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The Future of the Pipeline Industry

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Klaus-Dieter Kaufmann

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The Future of the Pipeline Industry

Without pipelines the world economy would simply not function. They are unquestionably the safest and the most economic way for the mass transportation of liquids and gases.

According to statistics there are worldwide about 2 million km (50 times the length of the equator) of pipelines in operation and a further additional 1 million km are scheduled for construction between now and the year 2030. These figures underline the importance of this essential industry, an industry comprising design, construction, operation and maintenance activities.

Pipelines will continue to play an important role in the world economy even if the energy market does change as currently envisaged.

The development of pipeline technology was always principally driven by meeting new technical challenges, by increasing cost efficiency and since the beginning of the 21ST century by mitigating the environmental impact during construction and operation in order to improve the image and hence gain public acceptance and support of such facilities. This general trend will continue to develop in the future through such technological efforts including the following:

» to increase the operating pressure of gas pipelines in combination with the development of higher steel grades
» to save energy and to reduce CO_2 emissions by improving the efficiency of the rotating equipment in pump- and compressor stations
» to mitigate the environmental impact during pipeline construction by taking advantage of the great advances in trenchless technology
» to extend the life time of aging pipelines by state of the art cathodic protection, inline inspection and risk based maintenance
» to improve the safety and security of operating pipelines by impact detection systems

In addition to the advances in technology the future of the pipeline industry will be determined by other factors like:

» The routes of long distance pipeline routes will increasingly reflect geopolitical objectives
» The gas pipeline network including its underground storage facilities has the potential to store and transport renewable energy (wind and solar) in the form of hydrogen.
» Pipelines can be used to transport CO_2 as an element of the CCS (Carbon Capture and Storage) chain.
» Research, which is already in progress, to develop the technology for transporting electric power by conductors installed in buried pipelines

Some of the challenges and opportunities which are expected to characterize the future of the pipeline industry are covered in papers of the present edition of the 3R Magazine.

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Design of Safe, Reliable And Economic CO$_2$ Pipeline Transportation Systems

By Klaus–Dieter Kaufmann

SUMMARY: Carbon dioxide (CO$_2$) capture from power plants, its transportation through pipeline systems and its long term deposition in suitable onshore and offshore storage formations is considered a feasible method to limit global warming due to anthropogenic activities. Three basic carbon capture technologies near fossil fired power plants are hereby presently considered: post-combustion, pre-combustion and oxy-fuel.
The availability of reliable calculation methods for the most relevant CO$_2$ properties (density, viscosity, critical point), respecting the influence of 'impurities' on the physical properties for determination of the optimum techno-economic pipeline diameter, is a pre-requirement for safe, environment-friendly and economic pipeline design.
The article gives an overview on the main aspects and requirements in designing and operating new CO$_2$ transportation systems, addresses health, safety and risk related aspects of CO$_2$ pipeline transport and finally describes further investigations required to close remaining gaps of knowledge.

INTRODUCTION

Carbon dioxide (CO$_2$) capture from power plants, its transportation through pipeline systems and its long term deposition in suitable onshore and offshore storage formations is considered a feasible method to limit global warming due to anthropogenic activities. Three basic carbon capture technologies near fossil fired power plants are hereby presently considered: post-combustion, pre-combustion and oxy-fuel [1].

Demonstration projects are being initiated worldwide to prove the feasibility of carbon capture and storage (CCS), e.g. Weyburn (Canada), In Salah (Algeria), Snøhvit (Norway), Hatfield (UK), Rotterdam (The Netherlands), Compostilla (Spain), Porto Tolle (Italy), Jänschwalde (Germany) and Belchatów (Poland) [1,2].

CO$_2$ pipeline systems with today more than approx. 5,800 km total length are installed in U.S.A. since more than approx. 25 years transporting mainly relatively pure CO$_2$ streams from natural sources for enhanced oil recovery (EOR) through sparsely populated areas [1,3]. CO$_2$streams separated in CCS plants in Western Europe may, however, run most probably through densely populated areas and may contain by-products ('impurities') like H$_2$S and SO$_2$.

HYDRAULIC LAYOUT CONSIDERATIONS

Phase Diagram and Normal Pipeline Operating Conditions

To ensure stable, controllable and economic CO$_2$ transport in pipelines, operation in the so-called 'dense phase' (a collective term for liquid and/or supercritical phase [4]) is recommended. **Figure 1** shows a phase diagram of pure CO$_2$ with assumed pipeline operating range up to 140 bar.

Considerable higher pipeline operating pressures might be required in cases where the CO$_2$ stream shall be injected into high-pressure offshore wells e.g. if additional injection facilities cannot be installed at the offshore injection site.

Density and Viscosity

Figures 2 and **3** show density and kinematic viscosity of pure CO$_2$ which were calculated based on high-accurate property calculation routines [5].

Hydraulic Profiles

Temperature and pressure profiles of CO$_2$ pipelines can be determined, similar as for oil and gas pipelines, using section-averaged density and viscosity values. For more accurate calculations, the influence of friction pressure losses (Joule-Thomson effect) and of major elevation differences (isentropic compression / expansion effect) on temperature profile should additionally be respected [6].

Figure 4 shows exemplary the typical pressure and temperature profile of a 24" (DN 600) pipeline system transporting 1,200 tons per hour of pure CO$_2$, assuming 130 bar and
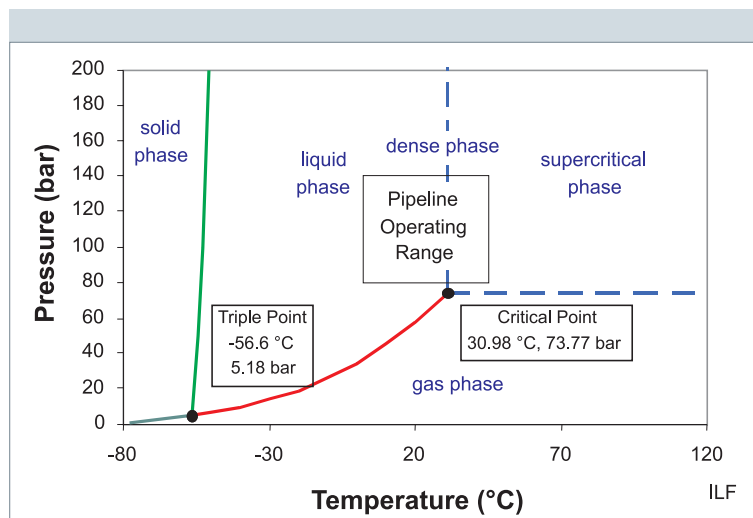

FIGURE 1: **Pressure-Temperature Phase Diagram of Pure CO$_2$**

40°C as inlet conditions. An intermediate transport station is incorporated after approximately 170 km. The pressure and temperature fluctuations in the profiles result from an assumed elevation profile along the route.

Influence of Impurities

Additional by-products ('impurities') in a CO_2 stream like O_2, H_2, SOx, NOx, H_2S, TEG, MEG and amines/NH_3 resulting from the individual CO_2 capture processes must be considered in the

FIGURE 2: **Density (kg/m³) of CO_2 as a Function of Pressure and Temperature**

FIGURE 3: **Kinematic Viscosity (mm²/s) of CO_2 as a Function of Pressure and Temperature**

FIGURE 4: **Pressure and Temperature Profile of a 24"(DN 600) CO_2 Pipeline System**

hydraulic design of a new CO_2 pipeline system. These components may take considerable influence mainly on CO_2 density, and on pressure and temperature of the Critical Point. This, in consequence, may require higher operating pressures, frictional losses and power demand to initially compress the CO_2 stream in the pipeline head station from the relatively low CO_2 separation pressure to the pipeline pressure.

Table 1 shows exemplary the DYNAMIS specification of a CO_2 stream captured in a co-production process of electricity and hydrogen taking also safety and toxicity limits into account [7].
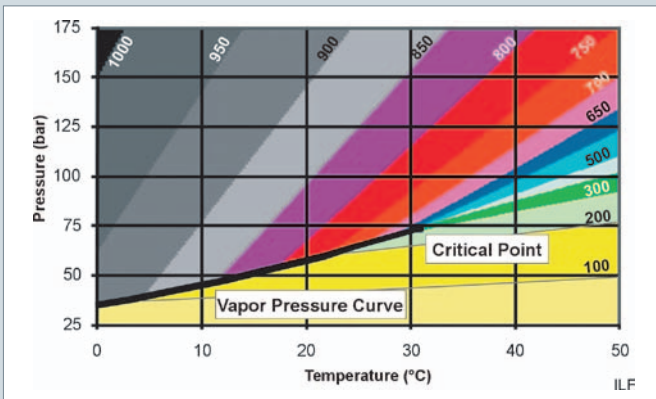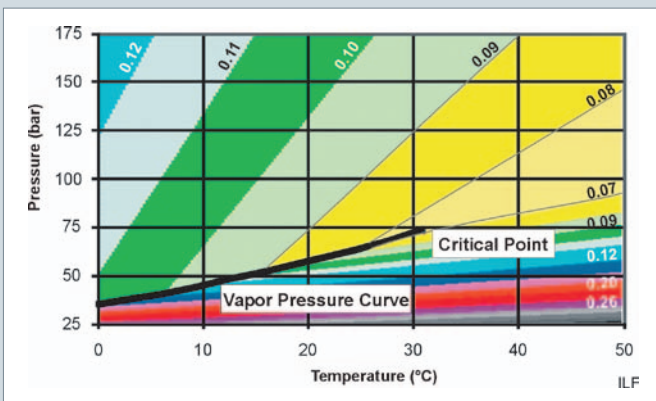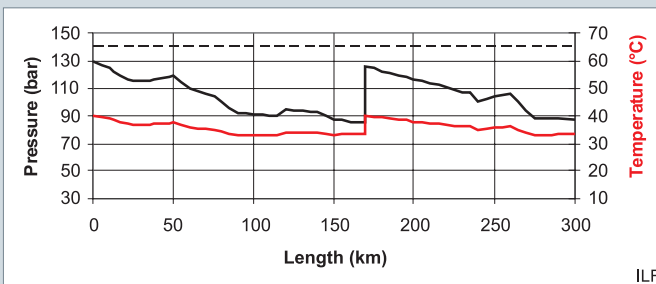
Initial Compression

In order to compress the CO_2 stream from the (relatively low) outlet pressure of the capture plant to the inlet pressure of the pipeline, the conventional design comprises a multi-stage compression process (approx. 4 to 8 stages) including inter-stage cooling and water separation. However, also other compression strategies via cryogenic liquefaction and pressure increase via pumps have been considered.

PIPE MATERIAL SELECTION

Corrosion and Material Compatibility

In order to avoid severe corrosion in CO_2 transportation systems, the water content has strictly to be controlled. Experts are still discussing the adequate maximum allowable water content (range 50-500 ppm) [1]. Related additional investigations are ongoing, investigating also the influence of impurities on corrosion [4]. Reducing the water content adequately can also prevent formation of hydrates which may plug pipe sections and equipment.

Corrosion resistant alloy steels (also as cladding material for carbon steel pipes) are an option for shorter pipeline sections or for the piping section(s) upstream the dehydration unit(s).

External pipeline coating materials must be qualified for all operating conditions, especially for low temperatures occurring during intended or unintended depressurization of the pipeline.

Sealing materials e.g. in valves and metering equipment must be compatible with CO_2 and with the 'impurities' transported, must be able to exclude so-called explosive decompression effects and must also resist potentially occurring low temperatures [8].

Appropriate Steel Toughness Specification

An initial cause for a so-called fast propagating ductile running fracture might be a third-party impact, e.g. caused by excavator work whereby the running fracture travels along the pipeline section with high velocity releasing hereby the CO_2 content of the pipeline section affected.

The probability of initiating a running fracture can be minimized by sound pipeline design and material selection, whereby especially the steel impact toughness to avoid ductile running fractures must be specified accordingly. The Battelle TCM model can hereby be used for first estimations [9,10].

When pipeline geometry (diameter, wall thickness), material and operating conditions cannot ensure arresting duc-

tile running fractures, so-called fracture arrestors can be installed in suitable distances to limit the length of the pipeline damage in a hypothetical loss of containment (LOC) event [8].

Material for Special Equipment

Special material requirements are to be considered e.g. for blow-down stations and related piping, valves, sealing systems, instrumentation etc., where due to pressure reduction to ambient conditions low temperatures (down to −78°C and deeper) and gas-solid two-phase flows can occur.

PIPELINE DESIGN AND LAYOUT
Design Codes and Standards

DNV Standard DNV-RP-J202 published in April 2010 [8] is considered as main standard for CO_2 transportation in CO_2 pipeline systems, referring also to other references, codes and standards, e.g. API, ASME, CSA, ISO, IEC, NACE, NORSOK, PHMSA and other DNV standards.

Route Selection

Routes for CO_2 pipelines shall be selected in sufficient distance to populated areas such that in the hypothetical case of a pipe leak / rupture the potential consequences for the population will be minimized. A main concern is hereby also the potential accumulation of CO_2 at topographical deep points and depressions. For people present in the vicinity of the pipeline, the expected risk shall be determined by performing a related quantitative risk assessment (QRA) and relevant measures (mentioned later) shall be taken to further minimize the risk.

Pipeline Diameter Optimization

For determination of the optimum pipeline transportation system in economical respect, a diameter optimization shall be performed respecting both, investment cost for pipeline sections and compression facilities, and energy cost for operating the compression facilities. **Figure 5** shows exemplary results of related pre-optimization calculations of comparable specific CO_2 transportation cost at a pressure level above 80 bar. The specific CO_2 compression cost from approx. atmospheric conditions to the pressure level of approx. 80 bar are to be added separately.

Line Valve Stations

Line valve stations shall be installed at appropriate distances in order to be able to isolate pipeline sections during maintenance and repair and to limit the loss of inventory in the hypothetical case of a leakage. Line valve spacing shall hereby be determined considering a series of factors like pipeline diameter, pressure, population density, blow-down time and topography.

Leak Detection Systems

Leak detection systems similar to those realized in oil in gas pipeline systems shall be implemented in order to quickly detect and localize a potential leak / rupture along the pipe-line route. Additionally, advanced leak detection methods e.g. based on fiber optical cables for damage prevention (vibration sensing), temperature anomaly detection caused by leaking CO_2, or acoustic leak detection methods shall be taken into consideration. After confirmed leak alarm, pipeline operation shall immediately be shut down and the line valves adjacent to the section subject to leakage shall be closed, in order to reduce the potential inventory loss to a minimum. If required or adequate in case of a leak, CO_2 can be vented in blow-down stations connected to the leaking section.

Blow-Down Stations

Blow-down facilities for CO_2 are typically installed at line valve stations and enable depressurization of individual pipeline sections. As during blow-down of CO_2 from the dense phase pressure a gas stream containing solid CO_2 particles will be emitted to the atmosphere, the blow-down facilities must be designed adequately. Special care must hereby also be taken to avoid extreme cooling of the pipeline sections due to too rapid expansion of the CO_2 inside the pipeline system.

Measures for Risk Reduction

In addition to suitable route selection, measures for further risk reduction to people and environment shall be taken into consideration, e.g. pipe wall thickness increase, deeper burial, laying of concrete sleeves above the buried pipeline, selection of shorter distances between line valve stations and implementation of crack arrestors to ensure that a propagating fracture will stop.

HEALTH, SAFETY AND RISK RELATED ASPECTS OF CO_2 TRANSPORT IN PIPELINES
Properties of CO_2 and of Accompanying 'Impurities'

CO_2 is a colorless, odorless, non-combustible gas with a relative density to air of approx. 1.5, being non-toxic at relatively low concentrations. While 3 vol.-%. CO_2 in air cause after 1 hour mild headache, sweating and difficult breathing at rest, 6 vol.-% CO_2 may cause visual and hearing disturbances within 1-2 minutes. CO_2 concentrations of 7-10 vol.-% may result in uncon-

TABLE 1: DYNAMIS Specification of CO_2 Streams [10]

Component	Aquifer	EOR	Remark/Limitation[1]
H_2O	500 ppm		Technical Aspects[2]
H_2S	200 ppm		Health & Safety Considerations
CO	2000 ppm		
O_2	< 4 vol %	100–1000 ppm	Technical Aspects[3]
CH_4	< 4 vol %	< 2 vol %	Reference to ENCAP Project
N_2	< 4 vol % (all non condensable gases)		
Ar			
H_2			Reduction Recommended[4]
SO_x	100 ppm		Health & Safety Considerations
NO_x	100 ppm		
CO_2	> 95.5 %		Balanced with other Components

1) abridged compared to original remark in /DYNAMIS/
2) expected in future in the range of 250 ppm (information by A. Brown, IMEcheE, 29.09.09, London)
3) range of EOR, because lack of practical experiments on effects of O_2 underground /DYNAMIS/
4) due to energy content /DYNAMIS/

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sciousness within a few minutes, and 17–39 vol.-% may result in loss of controlled and purposeful activity, unconsciousness, convulsions and death [4]. Some components ('impurities') in CO_2 streams like H2S or SO_2 pose additional major health risks on persons, requiring therefore related concentration limitation in the CO_2 stream.

Dense Gas Dispersion Modelling
Reliable dense gas dispersion modeling is one of the basic elements for the determination of the required safety distances between CO_2 pipelines and population especially in densely populated areas, and is also required for the development of a related hazard management strategy.

Currently available models are able to predict dispersion of dense gases, i.e. gases considerably heavier than air, like CO_2, but due to the relatively high CO_2 mass released in case of a pipe rupture, a validation of the model predictions with experimental data is still required.

Safety and Risk Assessment
Safety and risk assessment for pipeline systems comprise essentially the main elements hazard identification, consequence analysis, frequency analysis, risk summation, comparison of calculated risk versus tolerability criteria and definition of effective measures to reduce the remaining risk to an acceptable risk level.

The risk summation comprises the determination of the Individual Risk as a function of the distance to the pipeline route (e.g. determination of so called Risk Transects), and usually also the determination of the so-called Societal Risk, expressed usually as so-called FN-curve.

During the risk assessment, the calculated risks are compared to specified risk acceptance criteria [11] and the remaining risk shall then be further reduced by related measures to an acceptable level which may be as low as reasonably practicable (ALARP).

Related software for quantitative risk assessment (QRA) is basically available, however special adaptation to the CO_2-

specific conditions is required as well as validation with large-scale experimental data.

PIPELINE CONSTRUCTION, OPERATION AND MAINTENANCE
Pipeline Manufacturing, Construction and Commissioning
CO_2 pipelines are manufacturing and constructed very similar like oil and gas pipelines. Initial line fill must be performed considering the special properties of CO_2. In order to prevent extreme cooling downstream the inlet valves of individual pipeline section, compressed dry air or nitrogen might be required to intermediately fill the pipeline sections.

Operation and Maintenance
As for carbon steel pipes internal corrosion represents a major risk, reliable monitoring systems must be implemented to strictly limit the water content and prevent accidental free water ingress to the pipeline. In case of an off-spec condition, CO_2 stream injection into the pipeline system must be shut-down immediately and operational measures must be available for corrosion limitation of temporarily injected off-spec CO_2.

Unsteady-state conditions like pipeline start-up, flow variation, pipeline shut-down, closure of line valve stations or pump failure due to power supply failure require careful planning, modeling and performance in order not to exceed the allowable operation range of the pipeline system.

A pipeline integrity management system shall be implemented combining a variety of safety-directed elements [8,12].

FURTHER INVESTIGATION DEMAND
Aiming to close remaining significant gaps and to enhance the robustness of risk management for safe, reliable and economic CO_2 transportation in pipeline systems, certain areas and tasks of dense-phase operated CO_2 pipelines were identified during development of the guideline DNV-RP-J202 [8]:
1. Medium and large scale CO_2 release tests to validate existing models and to enable the development of improved dispersion models
2. Medium and large scale tests regarding crack extension velocity, crack arrest and decompression wave characteristics
3. Corrosion mechanism with and without water phase including impurity influence e.g. of O_2, H_2, SOx, NOx, H_2S, TEG, MEG and amines/NH_3
4. Material compatibility investigations regarding material qualification for safe use of polymers and elastomers
5. Effects of impurities on physical properties, e.g. bubble point, dew point, density, viscosity for design and operational purposes
6. Water solubility and hydrate formation regarding pipeline design and operation.

Related investigations are being performed within the scope of Phase 2 of the joint industry DNV CO2PIPETRANS project [4] and corresponding results are expected latest in 2012.
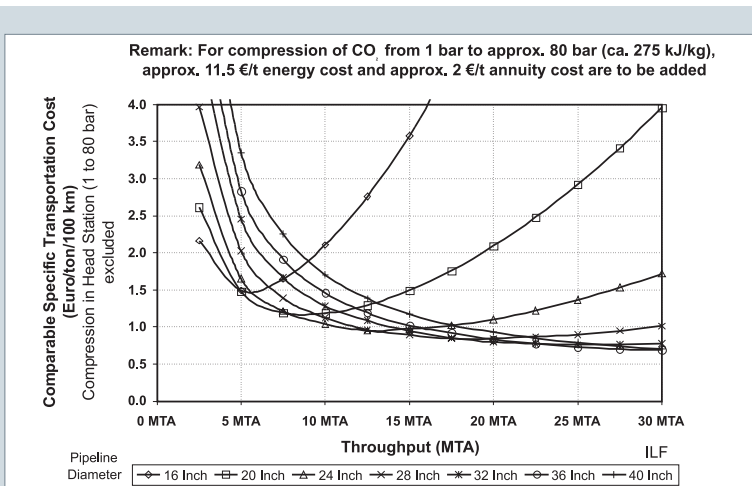

FIGURE 5: Pipeline Diameter Optimization Diagram

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Special Considerations Related to the Quantitative Risk Assessment (QRA) of Gas Transmission Pipelines

By Urban Neunert

SUMMARY: Performing quantitative risk assessments (QRA) is a well-established tool in process industry to quantify and assess the risks related to systems dealing with hazardous materials. The four main phases of a QRA are the hazard identification, the consequence and frequency analysis and the risk assessment. Several guidelines and commercial software exist for the performance of a QRA. However, carrying out a QRA for cross-country pipeline systems transporting natural gas requires special considerations during all study stages. The present article describes the general QRA procedure and gives special recommendations for performing a QRA for cross-country gas pipelines. A new method is introduced for the presentation of the Societal Risk of cross-country gas pipelines, which allows a more visible and comparable demonstration of the risk results.

INTRODUCTION

A quantitative risk assessment (QRA) for systems dealing with hazardous materials is a common tool in process industry to quantify and assess the risks related to scenarios involving the release of hazardous substances. Risk is defined as the product of consequence and frequency of an identified hazardous scenario and can be related to the population (Individual and Societal Risk), the assets, the environment and/or the reputation of the operator. However, a classical QRA covers solely risks on the population – i.e. Individual and Societal Risk. Regarding a system handling, transporting or storing dangerous substances, a hazardous scenario involves a loss of containment (LOC) accompanied by a release of hazardous material and finally leading to a single or multiple hazardous events, e.g. fire, explosion, toxic exposure. Several guidelines ([1], [2], [3]) and commercial software ([4], [5]) exist for the performance of a QRA. However, carrying out a QRA for cross-country pipeline systems transporting natural gas requires special considerations during all study stages. In [6] a guide to the application of pipeline risk assessment is given. Recently, Spoelstra et.al [7] presented a method for the QRA of underground pipelines transporting hazardous substances.

In the present article, recommendations are given additionally to the standard guidelines regarding special aspects of a QRA for cross-country pipelines transporting natural gas. The information is based on the experiences from several QRA studies of ILF projects concerning natural gas pipelines. A new method for the presentation of the Societal Risk is introduced, which allows a more visible and comparable demonstration of the risk results.

GENERAL METHODOLOGY OF QRA

The "Purple Book" [1] defines a QRA as follows:

"A Quantitative Risk Assessment (QRA) is a valuable tool for determining the risk of the use, handling, transport and storage of dangerous substances. QRAs are used to demonstrate the risk caused by the activity and to provide the competent authorities with relevant information to enable decisions on the acceptability of risk related to developments on site, or around the establishment or transport route."

Figure 1 shows the four main phases of the typical workflow of a QRA. In the following these phases are explained in more detail focusing on their application on cross-country gas pipelines.
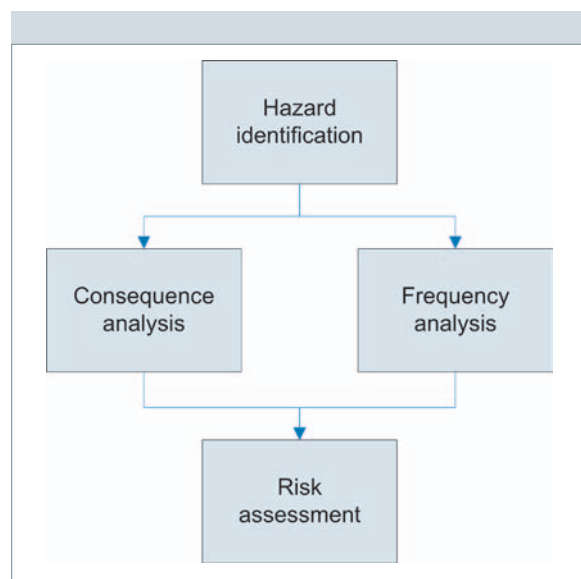

FIGURE 1:
General QRA workflow

HAZARD IDENTIFICATION

After defining the investigated system and the study goals, a QRA starts with the identification of the potential incidents that could lead to a release of hazardous material due to loss of containment (LOC). As proposed in [1], [6] and [7], a QRA for cross-country gas pipelines should cover a full bore rupture and typical leak scenarios. According to [7], leaks with a diameter below 20 mm are not considered, as their contribution to the overall risk is negligible. Since according to [8] external interferences (ground works, digging operations) are the main cause for pipeline failures in Europe, it is suggested to consider at least a leak with a diameter of 50 mm, which represents a typical digging tooth size.

In general cross-country gas pipelines contain high pressurized natural gas. The properties of natural gas are governed by its main component methane. Methane is a colorless, odorless and non-toxic gas. It is flammable with an ignition temperature of 595 °C. In cross-country pipelines natural gas is usually present in dry gaseous form. Since its density is lower than the density of air, natural gas (at normal conditions) propagates upwards when released to the atmosphere [9]. However, since in the investigated installations the gas is pressurized, it cools down significantly during discharge and depressurization. Jet expansion of methane from a high pressure source lowers the temperature but not sufficiently to make it denser than air, due to the fact that the high turbulence of the jet leads to a fast entrainment of air. Thus dense gas dispersion behaviour is not expected for releases of natural gas.

A possible LOC of a buried pipeline with bigger orifice diameters and under high pressures may yield to a crater formation with diameters up to 30 m [9] resulting in flying debris able to cause local damages. However, compared to the heat radiation impact zones from fire events, the endangered area due to flying debris is comparably low. A horizontally released gas mass of a buried or obstructed pipeline will impinge on the crater wall or obstacle. Impingement dissipates some of the momentum in the escaping gas and redirects the jet upward, thereby producing a fire with a horizontal profile that is generally wider, shorter and more vertical in orientation, than would be the case for an unobstructed horizontal jet [10].

Regarding the release direction of the gas for all LOCs related to below ground piping, it is suggested in [1] and [7] to consider vertical releases only. However, since fire events resulting from horizontal gas releases lead to higher heat radiation loads at ground level compared to fire events of vertical releases, it is suggested to consider both a horizontal and a vertical release. As mentioned above the horizontal released gas will impinge on the crater wall redirected vertically. The angle of redirection from horizontal to vertical direction is suggested to be assumed to 30° – 45°.

CONSEQUENCE ANALYSIS

Based on the output data of the hazard identification, a logical chain of subsequent consequences is modeled in a consequence analysis, which starts from the event of release of hazardous material and ends up in describing the consequences on the population (vulnerable impact). Regarding cross-country natural gas pipelines, the possible consequences are heat radiation and overpressure effects resulting from fire and explosion events, respectively. **Figure 2** presents the chain of subsequent consequences of a typical hazardous scenario related to a gas pipeline. The quantitative output results (heat radiation, overpressures) can be modeled based on physical equations. These are implemented in commercial QRA software ([4], [5]) or can be found in the literature [11].

The discharge behavior of the expelled gas depends mainly on the hole size of the considered LOC. Calculations show that for leak scenarios with smaller orifice diameters a continuous release of gas occurs, since due to lower discharge flow rates the conditions in the pipe are not changing significantly. For a full bore rupture event transient discharge behavior is expected. This includes initial instantaneous release of pressurized flammable gas, which lead to short duration effects (fire ball, early explosions, flash fires) followed by the events of a continuous release (jet fire). The dispersion behavior of the released gas is governed by the discharge momentum, buoyancy effects and the weather conditions. The occurrence of a fire or explosion event depends on the type of ignition (immediate/delayed). The subsequent development of a hazardous gas release in accordance to the influencing factors is presented in the event-tree shown in **Figure 3**.
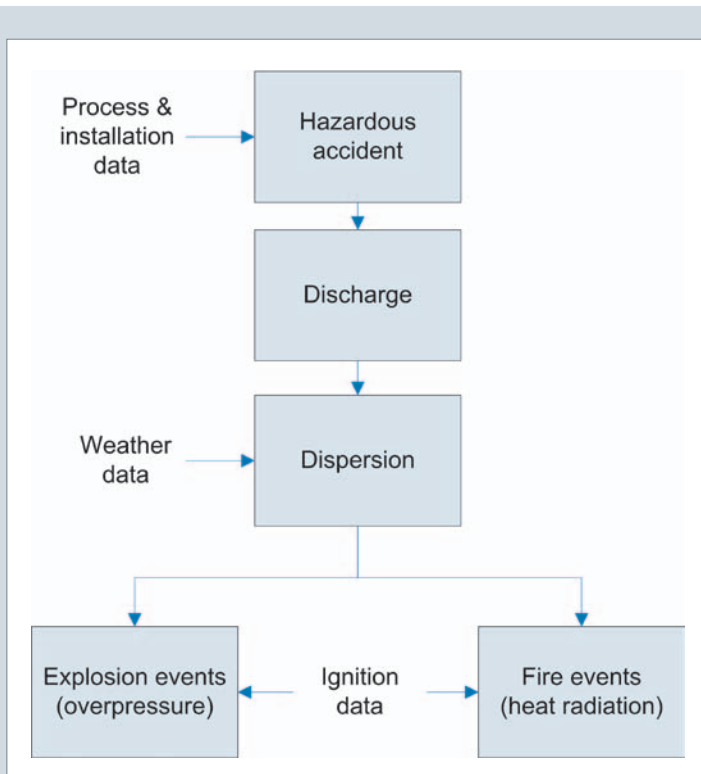

FIGURE 2: **Sequence of a consequence analysis**

For cross-country gas pipelines, the possibility of a significant flash fire at ground level resulting from delayed ignition is relatively low due to the buoyant nature of natural gas, which generally precludes the formation of a persistent flammable cloud at ground level [12]. Thus, the dominant hazard is thermal radiation from a sustained jet fire, which may be preceded by a short-lived fire ball [12].

In an accidental gas explosion the flame will normally start out as a slow laminar flame with a velocity of the order of a few m/s. If the cloud is truly unconfined and unobstructed, the flame is not likely to accelerate to velocities of more than 20-25 m/s, and the overpressure will be negligible [13]. In a partly confined area with obstacles the flame may accelerate to several hundred m/s, which may lead to significant overpressures [13]. However, it has to be investigated, if the pipeline is aligned through unconfined and uncongested environment in order to neglect explosion effects.

Since the process conditions, the weather and wind conditions, the environment and the ignition sources vary over the pipe length, different discharge, dispersion and fire & explosion behaviors are expected along the alignment of a cross-country pipeline.

FREQUENCY ANALYSIS

To calculate the quantitative risks of a hazardous accident, its likelihood of occurrence is required. Therefore, the frequency of a given LOC and the probabilities of the ignition (immediate/delayed) have to be taken into account.

The frequencies of the identified LOC scenarios related to a cross-country gas pipeline can be derived out of the data presented in [8]. In [8] historical incidents on European gas pipelines are gathered in a database in order to provide a broad basis for the calculation of safety performances of pipeline systems. The incidents are classified in terms of hole size and cause. The total frequency of a given LOC is the sum of the contributions of single frequencies due to external interference, corrosion, construction defect, material failure, ground movement and unknown causes like hot-tap made by error, design error, lightning, maintenance etc. Ignition probabilities can be additionally found in [8]. According to [6] and [14], influencing factors – e.g. higher wall thickness, higher soil cover or special safety measures (concrete slabs, warning tapes, etc.) – may lead to lower LOC frequencies and subsequently lower risks.

The failure frequency may vary significantly along the alignment of a cross-country pipeline, due to different probabilities of failure causes and varying influencing factors.

RISK ASSESSMENT

The final stage of a classic QRA is the risk assessment, which is schematically shown in **Figure 4**. The combination of the results of the consequence modeling and the frequency analysis leads to the determination of the different contributions to the overall risk. Risk results from a classic QRA are typically generated for risk to people, whilst one differentiates
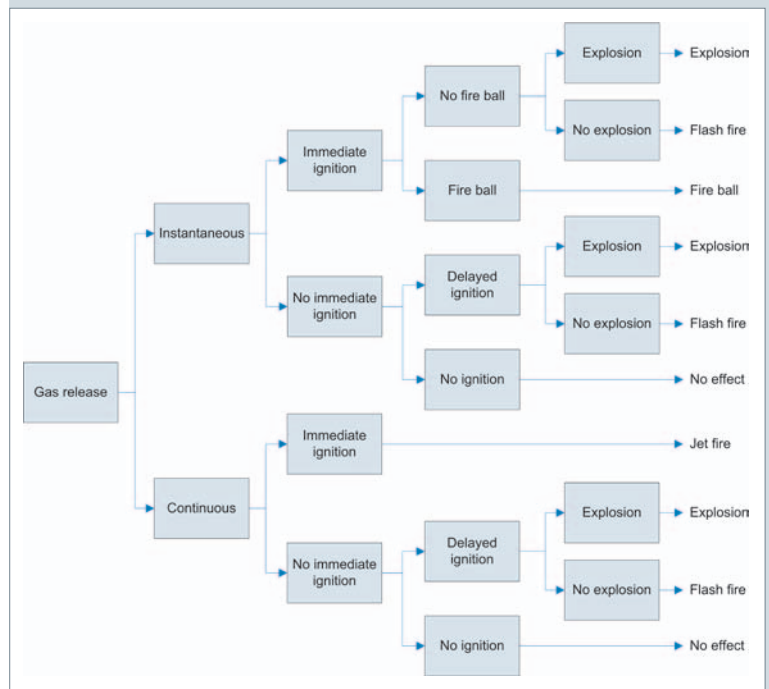
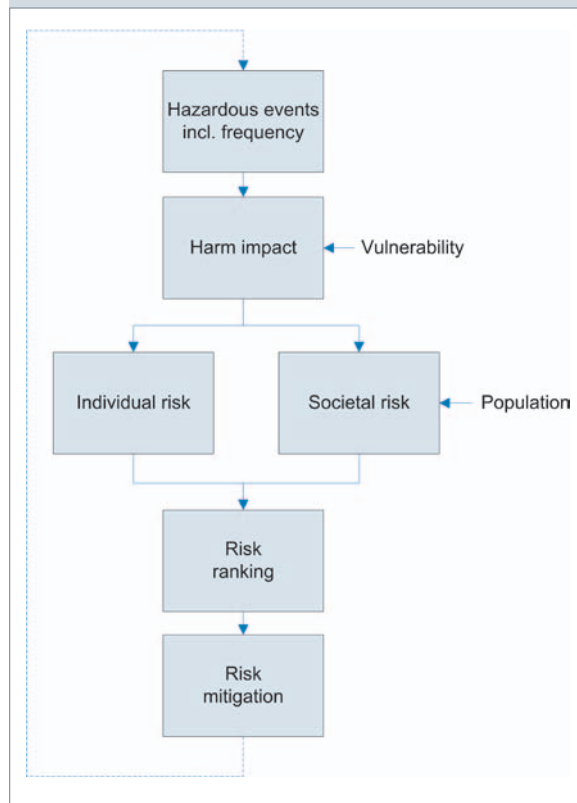

FIGURE 3: **Event tree of gas pipeline releases**

FIGURE 4: **Risk assessment: Schematic overview**

between Individual and Societal Risk. The Individual Risk can be calculated as 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. The Societal Risk gives information about the frequencies and the resulting total fatalities related to all hazardous events of the
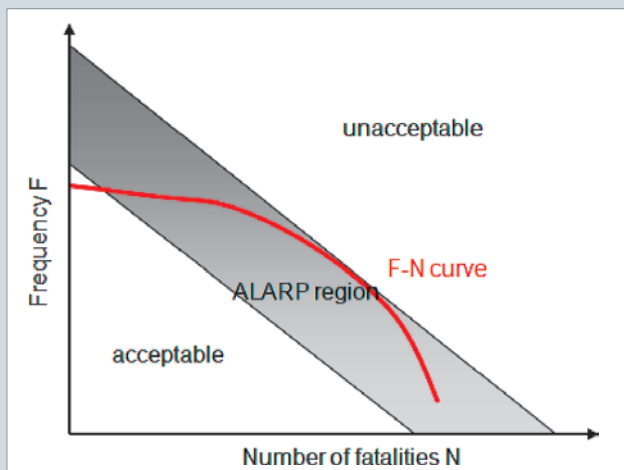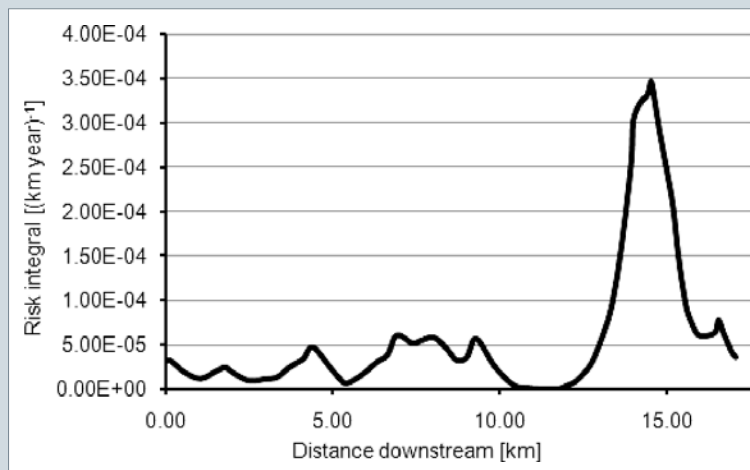
FIGURE 5: **Typical F-N curve plot**

FIGURE 6: **Societal Risk along a pipeline section**

facility, referring hereby to the site related population. The risk ranking procedure categorizes the Individual and Societal Risk levels and compares them against risk criteria. This approach leads to measures in order to minimize, mitigate and manage the risks.

Societal Risk is usually presented in F-N curves, which show the cumulative frequency of all system-related hazardous events that result in N or more fatalities. The F-N curve determines whether the risk of a given establishment is acceptable or not. **Figure 5** shows an exemplary F-N curve and the risk criteria.

Acceptable risk usually needs no further mitigation and is tolerated by the operator. Risk located in the ALARP region (as low as reasonably practicable) is only tolerable if risk reduction is impracticable or its costs are in disproportion to the gained improvement.

For both the Individual and the Societal Risk, in some countries risk criteria exist depending on governmental and/or company-related regulations [15]. Regarding the Societal Risk of cross-country pipelines in the Netherlands [7], the limiting frequency F_{lim} per km and year for the occurrence of an event with N fatalities is shown in Eq. (1):

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

Eq. (2) shows the appropriate tolerable Societal Risk limit of the frequency of an undesired event with N fatalities per km and year for the UK [6]:

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

For the presentation of the Societal Risk results of a total pipeline section it is recommended in [6] to determine the section related F-N curve and divide the risk values with the total pipe length in km. However, using this approach for the presentation of the Societal Risk of a pipeline has a major

shortcoming: The location of the events with the highest contribution to the Societal Risk cannot be determined obviously, which makes the application of risk mitigation measures difficult.

Therefore, a novel presentation method for the Societal Risk of gas pipelines is presented, which shows a Societal Risk curve over the pipeline alignment related to its length [16]. The appropriate risk values can be interpreted as the cumulative risk for persons involved, i.e. sum of Individual Risks caused by the pipeline at the related location. **Figure 6** shows the risk integral for a pipeline section with a length of 17 km.

The graph in Figure 6 clearly shows that in the given example the Societal Risk differs along the pipe length. At km 11, the risk integral is almost zero, indicating that the failure frequencies and/or the consequences of the identified LOC scenarios are comparably low; e.g. due to a low population density or a higher pipe wall thickness. The risk integral at km 14 is relatively high (e.g. due to a high population density adjacent). It is obvious, that effective risk mitigation measures are preferably to be applied at locations along the pipeline which show a comparably high Societal Risk.

SUMMARY AND CONCLUSIONS

The present article gives a compact overview of the methodology of preparing a QRA for cross-country gas pipelines. The main study phases are generally described – i.e. the hazard identification, the consequence and frequency analysis and the risk assessment – including special considerations and recommendations presented for cross-country gas pipelines. For the presentation of the Societal Risk results, a modified method to the common F-N curve approach is presented, which shows the Societal Risk over the pipe length. This method allows a more effective application of appropriate risk mitigation methods.

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