Using the Linear Risk Integral (LRI) approach in pipeline QRA for a better application of risk mitigation measures

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Abstract

Minimizing the risks resulting from hazardous scenarios during the design of a given system is of superior importance in order to ensure a safe operation and to demonstrate and satisfy regulatory requirements. A common approach in the process industry for this purpose is to use Quantitative Risk Assessment (QRA) as a decision-making tool to effectively apply risk mitigation measures. The results of a QRA allow quantifying individual and societal risks and assessing them against risk criteria. While individual risk is usually presented in risk contours showing the acceptable and tolerable risk limits, societal risk is often shown in an FN-curve which presents the cumulative frequency F of all system-related hazardous events that result in N or more fatalities.

Regarding cross-country pipelines, societal risk and hence the FN-curve results are related to the pipe length. However, the likelihood and the consequences of hazardous events and subsequently the risk vary along the alignment of a pipeline due to e.g. different environmental, geological and operational conditions, different pipe geometries and population densities. Therefore, using an overall FN-curve approach for a cross-country pipeline has a major shortcoming: A precise detection of the pipe sections which are mainly contributing to the risk is not possible, which makes an effective application of risk mitigation measures difficult.

This can be overcome by presenting the societal risk using the Linear Risk Integral (LRI) approach which addresses the societal risk along the length of the pipe route. The LRI can be interpreted as the cumulative risk for the society, i.e. sum of individual risks caused by the pipeline at the related location. The LRI approach allows comparing different pipeline systems and routes, providing an integrated overview of the pipe related risks and applying risk mitigation measures in a highly efficient manner.

1. Introduction

Cross-country pipelines are the safest and most economic way for transmission of hazardous substances. Nevertheless, reducing the environmental and societal impact of accidental pipeline incidents is getting more and more important in order to improve both overall safety and public acceptance of cross-country pipelines. Although the CONCAWE Report 2011 and the EGIG Report 2011 show that the number of accidental incidents at oil and gas pipelines is decreasing consistently over the last decades which bears witness to the industry's improved control of pipeline integrity, **incidents like the Manitoba gas pipeline explosion in 2014 (Young 2014) indicate that understanding, managing and reducing risks shall be still of superior importance during the design, construction, commissioning and operational stages of a pipeline system, in order to ensure a safe operation.**

Process safety's guiding principle "Keep it in the Pipes" reflects its main goal, i.e. to avoid loss of containment leading to a release of hazardous material. A loss of containment occurring at a pipeline transporting hazardous substances may lead to several risk scenarios affecting population and the environment. Depending on the material properties, explosions, fireballs, jet fires, pool fires or toxic contamination may occur. In order to prevent such incidents to happen, their risks have to be investigated, assessed and properly managed.

For the investigation and assessment of risks in process industry, several techniques like a Risk Based Inspection (RBI) or traditional risk analysis and risk assessments exist (API 2000). They can be performed according to a qualitative, quantitative or semi-quantitative approach. Their results are often used to apply risk mitigation measures during early design stages.

Pipeline laying, Procejt: West Austria Gas Pipeline System

Regarding quantitative approaches, a QRA is able to deliver results with a high level of detail and accuracy. QRA has been used since the late 1960s and has grown from a coarse tool to a precise tool demonstrating cost effective risk acceptability and risk minimization (Nalpanis 2011). Several guidelines (e.g. de Haag 2005, RIVM 2009) and commercial software exist for the general performance of a QRA for process facilities. However, carrying out a QRA for cross-country pipeline systems requires special considerations during all study stages. In BSI 2009 a guide to the application of pipeline risk assessment is given. Recently, Spoelstra 2011 presented a method for the QRA of underground pipelines transporting hazardous substances. Further, Spoelstra 2013 describes the risk methodology for transmission pipelines transporting chemicals with which the consequences for land-use planning can be calculated. Neunert 2011 recommends special considerations related to the QRA of gas transmission pipelines

Assessing the risks related to individuals and the society of a given system, the individual and the societal risk have to be quantified. For both, risk criteria exist depending on governmental or company-related regulations showing the acceptability and tolerability limits. The results regarding individual risk are usually mapped in risk contours around the investigated facility or presented in form of a risk transect. Their probability values show the chance of fatality of one individual staying 24 h/day outdoor without protecting clothes at a certain location on-site or adjacent to the establishment. However, since hazards associated with pipelines tend to be high consequence low frequency events, it is more appropriate to use societal risk in order to assess the acceptability of pipeline risk. The societal risk results are usually shown in an FN-curve which shows the cumulative frequency F of all system-related hazardous events that result in N or more fatalities.

Using the FN-curve approach for a cross-country pipeline provides valuable information on the overall societal risk. However, this method has also the major shortcoming that it cannot reflect the variations of the societal risk along the pipe length. These variations are due to location related parameters such as failure frequency, severity of consequences and density/distance of population. Therefore, following only the results shown in the FN-curve would make it difficult to identify the locations with the highest contribution to the overall risk and to apply selected measures to reduce the risk to as low as reasonably practicable (ALARP).

The present paper presents an alternative approach for the presentation of the societal risk and compares it with the conventional FN-curve method. It is shown that the novel approach based on calculating the Linear Risk Integral (LRI) as a function of pipeline length allows overcoming the shortcomings of an FN-curve.

2. QRA Approach

One general goal of a QRA is to quantify the risks to population related to a given facility - i.e. the individual and societal risk - and assess them against risk criteria in order to satisfy regulatory requirements. In order to ensure that the overall risk is acceptable or tolerable, risk reducing measures are applied by following the ALARP principle (as low as reasonably practicable). Since risk is the product of likelihood and consequences of an undesirable event, it can be quantified by knowing the outcome of the event (number of fatalities) and its frequency of occurrence. Summing up the risk numbers of all hazardous events leads to the overall individual and societal risk values.

A typical QRA is comprised of five steps:

a. System definition
b. Hazard identification
c. Consequence analysis
d. Frequency analysis
e. Risk assessment

In the following the QRA steps are explained roughly focusing on special considerations for their application on cross-country pipelines transporting hazardous materials.

2.1 System definition

In the system definition phase, the goals and objectives are clarified and the boundaries of the investigated system are defined based on the physical and operating limits. Regarding a pipeline, the physical system is usually a pipe section or a complete pipeline system. Additionally, site specific data is collected during the system definition phase including information on weather, material properties, population density, operating conditions, potential ignition sources and on existing risk reducing measures. Since all this data may vary along a given pipe alignment, the data collection for conducting a QRA can be very time consuming. Further, information about soil cover depth, soil quality, coating conditions and laying procedures has to be included for buried pipelines.

For long cross-country pipelines it is therefore recommended to perform a coarse screening of the pipeline and select dedicated 'worst case' pipe sections which will be investigated in the risk assessment. Since population density is the major parameter influencing the risk, pipe sections adjacent to high populated areas are considered to have the highest risk contribution. However, during screening of the pipeline route, critical sections have to be additionally identified and included in the investigations; e.g. road crossings, river crossings, seismic areas, etc.

2.2 Hazard identification

Several techniques exist for the identification of hazardous scenarios, i.e. a Hazard and Operability Study (HAZOP), a Failure Mode and Effects Analysis (FMEA), checklist approaches or a Fault-Tree Analysis (FTA). Regarding cross-country pipelines, the hazardous events are scenarios leading to a release of hazardous material followed by potential fire, explosion or contamination events. As proposed in BSI 2009 and Spoelstra 2011, a QRA for transmission pipelines should cover a full bore rupture and typical leak scenarios depending on the incident causes and the pipe diameter. A hazardous scenario occurring at a pipeline may occur due to different causes. However, depending on the amount and type of release (continuous, instantaneous) and the material properties, different hazardous events may occur. Since a loss of containment may appear at any position along the pipe alignment, the calculation of the events is related to discrete locations. Proper discretization plays an important role, as it affects calculation effort and accuracy. According to Jo 2005, the discrete pipe sections should be short enough so that the calculated results are not influenced. A value of 10 m applied for the discretization length is proposed in the regulatory standards for performing risk analysis of transmission gas pipelines in Switzerland (Swissgas 2010).

2.3 Consequence analysis

A given hazardous scenario is followed by a chain of consequences which is modelled starting from the release of hazardous material and ending up in the determination of quantified values describing the hazardous effects on the population. Performing an event-tree analysis allows to visualize and investigate the pathway from the point of release to the possible end events. Commercial software provides calculation results of the discharge and dispersion behaviour of the released material, which depends on the amount and physical properties of the material, on its toxicity and flammability, on leak size and release conditions as well as on weather data. The release from pressurized below ground pipelines is usually accompanied by a crater formation yielding the discharged material towards vertical direction. The hazardous effects of toxic or contaminating and persistent materials can be directly quantified from dispersion calculations. Considering flammable materials, the effects of heat radiation or overpressures are determined by calculating the fire or explosion events, respectively. Therefore, the presence of oxygen (air) and ignition sources have to be known. Regarding cross-country pipelines aligned in rural areas, explosive events creating overpressures are hardly expected to occur, since an explosive pressure build up needs a flammable vapour cloud trapped in a confined environment. However, several events like the Ghislenghien gas explosion (ARIA 2009) showed that explosions scenarios have to be considered in a pipeline risk assessment. Possible heat radiation effects occur due to flash fires, fireballs, jet fires or pool fires.

BTC project: Pipeline construction in difficult terrain

2.4 Frequency analysis

The quantification of the individual and societal risks within a QRA requires a frequency and probability analysis. This includes the frequency of occurrence of all identified hazardous scenarios, the probabilities of different weather scenarios, the immediate and delayed ignition probabilities and the probability of presence of population located indoor and outdoor at the affected area. Empirical data is used to define the appropriate frequencies and probabilities. For cross-country oil and gas pipelines, appropriate values can be found in the CONCAWE Report 2011 and EGIG Report 2011, respectively.

2.5 Risk assessment

As mentioned above, risk is the product of likelihood and consequence. Thus, the risk results for all investigated hazardous scenarios of a given system can be quantified by combining the results of the consequence analysis with the frequency and probability data. Individual risk results (i.e. individual risk contours) are generated out of a risk summation approach by summing up the probabilities of fatality from all identified hazardous events to a location-specific probability of fatality. The societal risk results measure the risk to all people located in the effect zones of the incidents. It generally shows the frequency distribution of multiple fatality events. As mentioned above the societal risk is usually presented in forms of FN-curves showing the cumulative frequency F of all events leading to N or more fatalities.

The acceptability and tolerability of the individual and societal risk is defined by assessing the risk results against risk criteria. In case the results show unacceptable or intolerable risks, appropriate risk reducing measures have to be applied following the ALARP principle. For cross-country pipelines it is more effective to reduce the risks at special locations which mainly contribute to the overall risk. Regarding the individual risk, these locations can be easily identified by analyzing the individual risk contour plots. However, using FN-curves to identify the locations of the hazardous events with the highest contribution to the societal risk is often difficult. Therefore, it is recommended to use a linear approach for the presentation method of the societal risks related to pipelines.

3. Presenting and assessing societal risk

Performing quantitative approaches for identifying, assessing and managing risks related to population, results in individual and societal risk values. In order to reduce risks with appropriate measures it is required to present and understand the risks properly. The most common way of presenting societal risk is generating FN-curves. An FN-curve shows the cumulative frequency F of all events leading to N or more fatalities related to the investigated system. Figure 1 shows a typical FN-curve for a given establishment and the appropriate societal risk criteria in the UK and the Netherlands according to CCPS 2009.

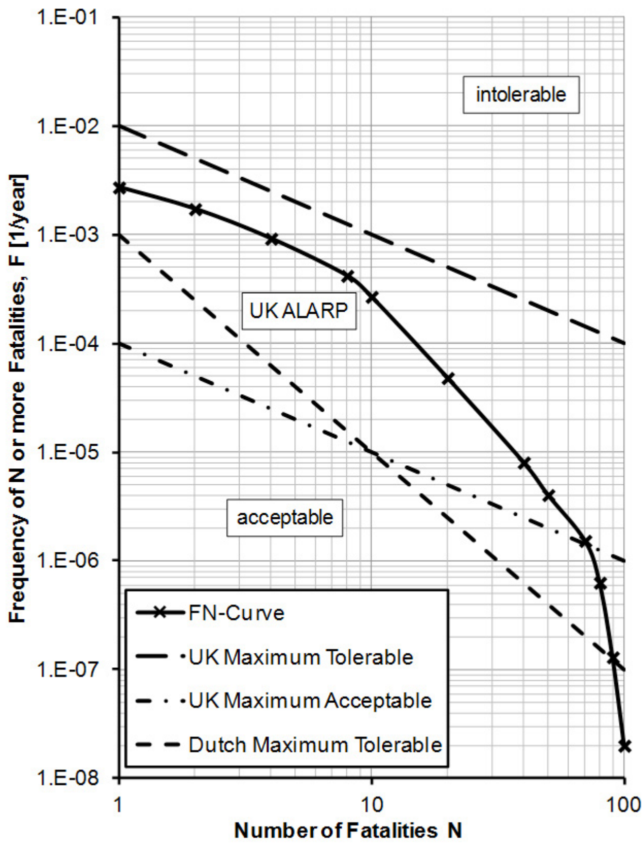

Figure 1: Typical FN-curve and UK/Dutch societal risk criteria for a process facility

As shown in Figure 1, by following the FN-curve approach the assessment of societal risk against given risk criteria can be easily performed. Depending on the risk limits the societal risk can be 'acceptable', 'intolerable' or 'tolerable but not acceptable'. In the latter case, risk reduction has to be performed according to the ALARP principle, i.e. the risk is only tolerable if risk reduction is impracticable or its costs are in disproportion to the gained improvement.

In order to enable a comparison between different facilities the societal risk can be reduced to a single number known as the Societal Risk Index (SRI) or Potential Loss of Life (PLL). According to API 2000, this index is generated by multiplying the frequencies of occurrence F with their corresponding numbers of fatalities N of each single event and summing up these numbers for all events related to the investigated facility. In order to assess societal risk the FN-curve is the most popular approach. However, regarding the presentation of the societal risk of cross-country pipelines it has a major shortcoming: A valid comparison between different pipelines or pipeline routes with different lengths is not feasible, since an overall FN-curve shows the cumulated frequencies of all events related to a facility. Therefore, several proposed methods exist in literature with appropriate length-related risk criteria. According to Spoelstra 2011, the societal risk of pipelines in the Netherlands is assessed per 1 km pipe length. The tolerability frequency limit F_{lim} of 1 km pipeline for the occurrence of an event resulting in N or more fatalities is given in Eq. (1).

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

A similar societal risk FN criterion exists in the UK. According to BSI 2009, the acceptability limit for the societal risk of any 1 km section of a pipeline route is defined by Eq. (2) separating the acceptable area from the ALARP area. The tolerability limit is defined as two magnitudes above the acceptability limit.

$$(2) \qquad F_{lim} = \frac{10^{-4}}{N}$$

Figure 2 shows the resulting frequency limits of Eq. (1) and Eq. (2) in an FN-diagram, corresponding to the societal risk criteria of 1 km pipeline in the Netherlands and UK, respectively.

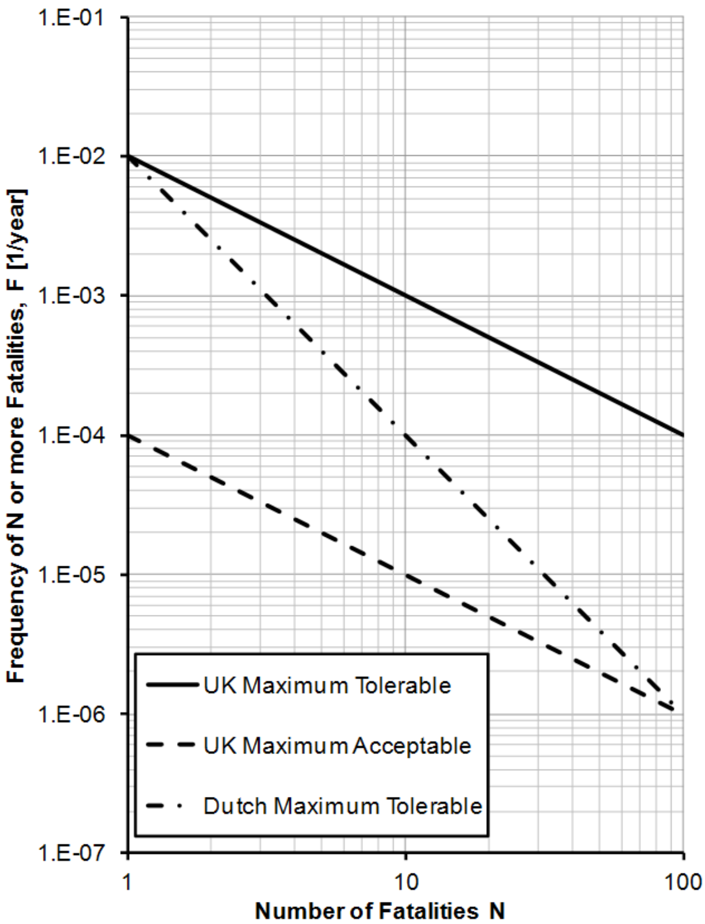

Figure 2: UK/Dutch societal risk criteria for 1 km of pipeline

BTC project: Ceyhan Terminal

In BSI 2009 it is proposed to generate a site-specific FN-curve by multiplying the frequency values F by a factor of 1 km divided by the total pipe length and to assess the resulting societal risk against the criteria shown in Figure 2.

In Swissgas 2010 a standardized approach is described to assess the societal risk of gas transmission pipelines in Switzerland. Following the Swiss methodology, the highest number of fatalities of the possible events occurring along the pipeline route is determined for each 10 m section of pipe. If events lead to consequences exceeding 10 fatalities at a given location, an FN-curve is generated for a pipeline segment of 100 m at this point. The FN-curve of each investigated 100 m pipe segment is assessed against risk criteria presented in Figure 3.

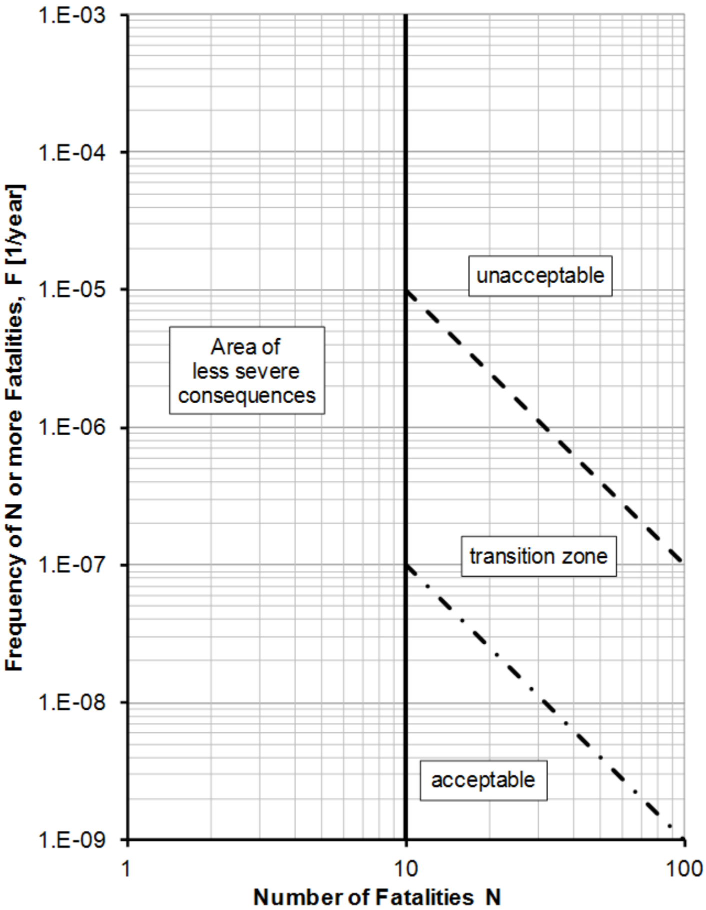

Figure 3: Societal risk criteria in Switzerland, Swissgas 2010

The above mentioned approaches indicate that for the successful assessment of pipeline risk, the FN-curve has to be related to a specific length allowing a comparison between different pipeline routes. However, they still have three major shortcomings which are described in the following:

a. Assessing societal risk is based on a section-wise determination of FN-curves and comparison against risk criteria. Besides the pipeline length, the segmentation and selection of the pipeline route sections is not defined in the regulatory regarding the exact position of the section's boundaries. It is obvious that this may have a significant impact on the societal risk results. To overcome this it is proposed in BSI 2009 to calculate a single site-specific FN-curve by multiplying the frequency values by a factor of 1 km divided by the total pipe length. However, using this method, peak areas prone to high risks can hardly be identified.

b. Consequences and failure frequencies of hazardous events usually vary along a given pipeline route. Therefore, significant differences of the societal risk over length exist. The efficient application of risk mitigation measures - e.g. re-routing, relocation of occupied zones, increased soil cover, increased pipe wall thickness, mechanical protection, visual signs (e.g. marker posts, warning tape), change in operational conditions, etc. - requires a precise detection of the pipe sections which are mainly contributing to the risks. Regarding long cross-country pipelines, the results and conclusions of a site-specific FN-curve are often insufficient for the application of adequate risk reduction measures. Further, for identifying the exact positions where to apply reduction measures, even sectional FN-curves related to 1 km or 100 m pipeline length are often not suitable.

c. For long cross-country pipelines, the presentation of the societal risk results requires the calculation and presentation of numerous FN-curves. This may often result in a documentation overload. Considering a pipeline system of 100 km length, the generation of 100 FN-curves is required in the Netherlands. In Switzerland a number of up to 1000 FN-curves may be required for the same pipeline

An alternative approach to present the risk of pipelines is addressing the societal risk results along its length, which is based on calculating the location-related Linear Risk Integral (LRI). The LRI can be interpreted as the Societal Risk Index (SRI or Potential Loss of Life, PLL) of a linear segment with a discrete length Δl. The LRI of a pipeline segment is calculated of the frequencies F and corresponding number of fatalities N of n contributing events related to the discrete segment length Δl. For a pipe segment located at a distance x the LRI can be determined with Eq. (3).

$$LRI(x) = \sum_{i}^{n} \frac{F_i(x) \cdot N_i(x)}{\Delta l} \qquad (3)$$

The LRI is understood as the measure of societal risk per km and year and can be interpreted as the cumulative frequency of fatalities per year caused by 1 km of pipeline at the related location. An example is shown in Figure 4. Figure 4 presents the LRI curve over pipe distance of a given pipeline with a length of 18.5 km.

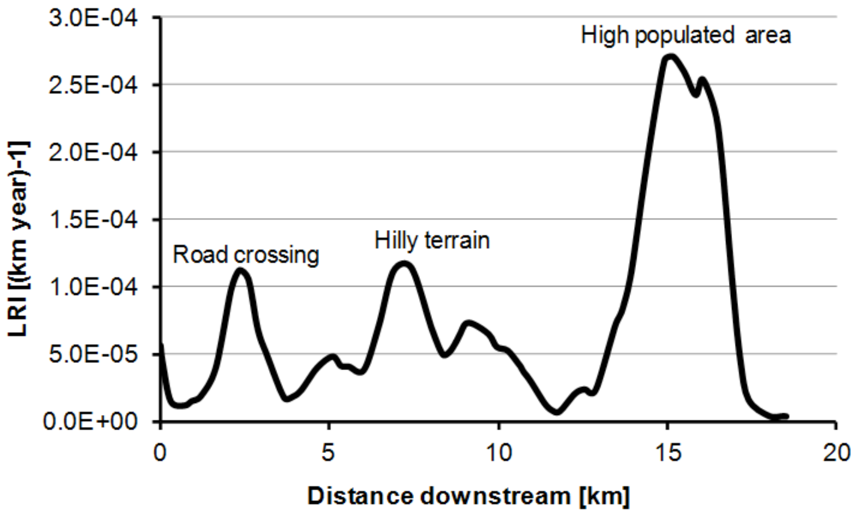

Figure 4: Societal risk of a pipeline: LRI curve over pipe distance

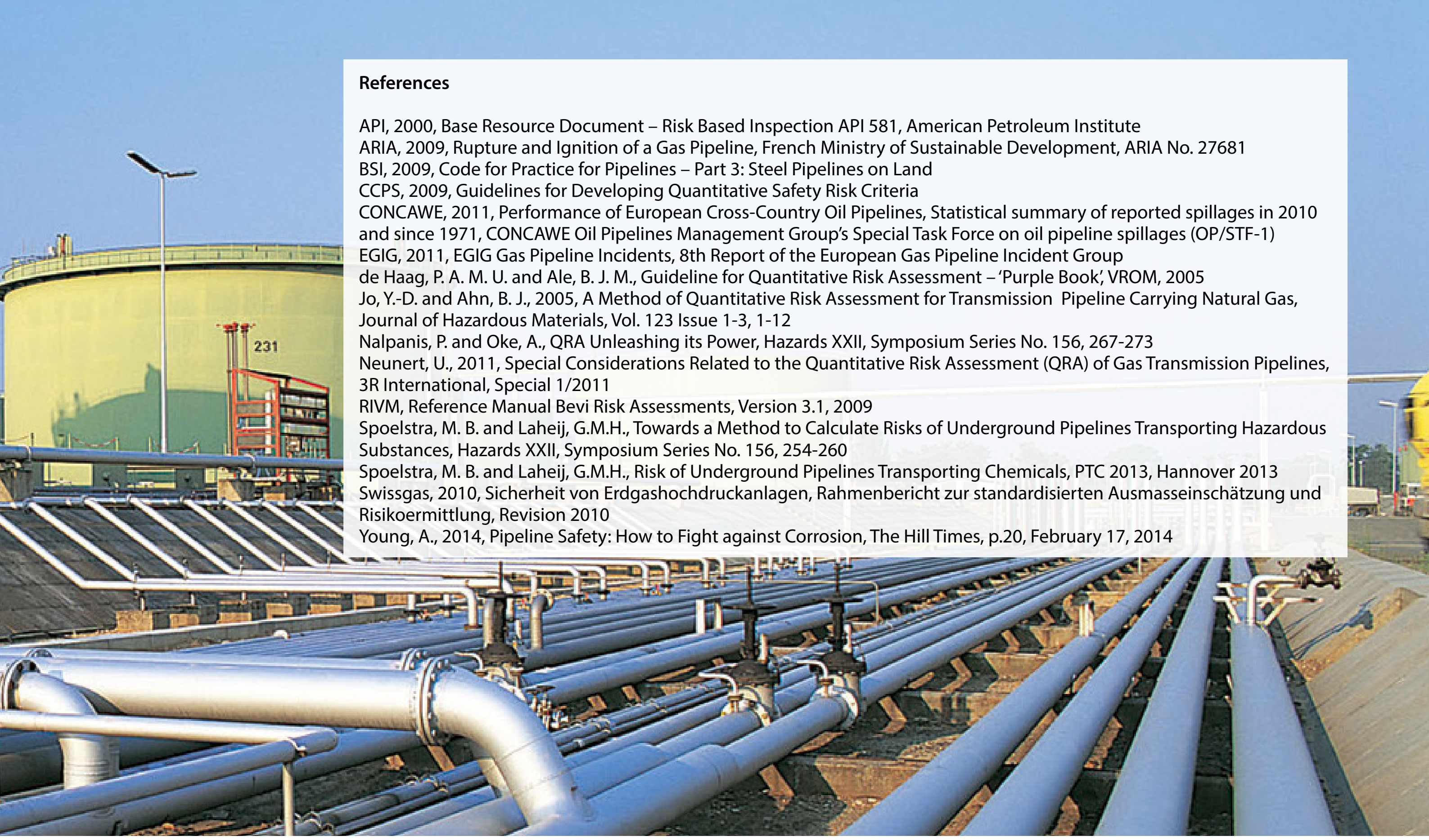

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Figure 4 indicates the location of pipe sections with a significant contribution to the societal risk. Near km 2.5 pipeline the frequency of incidents due to external impacts following vehicle accidents at a road crossing and subsequently the societal risk is increased. At km 7 the pipe is aligned through hilly terrain where a higher probability of land slides impacting the pipeline leads to a higher societal risk. For hazardous events occurring at the pipeline near km 15 an increased number of fatalities and therefore higher consequences are expected due to the vicinity of a high populated area. The results in Figure 4 clearly show where to implement measures in order to achieve the most effective risk reduction. As risk is composed of the frequency and consequences of several hazardous events which are based on several failure causes, a detailed investigation is required to select the best applicable risk reduction measures. Therefore, generating an LRI curve over pipe length is an advantageous method for comparing different pipeline systems and routes, to provide an overall view of the pipe related societal risk and to apply risk reduction measures efficiently. Due to the fact that regulatory risk criteria corresponding to the presented 'LRI over pipe distance'-curve in Figure 4 does not exist, the generation of section-wise FN-curves is additionally required to conduct a regulatory risk assessment.

4. Summary and conclusion

The present paper discusses different approaches for the presentation and assessment of societal risk results of cross-country pipelines generated with a Quantitative Risk Assessment (QRA). The different steps of a pipeline QRA are explained which lead to the quantified societal risk values which are usually presented in FN-curves. Based on the FN-curve approach the assessment of societal risk against risk criteria can be performed. Concerning the comparability of different pipeline systems and the application of risk reduction measures, it is shown that calculating and generating FN-curves is not sufficient. An alternative approach is presented based on a location specific determination of the societal risk along the pipe alignment by calculating the Linear Risk Integral (LRI). Presenting an LRI curve over pipe distance leads to a precise identification of the pipeline sections with the highest risk contribution. This allows a highly efficient implementation of potential risk reduction measures.

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