TOWARDS A METHOD TO CALCULATE RISKS OF UNDERGROUND PIPELINES TRANSPORTING HAZARDOUS SUBSTANCES

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The Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) has announced new legislation concerning pipelines transporting dangerous substances. This legislation deals with the spatial reservation of (new) pipelines and its effect on spatial planning. For pipelines transporting natural gas or flammable liquids risk methodologies have been revised in order to reflect new understandings in risk scenarios, failure frequencies and consequences. These methodologies are applied in Dutch risk calculations. The generic risk methodology for pipelines transporting hazardous substances other than natural gas or flammable liquids is currently drawn up. These pipelines have a total length of about 3000 kilometer and 18 different chemicals such as ethylene, hydrogen, chlorine and carbon dioxide are involved. As far as possible the experience from the already developed methods for pipelines with natural gas or flammable liquids is used. This paper describes the development of the risk method for underground pipelines transporting hazardous substances other than natural gas or flammable liquids. Subject of special interest is the determination of failure frequencies as for these pipelines only few failure data is available.

INTRODUCTION

The External Safety Establishments Decree (BEVI) and its associated Dutch regulation, the REVI, entered into force in late 2004 [VROM, 2004]. This legislation established linkages between public safety, land-use planning and disaster response. The Decree is essentially about managing risk through both limitations on land use and environmental licensing for hazardous establishments. It also makes it mandatory to perform risk calculations by means of the Reference Manual Bevi Risk Assessments [RIVM, 2009a] and a specific software program (Safeti-NL, the Dutch version of Phast Risk [DNV, 2010]). The reason for this is to obtain risk calculations that are as unified as possible. BEVI is meant for establishments; for pipelines transporting hazardous chemicals new legislation is being prepared and expected to be presented in 2011 External Safety Pipeline Decree (BEVB). In this, requirements and commitments similar to BEVI will be described for operators of pipelines as well as competent authorities.

A quantitative Risk Assessment (QRA) provides insight in the impact of possible releases of hazardous substances to surrounding areas. The risk indicators calculated in a QRA are the individual risk and the societal risk. The individual risk is a measure of the level of protection offered to each individual member of the public while the societal risk is a measure of the disaster potential for the society as a whole [BEVI, 2004]. The individual risk is expressed as the risk of fatality per year; this is defined as the probability that an unprotected person residing permanently at a fixed location will be killed as a result of an accident occurring at a hazardous source. The societal risk is defined as the probability that a certain number of victims will be exceeded during a single accident at a hazardous source; it is expressed as the relationship between the number of people killed (N) and the cumulative frequency per year (F) that this number will be exceeded. For both the individual risk and societal risk, criteria limits have been set. For dwellings and vulnerable objects like schools and hospitals, the individual risk limit is set at 10^{-6} per year. For less vulnerable objects like small office buildings, restaurants, shops and recreation facilities, the individual risk contour of 10^{-6} per year is a guidance value. The limit for the societal risk is an indicative limit. For transport routes, the limiting frequency (F_{lim}) per kilometer of pipeline for the occurrence of an event with N or more deaths is shown by:

$$F_{\text{lim}}(N) = \frac{10^{-2}}{N^2} \tag{1}$$

In zoning policy, the individual and societal risks complement each other. The individual risk creates a distance between the potential hazardous source and its surroundings. The societal risk limits the population density around the potential hazardous source.

The National Institute for Public Health and the Environment (RIVM) in the Netherlands has developed methods to calculate the individual and societal risk for two types of pipelines, namely pipelines transporting high pressure natural gas [Laheij, 2010], [Gielisse, 2008] and pipelines transporting flammable liquids [van Vliet, 2009]. This paper describes the process of developing a risk method for underground pipelines transporting hazardous substances other than natural gas or flammable liquids. The process of developing a risk method comprises sub processes such as collecting reliable data, performing calculations and discussions with the parties involved. The parties involved are the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM), the pipeline operators and RIVM. VROM has ordered that risk calculations of underground pipelines transporting other hazardous substances should be calculated with Safeti-NL.

For pipelines transporting high pressure natural gas sufficient data with respect to historical data, causes and consequences was available. To a lesser extent the same holds for pipelines transporting flammable liquids, but for pipelines transporting other hazardous substances data is rather scarce. This paper gives insight in the realization of the methodology for pipelines transporting other hazardous substances and shows the choices and decisions that were made as well their justification.

BACKGROUND

GENERAL BACKGROUND

In the Netherlands about 18,000 km of underground pipelines transport hazardous materials. 70% of these pipelines contain high pressure natural gas, 13% contain (highly) flammable liquids and 17% contain other hazardous substances. The risk method to be developed for pipelines transporting other hazardous substances comprises 18 chemicals which differ in hazardous properties and/or physical state. Table 1 presents the chemicals involved.

The amount of chemicals concerned complicates the development of the method, because the method should preferably be applicable to all the 18 hazardous substances. To simplify the method and in order to come to a well endorsed and supported risk method, it is our intention to attune as good as possible to the methods for pipelines transporting high pressure natural gas and flammable liquids. For that reason the next paragraphs give a short description of the methodologies already developed for these pipelines.

HIGH PRESSURE NATURAL GAS

The following aspects are included in the methodology for pipelines transporting natural gas:

- The only scenario considered is rupture as leakage does not significantly contribute to the risk.
- Rupture may lead to a jet flame and the consequences are determined by the resulting heat radiation. The overpressure effects don't contribute to the risk.
- The main cause of failure is external interference. The probability of a pipeline rupture is therefore a function of the diameter, pressure, wall thickness, yield strength and Charpy energy of the pipeline.
- Failure frequencies are derived from historical data of Nederlandse Gasunie N.V. comprising 12,500 kilometers of underground pipelines transporting high pressure natural gas.

FLAMMABLE LIQUIDS

The following aspects are included in the methodology for pipelines transporting flammable liquids:

- The only scenario considered is rupture as leakage from a hole ($\leq$20 mm) does not significantly contribute to the risk.
- Rupture may lead to a gusher. The content of this gusher is restricted to the sum of the amount of liquid being released within a closing time of 1 minute of the pump and the outflow of liquid due to expansion of compressed liquid. The total content forms a pool with a thickness of 0.05 meters.
- A generic failure frequency of 1.4×10^{-4} km^{-1} year^{-1} is used, derived from Dutch data included in the CONCAWE database.

METHODOLOGY

Risk is a function of the probability of a loss of containment (LOC) and the effect of that LOC to human beings. Some parameters determine the probability of failure while others may influence the consequences. In this paragraph the most important aspects in risk calculations of underground pipelines transporting hazardous substances are described. Some of these parameters are described in the Reference Manual Bevi Risk Assessments [RIVM, 2009a]

Table 1. Survey of the 18 chemicals that are transported in the Netherlands by underground pipelines

Property	Physical state		
	Liquid	*Liquefied gas*	*Gas*
Flammable	Isoprene Propylene dioxide Condensate	Ethylene n-Butane n-Butene Propylene Vinyl chloride	Hydrogen
Toxic	Formaldehyde (46%)	Chlorine	Carbon monoxide Hydrochloric acid
Flammable and toxic	Ethylene oxide	Ethylene oxide	Synthesis gas (H_2 and CO)
Asphyxiating			Carbon dioxide Nitrogen
Enhanced ignition			Oxygen

or in its predecessor the Purple Book [CPR, 1999]. The Reference Manual comprises establishments while the Purple Book includes pipelines as well. Both give guidelines for quantitative risk assessments. Parameters such as population and weather apply for all types of risk calculations and are therefore omitted in this paper. How to handle population is described elsewhere [VROM, 2007]. In the next paragraphs the development or derivation of the most important parameters is discussed.

SCENARIOS

The failure modes that should be assessed in a QRA for underground pipelines include leakage and rupture with the release direction always being vertical [CPR, 1999; Laheij, 2010]. When a defect is smaller than the so-called critical defect length, the puncture results in a leakage. This is modeled as a hole with a diameter of 10% of the pipeline diameter with a maximum of 20 mm. The owners of pipelines transporting other hazardous substances have suggested to use different hole sizes instead of one hole size. However, this implies that the distribution of failure frequencies for leakages from series of hole sizes should be known. As the owners could not deliver this distribution, the proposal was rejected.

When the diameter of a puncture is larger, the puncture will cause the pipeline to crack. This is modeled as a full bore rupture with a diameter equal to the internal diameter of the pipeline. The hazardous substance is released from both ends of the pipeline and therefore two-sided outflow is calculated.

In the methods for underground pipelines transporting natural gas and flammable liquids, leaks are not considered as they do not contribute to risk [Laheij, 2010; van Vliet 2009]. For flammable substances described in this paper, leaks are not considered for the same reasons. For pipelines transporting hazardous toxic substances leak scenarios might contribute to risk and are therefore always considered.

FAILURE FREQUENCIES

The failure frequencies for pipelines transporting other dangerous substances appeared to be a subject of many discussions between the parties involved. The first reason of course being the large influence to the risk, but a second reason was that this topic was something that owners of these pipelines could understand. How to cope with modeling the dispersion was much more difficult due to a lack of knowledge with the majority of the owners and due to the absence of reliable data.

The owners of pipelines transporting hazardous substances have suggested to use the failure frequencies according to British Standard PD8010-3:2009 where failure frequencies are given for onshore pipelines containing flammable substances (toxic substances are excluded) [BSI, 2009]. The starting point of PD 8010 is the UKOPA database in which historical data is gathered from 22,000 km of onshore pipelines [Arunakumar, 2007]. The major part of these pipelines transport natural gas (92%). According to the Dutch owners of underground pipelines involved the requirements in terms of design, construction, operations and maintenance are equal for pipelines transporting either natural gas or other hazardous substances. These requirements are covered by the Dutch standard NEN 3650 which applies to steel pipelines [NEN, 2006]. As the requirements are the same, the opinion is that this should result in similar causes of failure and failure frequencies.

The question to be answered is therefore whether the argument is conclusive that failure frequencies for pipelines transporting natural gas can also be used for pipelines transporting other hazardous substances. An RIVM protocol has recently been written that describes how failure frequencies should be derived or updated [RIVM, 2010]. The approach is to use first appropriate historical data, i.e. data from Dutch underground pipelines transporting other hazardous substances. If this data is somehow not available, data from similar or analogue pipelines can be used. Because of that, RIVM has asked the Dutch owners involved to dispose their historical data from 1975 to 2009. However, only a part of them had handed over their data which covers about 50% of the total length of pipelines transporting hazardous substances. From this a failure frequency for rupture of $5.9 * 10^{-5}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$ can be derived (including the statutory one-call system) and assuming that external interference contributes for 50% to rupture [Ham, 2010]. One operator handed over data of North-West Europe as well and when this is taken into account a value of $3.7 * 10^{-5}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$ for rupture is obtained. Assuming a ratio rupture – leak of 25–75 [Ham, 2010], a leak frequency of $1.10 * 10^{-4}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$ is obtained.

The state of affairs in December 2010 is that the draft method to calculate risks of underground pipelines transporting other hazardous substances prescribes that the owners that have not delivered historical data should use as starting point the failure frequency for rupture of $1.5 \cdot 10^{-4}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$. This failure frequency is used for pipelines transporting flammable liquids [van Vliet, 2009] and is thought to be the upper value for pipelines transporting other hazardous substances. The owners who have given insight in their historical data are allowed to use the failure frequency of $3.7 * 10^{-5}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$.

A small consequence study has shown that the risk contour of 10^{-6} per year for a number of pipelines has disappeared using the failure frequency of $3.7 * 10^{-5}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$. As this contour is used to distinguish safe and unsafe areas, the owners of these pipelines, RIVM as well as the Ministry of VROM have difficulties with this finding. The reason for the owners is that they want to protect their pipelines and thus want to prevent developments nearby. They want therefore significant risk contours and consequently want to use the maximum possible frequency for rupture of $1.5 * 10^{-4}\,\mathrm{km}^{-1}\,\mathrm{year}^{-1}$. The reason for RIVM is that it is an unsatisfactory situation to have two different failure frequencies. It is the opinion of

RIVM that the failure frequency obtained from suitable historical data of underground pipelines transporting other hazardous substances should be used instead of the maximum value. The reason for the Ministry of VROM is that with the absence of the risk contours of 10^{-6} per year it has no arguments towards the owners of the pipelines to improve pipeline safety by means of measures. Therefore the Ministry of VROM needs to make as soon as possible a decision which frequency is being used in which situation.

EVENTS

For the hazardous substances involved the most important events are outlined in Tables 2 and 3. The content of these tables are closely related to the scenarios that are taken into account. Overpressure effects are not considered, because the effects of overpressure are assumed to be smaller than the effects of heat radiation. Note that for substances that are both flammable and toxic, the flammable characteristics are only considered when direct ignition occurs.

IGNITION PROBABILITY

The probability of ignition of flammable releases can have a major influence on the estimated risks in a QRA. Therefore, care must be taken in specifying the ignition probabilities for flammable substances.

For pipelines transporting natural gas the ignition probabilities are outlined in more detail in [Gielisse, 2008]. It has been found that a linear relationship exists between the probability of ignition P_{ign} and the pressure p in the pipeline and the diameter D of the pipeline: $P_{ign} \sim pD^2$. Pign is 0.80 at the most with a P_{direct}:$P_{delayed}$ distribution of 0.75:0.25. The Purple Book only gives probabilities of direct ignition (P_{direct} is 0.09) and states that the probability of delayed ignition is (1-P_{direct}) at the most because there is a probability of no ignition at all [CPR, 1999]. Nevertheless, the only flammable gas to be considered in the methodology for hazardous substances is hydrogen. A high probability of direct ignition is necessary given its low minimal ignition energy. Given the high pressure by which hydrogen is transported (44–100 barg), it is reasonable to assume that with the release of hydrogen sufficient energy is developed to ignite hydrogen. Therefore P_{ign} is 1 with a P_{direct}:$P_{delayed}$ distribution of 1:0.

For pipelines transporting (highly) flammable liquids ignition probabilities are given in [van Vliet, 2009], although the flammable liquids considered in the method for other hazardous substances are all extremely flammable. For highly flammable liquids it is assumed that ignition will always occur with P_{direct} being 0.065 and $P_{delayed}$ 0.935. This is a conservative approach which is also used in risk calculations for establishments [RIVM, 2009]. The operators of pipelines transporting other hazardous substances have suggested to follow the report of UKOOA [Energy Institute, 2006] in which correlations and look-up tables for ignition probabilities of flammable substances are given. For (highly) flammable liquids the ignition probability for urban areas is 0.07 at the most. A strict distribution P_{direct}: $P_{delayed}$ for flammable liquids is not given, but may vary from 30:70 to 50:50. RIVM proposes to use the ignition probabilities as stated by Van Vliet as extremely flammable liquids are mostly related to highly flammable liquids.

For saturated liquids transported in pipelines the Purple Book only gives probabilities of direct ignition and states that the probability of delayed ignition is (1-P_{direct}) at the most, with P_{direct} being 0.30 [CPR, 1999]. The operators have suggested to use the results of the report of UKOOA. As with flammable liquids a strict distribution P_{direct}:$P_{delayed}$ is not given. As both sources employ the same probability of ignition and similar distribution for direct and delayed ignition, RIVM suggests to follow the Purple Book.

Regarding direct or delayed ignition, the release rate with direct ignition is calculated as the average release rate during the first 20 seconds. With delayed ignition the average release rate between 120–140 seconds is used.

Table 2. The main effects that are caused by rupture of an underground pipeline

Physical state	Direct ignition	Delayed ignition	No ignition
Flammable			
Gas	Jet fire	N.A.*	N.A.
Liquid	Jet fire + pool fire**	Pool fire	N.A.
Liquefied gas	Jet fire	Jet fire	No effect
Toxic			
Gas	N.A.	N.A.	Toxic cloud
Liquid	N.A.	N.A.	Toxic cloud
Liquefied gas	N.A.	N.A.	Toxic cloud
Flammable + toxic			
Gas	Jet fire	Toxic cloud	Toxic cloud
Liquid	Jet fire + pool fire	Toxic cloud	Toxic cloud

* N.A. = not applicable

** For flammable liquids a pool fire in combination with a jet fire is modeled. Although with flammable liquids a jet fire cannot be sustained for a considerable amount of time, it is still considered as the effects of the pool fire often dominates the risk.

Table 3. The main effects that are caused by leakage of an underground pipeline

Physical state	Direct ignition	Delayed ignition	No ignition
Toxic			
Gas	N.A.	N.A.	Toxic cloud
Liquid	N.A.	N.A.	Toxic cloud
Liquefied gas	N.A.	N.A.	Toxic cloud
Flammable + toxic			
Gas	Jet fire	Toxic cloud	Toxic cloud
Liquid	Jet fire + pool fire	Toxic cloud	Toxic cloud

MEASURES AND SPECIFIC MODELING

In order to reduce individual and/or societal risk, additional measures may be applied. These measures focus on reducing the probability of pipeline ruptures as there are hardly no measures available that reduce the effects of a pipeline rupture. The main cause of pipeline rupture is external interference for which RIVM has estimated the reduction factor of several applicable measures [Laheij, 2009]. However, as measures can be applied to all types of underground pipelines, measures are not considered in the current method. Instead, measures will be described in a separate module of an all-embracing method for underground pipelines that includes modules for each type of underground pipelines.

A fifth module will describe circumstances in which specific modeling is required. These are amongst other the presence of tunnels, fly-overs and fly-unders and situations in which underground pipelines will come aboveground. These facilities and situations may influence both the failure frequency and dispersion and need to be examined in more detail. Furthermore it is possible that this will imply that one needs to diverge from the agreed methods. As these considerations can be applied to all types of underground pipelines, specific modeling is not considered in the current method as well.

LOCATION

In order to keep calculations as simple as possible, rupture and leakage of a pipeline transporting other hazardous substances are calculated only once by the software program and the results are superimposed along the total length when the risks are calculated. Hereby a suitable spacing is used to create smooth risk contours. Failure of the pipeline occurs halfway a pipeline with a length of 50 km (or shorter when necessary). This approach therefore does not consider the actual location and circumstances in which a pipeline might fail.

In calculating the total release rate, the release rates of both ends of the pipeline are computed and summarized. For underground pipelines the release direction is always vertical. The reason for this is the idea that released material can only come aboveground by means of a vertical movement. However, the release direction can also have a horizontal component, but as the release angle is not known it is not taken into account.

AIR ENTRAINMENT

When a pipeline transporting pressurized gas ruptures, a crater is formed. The released gas forms a jet that will experience air entrainment as a result of turbulence along the edges of the jet and mixing of air into the jet at the base of the jet. Air entrainment at the base of the jet plays an important role as the velocity of the jet is considerably lowered and gas will be diluted in the jet. The higher the so-called pre-dilution air rate, the lower the discharge velocity of the released gas and the less the jet will be impulse driven. A jet fire with low momentum will be tilted due to wind effects and consequently will exert more heat at ground level compared to vertically oriented jet fires. For pipelines transporting high pressure natural gas, pre-dilution air rates are calculated using the Pipesafe program [ATP, 2010]. These values are also used for hydrogen, the only flammable gas that needs to be considered, as it is believed that these values are more or less independent of the transported substance.

With toxic gasses the jet converts to a toxic vapour cloud and air entrainment at the base of the crater should be taken into account in the dispersion calculations. However, preliminary calculations for several toxic gasses have shown that air entrainment hardly effects the consequences. For weak toxic gasses the discharge velocity is with or without air entrainment sufficiently high to give similar consequences. With the more toxic substances the differences are larger but do not exceed 5%. For that reason air entrainment is not taken into account with toxic gasses.

With liquefied gasses it is assumed that air entrainment at the base of the jet in the crater is not relevant as long as the released substance is flashing [Lees, 2005]. Therefore air entrainment is not taken into account with liquefied gasses.

PROBIT FUNCTIONS

When conducting a QRA, consequence models are used to predict the size, shape, and orientation of hazard zones. In order to compute the risk associated with each of these hazards, the impact on exposed humans is calculated. As outer limit of the hazard zones the boundary of 1% lethality is used, which is calculated by means of an appropriate probit equation. Probit equations are based on dose-response data and take the following form:

$$Pr = a + b \ln (C^n \times t) \qquad (2)$$

where Pr is the probit, C is the concentration of toxic vapor in the air being inhaled (ppm), t is the time of exposure (minutes) to concentration C and a, b and n are constants. Several probit equations are available from RIVM [RIVM, 2009a].

For flammable substances the following probit is used in the Netherlands [RIVM, 2009a]:

$$Pr = -36.38 + 2.56 \ln (Q^{4/3} \times t) \qquad (3)$$

where t is the exposure time in seconds and Q the radiation intensity (W/m^2).

Substances that are not toxic or flammable still may be hazardous due to asphyxiating effects or increased probabilities of ignition. Nitrogen for example is chemically inert but in large quantities it may cause asphyxiation. The following probit is used to calculate these effects [RIVM, 2009a]:

$$Pr = -65.7 + \ln (C^{5.2} \times t) \qquad (4)$$

Carbon dioxide is asphyxiating but has toxic properties as well. At present no appropriate probit is available although attempts are made by RIVM to obtain a robust probit by means of animal experiments [RIVM, 2009b]. Oxygen is not a hazardous substance in itself, but in large quantities it may increase the ignition probability of flammables. The effects can only be calculated qualitative [RIVM, 2009a].

SPECIAL TOPICS

- Hydrogen
  The level of heat radiated for hydrogen flames is smaller compared to hydrocarbon gasses due to the absence of soot particles. The software program however does not take this into account and therefore some characteristics of hydrogen needed to be altered. Unfortunately the extent of these adjustments are not known leading to no adaptation whatsoever, i.e. a conservative approach. Recently, the owners of hydrogen pipelines have given information in which it is stated that for large hydrogen jet fires the level of heat radiated is comparable to hydrocarbon gasses. The data for these findings are not complete yet but do found the conservative approach.
- Ethylene
  Ethylene is transported under supercritical conditions, a state that is up to now almost impossible to model. In close consultation with the owners involved agreement with respect to some modeling aspects are reached. It implies that the liquid phase of ethylene is considered.

FUTURE PLANS

The risk method described in this paper is currently being used by the owners of the pipelines involved to do some preliminary calculations. Based on their results in terms of errors, outcomes and questions the risk method might be adapted. In addition, due to improved insights with respect to the modeling of fluids there's a possibility that these may affect the risk method in the short-time. When the risk method is definitive a consequence investigation will be performed to reveal the so-called pressure points with respect to spatial planning. In the last stage the risk method will be formalized and come into force as part of the External Safety Pipeline Decree (Bevb).

CONCLUSIONS

In preparation of new legislation a quantitative risk analysis method for underground pipelines transporting other hazardous substances has been developed. This development has been done in close cooperation with the owners of the pipelines concerned. The outcomes of the development are presented.

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