Considering the hydrogen systems implemented in hydrogen fuelling stations, the following boundaries have been adopted for the size pressure-categories defined in section 6:

Small systems

- Maximum internal diameter (MID): up to 8 mm
- Medium to high pressure (Size-pressure category 1):
    - Operating pressure: up to 55 MPa (as previously defined in section 6)
    - Very high pressure: above 55 Mpa, up to 105 MPa

Large systems

Pressure and maximum internal diameter characteristics considered for this Large systems are those of the typical systems that this class is intended to cover, as reflected by the following examples:

- Tube trailers: 20 MPa operating pressure, maximum internal diameter of 12,4 mm
- Stationary medium pressure storage capacity: 5,5 MPa operating pressure and maximum internal diameter of 24,9 mm

According to the risk model used, for a given flow section % leak size, the leak rate is proportional to $SP^{0,46}$ x MID

With the following notations:

- SP: Service pressure in MPa
- MID: Maximum internal diameter in mm

For the two systems above, the value of this figure, hereafter called Leak Magnitude Indicator (LMI), is 55. This value of the LMI is the one retained for determining the separation distance requirements for Large systems.

8.9 Consequence Model

The consequence model is derived from results of consequence modeling performed by W. Houf presented in the Sandia Report. It allows to estimate (i) the extension of the flammable hydrogen-air cloud produced by a release, (ii) the flame length in case of jet fire.

The minimum concentration level considered to be the source of feared effects is 4%.

Thermal effects from jet fires are conservatively considered to have a potential for generating a feared event within a distance equal to twice the flame length.

The resulting safety distances with regards to flash fire and hazardous thermal effects are given by the following formulas:

<u>Notations and units:</u>

SD: separation distance in m ; LD: leak diameter in mm ; SP: service pressure in MPa; LQ: leak flow in g/s ; LA: leak area in mm^2

Table 5. Consequence model formulas

Targeted hazardous effect: Flammable atmosphere	**Targeted hazardous effect: Thermal effects**
$SD = 1{,}02 \times LD \times SP^{0{,}46}$ Or alternatively: $SD = 1{,}34 \times LQ^{0{,}5}$	$SD = 0{,}84 \times LD \times SP^{0{,}46}$ Or alternatively: $SD = 1{,}11 \times LQ^{0{,}5}$
With $LQ = 0{,}58 \times LD^2 \times SP^{0{,}92}$, which is equivalent to $LQ = 0{,}73 \times LA \times SP^{0{,}92}$	

Note: overpressure effects are considered only with regards to bay windows. The determination of this separation requirement is not covered in this document.

9 APPLICATION OF RISK MODEL TO EQUIPMENT AND EXPOSURE CATEGORIES

Table 6 recalls all the defining parametric values associated to each system, as well as the risk targets associated to each exposure category (all in italics), and shows the result of the application of the risk model, based on the component leak statistic data input detailed in section 8.3, component leak geometric factors detailed in section 8.4, and the consequence model detailed in section 8.9.

Table 6. Risk model hypothesis and resulting reference leak sizes

					System characteristics							
					Small (<= 3000L and <=100 kg)						**Large (> 3000L or > 100 kg)**	
					Category 1[a] (<= 55 Mpa)			**Category 2[a] (> 55 Mpa)**			**Category 3[a]**	
					Very simple	**Simple**	**Complex**	**Very simple**	**Simple**	**Complex**	**Simple**	**Complex**
Hypoth.	**System**		MID	mm	*8*	*8*	*8*	*8*	*8*	*8*	*12,3*	*12,3*
			P	Mpa	*55*	*55*	*55*	*110*	*110*	*110*	*25,0*	*25,0*
			HPI	Joint eq.	*15*	*60*	*135*	*15*	*60*	*135*	*45*	*100*
	Ignition		Probability		*0,04*	*0,04*	*0,04*	*0,04*	*0,04*	*0,04*	*0,106*	*0,106*
Exposure	**Regular**	**Target :** *10⁻⁵/yr*	**Leak size**	mm		0,32	0,52		0,32	0,52	0,76	1,07
				%		**0,16%**	**0,42%**		**0,16%**	**0,42%**	**0,38%**	**0,75%**
				g/s		2,4	6,3		4,5	12,0	6,5	12,9
			Flash fire distance	m		**2,1**	**3,4**		**2,8**	**4,6**	**3,4**	**4,8**
			Therm. effects dist.	m		**1,7**	**2,8**		**2,4**	**3,9**	**2,8**	**4,0**
	Critical	**Target :** *4 10⁻⁶/yr*	**Leak size**	mm	0,24	0,56	0,91	0,24	0,56	0,91	1,51	2,14
				% flow area	**0,09%**	**0,48%**	**1,30%**	**0,09%**	**0,48%**	**1,30%**	**1,50%**	**3,00%**
				g/s	1,3	7,3	19,7	2,5	13,8	37,3	25,9	51,8
			Flash fire distance	m	**1,5**	**3,6**	**5,9**	**2,1**	**5,0**	**8,2**	**6,8**	**9,6**
			Therm. effects dist.	m	**1,3**	**3,0**	**4,9**	**1,8**	**4,1**	**6,8**	**5,7**	**8,0**

No separation distance is required with regards to regular exposures for very simple systems.

The ref leak size percentage, which is provided in reference to the maximum flow area for the category (specified through the MID), depends on the HPI value as well as the leak ignition probability.

With the parametric values adopted for Large Complex systems, the resulting reference leak size, is 3% of maximum flow section.

In NFPA 55, a leak size of 3% of maximum flow section has also been adopted to determine the reference leak size on which the safety distances are based. However, in NFPA 55 this value is the same for all systems, which means that the safety distance requirements are only based on MID and pressure, without taking into account other risk factors such as inventory or number of sources of leaks, nor the type of exposure.

Table 7 indicates for each category, the MID for which NFPA 55 and the model implement in the ISO 20100 provides the same distance requirements.

Table 7. MID for which NFPA 55 and ISO 20100 approaches provide the same safety distance

		System characteristics							
		Small (<= 3000L and <=100 kg)						Large (> 3000L or > 100 kg)	
		Category 1[a] (<= 55 Mpa)			Category 2[a] (> 55 Mpa)			Category 3[a]	
MID for which ref leak size is 3% of flow section		Very simple	Simple	Complex	Very simple	Simple	Complex	Simple	Complex
Exposure: Regular	mm		1,8	3,0		1,8	3,0	4,4	6,2
Exposure: Critical	mm	1,4	3,2	5,3	1,4	3,2	5,3	8,7	12,3

10 EXPOSURES

Table 8 provides the list of exposures addressed, specifies which hazardous effect is considered for determination of the separation distance requirement, and indicates whether or not the exposure is considered critical.

The risk model is not applicable to some exposures which are also sources of hazard for the hydrogen systems, indicated by gray shading. For these exposures separation requirements are determined by other means.

Table 8. List of exposures considered, hazardous effect of concern, and criticality

Exposures	Hazardous effect determining SD	Critical exposure ?	Comments
Occupied buildings openable openings and air intakes	Flammable atmosphere	**YES**	
Occupied buildings - bay-windows	Over pressure effects	**YES**	
Unoccupied buildings openable openings and air intakes	Flammable atmosphere	NO	
Building of combustible material	Thermal effects	**YES**	Exposure is also a source of hazardous escalation*
Flammable liquids above ground < 4000 L	Thermal effects	NO	Exposure is also a source of hazardous escalation*
Flammable liquids above ground > 4000 L	Thermal effects	**YES**	
Underground flammable liquid storage - vents and fill openings			Source of hazardous escalation*
Stock of combustible material	Thermal effects	NO	Exposure is also a source of hazardous escalation*
Flammable gas storage above ground > 500 Nm3	Thermal effects	NO	Exposure is also a source of hazardous escalation*
Facility lot line	Flammable atmosphere	NO	
Areas not subjected to restrictions of activity	Flammable atmosphere	NO	
Pedestrian an vehicle passage ways	Flammable atmosphere	NO	
High voltage lines and trolley or train power line			Source of hazardous escalation* (EM induced discharges or projected sparks)
Other overhead power lines			Source of hazardous escalation*
Public roadway			Source of hazardous escalation* (Vehicle impact)

* Large storage systems are classified as critical exposure for sources of hazardous escalation

11 SAFETY DISTANCE TABLE

Application of the distances provided in Table 5 to the exposures listed in section 10 according to their type, with rounding to a set of predefined distance figures, results in the separation requirements shown in Table 9.

Table 9. Separation distance requirements for hydrogen storage systems

Distance in meters

Safety distances (m)		Passive hydrogen systems							
		Category 1 (SP <= 55 MPa)			Category 2 (55 < SP <= 110 MPa)			Cat. 3 (Q > 100 kg)	
		VS	S	C	VS	S	C	S	C
Exposures or Sources of hazard	Occupied buildings - openable openings and air intakes	1,5	4,0	6,0	2,0	5,0	8,0	7,0	10,0
	Occupied buildings - bay-windows*	-	5,0	8,0	-	7,0	12,0	9,0	15,0
	Unoccupied buildings - openable openings and air intakes	-	2,0	3,0	-	3,0	5,0	4,0	5,0
	Buildings of combustible material	1,5	3,0	5,0	2,0	4,0	7,0	8,0	8,0
	Flammable liquids above ground <= 4000 L	1,0	2,0	3,0	-	2,5	4,0	8,0	8,0
	Flammable liquids above ground > 4000 L	1,5	3,0	5,0	2,0	4,0	7,0	8,0	8,0
	Underground flammable liquid storage - vents and fill openings	-	3,0		-	3,0		5,0	5,0
	Stocks of combustible material	1,0	2,0	3,0	-	2,5	4,0	8,0	8,0
	Flammable gas storage above ground > 500 Nm3	1,0	2,0	3,0	-	2,5	4,0	8,0	8,0
	Facility lot line	-	2,0	3,0	-	3,0	5,0	4,0	5,0
	Areas not subjected to restrictions of activity	-	2,0	3,0	-	3,0	5,0	4,0	5,0
	Pedestrian and vehicle low-speed passage ways	-	2,0	3,0	-	3,0	5,0	4,0	5,0
	High voltage lines and trolley or train power line	-	5,0		-	5,0		10,0	
	Other overhead power lines	-	5,0		-	5,0		5,0	
	Roadways	-	5,0		-	5,0		5,0	

* non-re-enforced to withstand overpressure effects

Separation distance adjustment for systems having a larger risk impact than those considered by the separation distance table.

The validity of table 8 rests on the hypothesis that systems to which it is applied fall within the definitions of system categories it refers, in terms of Maximum Internal Diameter (MID), service pressure (SP), Hazardous event Probability Indicator (HPI), and Leak Magnitude Indicator (LMI – for large systems)

If the boundary values (specified in sections 8.6 and 8.8) for the MID or the LMI are significantly exceeded, or if the boundary value for the SP or the HPI are exceeded by more than 30 %, the separation distances to be applied need to be determined by application of a correction factor to the tabled distances. This correction is quite simple to carry out and is covered by ISO 20100.

It is to be noted that the ISO 20100 does not allow a reduction of distances specified by the table in consideration of actual system parameters. The tabled distances have been reviewed and are considered to provide the right level of protection for all the systems covered.

12 COVERAGE OF PROCESS SYSTEMS

Process systems are systems including a hydrogen generation and/or compression function. These are all considered to have a relatively high level of complexity, and relatively small inventory, and are therefore only categorized according to pressure. As a result only two categories are defined for process systems, based on operating pressure.

The Hazardous effects probability of process systems is assumed to be that of a system combining a compressor and a small complex system. (The combination of a process systems with a large system is not permitted).

Application of the risk model yields a reference leak area of 1.8% flow area for critical exposures and of 0.65% of flow area for regular exposures.

Separation distance requirements are determined assuming a MID of 8 mm. This results in the separation distance requirements shown in Table 10.

Table 10. Separation distance requirements for process systems

distance in meters

Separation distances (m)		Active hydrogen systems	
		Category 1 (SP <= 55 Mpa)	Category 2 (55 < SP < 110 Mpa)
Exposures or Sources of hazard	Occupied buildings - openable openings and air intakes	7,0	10,0
	Areas of occupancy	7,0	10,0
	Occupied buildings - bay-windows*	9,0	15,0
	Unoccupied buildings - openable openings and air intakes	4,0	6,0
	Buildings of combustible material	6,0	8,0
	Flammable liquids above ground < 4000 L	4,0	5,0
	Flammable liquids above ground > 4000 L	6,0	8,0
	Underground flammable liquid storage - vents and fill openings	3,0	
	Stocks of combustible material	4,0	5,0
	Hydrogen or Flammable gas storage above ground > 500 Nm3	4,0	5,0
	Facility lot line	4,0	6,0
	Areas not subjected to restrictions of activity	4,0	6,0
	Pedestrian and vehicle low-speed passage ways	4,0	6,0
	High voltage lines and trolley or train power line	5,0	
	Other overhead power lines	5,0	
	Roadways	5,0	

* non-re-enforced to withstand overpressure effects

13 CONCLUSION

A risk informed approach has been developed to determine the separation distance requirements applicable to the hydrogen systems installed in a fuelling station. The resulting requirements consider the key risk factors that are judged to determine risk impact, including exposure criticality, and allow to optimize the use of available space to achieve the targeted safety level. As these requirements are expressed in the form of table, they can be readily applied early on in a fuelling station development project, before detail design is initiated.

The fact that the application of the risk model to Large systems results in the selection of a reference leak size of 3% of flow, a value adopted as well in NFPA 55 for bulk supply systems, indicates consistency of the frequency data input to the risk model with pre-existing analysis.

14 TABLE OF REFERENCE

1. ISO/DIS 20100 *Gaseous hydrogen – refuelling stations*, ISO draft standard, April 2011
2. NFPA 55, “Standard for the Storage, Use, and Handling of Compressed Gases, and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks”, 2005 Edition, National Fire Protection Association.
3. “Determination of Safety Distances”, European Industrial Gases associations, IGC Doc 75/01/E/rev, 2001
4. J. LaChance, W. Houf, B. Middleton, and L. Fluer, “Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards”, Sandia report SAND2009-0874, March 2009.