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QRA Method for Land-Use Planning around Onshore Natural Gas Production and Processing Plants

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In the Netherlands, companies that handle or store large amounts of hazardous substances must carry out a quantitative risk assessment (QRA) for permitting and land-use planning purposes. The outcomes of the QRA determine at what distances objects such as houses and schools are tolerable. A directive for such QRA calculations is already in place for the risks generated by general chemical industries. A new methodology has been proposed for on-shore sites for production, injection and processing of oil and gas. This method is presented in the current paper with a focus on gas production and processing.
The method includes an identification of release scenarios and release frequencies, and an assessment of the consequences and impact of a release. As the outcomes are used for public decision making, transparency and validity of the assumptions used are important conditions for the development of the method.
The outcomes of the method will be evaluated against a set of realistic cases in 2013. Implementation in legislation is scheduled for 2013 but depends on the outcomes of the case evaluation.

1. Introduction

In the Netherlands, legislation is in place to protect the general public from accidental releases of hazardous substances from industrial sites. The risk to which the public is exposed, is assessed with two variables: Individual Risk (IR) and Societal Risk (SR). Both variables are calculated in a Quantitative Risk Assessment (QRA). Buildings for the general public are not acceptable at locations where the Individual Risk for mortality exceeds one in a million (10^{-6}) per year. For Societal Risk, the responsible public authorities must account for the outcome of the risk calculation in relation to the possibilities and costs to reduce risk and the benefits of the activity for the society. A more detailed description of the Dutch legislative context is supplied in (Uijt de Haag et al., 2008) and (Uijt de Haag et al., 2012).
The current work is carried out to define the requirements for the Quantitative Risk Assessment for on-shore sites for production, injection and processing of oil and gas. This includes the identification of the release scenarios to be used, a specification of the corresponding release frequencies, and an assessment of the consequences and impact of the release. These requirements will be included in the next version of the Reference Manual for Bevi Risk Assessments. The current version of this manual (RIVM, 2009) already contains the requirements for various other types of activities, including general chemical industries, refineries, chemical warehouses and LPG filling stations.

The project was carried out by RIVM (Dutch National Institute for Public Health and the Environment). NOGEPA (Netherlands Oil and Gas Exploitation and Production Association) provided data for release frequencies for wells and interunit pipelines. The project was supervised by the Ministry of Infrastructure and Environment and the Ministry of Economic Affairs, Agriculture and Innovation.

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2. Constraints for the method development

As the outcomes are used for public decision making processes with important consequences for permitting and land-use planning, a number of conditions apply to the method used. The most important ones are:

- Validity: the outcomes should be realistic for the sites considered. The data used should be representative for the activities to which the method applies. The codes and standards used, should be taken into consideration when appropriate.
- Verifiability: all stakeholders must be able to verify the validity of the assumptions and outcomes of the method. As a consequence, only publicly available data can be used for the model development. The amount of expert judgement used, should be minimised.
- Robustness: if substantial uncertainties pertain, a conservative approach must be used. Average values (for example for release frequencies) do not always provide the desired level of robustness.
- Complexity: the method must yield to realistic outcomes for the IR 10^{-6} contour and for societal risk. It must also be possible to carry out or approve the QRA within reasonable time constraints. Therefore, the method must be simple when possible and detailed when necessary.
- Reproducibility: all skilled risk analysts should arrive at the same outcomes. In particular, according to Dutch legislation, all risk analysts must use the same software.

Requirements for Quantitative Risk Assessment had already been defined for general chemical industries (see previous section). In order to limit the scope of the work, only issues for which the sites under consideration differ considerably from general chemical industries, were investigated. This typically reflects differences in the design, operation and control of the (high-pressure) equipment.

It was assumed that the establishments to which the method applies are designed, operated and maintained in accordance with the prevailing Dutch standards for storage, production and treatment of gas.

3. Release scenarios and release frequencies

It was assumed that the risk associated with failure of the integrity of the reservoir (‘geological failure’) could be neglected compared to failure of the wells and the associated aboveground (process) equipment. This assumption is in line with (Keeley 2008) that shows that release rates for geological failures are substantially smaller than release rates for failure of the well and associated aboveground piping and instrumentation while the release frequencies are in the same order of magnitude.
Release scenarios were subsequently defined for the different types of equipment that may be present at the gas production and processing sites. A distinction was made between the well, interunit piping, process piping, various types of installations for gas processing (such as compressors, heat exchangers, separators, adsorbers, filters and storage vessels) and transportation units (ships, road and rail tankers).
New scenarios and frequencies were derived for wells, interunit piping and high-pressure compressors. These are discussed in the following subsections. In addition, new release frequencies were proposed for slug catchers and flexible pipes, based on analogies with other types of equipment. For all other types of equipment, it was proposed to use the release scenarios and frequencies that are already in use for general chemical industries (RIVM, 2009).
The release frequencies for wells, interunit piping and compressors were all derived from accident statistics. In general, the number of accidents was low and therefore large uncertainties pertained to the average accident rate. In order to be more robust (more conservative and less vulnerable to fluctuations in average values), the upper limit of a one-sided confidence interval was used to determine the release frequency. As yet, it has not been decided if the confidence level should be 50 % or 95 %. Therefore, both values are reported in this paper.

3.1 Releases from wells

A report from SCANDPOWER (SCANDPOWER, 2008) was used as the primary data source for the derivation of release scenarios and frequencies. This report provided the most reliable and representative data that are publically available. In this report, accidents from the SINTEF Offshore Blowout Database (SINTEF, 2006) are analysed and combined in order to derive frequencies for different release scenarios. A distinction is made between ‘blowouts’ and ‘full releases’, the difference being whether any of the barrier systems present on the well prior to the start of the release succeeded in stopping the flow (well release) or not (blowout). The duration of blowouts and full releases is not reported. In particular it is possible that a well release initially behaves just like a blowout. The report further distinguishes between ‘full releases’ and ‘restricted releases’ but a precise definition was not available. From personal correspondence it was understood that a full release is a full bore release and a restricted release are mostly leaks. For the derivation of release frequencies, SCANDPOWER uses different selections of data for various steps, including references to external reports. According to RIVM, these shifts between datasets compromise the reliability of the overall outcomes. SCANDPOWER also uses trends in time that are not statistically significant.

RIVM used the data for North Sea Standard wells but made several choices with respect to the categorisation of accidents and derivation of frequencies that differ from the choices from SCANDPOWER. The distinction between blowouts and well releases was dropped because the difference in (initial) release rate could not be quantified. The distinction between full releases and restricted releases was maintained and restricted releases were associated with a leak scenario in which the orifice diameter is 10 % of the casing or tubing (depending on the scenario). RIVM decided to not use decreasing trends in time for the release frequencies, as these trends were not statistically significant. Lastly, in order to be more robust, RIVM decided not to use average values for release frequencies but estimates associated with confidence levels. A more detailed description is provided in (Kooi and Spoelstra, 2011).

The release scenarios and frequencies resulting from the analysis are displayed in Table 1. These frequencies apply to the entire well including all safety valves present between the reservoir and the wing valve. A release can occur during standard operation (production or injection) or during well interventions (wireline, coiled tubing, snubbing or workover). A distinction is made between full bore releases and leaks. For leaks, a leak diameter of 10% of either the casing or the tubing is assumed, depending on the activity. For the release direction, a distinction between vertical and horizontal releases is made.

Table 1: Release scenarios and release frequencies for gas wells

Activity	Release scenario	Release direction	Release frequency (50 % confidence level)	Release frequency (95 % confidence level)
Production and injection	Tubing full release	Vertical	3.3×10^{-5} (y^{-1})	7.8×10^{-5} (y^{-1})
	Leak from tubing	Vertical	5.2×10^{-5} (y^{-1})	6.8×10^{-5} (y^{-1})
	Leak from tubing	Horizontal	9.4×10^{-6} (y^{-1})	1.6×10^{-5} (y^{-1})
Wireline	Tubing full release	Vertical	8.9×10^{-6} (per event)	2.1×10^{-5} (per event)
	Leak from tubing	Vertical	1.4×10^{-5} (per event)	1.8×10^{-5} (per event)
	Leak from tubing	Horizontal	2.6×10^{-6} (per event)	4.4×10^{-6} (per event)
Coiled tubing	Tubing full release	Vertical	1.9×10^{-4} (per event)	4.5×10^{-4} (per event)
	Leak from tubing	Vertical	1.1×10^{-4} (per event)	1.4×10^{-4} (per event)
	Leak from tubing	Horizontal	3.3×10^{-5} (per event)	6.5×10^{-5} (per event)
Snubbing	Tubing full release	Vertical	4.2×10^{-4} (per event)	8.8×10^{-4} (per event)
	Leak from tubing	Vertical	2.6×10^{-4} (per event)	3.3×10^{-4} (per event)
	Leak from tubing	Horizontal	7.6×10^{-5} (per event)	1.3×10^{-4} (per event)
Workover	Casing full release	Vertical	6.1×10^{-5} (per event)	9.9×10^{-5} (per event)
	Tubing full release	Vertical	2.4×10^{-4} (per event)	4.0×10^{-4} (per event)
	Leak from tubing	Vertical	2.7×10^{-4} (per event)	3.1×10^{-4} (per event)
	Leak from tubing	Horizontal	6.4×10^{-5} (per event)	9.0×10^{-5} (per event)

3.2 Interunit piping

For high pressure interunit natural gas pipelines, new failure frequencies were derived (Van Vliet et al., 2011) because it was expected that the existing frequencies (RIVM, 2009) were not representative for the considered pipelines. These pipelines were defined as pipelines with a length of at least 25 m, a pressure of at least 16 bar (1.6×10^{6} Pa), an internal diameter of at least 2" (0.05 m) and a condensate to gas ratio not higher than 80 m^3 condensate per million standard m^3 gas.

As a start, the possible release scenarios were investigated. For the considered pipelines a leak with a hole diameter above 50 mm is believed to propagate into a full bore rupture. Consequently, the resulting QRA scenarios for piping are full bore rupture and leak with a maximum hole diameter of 50 mm. For flange connections, an analysis of fracture mechanics showed that rupture at a flange connection will not

occur because the flange connection can withstand a larger impact and stress than the pipe itself. Leaks from flange connections do occur and should be included in the risk assessment.
For the derivation of failure frequencies, a detailed investigation was carried out, using accident data from oil and gas companies that operate in the Netherlands, the HCRD offshore data and EGIG data for cross-country transmission pipelines amongst others (Van Vliet et al., 2011). The resulting frequencies are presented in Table 2. The presented frequencies do not include failure due to lifting activities, vehicle movements or domino effects from leaks of nearby equipment. These contributions should therefore be assessed independently and be added to the frequencies presented in Table 2.

Table 2: Release scenarios and release frequencies for interunit gas pipelines

Release scenario	Release frequency (50% confidence level)	Release frequency (95% confidence level)
Full bore rupture	5.6×10^{-9} (m^{-1} y^{-1})	8.1×10^{-9} (m^{-1} y^{-1})
Leak from pipeline	2.0×10^{-8} (m^{-1} y^{-1})	2.2×10^{-8} (m^{-1} y^{-1})
Leak from flange connection	9.3×10^{-7} (y^{-1} per connection)	2.6×10^{-6} (y^{-1} per connection)

* The presented frequency for full bore rupture of a pipeline does not include failure from on-site lifting activities or vehicle movements, nor the probability of a domino event from a leak of nearby equipment.

3.3 High pressure centrifugal compressors

As with high pressure (interunit) piping, the generic leak frequencies for pumps and compressors that are reported in (RIVM, 2009), were not deemed representative for the pumps and compressors that are used by Dutch gas industries. This applies particularly to high pressure centrifugal gas compressor systems. These were defined as compressor systems where the pressure at the high pressure end is 16 bar (1.6×10^{6} Pa) or higher.
For high pressure centrifugal gas compressor systems, Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) showed that rupture of the compressor body is unlikely. For QRA, only failure of the associated piping needs to be considered. An extensive description of the investigation will be provided in (Uijt de Haag, 2013).
The resulting failure scenarios and frequencies for high pressure centrifugal pumps are reported in Table 3. In the derivation of these frequencies, it was assumed that a standard centrifugal compression system has 20 m of associated supply and discharge piping with three valves and seven flange connections and 10 m of recycle lines with two valves and two flange connections.

Table 3: Release scenarios and release frequencies for high pressure centrifugal gas compressors

Release scenario	Release frequency (50% confidence)	Release frequency (95% confidence)
Full bore rupture of the recycle line	5.6×10^{-8} per year	8.1×10^{-8} per year
Leak from the recycle line	3.9×10^{-6} per year	1.1×10^{-5} per year
Full bore rupture of the supply line	1.1×10^{-7} per year	1.6×10^{-7} per year
Leak from the supply line	9.7×10^{-6} per year	2.6×10^{-5} per year

3.4 Domino effects and fire and gas detection systems

The failure frequencies presented in the previous sections do not include the contribution from domino effects. For standard equipment scenarios, such as the catastrophic rupture of a vessel, the underlying causes are not known in sufficient detail in order to specify the contribution of domino effects (RIVM, 2009). For interunit pipelines, the new failure frequencies only include mechanical failure (Van Vliet, 2011). Domino effects can be relevant (Landucci, 2012) and should be assessed independently. Fire and gas detection systems can reduce the inventory released in case of a domino effect and should be taken into consideration when present (see section 4.3).

4. Consequence and impact assessment

For consequence analysis the dominant parameters are the released volume and release rate, the release direction, the probability of ignition and time of ignition and the events associated with ignitions. These parameters will be discussed in the following subsections. Currently, no toxic effects are considered for installations within the Netherlands because the amount of toxic components in the natural gas (predominantly H_2S) is low (see Section 4.5)

As a result of the requirement of reproducibility of QRA outcomes, the use of the software tool SAFETI-NL is prescribed. SAFETI-NL was selected as the unified software tool following a European tender in 2005 (Uijt de Haag, 2007).

The presented requirements for consequence analysis deviate from the requirements that were used before. The method must therefore be evaluated against realistic cases before it can be implemented in legislation. This evaluation will be carried out in 2013.

4.1 Release direction

A vertical release direction is assumed for well blowouts and the majority of leaks from wells (see Table 1). A vertical release direction is also used for buried pipelines and pipelines in a ditch. The exact criteria – how deep should the ditch be? – are still under debate. For all other releases a horizontal release direction is assumed.

4.2 Ignition probability

For horizontal releases, we proposed to use the methodology of (RIVM, 2009). For natural gas release, the probability of immediate ignition is 0.02 for release rates below 10 kg/s, 0.05 for release rates between 10 and 100 kg/s and 0.09 for higher than 100 kg/s. Delayed ignition is supposed to occur if the flammable cloud meets an onsite ignition source or if it crosses the site boundary. The latter is a conservative assumption that is implemented in the Dutch legislative framework and accounts for possible future off-site spatial developments. A report from the Energy Institute (2006) was used to verify the probability of immediate ignition but no specific data for (natural) gas plants were available. Moreover, the overall probability of ignition varied substantially between the various literature sources reported in (Energy Institute, 2006). A more detailed description of the limitations of the correlations proposed by the Energy Institute is provided by (Pesce, 2012).

For vertical releases an analogy with natural gas (cross-country) transportation pipelines was proposed, for which ignition probabilities have been derived from accident statistics (Acton et al., 2002). The total ignition probability depends on the pipe pressure and diameter and varies between 0.08 for a 2" (0.05 m) diameter pipeline at 20 bar (2×10^6 Pa), to 0.80 for a 48" (1.22 m) pipeline at 100 bar (1×10^7 Pa). A fraction of 0.75 is associated with immediate ignition and 0.25 with delayed ignition.

4.3 Released inventory and release rate

For standard release scenarios, it is assumed that the failing installation is not isolated prior to the start of the release (see section 3.4). The inventory of the vessels at gas production and processing plants is usually small compared to the gas that can flow from adjacent equipment after the start of the release (if the equipment is not isolated). Therefore, this back flow is highly important and should be taken into account in the risk analysis. For domino effects, a fraction of the contribution can be considered as isolated prior to failure when fire and gas detection systems are present.

High pressure gas systems rapidly depressurise and therefore the time-dependency of the release rate is taken into consideration. Immediate ignition is associated with the average release rate during the first 20 s of the release, while delayed ignition is assumed to occur after 120 s. This assumption is in line with the methodology used for cross-country pipelines. For Emergency Shut Down, Valves one scenario is used in which the shut down is successful and one in which it is not. For complex systems it is not easy to determine the time-dependency of the release rate. It is currently investigated if it is possible to provide further guidance to determine the (time-dependent) release rate for complex systems.

4.4 Associated events

Because flow from adjacent equipment is considered for all standard release scenarios (such as the catastrophic rupture of a vessel), nearly all releases have effectively become continuous releases. Subsequently, immediate ignition and delayed ignition are both associated with the occurrence of a jet fire. The release rate for the two jet fires differs for immediate and delayed ignition (see previous subsection). It was verified that the footprints of these jet fires are larger than the footprints of the flash fire and vapour cloud explosion that may also occur when the flammable cloud ignites. A tailor-made risk assessment is advised for High Integrity Pressure Protection Systems that respond extremely fast (valves closing within seconds).

4.5 Toxicity

Natural gas usually contains a small amount of hydrogen disulfide (H_2S) and therefore consequence and risk calculations were carried out to determine if toxic effects were relevant for the risk assessment. For Dutch gas fields, the amount of H_2S is usually lower than 1 vol.% but can be as high as 3 vol.%. In the

SAFETI-NL framework, flammable effects are modelled when ignition occurs and toxic effects if ignition does not occur. Two types of risk calculations were compared: one for flammable effects (presuming delayed ignition occurs) and one for toxic effects (assuming delayed ignition does not occur). For mixtures with 3 vol.% of H_2S or less, the calculated risk was highest when flammable effects were modelled. For these mixtures, it is therefore a conservative approach to assume that delayed ignition occurs and to omit the possibility of non-ignition with subsequent toxic effects. It is stressed however, that the presence of H_2S in natural gas can yield to lethal toxic effects outside the terrain boundary. Furthermore, a new and more conservative probit for the toxicity of H_2S is proposed (Hansler, 2012). This could yield to different outcomes if this probit were approved by the responsible parties in the future.

4.6 Vulnerability parameters

For consistency reasons, the same parameters are used as for other types of chemical industries (RIVM, 2009). For the jet fire, a heat radiation of 35 kW/m^2 or higher is assumed to be 100% lethal. For lower radiation levels a probit function is used presuming an exposure duration of 20 s. A heat radiation of 9.8 kW/m^2 results in a calculated probability of fatality of 1 %.

5. Conclusions

A method is proposed for the calculation of Individual Risk and Societal Risk for onshore natural gas production and processing plants. New release frequencies had to be defined for wells, interunit pipelines and high pressure centrifugal compressors. For consequence analyse, back flow from adjacent equipment must be considered. The time-dependency of the release rate is accounted for by using two release scenarios; one for immediate ignition and another for delayed ignition. For plants with a complex site lay-out, the time-dependent release rate may be difficult to assess and may require further guidance. Tailor-made solutions may be required for installations where fast response shut-down systems are installed.
The outcomes of the method will be evaluated against a set of realistic cases in 2013. Implementation in legislation is scheduled for 2013 but depends on the outcomes of the case evaluation.

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