Project no.:
226317

Project acronym:
CO2Europipe

Project title:
Towards a transport infrastructure for large-scale CCS in Europe

Collaborative Project

Start date of project: 2009-04-01
Duration: 2½ years

D3.2.1
WP3.2 Societal and Environmental Aspects
CO_2 transport through pipelines: risk characterization and management

Revision: November 2011

Organisation name of lead contractor for this deliverable:
ECN

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential , only for members of the consortium (including the Commission Services)	

Deliverable number:	D 3.2.1
Deliverable name:	
Work package:	WP 3.2 Societal and Environmental Aspects
Lead contractor:	ECN

Status of deliverable		
Action	**By**	**Date**
Submitted (Author(s))	Jacques Grupa, Ad Seebregts (ECN), Mark Spruijt, Ingrid Raben, Corina Dam, Xialong Zhang (all TNO), Dennis Triezenberg (Gasunie)	2011.11.23 (Final version)
Verified (WP-leader)	Ad Seebregts	2011.11.25
Approved (SP-leader)	Ad Seebregts	2011.11.25

Author(s)		
Name	**Organisation**	**E-mail**
Jacques Grupa	ECN	grupa@ecn.nl
Ad Seebregts	ECN	seebregts@ecn.nl [1]
Dennis Triezenberg	Gasunie	Dennis.Triezenberg@gasunie.nl
Corina Dam	TNO	Corina.Dam@tno.nl
Mark Spruijt	TNO	mark.spruijt@tno.nl
Ingrid Heidebrink	TNO	ingrid.heidebrink@tno.nl
Ingrid Raben	TNO	Ingrid.raben@tno.nl
Xialong Zhang	TNO	xiaolong.zhang@tno.nl

Abstract

The objective of this work package is to characterize the risks related to CO2 transport through pipelines for society and the local environment, and to describe strategies to manage these risks.

Acknowledgement

The CO2Europipe partners that have contributed to review of earlier draft material are acknowledged.

[1] Corresponding author/editor for this report.

Project summary

The CO2Europipe project aims at paving the road towards large-scale, Europe-wide infrastructure for the transport and injection of CO_2 captured from industrial sources and low-emission power plants. The project, in which key stakeholders in the field of carbon capture, transport and storage (CCTS) participate, will prepare for the optimum transition from initially small-scale, local initiatives starting around 2010 towards the large-scale CO_2 transport and storage that must be prepared to commence from 2015 to 2020, if near- to medium-term CCS is to be effectively realized. This transition, as well as the development of large-scale CO_2 infrastructure, will be studied by developing business case using a number of realistic scenarios. Business cases include the Rotterdam region, the Rhine-Ruhr/Hamburg region, an offshore pipeline from the Norwegian coast and the development of CCS in the Czech Republic and Poland.

Objectives

The project has the following objectives:

1. describe the infrastructure required for large-scale transport of CO_2, including the injection facilities at the storage sites;
2. describe the options for re-use of existing infrastructure for the transport of natural gas, that is expected to be slowly phased out in the next few decades;
3. provide advice on how to remove any organizational, financial, legal, environmental and societal hurdles to the realization of large-scale CO_2 infrastructure;
4. develop business case for a series of realistic scenarios, to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure;
5. demonstrate, through the development of the business cases listed above, the need for international cooperation on CCS;
6. summarise all findings in terms of actions to be taken by EU and national governments to facilitate and optimize the development of large-scale, European CCS infrastructure.

This report

This deliverable describes the necessary input for CO_2 quality standards, by which is meant the composition of the CO_2. With adequate CO_2 quality standards, the first objective is partly met. The CO_2 composition is the characteristic influencing each and every component in the chain from capture to storage. This report provides input for a CO_2 quality standard that enables a safe, reliable and cost-efficient CCS chain.

Project partners

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall Research & Development AB	Sweden
Linde Gas Benelux BV	Netherlands
Siemens AG	Germany
RWE DEA AG	Germany
E.ON Benelux NV	Netherlands, Belgium, Luxemburg
PGE Polska Gruppa Energetyczna SA	Poland

CEZ AS	Czech Republic
Shell Downstream Services International BV	Netherlands, United Kingdom
CO2-Net BV	Netherlands
CO2-Global AS	Norway
Nacap BV	Netherlands
Gassco AS	Norway
Anthony Veder CO_2 Shipping BV	Netherlands
E.ON New Build & Technology Ltd	United Kingdom
Stedin BV	Netherlands
N.V. Nederlandse Gasunie	Netherlands

The CO2Europipe project is partially funded by the European Union, under the 7th Framework program, contract n^{o} 226317.

TABLE OF CONTENTS

Page

1 Introduction

Transport of CO_2 poses health and safety risks. Under certain conditions, leakage or rupture of a pipeline can result in the dispersion of CO_2 with the potential to affect humans and the environment. CO2Europipe's scope is on societal and environmental aspects but restricted to external (i.e. safety related) risk to the environment[2]. In addition, the assessment is restricted to the CO_2 pipeline part of the total CCS chain, and to onshore pipelines. Risks of CO_2 transport by ships have not been addressed.[3] Onshore pipeline infrastructure in particular located in densely populated areas will pose the highest health and safety risks. Safety risks in other parts of the CCS chain (e.g. capture of CO_2 or risks associated with CO_2 injection into the underground storage) are also beyond the scope.

Comparison of risk figures for various industrial (hence involuntary) activities or (energy) infrastructures and risk figures for the various elements in the CCS chain or the various energy chains may give the public a more balanced view on the magnitude of the additional risk of CO_2 pipelines. Purely as an illustration, Figure 1.1 below provides a comparison.

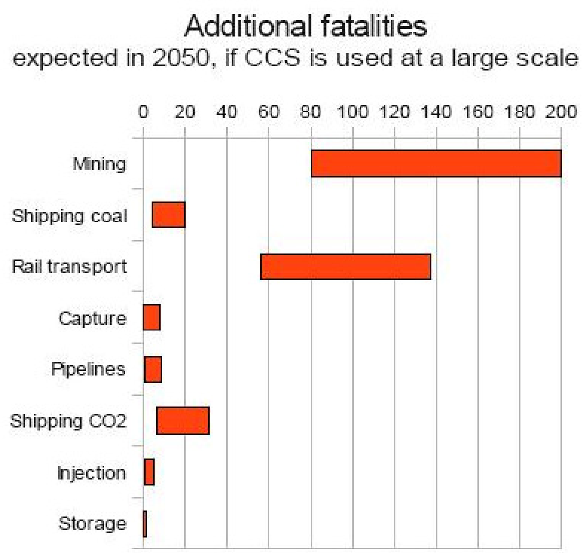


Figure 4: Result summary: Actuarial estimates of the human cost of 1 GtC of CO2 emissions mitigation by using carbon capture and storage at 1500 baseload coal fired power plants.

Figure 1.1 Risk comparison between various stages in the CCS chain based on CCS at 1500 coal power plants (Source: CIRED, 2010)

[2] In accordance with the Annex A description of the WP 3.2 work content.
[3] See recent report (DNV, 2011) for risks of CO_2 transport by barge or sea going vessels.

2 Overview

The activities in WP 3.2 have been divided into four tasks (with leads between brackets):

1. Characterisation and prevention of pipeline risks (Chapter 3, Part 1, Gasunie and TNO)
2. Frameworks for risk assessment (Chapter 4, Part 2, TNO)
3. (Semi-)Quantitative risk assessment (Chapter 5, Part 3, TNO)
4. Risk Management (Chapter 6, Part 4, ECN)

'Risk' can have a much large scope e.g. related to financial and policy risks, organisational risks or other Health, Safety and Environmental (HSE) risks. An overview of such other risks can be found in the recent EU CCS Network report (CCSNetwork.eu, May 2011) showing the lessons learned from the first year of work on the six CCS demonstration projects funded under the EERP programme. Financial, policy and project risks are addressed to some extent in some of the WP 4 case studies (Rotterdam area, Rhine/Ruhr and Hamburg area, Karsto case and Poland and Czech Republic cases, see deliverables D4.1.1, D4.2.2, D4.3.1 and D4.3.2, D4.4.1, D4.4.2, D.4.3) and in WP 3.3 (Mikunda et al, 2011).

Ongoing permitting procedures of recent or ongoing projects for CCS may include Environmental Impact Assessments (EIAs). In such EIAs, external risk and safety to the environment is usually covered. Examples are the Barendrecht case in the Netherlands (stopped due to much local public resistance and a decision by the Dutch government not to store CO_2 at onshore locations) or the ROAD project (one of the six demos) for which the EIA is due in the second half of 2011, as part of the permitting process.

In its final stage of dealing with such external risks, residual risks that are not acceptable according to risk criteria or norms need to be managed. In addition, risks that can change over time will need to be managed, see also (CCSNetwork.eu, May 2011).

Although risk identification, analysis and management methodologies for industrial activities and similar pipeline infrastructure are well established, the case of CO_2 pipeline infrastructure is somewhat different than other pipeline infrastructures. The work conducted in CO2Europipe and recent other studies indicate the differences and ways to deal with the peculiarities of CO_2 transport.

3 Risk characterisation, prevention and mitigation

3.1 Introduction

The scope of this section is to:
- define the threats and consequences related to a CO2 pipeline rupture
- define the possible prevention and mitigation measures

To achieve the goals set in the scope a methodology called the Bowtie analysis is used. The methodology, the results and the conclusions and recommendations will be explained in the next chapter.

The bowtie analysis has been performed for the hazardous event 'CO2 transport pipeline rupture'. Another possible hazardous event is CO2 transport pipeline leakage. The leakage case is not presented here because the threats, consequences, prevention and mitigation measures are similar to the rupture case. Also, it is presumed that the CO2 pipeline is located onshore and is buried. Furthermore, threats like sabotage and terrorism are excluded from this exercise.

3.2 BowTie RISK analysis of CO2 transport

3.2.1 Methodology

The bowtie has become popular as a structured method to assess risk where a quantitative approach may not be possible or desirable. The success of the diagram is that it is simple and easy for the non-specialist to understand. The idea is a simple one of combining the cause (fault tree) and the consequence (event tree). When the fault tree is drawn on the left hand side and the event tree is drawn on the right hand side with the hazard drawn as a "knot" in the middle the diagram looks a bit like a bowtie, as shown in Figure 3.1.

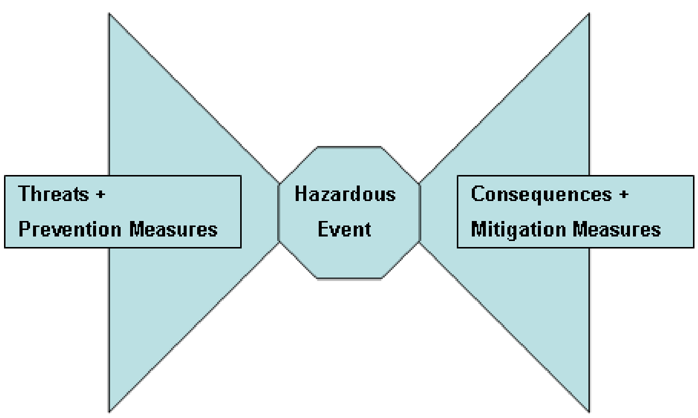


Figure 3.1 Schematic overview of a bowtie analysis

A bowtie diagram can be created by defining the:

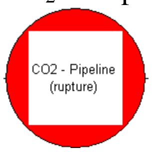
1. Event to be prevented

2. Threats that could cause the event to occur
3. Consequences of the event occurring
4. Controls to prevent the event occurring
5. Controls to mitigate against the consequences.

The bowtie analysis has been performed for the hazardous event CO_2 transport pipeline rupture'. Another possible hazardous event is CO_2 transport pipeline leakage. The leakage case is not presented here because the threats, consequences and prevention /mitigation measures are similar to the rupture case..

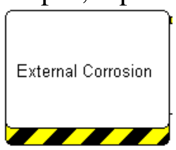
3.2.2 BowTie

The red circular area or the "knot" in the middle represents the hazardous event, in this case 'a CO_2 transport pipeline rupture'.



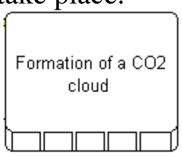
The hazardous event

The first boxes to the left of the hazardous event, which are underlined with yellow black stripes, represent the threats that can cause the event to occur.



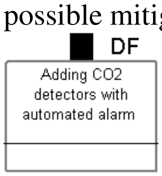
A threat

The final boxes to the right of the hazardous event represent the consequences should the event take place.



A consequence

The boxes between the threat and the hazardous event represent the control measures that are available and the boxes between the hazardous event and the consequences represent the possible mitigation measures.



Control or mitigation measures

The control and mitigation measures can be divided into different categories.

Table 3.1 provides an overview of the codes used for control and mitigation measures.

Table 3.1 Overview of control/mitigation measures codes

Code	Description
CO	Communication
DE	Design
DF	Defences
EC	Error-enforcing conditions
HK	Housekeeping
HW	Hardware
IG	Incompatible goals
MM	Maintenance Management
OR	Organisation
PR	Procedures
TR	Training

In Figure 3.2 the result of the bowtie analysis is given for the hazardous event 'CO_2 pipeline rupture'

It is explicitly stated that the control to the threat faces threats of its own. For example, a control to the threat 'Internal Corrosion' is 'removal of H_2O and impurities'. However, when this removal process is interrupted or incomplete, the control can be rendered useless. In other words, the control measures also have failure frequencies.

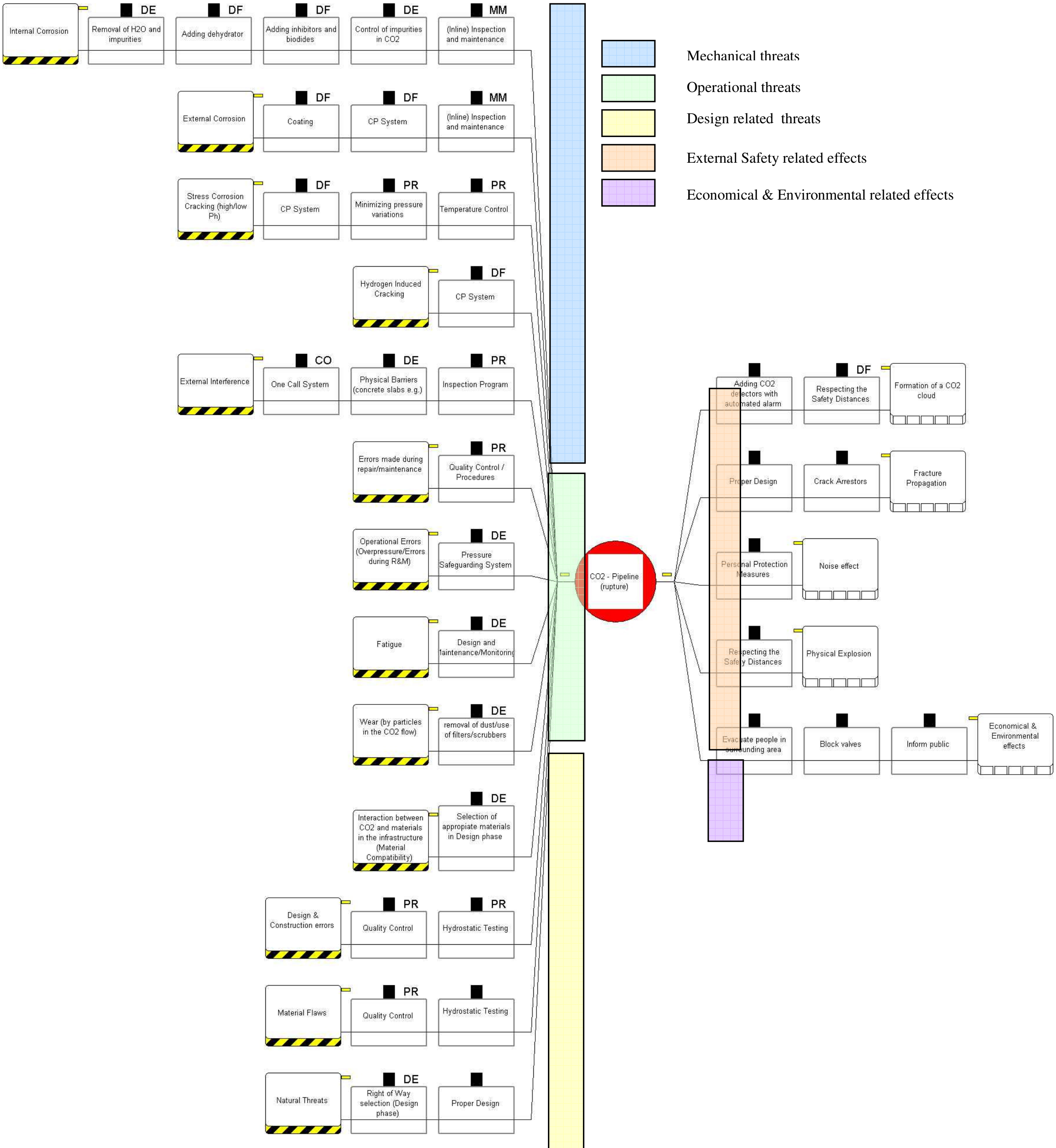


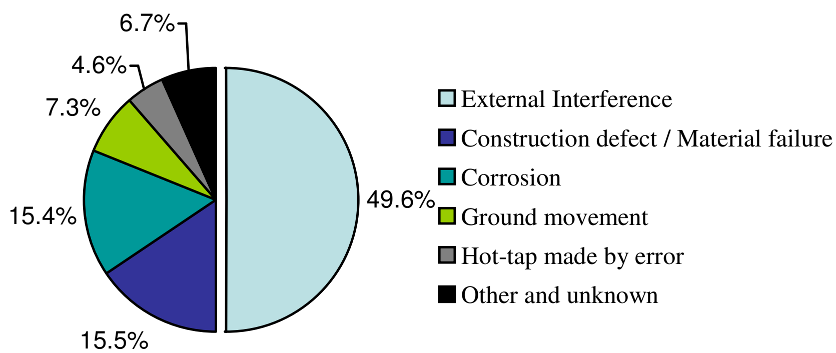
Figure 3.2 Bowtie figure (CO_2 pipeline rupture)

3.2.3 Threats

It is presumed that the CO_2 pipeline is located onshore and is buried. Furthermore, threats like sabotage and terrorism are excluded from this exercise.

In the next paragraphs the threats that can lead to the event CO_2 pipeline rupture are discussed briefly.

3.2.3.1 External Interference / Third Party Damage



According to European Gas Pipeline Incident Data Group or EGIG D. van den Brand, et al. 2009 External interference is the biggest threat posed to a gas transport pipeline. The EGIG database, which dates back to 1970, shows that approximately 50 percent of registered gas transport pipeline incidents were the result of external interference. According to P.M. Davis, et al. 2008, the main cause for spillage incidents of European oil is also external interference of third party activity.

The fact that gas transportation pipelines are buried constitutes the first line of defense against external interference. The deeper the pipeline is buried, or the higher the depth of cover, the less likely it will be hit by a third party.

At those points along the right of way of a pipeline where the depth of cover is not high enough physical barriers like concrete slabs are used to mitigate the risk by lowering the hit frequency of the pipeline.

The pipeline markers that are located along the right of way of a pipeline aim to signal people that a pipeline is present and care should be taken when performing digging activities in the area.

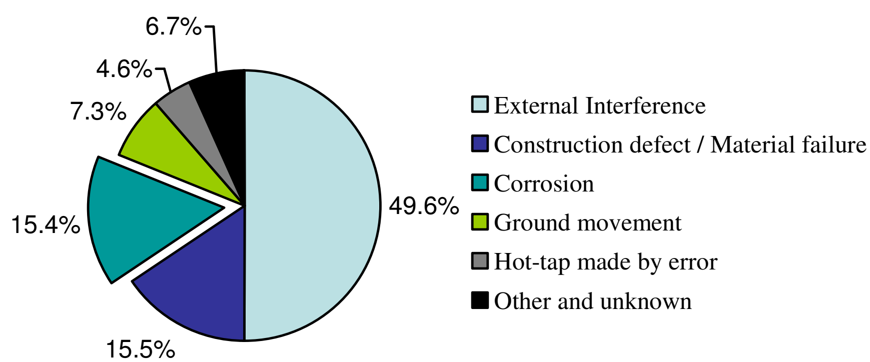
In the Netherlands, as well as in numerous other countries, one-call systems are introduced. When a contractor/farmer etc. plans on digging, he is obliged to call an agency to inform them of the work to be carried out. The agency will point out whether utilities (pipelines/cables etc) are present in the area and if so, tells them the specific location of these utilities. Often a representative of the transport system operator will be present during the digging activities.

In addition, the main transport system operator, Gasunie, has an inspection program. Every two weeks a helicopter performs a flight along the entire gas network to see whether digging activities take place without Gasunie knowing about it.

Another way to lessen incidents as a result of external interference is public education. Normally, no one intentionally damages a pipeline, so public knowledge about procedures and the dangers of digging in the vicinity of gas transportation pipelines is important

Preventing Control	***Examples***
Depth of cover	For example >1,5 metres
Physical Barriers	Concrete slabs above the pipeline or
Pipeline markers	Markers along the right of way of a pipeline
One call system	Centralized agency to provide locations of utilities to parties who plan on digging
Inspection Program	e.g. Inline Inspection or DCVG
Public education	

3.2.3.2 External Corrosion



According to D. van den Brand, et al. 2009 and P.M. Davis, et al. 2008 Corrosion is the third biggest threat to a transport pipeline.

External corrosion includes atmospheric corrosion and subsurface corrosion. When the coating on the pipeline is damaged and the pipe steel is exposed to a humid environment, it will suffer from atmospheric corrosion. Moisture, CO_2, contamination of chemicals such as chlorine, SO_2 etc. and high temperature, can enhance the corrosion of steel. Atmospheric corrosion is a relatively rare failure for most of pipelines. Most of pipelines are buried in soil and soil is often an effective electrolyte. So pipelines suffer subsurface corrosion more than atmospheric corrosion. The soil corrosivity, pH, microorganism in the soil, temperature, stress etc. can promote the corrosion process.

The coating of a pipeline should ensure that no H_2O can reach the outer surface of the pipeline so that corrosion can't take place. However, there is always a risk that the coating does not cover the pipeline completely. Especially the coating that is applied in the field around the welds is a critical component, since the procedures are not always carried out correctly.

The second line of defense is the Cathodic Protection system (CP system). The pipeline metal can be protected as cathodes by applying impressed current or artificial anodes. When the potential of a metal is below its corrosion potential it is protected.

Another control is regular inspection and maintenance. A distinction can be made between direct inspection and indirect inspection. Running a Magnetic Flux Leakage inline inspection tool through a pipeline will give you direct information about the level of metal loss in your pipeline (internal and external) and measures can be taken or planned to prevent corrosion defects from becoming critical. Direct Current Voltage Gradient (DCVG) measurements on a pipeline can give you information about coating defects, which are an indication that corrosion might be taking place (when the CP system is failing) and actions could be necessary.

In order for DCVG to deliver accurate measurements the soil has to be conductive. When some water is present in the ground DCVG will work best. In dry areas measurements will be inaccurate, but because of the absence of water, the probability of active corrosion will be low anyhow.

Stray current from electric railways, grounded DC power or AC power transmission facilities may cause coating or metal damage at areas where the current leaves the pipeline to enter the soil or water. The common mitigation measures include interference bonds, isolators, intentional anodes, and cathodic protection.

Another form of external corrosion is Microbiologically Influenced Corrosion (MIC)
Microorganisms contribute to corrosion by forming crevices, forming concentration cells, forming acids, concentrating halides, mineral acids, ammonia or hydrogen sulfides, and by destruction of coatings. Cement or polyester coatings, in good conditions, can be effective in preventing MIC by shielding the metal surface from organisms.

Preventing Control	***Examples***
Coating	e.g. Polyethylene or coal tar
CP System	Impressed current
(Inline) Inspection and Maintenance	Monitoring metal loss and planning repairs
Stray current control	e.g. Insulators

3.2.3.3 Internal Corrosion

According to, D. van den Brand, et al. 2009 and P.M. Davis, et al. 2008, corrosion is the third biggest threat to a transport pipeline.

Internal corrosion is pipeline wall metal loss or damage caused by a reaction between the inside of the pipeline and the product being transported. Dry CO_2 poses no threat to steel, but with presence of free water, corrosion can be promoted. Impurities such as oxygen, chlorides, H_2S, organic acids, precipitates or sulfur-bearing compounds may enhance corrosion. Pitting and crevice corrosion are commonly seen in cases of internal corrosion. Removal of free water and impurities, adding dehydrator, and using internal coatings are valid methods to protect the pipeline from internal corrosion.

Preventing Control
Removal of H_2O and impurities
Adding dehydrator
Adding inhibitors and biocide
Internal coating
Control of impurities in CO_2
(Inline) Inspection and maintenance

3.2.3.4 Stress Corrosion Cracking (high-low PH)

Stress Corrosion Cracking (SCC) refers to the initiation or acceleration of a cracking process due to the conjoint action of a chemical environmental and tensile stress. The stress can be due to applied loads or a residual stress from fabrication. Carbon steel in carbonate solution and hydrogen sulfide under load may suffer from SCC. Stress corrosion cracking is difficult to detect and SCC failures are not predictable. The effects can be highly localized. The high stress, high pH level and high temperature are contributing factors. The presence of certain bacteria such as sulphate reducing bacteria (SRB) will increase the risk. The materials with high ductility and high fracture toughness are less susceptible to SCC.

Selecting suitable material, controlling the operation conditions such as low pressure and stable temperature, in a benign environment, is the best condition. Any method that lowers stress concentration of the pipeline and the occurrence of localized corrosion can relieve the SCC.

Preventing Control	*Examples*
CP system	
Thoughtful/responsible operation	Minimizing pressure variations
Temperature control	

3.2.3.5 Wear by particles in the CO_2 flow

Erosive wear (erosion) can happen inside the CO_2 pipelines. Erosion is the loss of material due to wear caused by the moving fluid or suspended solids. A joint process of corrosion and erosion in the presence of a flowing corrosive CO_2 can lead to the accelerated loss of pipe material. High liquid velocity and turbulence, entrained solids and bubble collapse due to cavitation can cause serious erosion near elbows, tees, orifices and control valves, Antaki, 2005. To prevent erosion, carbon steel can be clad with a layer of material more resistant to erosion.

Preventing Control	*Example*
Removal of dust / Use of filters / Scrubbers	Coating with erosion resistant material

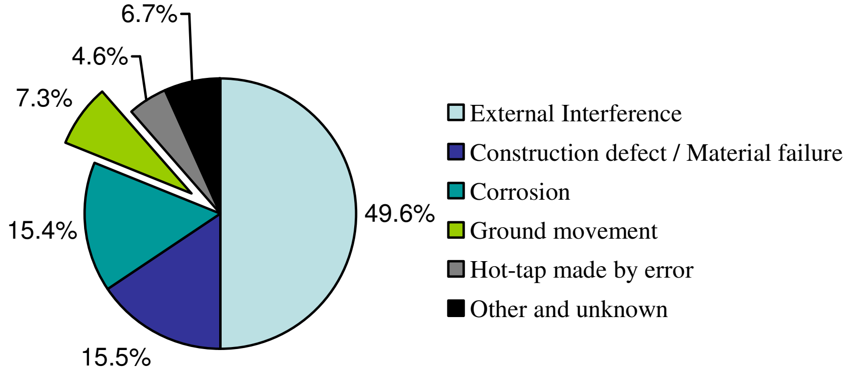
3.2.3.6 Interaction between CO_2 and infrastructure materials

In the design phase care should be taken when selecting the materials used in the system. The fact that CO_2 is transported can lead to different material property requirements.

Dense phase CO_2 can damage some elastomer sealing materials. High durometer(>90) elastomer seals are normally specified. (Viton valve seats and Flexitallic, nitrile and EPDM gaskets are often used in the USA for CO_2 pipelines, J. Gale, et al. 2004.

Preventing Control
Proper Design

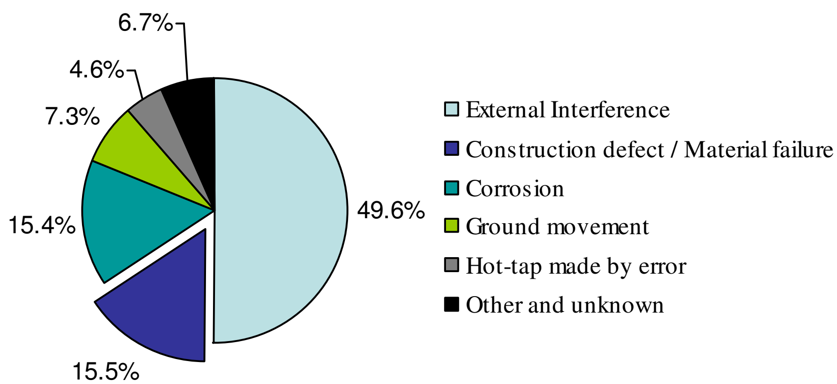
3.2.3.7 Natural threats



Forces exerted on the pipeline by natural occurrences like landslides, earthquakes or settlement can be high and in some cases can lead to failure of the pipeline. The main mitigating measure is an appropriate selection of the right of way.

Preventing Control	***Examples***
Right of way selection	Using knowledge of subsurface and subsequent likeliness of earthquake/landslide etc.

3.2.3.8 Design & Construction errors / Material flaws



In order to minimize the occurrence of design and construction error and flaws in the used materials several controls can be identified. First of all, the transport company only selects suppliers that can show a suppliers declaration. In this declaration it should be stated that the materials and the procedures are in compliance with the national and international norms and standards (e.g. NEN 3650, EN10208-2, ISO03183, ISO14313). Next to requirements on material properties the standards also dictate what kind of quality control is necessary. For example, in NEN 3650 it is stated that a hydrotest should be performed before taking a new pipeline in operation.

Besides the national and international standards, every company can define supplementary requirements in company standards. Because at the moment no
(international) standard for CO_2 transport pipelines exist, it is advisable that CO_2 specific requirements are set in these company standards.

The design of CO_2 transportation pipelines should be conducted with the threat of a CO_2 loss of containment in mind. This could mean that additional requirements on materials, design, testing and commissioning are needed.

Preventing Control
Quality control
Proper design

3.2.3.9 Fatigue

Fatigue is a progressive and localized structure damage caused by cyclic tensile stresses. The cyclic stresses can be due to mechanical loads or due to thermal cycling. Cracking proceeds perpendicularly to the tensile stress and is usually transgranular. In a corrosive environment, corrosion fatigue can occur at lower stress levels and progresses at a faster rate than fatigue in a noncorrosive environment. Carbon steel has an endurance limit, a stress below which fatigue cracking will not occur. The endurance limit is in an order of 30 percent of the ultimate strength of the metal.

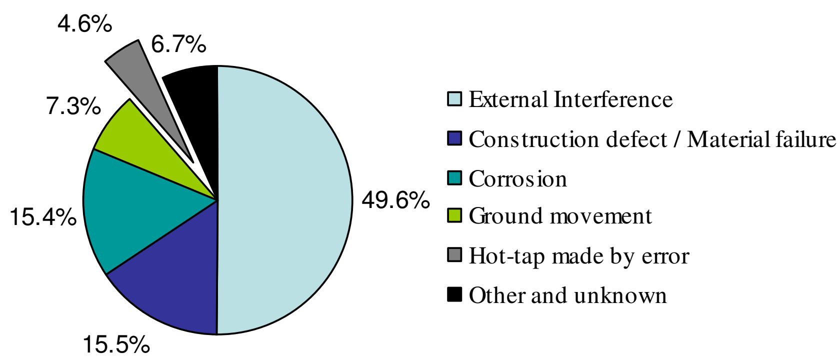
Preventing Control
Proper design
Maintenance/Monitoring

3.2.3.10 Hydrogen Induced Cracking

Hydrogen induced cracking is caused by absorption of hydrogen into the material to cause degradation in mechanical performance. Hydrogen has a considerable accelerating effect on crack growth in susceptible steels. Hydrogen can be generated by welding, corrosion, cathodic protection and biological activity. If the pipeline metal is exposed to an anaerobic environment where sulphate reducing bacteria (SRB) are present, SRB will be active in the areas where hydrogen is generated under cathodic protection. Hydrogen sulphide produced by the SRB can promote hydrogen absorption into the steel which results in hydrogen embrittlement. In this case the application of antibacterial coatings is worthwhile.

Preventing Control
Anti-bacteria coating

3.2.3.11 Errors made during repair/maintenance



Wherever people are working, people make mistakes. Unfortunately, a mistake in the gas industry can have disastrous consequences. In order to minimize the occurrence of mistakes it is important to work according to procedures and have a quality control system in place.

Preventing Control
Quality control/procedures

3.2.4 Consequences of the event

In the next paragraphs the consequences of the event CO_2 pipeline rupture are discussed briefly.

It is possible that a rupture of a CO_2 pipeline is the triggering event for another hazardous event to occur, for example the failure of a parallel natural gas transport pipeline. In the selection of possible consequences these so-called domino effects are not taken into account

3.2.4.1 Formation of a CO_2 cloud

Because the density of CO_2 in the gaseous phase is higher than that of air, CO_2 has the tendency to form a cloud that covers the surface. Breathing CO_2 is extremely hazardous to people. A continuous exposure at just over 2 percent can cause depressions of the central nervous system. At concentrations higher than 10 percent it can cause severe injury or death due to suffocation.

To warn people around the pipeline when CO_2 is present in the surrounding atmosphere CO_2 detectors with an automated alarm could be installed at critical points in the CO_2 transport infrastructure. In general it is advisable to respect the safety distances that apply for the pipeline.

When a loss of containment is detected and is considered dangerous the people in the surrounding area have to be evacuated. The block valves have to be closed and the remaining gas in the block segment has to be vented.

Mitigating Control
Installing CO_2 detectors with automated alarm
Respecting the safety distances

3.2.4.2 (Physical) explosion

For (physical) explosion hazards, safety distances can be defined and respected.

Mitigating Control
Respecting the safety distances

3.2.4.3 Fracture propagation

Fracture propagation is a problem in pipelines conveying gas or liquids with high vapour pressures. Fractures can propagate in either the fully brittle or fully ductile modes for long distances, and in theory, could propagate almost indefinitely. In the literature on CO_2 pipelines, many authors have indicated that ductile fracture propagation may be an issue and indeed, the requirements to consider fracture propagation in CO_2 pipelines is included in the federal regulations in the USA.

In the design of gas pipelines, the fracture arrest pressure is generally controlled by specifying a required material toughness.

When the pipelines are not designed with sufficient toughness to arrest propagating ductile fractures it is common to install crack arrestors along the pipeline.

Mitigating Control
Crack arrestors

3.2.4.4 Economical & Environmental effects

When a rupture of a CO_2 pipeline occurs it is inevitable that a considerable amount of CO_2 is released into the atmosphere. Because emission of CO_2 is considered harmful to the environment an emission trading system is in place where the polluter has to pay a certain amount of money per ton of CO_2. The current 'price' of CO_2 is between 10 and 20 €/ton CO_2.

A blockage of the CO_2 flow will also have its effect on other parts of the CC(T)S chain. It is advisable to design the infrastructure keeping the possibility of a rupture in mind.

Mitigating Control
Block valves
Vent remaining CO_2 to atmosphere

3.2.4.5 Noise effect

A rupture of a CO_2 gas transport pipeline will produce a large amount of noise. People who are near the event should wear their personal protection measures to minimize damage to their hearing.

Mitigating Control
Personal Protection Measures

3.3 Discussion

A Bowtie diagram gives a clear overview of the causes and consequences of hazardous events. It shows transport system operators what methods can be used to prevent an event and what actions need to be taken to mitigate the damage if this event takes place.

Statistical analysis of incidents in the oil and gas industry reveals that some failure causes are more likely to cause damage to the pipelines than other causes.

A risk assessment such as risk matrix analysis may be necessary to indentify the risk levels of threats. Risk assessment can be based on either qualitative or quantitative methodologies. Qualitative assessments are based on experience and engineering judgment. Quantitative assessments use engineering disciplines to set priorities and develop programs for system inspection.

The following equation is commonly used as a definition of risk, Roberge, 2007.

Risk = probability of failure (POF) × Consequence of failure (COF)

where the POF is based on failure frequency or remaining lifetime, while the COF is usually related to safety, health, environment, and economics issues.

A risk matrix method is an example of qualitative risk assessment It uses a matrix dividing the dimensions of frequency (POF) and consequence (COF) into typically three to six categories. Risk matrices can use quantitative definitions of the frequency and consequence to rank the risks of the each hazard or each box on the risk matrix (see Figure 3.3(Roberge, 2007). In the matrix A represents very low (VL), B low (L), C medium (M), D high (H) and E very high (VH) level effect on the environment and public safety. If an event happens frequently and has a fatal effect on environment or public safety, the event is located in the high risk region.

It is worth mentioning that the risk matrix method has its limitations. For example, it may underestimate total risk by ignoring accumulation of small risks, because sometimes many small risks can accumulate into an undesirably high total risk.

Bowtie analysis combined with risk matrix assessments can help regulators and transport system operators to make regulations and/or requirements for the design, construction, operation, inspection and maintenance of the CO_2 transport systems.

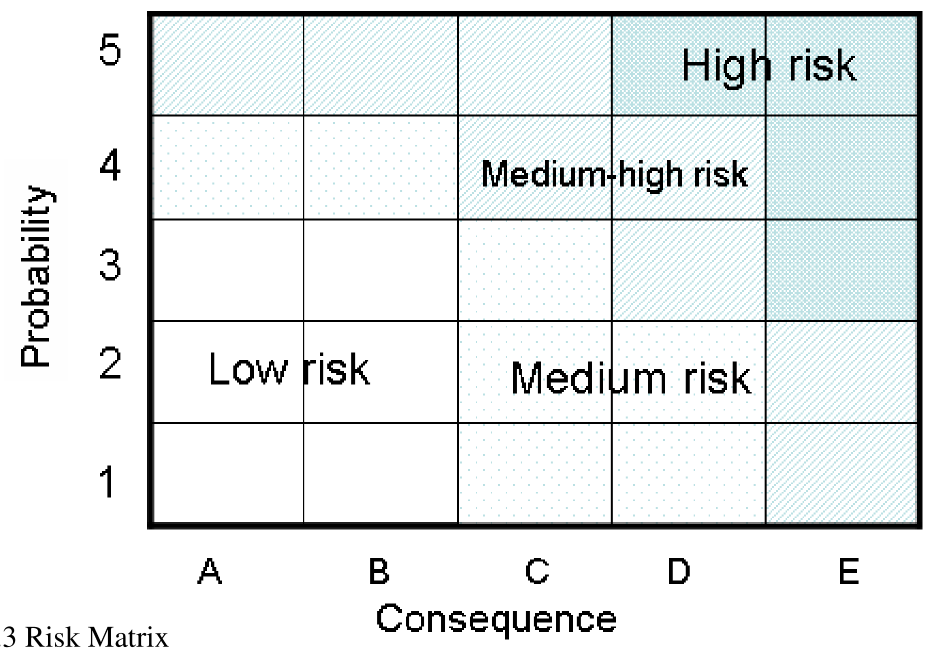


Figure 3.3 Risk Matrix

3.4 Conclusions & Recommendations

A Bowtie analysis has been performed to give an overview of the threats and consequences of a rupture in a CO_2 transport pipeline. The prevention methods and mitigation measures if a rupture occurs are described.

Literature shows that the main threat to a transport pipeline is 'external interference', followed by 'material and/or construction failure' and 'corrosion', see Appendix A.

Special care should be taken in the design phase of a CO_2 transport pipeline since the fact that CO_2 is transported can lead to different requirements on the materials used. When pipelines that were designed for another purpose that CO_2 transport are used this goes without saying.

A Bowtie diagram combined with the risk matrix method can be used to assess the risk in CO_2 transport systems to help regulators and operating company to make regulations for the design, construction, operation, inspection and maintenance of the CO_2 transport systems.

3.5 Appendix A to Chapter 3: Risk characterization, prevention and mitigation

There are 54 spillage incidents in European cross-country oil pipelines in 5 years (2002 – 2006) (Davis, Dubois et al. 2008).

Table 3.2 Five-year comparison of spillage incidents by causes in European oil pipelines (2002-2006)

Failure causes	times	%
Mechanical failure		29.6
construction	7	
material	9	
Operational		3.7
system	2	
human	0	
Corrosion		20.4
external	7	
internal	3	
stress corrosion cracking	1	
Natural hazard		1.9
subsidence	0	
flooding	0	
other	1	
Third party activity		44.4
accidence	13	
malicious	7	
incidental	4	

Table 3.3 There were 10 incidents in CO_2 pipelines in USA in the 1990-2001 period J. Gale, et al. 2004.

Failure causes	times	%
Material	Relief valve, 4	70
	Weld/gasket/valve packing, 3	
Corrosion	2	20
Outside force	1	10

Table 3.4 The principal causes of pipeline accidents in natural gas pipelines in the USA in the 1986 -2001 period J. Gale, et al. 2004.

Failure causes	%
Material	13
Corrosion	32
Outside force	35
Operator error	3

Other	17

Table 3.5 Incident causes percentages in natural gas pipelines in Europe (EGIG data D. van den Brand, et al. 2009)

Cause	Overall Percentage [%]
External Interference	49.6
Construction defect / Material Failure	16.5
Corrosion	15.4
Ground movement	7.3
Hot-tap made by error	4.6
Other and unknown	6.7

3.6 References Chapter 3

[1] D. van den Brand, et al. Safety in European Gas Transmission Pipelines, Report of the European Gas Pipeline Incident Data Group, IGU paper 2009

[2] J. Gale and J. Davison, Energy 29, 1319 – 1328 (2004)

[3] P.M. Davis, J. Dubois, et al. (2008). Performance of European cross country oil pipelines, statistics of summary of reported spillages in 2006 and since 1971. Brussels.

[4] Antaki 2005, Fitness-for-service and integrity of piping, vessels, and tanks, Mcgraw-Hillcompanies, Inc.

[5] Roberge 2007, Corrosion inspection and monitoring, John Wiley & Sons, Inc.

4 Frameworks for risk assessment

4.1 Introduction

This literature survey is focussed on the question: Could releases of CO_2 during incidents endanger the safety of the outside world? The reason for the survey is the fact that large scale transport of CO_2 is relatively new. In addition CO_2 behaves differently from other transported substances, which introduces more uncertainties for risk and effect calculations.

In the USA and Canada long distance transport pipelines for CO_2 are already in use. The operating pressures vary between 100 and 200 bars. Most of these pipelines are located in remote, non-populated areas. The CO_2 is mostly used for Enhanced Oil Recovery (EOR). In Norway (Statoil) a 200 bar off-shore pipeline is in use. In the Netherlands also CO_2 is transported, however, at much lower pressures and at a much smaller scale: 10-22 bar (Zoetermeer).

For CCS (Carbon Capture and Storage) projects the most likely option for CO_2 transport is transport as a dense liquid as this is the most economical way. In addition, the CO_2 will be transported at pressures above its critical point ($p_{critical}$=72.9 bar) to prevent two-phase flow under normal operating conditions.

However, in case of an accidental release the amount of CO_2 released from the pipeline is larger in case of liquid or dense phase transport than in case of vapour transport. In order to be able to assess these risks, proper validated models for the outflow and dispersion of CO_2 are needed.

Effect and risk calculations are the tools to answer the question about safety during CO_2 releases. However, the situation is complicated due to the different tools that are available. Before presenting the results of the literature review, the risk assessment concepts are briefly outlined in Section 4.4.2, examples of safety approaches for pipelines in Europe are presented in Section 4.4.3. Section 4.4.4 starts with the elements of effect and risk calculations and presents which of these elements are presented in the various literature sources.

4.2 Effect and risk calculations

4.2.1 Safety policy

Effect and risk calculations play a role in the safety policy of industries, of the competent authorities on external safety and of the emergency services. The organization of safety policy may be described by the so-called safety chain. The safety chain consists of five links. The role of effect and risk calculations varies depending of the link in safety chain that is considered.

The five links of the safety chain are:

1. removal,
2. prevention,
3. preparation,
4. repression and
5. aftercare.

They are discussed below.

4.2.1.1 Removal

Removal refers to the removal of structural causes of hazards, especially in the field of land-use planning and infrastructure. An example is the creation of an industrial area where safety aspects can be taken into account at an early stage.

4.2.1.2 Prevention

Prevention refers to the restriction of risks and accidents, for example by making demands in permits for building and permits for storage and transport of dangerous goods. Upholding of these permits is the next step.

4.2.1.3 Preparation

The preparation on the control of accidents and disasters requires a strategy, supply of information, instruction and training of employees and the acquisition of tools.

4.2.1.4 Repression

Repression refers to the actual combat of the accident and the provision of subsequent relief.

4.2.1.5 Aftercare

Aftercare refers to the return to normality. These are the medical and psychological care for victims and relief workers, handling of claims and taking care of the environment. Also evaluation by the authorities and giving account for the followed procedures are part of the aftercare link.

Risk calculations are vital input for the first three links in the safety chain: pro-action, prevention and preparation. In order to understand the significance of effect and risk calculations an introduction to risk assessment is presented in section 4.2.2.

4.2.2 Risk assessment: how are target groups affected?

Public safety involves the prevention of and protection from events that could endanger the safety of the general public from significant danger, injury/harm or damage.

When tasked with the safety assessment of a product, technology or process various parameters should be considered. The choice of the most suitable assessment method will depend on these considerations. The following should be taken into account:

- What is the target group (personnel, customers, the general public, other equipment) that might suffer adverse consequences (domino effects)?
- In which stage of development is a process (design, engineering, construction, commissioning, operation, maintenance, decommissioning)?
- What type of regulations applies (e.g. prescribed techniques, specific norms and criteria, probabilistic or deterministic assessments)?
- Is a quantitative or qualitative assessment required?
- What is being considered: undesired events (accidents) or safety during regular use (operational and workers safety)?
- What is the purpose of the assessment, e.g. is it selecting a safe location for a process (unit), or selecting the safest process from a range of alternatives (relative ranking), or assessing safety in comparison to other processes or techniques (benchmarking)?

- What are the input data requirements and how much data is available at the time of assessment; i.e. is the technology new (which means limited data is available), or is the technique tried and tested and has safety relevant data been collected?

In the context of this survey the events that could endanger the safety of the outside world are releases of hazardous materials during incidents. Releases of hazardous materials may occur at companies that produce or use those materials or during transport of these by rail, road, water or pipeline systems. Hazardous materials are flammable, explosive or toxic chemicals that may form a threat for public health or can cause damage to buildings and constructions.

An important element of a safety analysis in this context is the determination of the distance at which damage may occur as a result of an accident with hazardous substances. This is the so called “effect distance”.
This is illustrated by the presentation of an accident with a pipeline transporting petrol, see Figure 4.1 . Discharged petrol forms a pool and is put to fire resulting in a ‘pool fire’. The radiation of the flames may cause injuries to people in the neighborhood or cause damage to buildings, installations or other targets.
Risk analysis focus on the question: how are target groups affected by a release of hazardous materials? There are various approaches to perform risk analyses that are described in section 4.2.3

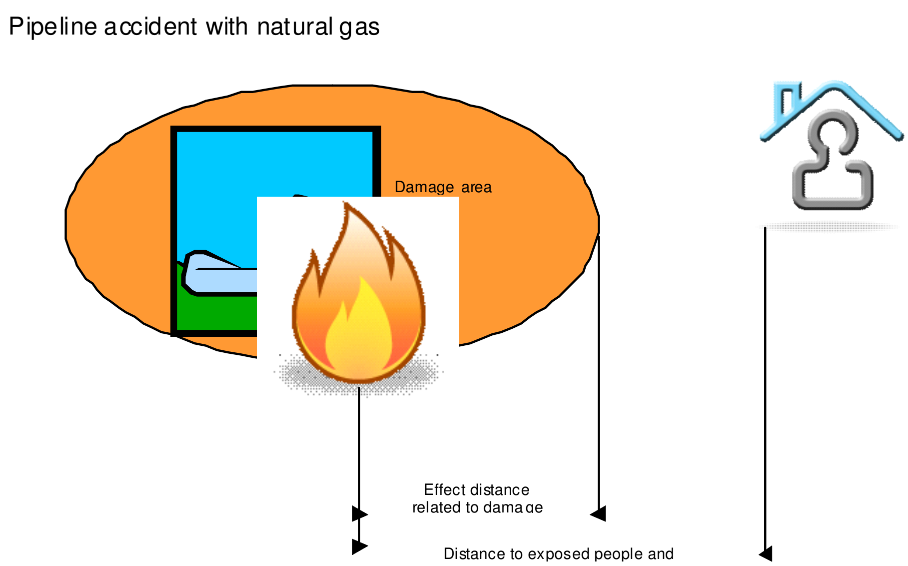


Figure 4.1 risk assessment – effect distance

4.2.3 Risk assessment: various approaches

Risk assessment is a structured procedure to evaluate qualitatively and/or quantitatively the level of risk imposed by hazard sources [8].
Due to political, cultural, structural, technical and other differences there is no unique procedure for risk assessment in the European Union [21].
The risk assessment of major accident hazards can be grouped into three broad categories namely:
– The establishing of generic distances
– The consequence based risk assessment
– The ‘risk based’ risk assessment
The latter two are both Quantitative Risk Analysis methods.

4.2.3.1 Generic safety distances

The development and use of generic safety distances is based on the principle that uses of land which are not compatible with each other should be separated. The extent of this separation zone is assumed to depend only on the type of industrial activity or on the quantity and type of the hazardous substances present. The generic approach can provide a separation between the developments and the hazardous activity. The safety distances usually derive from expert judgement and are based on historical data, the experience from operating similar plants, rough consequence estimates or on the environmental impact of the plant [8].

4.2.3.2 Quantitative Risk Assessment (QRA)

In a Quantitative Risk Assessment (QRA) all accident or Loss of Containment (LOCs) scenarios are fully quantified and the results are compared to risk acceptance criteria. If risk acceptance criteria are met no safety measures or Layers of Defence (LODs) are required. If risk criteria are not met measures need to be taken. Such measure can be either preventive, i.e. LODs in the fault tree, or mitigative, i.e. LODs in the event tree.

Risk acceptance criteria might be a result of company policy (often the case if effects stay within the boundaries of the site) or may be set by regulators (which is usually the case if effects extend beyond site boundaries - the domain of external safety).

The consequence based risk assessment

The consequence based risk assessment considers

- The distance at which a hazardous concentration occurs with or without accounting for the duration of the exposure.
- The distance at which thermal radiation reaches a threshold value for thermal effects
- The distance at with overpressure reached a threshold for undesired effects (e.g. eardrum damage)

Various hazardous concentrations/threshold values are in use [8] :

- The lethal concentration (LC1%) is the concentration corresponding to 1% lethality for toxic releases
- The IDLH (Immediately Dangerous for Life and Health) for toxic releases
- The ERPG-2 (Emergency Response Planning Guideline) for toxic releases
- SLOT: significant level of toxicity
- SLOD: significant level of death
- Thermal radiation corresponding to 3rd degree burns
- The overpressure corresponding to eardrum rupture (e.g. 140 mbar) for explosions

Another designation for consequence based risk assessment is deterministic risk assessment

The 'risk based' risk assessment

Quantitative Risk Analysis (QRA) is a method for quantifying the risk and physical effects of industrial installations with hazardous materials. First the incident scenarios are identified followed by the determination of the physical effects (outflow phenomena, gas dispersion). Dangerous levels of hazardous gas may lead to casualties and/or lethality. For every scenario and corresponding effect and damage, the probability is to be determined. Next, corresponding probabilities and damage calculations are multiplied and added to calculate the total risk.
Another designation for the 'risk based' risk assessment is the probabilistic risk assessment

4.2.4 Variability of the risk assessment procedure

In paragraph 4.2.3 the various approaches of a risk assessment are presented. However, even for the same approach the outcome of a risk assessment may vary due to a number of factors:

– The hazard identification phase may be critical because the role of expert judgment is fundamental.
– The estimation of scenarios' frequencies by the analysts may differ.
– The effect models do have limitations: for instance they are valid for a restricted temperature range or not applicable for the particular behavior of the chemical of interest.

Therefore it is important to have apprehension of the uncertainties in assumptions, data and calculation methods of a risk assessment. These topics will be discussed in this report.

4.2.5 The role of risk assessment in Land-Use-Planning (LUP)

In the introduction it is stipulated that risk assessment is of importance in various links of the safety chain. In the Pro-Action link Land-Use-Planning issues are of great importance. In countries where the risk-based approach is in use, two measures of risk are determined: the individual risk contour and the societal risk curve. For both risk measures criteria are in use.
The individual risk criterion is applied for the protection of each individual against hazards involving dangerous chemicals. The societal risk criterion is established for the protection of the society against the occurrence of large scale accidents.

In countries where the consequence based risk assessment is in use, the extent of consequences is the only criterion for LUP. In Table 4.1 an overview is presented of the land-use planning practices in the European Union [8].

Table 4.1: Overview land-use planning practices in the European Union (1999)

Country	Generic safety distances	Consequence based approach	Risk based approach	Land-use planning criteria	Arrangements still being developped
Austria					X
Belgium		X (Wallonia)	X (Flanders)		X
Denmark					X
Finland		X			
France		X		X	
Germany	X	X		X	
Greece					X
Ireland					X
Italy					X
Luxembourg		X		X	
Netherlands			X	X	
Portugal					X
Spain		X			X
Sweden	X	X			X
United Kingdom			X	X	

A more recent paper [21] provides a review on the implementation of article 12 of the Seveso II Directive, providing information on industrial risks and LUP in several selected EU member states. This reference is highly recommendable reading, for several risk analysis approaches are described and the link to LUP issues is outlined.

Specially the Annex of this document is of interest, whereas several selected practices systematically are described for the EU-members United Kingdom, France, Italy, Germany and The Netherlands. For each of these five countries separately the following items are explained in detail (including a list of the selected countries references and web links):

- Background (countries history – present characteristics)
- Operation permits procedure
- Territorial governance and planning instruments
- Planning procedure
- Systematic method in use for land us planning in risky areas
- What 'tolerable' means in the countries regulation – status of adopted criteria
- Environmental assessment
- Subjects and competences: transparency of the process – involvement of the public

Norway, Poland, Sweden and Czech Republic are not mentioned in the two references [8,21]. Together with United Kingdom, The Netherlands, France and Germany also these countries risk assessment practice is discussed in the next chapter.

4.3 *Safety Approaches for Pipelines in Europe*

The first approach to ensure that pipeline systems operate 'safely' is to design, construct and operate pipeline systems according to the relevant standards governing the safety of pipelines. This Section will discuss the 4 levels for standard pipelines in Europe and discuss the local pipeline safety regulations in Germany, the Netherlands, France, Norway and the UK.

4.3.1 European standards for Pipelines [24]

There are 4 levels of standards for pipelines in Europe.
- European Gas Directives that focus on common rules for transmission, distribution, supply and storage whereas also specific directives are in power.
- European Standards (ISO, CEN) cover aspects concerning the design, construction and operation of safe pipelines.
- National regulations or specifications for design, construction and operation of pipelines based on the European Standards
- Particular safety aspects incorporated in national legislation, codes or specifications

None of these standards has been specifically developed for CO_2. Recently a document has been published with recommended practices for CO_2 pipeline design and operation. [19]

4.3.1.1 European level

- First Gas Directive 98/30/CE in 1998
- Second Gas Directive 2003/55/CE in 2003
  (Common rules for transmission, distribution, supply and storage)
- Specific Directives (Seveso, PED, ATEX...)

4.3.1.2 International /European Standardization (ISO, CEN)

Basic Functional standard: EN1594:2000 – For contents see ANNEX A

4.3.1.3 National regulations based on European Standards – example UK

European standards implemented in the UK as British Normative Standards (BS EN series) and supported by published documents (such as the British Standards PD Series) provide a sound basis for the design of pipelines.
European Harmonised Standard: BS EN 14161: Petroleum and natural gas industries – Pipeline transportation systems.
European Harmonised Standard: BS EN 1594: Gas Supply Systems - Pipelines for maximum operating pressure over 16 bar - Functional requirements.

4.3.1.4 Particular safety regulations

For a few countries particular pipeline safety regulations are described in section 4.3.2. They are just examples to show the various approaches. All countries represented among CO_2Europipe participants are included.

4.3.2 Pipelines Safety Regulations - examples

4.3.2.1 Pipelines Safety Regulations – UK

The principal legislation governing the safety of pipelines (Pipelines Safety Regulations 1996[1]) is goal setting requiring that pipelines are designed, constructed and operated so that the risks are as low as is reasonably practicable (ALARP[2]). In judging compliance, HSE expects duty-holders to apply relevant good practice as a minimum. For new plant/installations/situations, this will mean the application of current good practice. For existing plant/installations/situations, this will mean the application of current good practice to the extent necessary to satisfy the relevant law (ALARP and use of good practice [3]).

In the pipeline industry there are many well established standards, covering design, operations and maintenance of UK sector major accident hazard pipelines, both onshore and offshore, which can be used to demonstrate risks are ALARP. If a duty holder wishes to use other standards, recommendations or guidance then this may be acceptable, provided they can show that they achieve equivalent levels of safety. A gap analysis should be undertaken to confirm this.

In the UK CO_2 will be treated as if it were a "dangerous fluid" under Schedule 2 of The Pipelines Safety Regulations (PSR) 1996. That designates the pipeline as a "major accident hazard pipeline" (MAHP) under Part III of the Regulations (see http://www.hse.gov.uk/pipelines/hseandpipelines.htm), meaning that a "major accident prevention document" (MAPD) needs to be prepared under Regulation 23. Under this, the operator needs to demonstrate that:

- all hazards relating to the pipeline with potential to cause a major accident have been identified;
- the risks arising from those hazards have been evaluated [i.e. a risk assessment];
- the safety management system is adequate; and
- the operator has established adequate arrangements for audit and for the making of reports thereof

One should be aware that there are other additional requirements for an MAHP including notification (Regs 20 & 21) and emergency plans (Regs 24 & 25).

There is an Approved Code of Practice (ACOP) for the PSR, which sets out in more detail how the four items (bullets) above should be addressed in the MAPD document. This will obviously need adapting for the particular risk characteristics of CO_2. Therefore the following references would be considered relevant:

- The DNV Code of practice DNV-RP-J202 [19].
- IGEM/TD/2 "Application of pipeline risk assessment to proposed developments in the vicinity of high pressure Natural Gas pipelines", again altered according to the characteristics of CO_2.
- The main pipeline standards in use in the UK are BS PD8010 Part 1 and Part 2. Natural gas also uses an additional guidance document – IGEM/TD1.

Additional UK (safety) regulations can be found on the links below:

http://www.hse.gov.uk/pipelines/faqs.htm#mhlupassessment
http://www.hse.gov.uk/gas/supply/information.htm
http://www.hse.gov.uk/pipelines/co2conveying.htm
http://www.ucl.ac.uk/cclp/ccsdata.php

4.3.2.2 Pipelines Safety Regulations – Norway

Norway has a risk based safety approach. Norwegian regulations specify that risk analyses should be performed to identify risks. The operators however are free to use the tools they themselves consider appropriate. Operators may include what is evaluated to be relevant (and thus also allowed to exclude issues evaluated as not relevant). Each company is also expected to establish their own risk acceptance criteria, meaning that the same risk level may be considered as acceptable for one company, and unacceptable for another. The philosophy is that each company is forced to do a realistic and thorough evaluation of what they are doing, rather than following a "common recipe". To a large extent the authorities' task is to evaluate and regulate the way operators work and think, rather than evaluating the detailed results of each analysis.

In Norway, specific regulations related to CO_2 pipeline transport have not been established yet, but the authorities are in the processing of developing such regulations.
It is expected that the same principles will apply for CO_2 transport as for petroleum related pipeline transport. Regulations already in place for the petroleum industry are functional requirements, specifying what is to be achieved rather than what should be done in details.

A summary of the Norwegian pipeline (safety) regulations can be found on the link below:

http://www.ptil.no/regulations/the-continental-shelf-article4246-87.html

this is a condensed version of the Norwegian safety regulations, and in particular the last half of the text is informative. The above link contains further links to regulations and standards.

4.3.2.3 Pipelines Safety Regulations – NL (Decree Public Safety Pipeline systems)

Zoning plans
According to the concept-Decree, municipalities are obliged to consider the Individual Risk Contour (IR) and the Societal Risk when zoning plans are developed. For IR the 10^{-6} contour is the limit value for vulnerable objects and a guide value for reduced vulnerable objects. Societal risk must be justified within

the area of influence of the pipeline system. For flammable substances that extends to just outside the 10^{-6} contour, for pipeline systems with natural gas and chemicals the area of influence has to be calculated on an individual basis. Besides in each zoning plan space is allocated for maintenance activities on the pipeline: in a strip of minimal 5 m at both sides of the pipeline applies a building ban and a permit system for constructions.

Obligations pipeline operator
At the construction or replacement of pipelines in principle the 10^{-6} contour should be located within 5 meters of the pipeline. Further all modifications should fit within the zoning plan. The pipeline operator informs the Risk Registration Office Hazardous Materials about the modifications. In addition the concept Decree contains a provision concerning the duty to provide for the prevention of unusual incidents. Compliance with NEN 3650 (construction demands) and the NTA 8000 (availability of a safety management system) is obligatory

Regulation Public Safety Pipeline System
Part of the Decree Public Safety Pipeline systems is the Regulation describing amongst others the safety distances and calculation methods for the various pipeline systems. The Decree and the regulation will come into force in phases, to start with the high pressure natural gas pipelines. For natural gas pipelines the calculation tool CAROLA is available. For pipeline systems with flammable liquids the RIVM has already published safety distances. The safety distances or calculation methods for pipeline systems with other substances will be announced at a later stage.

4.3.2.4 Pipelines Safety Regulations – France

Since a few years France applies a specific methodology to analyse the risks: Plan for the Prevention of Technological Risks (PPRT). [20]
This method is as follows:

- Execution of a safety report. This safety report includes the definition of scenarios and the determination of consequence distances for 3 or 4 levels of consequences: very severe damage, severe damage, significant damage, and indirect damage.
- Determination of the probability for each scenario. This ranges from: extremely unlikely to common.
- Determination of the kinetics of a scenario: distinction between fast and slow. A fast scenario implies that no safety measures can be taken to prevent damage/ lethality outside the site limit, e.g. an explosion. A boil over has a slow kinetic characteristic.
- Fast kinetics:
    - For a specific location, the probabilities of the scenarios are summed.
    - The sum of the probabilities is grouped in 3 categories.
    - The consequences and the summed probabilities are grouped in 7 levels as follows to obtain the risk: very strong+, very strong, strong+, strong, average+, average, and low.
- Slow kinetics: in contrast with the fast kinetics, for the slow kinetics, one does not look at each individual scenario, but at one specific effect (toxic, overpressure, radiation). No use is made of the risk; one only looks at the total envelope of one particular effect.
- Maps are made for the risk for the fast kinetic scenarios and for the effect envelopes of the low kinetic effects.
- In the maps obtained in the previous step, all objects (building, houses etc) that are present within a risk/ effect envelope are represented.

- Based upon the maps (taking into account type of effect, kinetics, vulnerability, etc), decisions are made:
    - Definition of area of expropriation
    - Definition of area of pre-emption
    - Definition of area of cession : owner has right to demand that his property will be bought by local authority
    - Which risk reducing measures are taken in which area (heat resistant walls, etc)

:

4.3.2.5 Pipelines Safety Regulations – Germany

Some information on the safety regulations in Germany can be found in reference [21]. Germany is a federal country with 16 states. The Land-Use-Planning is regulated on federal and state level.

The method generally used for risk analysis is the consequence based approach. In exceptional cases different tools can be applied, e.g. a probabilistic approach or a case-by-case approach.

Some reference (inter)national standards used in Germany are:

- DIN: EN 14161:2003 Petroleum and Natural Gas Industries – Pipeline Transportation Systems
- ISO 3183-3 Petroleum and Natural Gas Industries Steel Pipe for Pipelines – Technical Delivery Conditions
- PD 8010-2:2004 Subsea pipelines (British Standard for offshore pipelines)

Normally, pipelines in Germany with pressures >16bars go through a long-lasting procedure of land use planning. Every state is responsible for land use planning (ROV), a combination in responsibility of the state ministry of Interior and the one of Environment. Pipelines with pressures <16bars are in municipal regulation. [22]

The ROV legal framework is used for pipelines with pressures >16bars. It is coordinated by the AFR (Ausschuss für Rohrleitungen; part of the federal Ministry of Environment) and the cooperation DVGW. They define the Gas-HD-Rohrleitungs-VO and the TRFl (technische Regeln für Fernleitungen) and plan to add an attachment M to these TRFl rules by end 2011. This attachment M will deal with CO2 and will incorporate the regulations defined in the new German CCS law KSpG. However, the KSpG will not be in place before end 2010.

The moderate German mining law is applied for short field pipelines within oil and gas producing fields. There, pressures may reach 100 to 500 bars.

4.3.2.6 Pipelines Safety Regulations – Poland

In Poland both risk based and deterministic risk assessments are performed.
Formally, the Polish regulation in major accident area only describes what should be contained in the required documents, which are: a major accident prevention policy (MAPP), Emergency Plans (EP) and Safety Reports (SR). In Poland, there is no approved framework methodology for the realisation of these documents. Nevertheless several EU-guidelines are used in practice.

The Polish safety approach can be grouped into two categories:

- The structured ones, where all formal requirements are (MAPP, EP and SR) are combined and form one integrated system with clearly defined goals, tools and results for the demonstration of safe operation
- Casual ones (stochastic) ones, only descriptive, devoted to the presentation of required information without judgement of safe operational assessment

Polish SEVESO II regulation does not require the use of QRA or any other risk assessment methods, which are available. The selection and effective use of those methods (to do risk assessment and hazard identification) belong to the operator who needs to prove their use.

4.4 Risk analysis data on CO2 pipelines – literature review

4.4.1 Introduction

As explained in section 4.2.3 there are various approaches to perform a risk assessment. This Section 4.4 reviews the literature on risk assessments of CO_2 .The following system characteristics affect risk of loss of containment [9]:

- Pipeline design and construction (materials choice and characteristics, number of intersections, connection of intersections, number of valves per unit length)
- Pipeline location (above ground or buried/covered, geology and terrain features, urban areas, protected nature environment)
- Pipeline use (operational circumstances, throughput)
- Pipeline maintenance (monitoring technologies, mean time to failure)

First the elements of a risk assessment are shortly described. Next it is reported which of these elements are presented in the various literature sources.

4.4.2 System description

In the scope of this literature survey the risks of a release of CO_2 that is transported by pipelines, is reviewed. For modelling the outflow of material from a pipeline, data is necessary on the pipeline system such as the diameter of the pipeline, the length of isolatable sections and the presence of soil coverage.

Buried as well as above ground pipelines are considered in several references. Pipelines are connected through flanges and welds and may contain valves. These are part of the pipeline system, pumps are excluded. In most literature references it is mentioned that risk analyses adopt a generic system because a final system design is not yet available.
It is expected that CO_2 will be transported as dense liquid at pressures up to 200 bars. The diameter of pipelines operated at pressures of 100 up to 200 bars (300 bars off-shore) varies from respectively 406 mm (16 inch) up to 914 mm (36 inch).

4.4.3 Failure scenarios for pipelines

Loss Of Containment events (LOC's) of pipe line systems are (full bore) rupture, leakage, fissure, hole and split.
The definition of rupture is not univocal.
Definitions of rupture are for instance:
- a leakage bigger than half of the diameter of the pipelines [2]
- a crack of 75 mm or longer and 10% of the minimal width [3]

The LOC's modelled in risk analysis are rupture and leakage. Pinhole leakages are not modelled because their contribution to risk is minimal.
According to [4] in the event of a rupture outflow occurs on both sides of the rupture. The location of the rupture is determining the flow rate.
According to [4] a leakage has an effective diameter of 10% of the nominal diameter, with a maximum of 50 mm. For underground pipelines leakage is modelled as outflow from a 20 mm hole. According to the Purple Book [1] the material of the pipeline, the presence of lining and the design pressure are of no influence on the scenarios and failure frequencies.

4.4.4 Failure frequency

The failure frequencies are reported in Table 4.5. For the use of general failure data of pipelines and fittings, the properties of CO_2 in the supercritical state as well as the influence of impurities in combination with water should be reminded. The solvating ability of supercritical CO_2 demands that the design/construction of e.g. gaskets, seals and internal linings is compatible with the use of the pipeline for CO_2 transport. In general it should be considered if due to different failure mechanisms, existing pipelines have to be re-qualified for transmission of CO_2.

Reference [5] states whether failure rates for natural gas pipelines can be used for CO_2 pipelines. Rates that have been used in other QRA's and in this study are between $0.7*10^{-4}$ and $6.1*10^{-4}$ km^{-1} $year^{-1}$. As a result the distance to the $1*10^{-6}$ risk contour may vary between 48 and 204 meter.

4.4.5 Crater formation

A full bore rupture of a pipeline can occur during digging activities of a buried pipeline. During such an accident, the crack may propagate until a so called 'crack arrestor' is reached (e.g. a weld, reinforcement). In the event a gas pipeline bursts open very rapidly, the escaping gas expands instantaneously and will possibly result in a pressure wave in the environment. In this case the physical explosion will possibly result in a bigger crater and the dimensions of the crater (length, width and depth) determine whether the outflow will loose its momentum. Reference [11] refers to a study whereby the angle of the crater is determined in order to calculate the conditional probability of a jet dispersion. According to reference [11] larger hazard ranges are produced by smaller crater angles. If horizontal jets in the crater collide with each other in the event of a two sided outflow, the outflow may loose its momentum completely [12]. However there is a clash of opinions in [10] and [7] about the loss of momentum as well as about the mixing with air in the event of colliding horizontal jets in a crater. According to [10] statements should be based on outflow experiments under high pressure.

4.4.6 Physical processes during the outflow of pressurised gasses

The outflow process of a general, pressurised gas can be described in this way. After rupture of the pipe, the processes inside the pipe determine the outflow (choke) pressure, flow rate, and vapour mass fraction of the flow. Just outside the pipe there is an expansion region where the pressure drops to ambient and the fluid flashes, resulting in a two-phase, turbulent jet of vapour and droplets. Due to the high velocity, ambient air will be entrained into the free jet. During the flashing droplets are formed and, depending on their size, the droplets will either rain out and form a liquid pool on the ground, or remain airborne and eventually vaporise. Due to the mixing with the ambient air the momentum of the jet decreases and the cloud is further dispersed by the surrounding air movements. In a separate process the liquid pool will evaporate and also be dispersed.

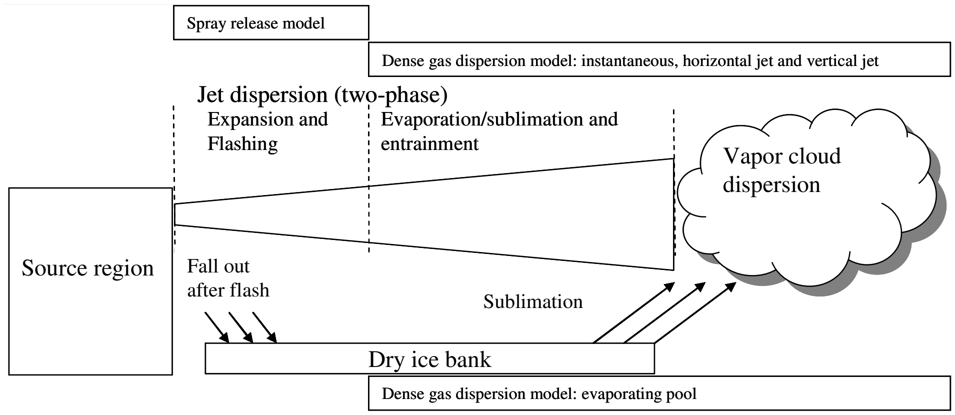


Figure 4.2 Overview of processes during outflow of pressurised CO_2

These steps are indicated for CO_2 in 4.2 However, at atmospheric pressure CO_2 can only exist as solid and gas, instead of liquid and gas, see phase diagram in Figure 4.3. This changes the outflow process, i.e. solid CO_2 is formed instead of droplets during the flashing and the rain out results in a solid CO_2 ice bank. See Table 4.2 for characteristic pressures and temperatures for CO_2. At atmospheric pressure solid CO_2 directly transforms into gaseous CO_2 without first forming a liquid.

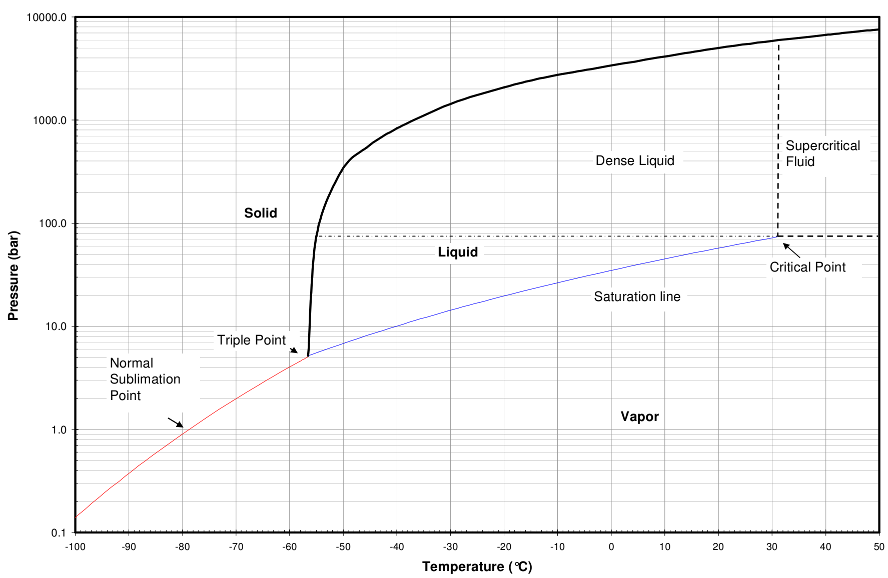


Figure 4.3 Pressure-temperature phase diagram for CO_2.

Table 4.2 Overview of parameters for critical point and triple point of CO_2

p_{triple}	5.18 bar
T_{triple}	-56.6 °C
$p_{critical}$	72.9 bar
$T_{critical}$	31.1 °C

The main process conditions that determine the outflow from a pipeline are the operating pressure and temperature. As long as the pressure remains above the triple point pressure, CO_2 will behave as any other liquefied gas. However during a depressurization event the inventory pressure will drop below the triple point (5.2 bar). The formation of dry ice is a possibility. Exactly this possible solid formation process gives rise to the question whether existing release and dispersion models can be used for CO_2, or that improvements or changes should be made.

The amount of solid CO_2 that is formed depends on the starting conditions (p and T). Initial conditions can be found for which solid formation does not occur, or only a small mass fraction will become solid. In these situations the outflow and dispersion of CO_2 will be no different than any other heavy gas, e.g. propane, and normally available release and dispersion models can be used for the accidental release of CO_2.

On the other hand, for initial conditions which result in liquid and two-phase outflow the CO_2 release will be both solid and vapour at the final conditions. Then regular models for release and dispersion are possibly no longer valid and should be adapted.

4.4.7 Initial cloud of CO_2

According to [7] the occurrence of a vertical jet release with momentum is the most likely scenario. In the event of buried pipelines a crater may be formed that is of great influence on the momentum of the release. The initial momentum of a jet release will diminish due to entrainment of air; in this way the released CO_2 is also diluted to non-lethal concentrations when the momentum becomes negligible.

According to [12] horizontal jets of CO_2 will appear from both sides of the pipeline after rupture. It is assumed that a crater is formed and the two jets will collide and loose their momentum. CO_2 will expand and cool down. In the event the two jets loose their momentum, dispersion out of the crater can be considered as emission from a surface source and not as a jet any more.

The above mentioned two approaches lead to different input parameters for the dispersion of the cloud. The scenario of a gas loosing all of its momentum and emerging from the ground slowly is considered to be a worst case scenario for buried pipelines[4].

4.4.8 Dispersion of the cloud

CO_2 is a heavy gas under atmospheric conditions. In combination with the assumption that the jet will lose its momentum, a heavy gas model for modeling dispersion is appropriate [12]. However, the heavy gas models have restrictions because they give unreliable results under certain conditions, such as low wind velocity, complex terrain or congested buildings.

CFD (Computational Fluid Dynamics) modeling of the dispersion of CO_2 is a challenge, and presently under development. CFD modeling enables to take into account the influence of obstacles in the dispersion of CO_2.

The two models can be used in combination to provide confidence in the consequence analysis. For every situation the best solution should be chosen.

[4] A release with a large proportion of its momentum removed due to leak orientation, crater size and shape would likely lead to low dispersion rates and correspondingly high hazardous distances.

4.4.9 Exposure to CO_2: probit functions and concentration thresholds

In the QRA probit functions are used to calculate the consequences of exposure of human beings to levels of toxic or oxygen dissipating gases. Also effects on respiration should be taken into account. The general probit function for inhalation of "toxic" gases is presented as:

$Pr = a + b \ln (C^n * t)$.

Where *C* is the concentration and *t* is the exposure time (varying dimensions), *a*, *b* and *n* are constants related to the toxicity of the toxic gas. The factor *a* depends on the dimensions of C and t.

Literature sources show both scenarios that include probit functions, and scenarios that include concentration thresholds (with or without a specification of the duration of the exposure). A concentration threshold is a fixed value. Concentration thresholds may use conservative endpoints for which an adverse impact is assumed on human health [5].

Risk calculations include also a vulnerability distribution that is expressed in the probability. An overview of probit functions and exposure thresholds for CO_2 is presented in Table 4.3. Due to the different end-points a direct comparison between the results of effect and risk calculations presented in Table 4.6 is not possible.

Table 4.3: Probit functions and exposure thresholds for CO_2

Literature sources	**Toxic data on CO_2 / Exposure threshold(s)**						
	Probit	**STEL**	**1% mortality**	**50% mortality**	**100% mortality**	**Toxic n value**	**No lethality**
Koornneef [5]	$4.45+\ln(C^{5.2} * t)$ C in [kg/m^3], t in [s]					5.2	
Molag [12]	$4.45+\ln(C^{5.2} * t)$ C in [kg/m^3], t in [s]					5.2	
McGillivray [11]	$-90.8+1.01\ln(C^8 * t)$ C in ppm, t in min		$1.5x10^{40}$ ppm^8.min[5]	$1.5x10^{41}$ ppm^8.min[6]		8	
Tebodin [13]	$-98.81 + \ln (C^9 * t)$ C in ppm, t in min				10% (vol) 100.000 ppm	9	< 5% (vol) 50.000 ppm
Mazzoldi [14]		1.5% 15.000 ppm					

[5] SLOT DTL
[6] SLOD DTL

In the Netherlands the National Institute for Public Health and the Environment (RIVM) has concluded in 2008 that available data on the effects of CO_2 is insufficient to deduce a probit relation for CO_2. For exposures below 10% CO_2 no lethality is expected [12].

Reference [5] states: In addition, uncertainty is caused by the absence of a dose-effect relationship as well as internationally standardized exposure thresholds for CO_2 for use in QRAs. This results in a large divergence of results in QRAs for CO_2 pipelines. In this study the risk contour is found at a distance between 0 and 124 meters with varying the probit function. The results of earlier risk assessments varied between <1 m and 7.2 km assuming different exposure thresholds.

The HSE in the UK has used a probit based on SLOT and SLOD values from literature. [23]

Literature sources	Pipeline data / phenomena								
	Description	**Internal diameter (mm)**	**Operating pressure (barg)**	**Operating temperature (K)**	**Phase of CO_2**	**Length of isolable section (km)**	**Inventory full bore rupture (kg) or total mass released release rate (kg/s) duration (s)**	**Depth of soil coverage (m)**	**Crater formation**
Koornneef [5]	NEN 3650	406 (16")	110	290	Dense liquid	20	$4.5*10^5$ kg (instantaneous) $2.25*10^6$ kg (horizontal jet) $4.5*10^5$ kg (sublimating bank 20%)		no
Vendrig [[15]	Onshore pipeline	760 (30")	100	285	Dense liquid	10			
	Offshore pipeline	1020 (40")	300	279	Dense liquid	10			
Lievense [16]	NEN 3650								
Molag [12]	NEN 3650	660 (26")	16.5	283	Gas	16.9	190.000 kg (6146 m^3) 408 kg/s during 465 s. (two-sided outflow)	1.3	yes
			40		Gas				yes
Turner [17]		1070 (42")					Horizontal release		
		610 (24")					Horizontal release		

Table 4.4: Pipeline data and phenomena in literature sources

Literature sources	Pipeline data / phenomena								
	Description	**Internal diameter (mm)**	**Operating pressure (barg)**	**Operating temperature (K)**	**Phase of CO_2**	**Length of isolable section (km)**	**Inventory full bore rupture (kg) or total mass released release rate (kg/s) duration (s)**	**Depth of soil coverage (m)**	**Crater formation**
McGillivray [11]		736.6	32	278	Gas	18		1.1	19° [7]
		736.6	15	278	Gas	18		1.1	19° [8]
Tebodin [13]	NEN 3650 - 2003	356 (14")	Max. 44	189 - 283	Gas	300 m and 73 m[9]		No coverage	no
		711(28")				300 m and 73 m[10]		No coverage	no
		356 (14")				4.4 [11]		No information	no
		711(28")				4.4 [12]		No information	no
Mazzoldi [18]	Generic – not specified		About 100 bar		Dense liquid		1.080.000 kg – 1800 kg/s - 600 sec		

[7] length/ depth approach: average crater angle, θ (according Kinsman and Lewis, 2002)
[8] length/ depth approach: average crater angle, θ (according Kinsman and Lewis, 2002)
[9] Pipeline in tunnel, the tunnel is provided with hatches at both ends. It is assumed that the hatches are blown away in the event of a rupture of the pipeline
[10] Pipeline in tunnel, the tunnel is provided with hatches at both ends. It is assumed that the hatches are blown away in the event of a rupture of the pipeline
[11] Burried pipeline in pipeline lane
[12] Burried pipeline in pipeline lane

Table 4.5: Physical effect modelling: overview of input data in literature sources

Literature sources	Modelling aspects		Failure frequencies for pipelines (m^{-1} yr^{-1})		
	(Probability of) jet dispersion	**Models used / parameters**	**Generic frequency**	**Leakage (operating pressure (bar))**	**Rupture (operating pressure (bar))**
Koornneef [5]	Instantaneous - horizontal and vertical jet	Full bore rupture[13]: • Non—stationary two-phase outflow from large pipeline • Spray release model - adjusted[14] • Vapour mass fraction: 70% Jet diameter: 0.6-0.8 m Puncture: • TPDIS and Spray release model– adjusted • Dense gas, based on SLAB • Vapour mass fraction: 21-22% Software package used: EFFECTS 7.6 adjusted and RiskCurves (TNO 2007)	$6.1*10^{-7}$		$0.25*6.1*10^{-7}$ (110)
	Vertical jet	For all puncture scenarios a hole size of 20 mm is assumed. • Pipeline roughness: 0.045 mm, • wind speed (at 10 m height):2 m/s, • ambient temperature: 9°C, concentration • Averaging time: 600 s, • height of release and receptor: 1 m, • ambient relative humidity: 83%, • wind direction is equal to direction of release,	$6.1*10^{-7}$	$0.75*6.1*10^{-7}$ (110)	

[13] Assesment done with software package EFFECTS 7.6 adjusted and RiskCurves (TNO 2007)
[14] Includes description of flashing and aerosol formation and evaporation. No fallout of solid CO_2 is expected

Literature sources	Modelling aspects		Failure frequencies for pipelines (m^{-1} yr^{-1})		
	(Probability of) jet dispersion	Models used / parameters	Generic frequency	Leakage (operating pressure (bar))	Rupture (operating pressure (bar))
Vendrig [15]		• roughness length description (roughness of terrain): 0.25 m (high crops; scattered large objects, upwind distance < 15 m., height of obstacles < 20 m), • discharge coefficient full rupture: 1, • discharge coefficient puncture: 0.62 • Full-bore pipe rupture (applied to all leaks of equivalent diameter > 150mm) • Large leaks, 100mm equivalent diameter (covering leaks from 50 to 150mm) • Medium leaks, 30mm equivalent diameter (10 to 50mm), and • Small leaks, 7mm equivalent diameter (3 to 10mm)	$3.5*10^{-8}$	Small: $1.4*10^{-8}$ Medium: $9,5*10^{-9}$ Large: $2*10^{-9}$	$8.5*10^{-9}$
Molag [12]		Dispersion out of the crater is modelled as pool evaporation of a heavy gas.		$0.75*6.1*10^{-7}$ (16.5)	$0.25*6.1*10^{-7}$ (16.5)
McGillivray [11]	0.4[15]	• Rupture scenario's assume a hole with a diameter of 150 mm. • Leakage scenario's assume a hole size of 50 mm • Weather classes: D5 en F2		4.65×10^{-8} (32) 4.65×10^{-8} (15)	3.39×10^{-8} (32) 3.39×10^{-8} (32)
Tebodin [13]	Vertical outflow[16] Vertical outflow with	Software package used: Safeti-NL • For leakage scenarios a hole size of 20 mm is assumed.	$6.1*10^{-7}$	$6.3*10^{-8}$ (44)[18]	$7*10^{-9}$ (44)[20]

15 P_{jet} : 2 x (90-θ) /360

16 Outflow out of a pipeline subway: vertical continuous outflow with low velocity.

Literature sources	Modelling aspects		Failure frequencies for pipelines (m^{-1} yr^{-1})		
	(Probability of) jet dispersion	**Models used / parameters**	**Generic frequency**	**Leakage (operating pressure (bar))**	**Rupture (operating pressure (bar))**
	high velocity	• Outflow calculations with multiple rate long pipeline model with time dependent outflow in 5 steps followed by user defined source. Software package used: Safeti-NL/ Phast Pro.	$6.1*10^{-10}$ [17]	$0.75*6.1*10^{-7}$ (44)[19]	$0.25*6.1*10^{-7}$ (44)[21]
Mazzoldi [18]	Zero release velocity and release velocity of 49 m s^{-1} (jet release)	Software package used: CFD Fluidyn-PANACHE (3.4.1)			

[17] Pipe line in tunnel: reduction factor 100: damage third parties excluded/ additional wall thickness 50% reduction factor 10.
[18] Pipe line in pipeline corridor
[19] Underground not in pipeline corridor
[20] Underground in pipeline corridor: reduction factor van 8.71 for pipeline in corridor/ additional wall thickness 50% reduction factor 10.
[21] Underground not in pipeline corridor

Table 4.6: Overview of results of effect and risk calculations, reported in literature sources

Literature sources	Results of effect and risk calculations						
	Range distances to 10^{-6} contour (m)	**Ranges endpoint 2000 ppm (m)**	**Ranges endpoint 15000 ppm (m)**	**Ranges endpoint 70000 ppm (m)**	**Ranges endpoint 100000 ppm (m)**	**Risk 0.1 cpm based on SLOD (m)**	**Risk 0.3 cpm based on SLOT (m)**
Koornneef [5]	0 - 204						
Lievense [16]	3.5						
Molag [12]	21 - 90						
Vendrig [15] on shore		3000-3800†	1330-2000†				
Vendrig [15] off shore		3600-7200†	1650-2500†				
Turner [17]				1903-2441			
McGillivray [11]						45-65	45-70
Tebodin [13]	no10^{-6} contour						
Mazzoldi			374-1290		52-852		

† Large leak and full bore rupture

4.4.10 Review Effect and Risk Calculations

In most literature sources diameter of pipeline, operating pressure and temperature are available. Crater formation is only considered in references [11] and [12]. The influence of the input parameters on modelling the release of CO2 from a failing pipeline is determined in reference [5]. Variance in the maximum release rate of a pipeline failure, which ranges between 0.001 and 22 tonne/s, is mostly influenced by, in order of importance: the size of the orifice, the diameter of the pipeline (in the case of a full bore rupture), operating pressure, operating temperature and section length. [5].

Tables 5 and 6 show an overview of input data and results from several published risk calculations[22]. The following can be learned from them:

- With respect to the modelling of physical effects, information on the software packages used is available, but little information on used models and their input in QRA's except for Reference [5].
- In Dutch QRA's leak in underground pipelines is modelled as a leakage with an effective diameter of 20 mm, whereas in other countries a large leak ranges from 50 up to 150 mm.
- Most literature references assume a vertical outflow except for reference [5] and [12]. Reference [5] assumes dispersion out of a crater as pool evaporation of heavy gas. Reference [5] considers the following release types: horizontal release, instantaneous release, vertical release and sublimating bank. No fallout of solid CO_2 is expected. Sublimating dry ice banks and instantaneous releases result in the highest concentration near the source. These types of releases are without momentum. For vertical and horizontal releases highest concentrations are found further away from the source. The 10^{-6} contours vary from 0 up to 204 m.
- Reference [5] presents the influence of initial pressure and temperature on the flash fraction at the orifice exit for pressures above the critical pressure. The higher the initial pressure the sooner the maximum vapour mass fraction in the release is reached. With an increase in the initial temperature an increase in the initial and maximum vapour mass fraction is seen but at higher temperatures it takes longer before the maximum vapour mass fraction is reached. The effect of varying the vapour fraction on the final risk profile is large.
- A direct comparison between the results of effect and risk calculations presented in Table 6 is not possible because risk calculations include a vulnerability distribution that is expressed in the probability.
- The effect of meteorological conditions is not very clear yet but reference [5] states that preliminary results show that when these conditions are varied that concentration profiles surrounding the pipeline after release also vary considerably. Under F2 conditions higher concentrations can be expected at great distances downwind.

---

[22] Not all data could be incorporated in the tables. Where parameters are given (such as the vapour mass fraction) the conclusions in the reference of interest are given as well.

4.4.11 Knowledge gaps and uncertainties in modelling reported in literature sources

As long as the pressure remains above the triple point pressure, CO_2 will behave as any other liquefied gas. However during a depressurization event the inventory pressure will drop below the triple point (5.2 bar).

Below some statements found in literature about modelling with respect to QRA studies are mentioned:

- Saturated liquid inventories: If the pressure falls below 5.2 bar the HEM and ω-method models are invalid. There is considerable uncertainty around modelling dense phase CO_2 releases [6].
- Outflow models (e.g. Morrow model) in the event of rupture of pipelines are not suitable to incorporate the formation of solid CO_2. Furthermore, there is a lack of knowledge about the vapour and dry ice fraction in the release. These parameters have a large influence on the dispersion and consequently on the risk profile of CO_2 releases [5]
- A methodological choice that affects the QRA's outcome to a large extent is the direction and momentum of release. Currently, there is no consensus on the type of release that is characteristic for a CO_2 release from a failing pipeline. The results indicate that when varying the type of release (horizontal jet, vertical jet, instantaneous, sublimating bank) the calculated distances from the pipeline to the $1*10^{-6}$ risk contour may be larger than currently regulated for high pressure natural gas pipelines [5].
- Many dispersion models start with a mean value for the outflow instead of taking into account the course of the outflow in time.
- Validity of the outflow and dispersion models in the event of accidental releases from high pressure pipelines is uncertain. The hazard ranges and therefore risks are expected to be substantially larger for releases at higher pressure (which would therefore be in the dense phase) [11].
- As representative substances for CO_2 propane and ammonia are sometimes used. If this is the case, it should be taken into account that the temperature behaviour of high pressure CO_2 is very different from propane and ammonia.

4.5 Conclusions

A general conclusion that can be drawn is that there is not an EU-standard process or procedure for the calculation of the effects and risk of hazardous releases. This statement is not only true for CO_2, but also in a more general situation. In fact each country has independently implemented the SEVESOII directive.

Existing European regulations and standards for (natural) gas transport pipelines have not yet been used as a basis for the development of specific CO_2 pipeline regulations and standards. The DNV-RP-J202, a code of practice for the design and operation of CO_2 pipelines (April 2010), is a first step.

In addition, the endpoint of which risk is accepted is not also uniquely defined.

At many points in the process of determining the risk of CO_2 transport uncertainties are present:

- Operating conditions: for most pipe lines these are not know yet
- Failure frequencies: insufficient data is available on the failure frequency of pipelines carrying CO_2
- Models describing outflow and dispersion of CO_2: the formation of solid CO_2 prevents using the standard, validated models used for other materials
- Probit function: no probit relation has officially been established

At these points more development is needed to come to a validated and generally accepted way of performing risk calculation for CO_2 transport by pipelines.

4.6 References Chapter 4 'Frameworks for risk assessment'

[1] Purple Book (PGS 3) - Guidelines for quantitative risk assessment
[2] Risks from gasoline pipelines in the United Kingdom. HSE 1999. Contract Research Report 206/1999
[3] D.Lyons. Western European cross-country oil pipelines 30-year performance statistics. Concawe Report 1/02 2002]
[4] Guideline Risk calculations Bevi version 3-2 RIVM July 2009
[5] J. Koornneef, M. Spruijt, M. Molag, A. Ramírez, W. Turkenburg, A. Faaij, Quantitative Risk Assesment of CO2 Transport by Pipelines – A review of Uncertainties and their Impacts, Journal of Hazardous Materials, 177, 2010, pp. 12-27
[6] K. Johnsen, Mapping of potential HSE issues related to large-scale capture, transport and storage of CO_2. DNV report no 2008-1993
[7] RIVM standpunt modellering CO_2 leiding Zoetermeer, kenmerk 219/07 CEV Rie/am-1636, Bilthoven 20 Augustus 2007
[8] M.D. Christou. The control of major accident hazards: the land-use planning issue. Journal of Hazardous Materials, 65, 1999, pp. 151-178
[9] Technical Assistance for the development of CO_2 geological storage. EnBW_Geogreen_TNO. December 2008
[10] M. Molag, Actualisatie Externe veiligheid onderzoek CO_2 buisleiding bij Zoetermeer Utrecht, (2008) TNO**,** 17
[11] A. McGillivray, J. Wilday, Comparison of Risks from Carbon Dioxide and Natural Gas Pipelines, HSE report rr749 (2009)
[12] M. Molag and I. M. E. Raben, Externe veiligheid onderzoek CO_2 buisleiding bij Zoetermeer Apeldoorn, (2006) TNO**,** 46.
[13] M. Heijne, and F. Kaman, Veiligheidsanalyse Ondergrondse Opslag van CO_2 in Barendrecht TEBODIN (2008)
[14] A. Mazzoldi, T. Hill, J.J. Colls, CO_2 Transportation for Carbon Capture and Storge: Sublimation of Carbon Dioxide from a Dry Ice Bank, International Journal of Greenhouse Gas Control 2 (2008) 210-218

[15] M. Vendrig, J. Spouge, A. Bird, J. Daycock and O. Johnsen, (2003). Risk Analysis of the Geological Sequestration of Carbon Dioxide, Department of Trade and Industry, London, UK
[16] Lievense, OCAP CO_2 v.o.f. CO_2 Greengas project - Risico analyse NPM-leiding document 042282 rev. 3. Breda, Raadgevend Ingenieursbureau Lievense B.V. (2005)
[17] R. Turner, N. Hardy and B. Hooper, Quantifying the Risks to the Public Associated with a CO_2 Sequestration Pipeline: A Methodology & Case Study, Greenhouse Gas Control Technologies 8, Trondheim, (2006a)
[18] A. Mazzoldi, T. Hill, J.J. Colls, A Consideration of the Jet-Mixing Effect when Modelling CO_2 Emissions from High Pressure CO_2 Transportation Facilities, Energy Procedia 1 (2009) 1571-1578
[19] DNV-RP-J202, Design and operation of CO_2 pipelines, April 2010
[20] Plan de Prevention des Risques Technologiques – Guide Methodologique, 16 December 2005, (pdf can be found at: http://catalogue.prim.net/73_le-plan-de-prevention-des-risques-technologiques-pprt---guide-methodologique.html)
[21] C. Basta, M. Struckl, M. Christou, Implementing Art. 1 of the Seveso II Directive: Overview of Roadmaps for Land-use Planning in Selected Member States, JRC Scientific and Technological Reports (2008)
[22] email communication between M.Spruijt (TNO) and T. Thielemann (RWE), July 2010
[23] A.S. Markowski, The implementation of the SEVESO II legislation in the Polish major hazard industry, Journal of loss prevention in the process industries 18 (2005) 360-364
[24] D. Hec, Marcogaz, Technical Association of the European natural gas industry, presentation given at UN-ECE, Geneva 22nd -23rd January 2008.
[23] Comparison of risks from carbon dioxide and natural gas pipelines, HSE report RR749, 2009

A Annex to Chapter 4: Contents of European Standard EN1594:2000

EN 1594:2000 Gas supply systems - Pipelines for maximum operating pressure over 16 bar
Generally taken as basis for national regulation or specifications for design, construction and operation of pipelines
Particular safety aspects are complemented in the different European countries by national legislation, codes or specifications

Covers all aspects concerning the design, construction and operation of safe high pressure gas transmission pipelines (MOP $\geq$ 16 bar)
Functional standard: established for the user (gas system operator) not for the producer !

1 Scope
2 Normative References
3 Definitions, symbols and abbreviations
4 Quality system
5 Safety and the environment
6 Pressure safety
7 Design (7.7 Depth of cover)

EN1594:2000 has only a general comment on the toughness values, and refers for pipes to the EN10208-2 which mentions specific minimal toughness values in order to avoid ductile fracture propagation.

Second Gas Directive 2003/55/CE in 2003: common rules for transmission, distribution, supply and storage.
Article 5: Security of supply
- quality and level of maintenance
- technical emergency response

Article 6: Technical rules for interoperability
- technical safety criteria
- minimum technical design and operational requirements

5 Quantitative risk assessment

To test a formal risk assessment methodology on a concrete CO2Europipe case, the German case was selected and used for that purpose. Although the risk assessment procedure in Germany is of a deterministic nature, a formal (probabilistic) quantitative risk assessment (QRA) was applied. The details of that QRA are reported as part of the WP 4.2 German case Deliverable D4.2.2 (Thielemann et al, 2011).[23] To be self-contained, the Synthesis chapter summarises also the findings from that risk assessment.

23 Thielemann, Th. et al (2011): D4.2.2 WP4.2 final report Second deliverable (month 27) - Making CO2 transport feasible: the German case Rhine/Ruhr area (D) – Hamburg (D) – North Sea (D, DK, NL), Revision: 7, July 2011.

6 Risk Management

6.1 Introduction

At the start of the CO2Europipe project questions were asked[24] about the organization of risk management, role of inspections, the responsible bodies, the availability of standards, and the safety regulations in the United States, in relation to risk for society and the local environment related to CO_2 transport through pipelines.

To answer the questions, first a description of risk management is given. A complication is that there is no common understanding of what risk management precisely means. This is mainly caused by differences in terminology (e.g. the definition of ‘risk’) and, more importantly, what is covered by ‘management’. Sometimes risk management is regarded as identical to ‘risk treatment’, sometimes risk management is seen as a way to control processes and even organisations with regard to uncertainties in achieving objectives. Moreover, many organisations prefer terminology like ‘safety’ and ‘integrity’.

The role of inspections and authorities is defined in the legal frameworks. Since the pipeline networks (especially for natural gas) are extensive, a very complex legal framework has been established. A small part of this legal framework concerns safety issues. It will be described how the CCS Directive 2009/31 EC drives the development of the legal frameworks in the EU member states with respect to risk management of CO_2-pipelines, and provides the legal basis for licensing authorities and inspections. A comparison will be made with the United States.

An important instrument in providing safety is the development and enforcement of Standards. At some point in national legislation the authorities will require the use of one or more specified national or international Standards for the design, construction and operation of the pipeline system. Standards exist for natural gas pipelines, but there are at present only a few Standards for CO_2-pipelines. These CO_2 specific Standards are extensions of or part of the existing Standards. The expectation is that new Standards will be extensions of existing Standards.

The key message of this chapter is that the basic concepts of risk management in the member states are very similar, as well as the related legal implementations. On the other hand, there are large differences in terminology - partly due to translations, partly due to the fact that concept of risk management may still be somewhat premature.

[24] See the description of Task 3.2.4 in the Work Plan of the CO2Europipe project (Annex B of the Contract)

6.2 The Concept of Risk Management

Various approaches to risk management have been developed. Ideas about risk management are often based on the observation that major accidents are often a result of managerial and/or organizational shortcomings. Many organisations have implemented additional management systems for Integrity Management or (physical) Asset Management as laid down in e.g. ASME B31.8S-2004: Managing System Integrity of Gas Pipelines. However, recognising that an organisation is more than a set of management systems, the International Organization for Standardization (ISO) published in 2009 ISO 31000 "Risk management - Principles and guidelines" Recent literature usually refers to ISO 31000 concerning risk management. Both will be discussed in the following sections. In Section 6.2.3, eventually, the risk management process will be described, which will be very useful as a mould to compare various approaches to risk management, mainly by resolving terminology issues by considering the context of each step in such risk management approach, rather than the terminology that was used to describe the step.

6.2.1 ISO 31000 Risk management - Principles and guidelines

All organisations manage risks in one way or another, some in a systematic way, some on an ad hoc basis. In 2009, the International Organization for Standardization (ISO) published ISO 31000 "Risk management - Principles and guidelines" (ISO 31000:2009, IDT). Recent literature usually refers to ISO 31000 concerning risk management.

ISO 31000 distinguishes between the *principle*, the *framework* and the *process* of risk management.

Principles	are typically: that risk management should be an integral part of organisational processes; that uncertainties should be addressed explicitly; and that risk management should be tailored to the external and internal context and the risk profile of the organisation.
Framework	means that risk management is part of the overall management system, there is a mandate and commitment, and there is understanding the organisation and its (internal and external) context
Process	means that there is 1) a well defined communication and consultation plan, there is 2) a risk assessment containing the context, risk analysis, and risk treatment, and there is 3) a monitoring and review program

Graphical representations, based on ISO 31000 risk management, are given in Figure 6.1 and Figure 6.2.

The ISO 31000 guideline regards risk management as an organisational routine, with emphasis on the management and organisational issues. This is justified, since the majority of the large accidents reported in the Community are the result of managerial and/or organizational shortcomings. This is also addressed in the preamble of the Seveso-

II Directive; in which Annex-III provides a description of a ‘safety management system’, which is in effect very similar to the ISO 31000 definition.

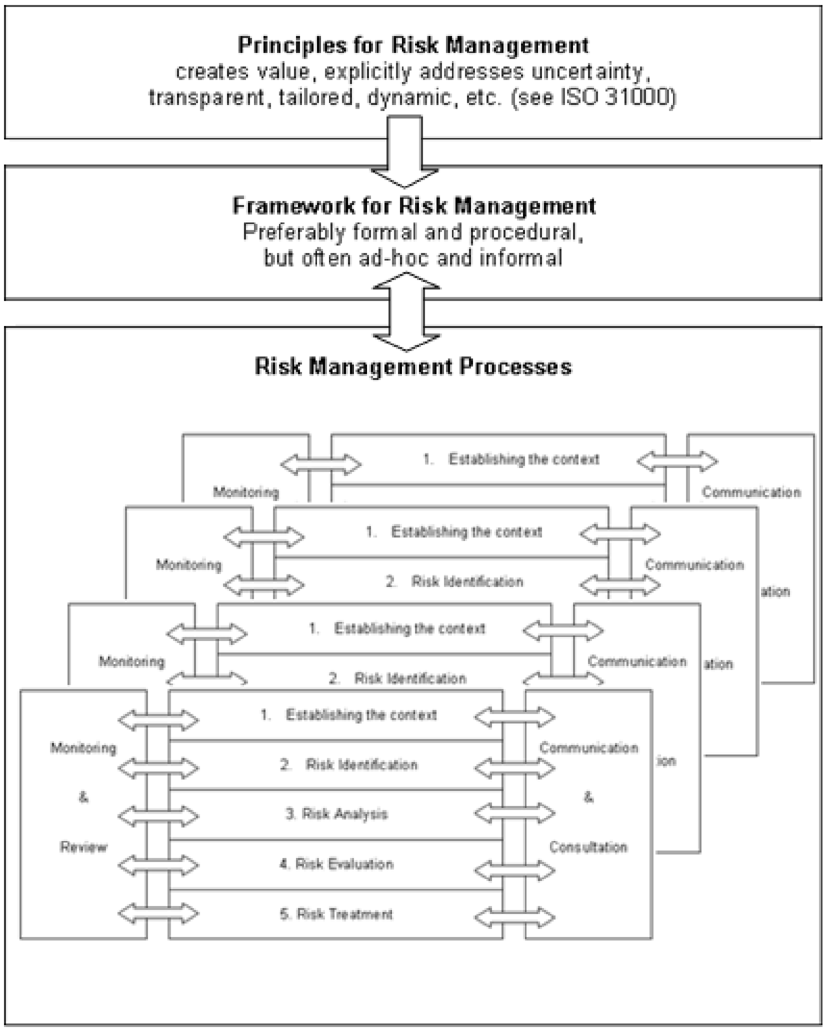


Figure 6.1 Graphical representation of Risk Management, based on ISO 31000

6.2.2 ASME B31.8S-2004: Managing System Integrity of Gas Pipelines

The purpose of these programs is to enhance safety by identifying and reducing pipeline integrity risks, and in this sense they can be considered as applicable to risk management. ASME B31.8S-2004 is a supplement standard to the ASME code for pressure piping B31. The Integrity Management Plan Process described here contains five elements:

1. Identify Potential Pipeline Impact By Threat
   Threats are: Time Dependent (e.g. external corrosion); Stable (e.g. manufacturing-related defects); Time Independent (e.g. outside force).
2. Gathering, Reviewing & Integrating Data
   Gather technical and historical pipeline data to support the risk assessment

3. Risk Assessment
   Location specific events and/or conditions are identified that could lead to a pipeline failure. Probabilities and consequences are estimated in order to rank pipeline segments for integrity assessments.
4. Integrity Assessment
   In-line inspections, pressure testing and other integrity assessment methods
5. Response to Integrity Assessment & Mitigation
   Procedures and plans to respond to Integrity Assessment results

The American Petroleum Institute (API) has developed a similar industry consensus standard (Standardisation of Pipeline Integrity Management for Liquid Lines - API 1160), and also U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) has issued a final rule to require operators of gas distribution pipelines to develop and implement integrity management (IM) programs. The generic description of the IM program in this Final Rule is discussed in more detail in Section 6.3.1.

These systems typically focus on Integrity Assessment (i.e. inspections, etc.), but use different wordings and different schemes for roughly the same process.

6.2.3 Risk management process

To enable discussion of various risk management approaches, the ISO 31000 approach is chosen as a reference, since it is at the highest level of abstraction and is able to reflect the other approaches considered in this chapter. In particular, the ISO 31000 risk management process is useful for this purpose. A graphical presentation of the risk management process, as defined in ISO 31000, is given in Figure 6.2.

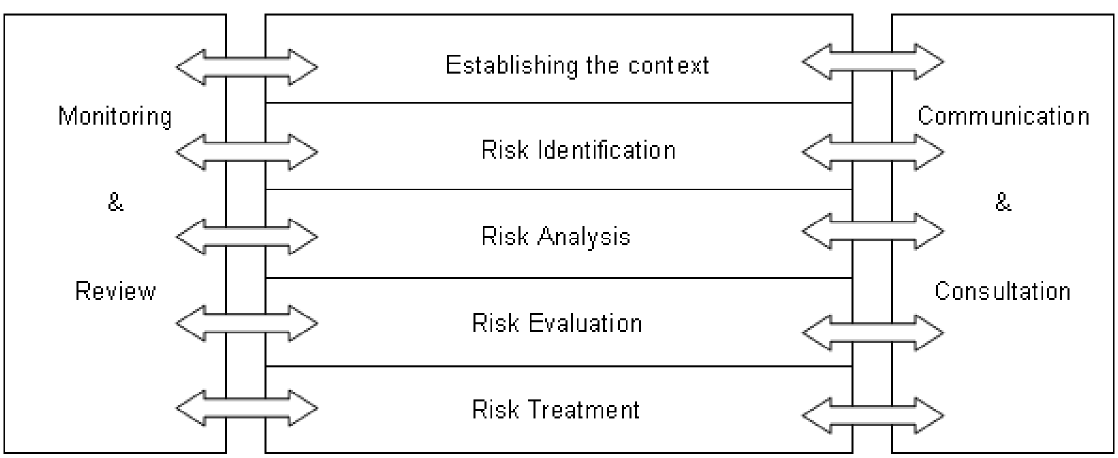


Figure 6.2 Graphical representation of the Risk Management Process (ISO 31000)

The first step of the risk management process is to develop a communication and consultation plan (box on the right side of Figure 6.2) to involve all internal and external stakeholders. The plans should contain placeholders for addressing the risk, and its causes, consequences, and treatment. Early internal and external communication helps to establish the context, ensure that the interest of the stakeholders are considered, and creates (external) support.

The second step is to establish the context (top middle box of Figure 6.2). The context consists of three ingredients: the objectives of the operator, the operator's internal context and the external context of the activity.

The first and second step are often done on an ad-hoc basis, there is no written communication plan and context, but people involved are communicating and are intuitively aware of the context. This may be sufficient for straightforward routine operations, but a more formal approach should be considered in case of more complicated operations or political and societal sensitive issues.

The next steps, risk identification, analysis and evaluation (often addressed as 'risk assessment'), and risk treatment and monitoring and review are usually very explicit, a.o. because these steps are in one way or another part of the licensing process.

To illustrate how ISO 31000 is used as a reference, the five elements of the Integrity Management Plan Process as described by ASME are projected on the ISO 31000 Risk Management Process – see Figure 6.3.

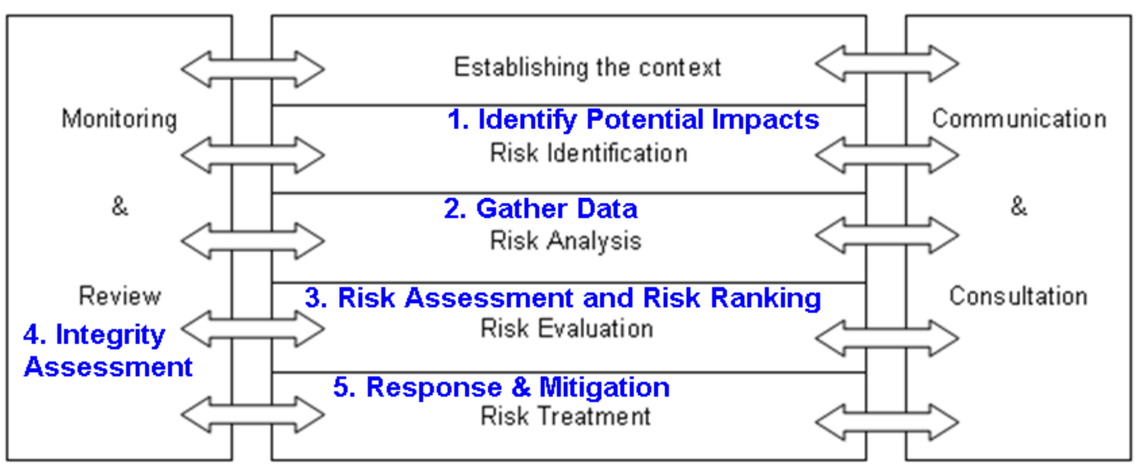


Figure 6.3 Projection of the ASME Integrity Management Plan Process on the ISO 31000 Risk Management Process.

6.3 Legal perspective

The ISO 31000 guideline is not a standard for certification and/or legal requirements. Risk management, as defined in ISO 31000 is not part of any legislation. However, in most countries the major elements of the risk management process are explicitly required. Moreover, at present there is a tendency to incorporate more and more elements of the risk management process, and to a lesser extent, the risk management framework, into the regulations.

6.3.1 USA

If CCS is successful in the USA, as much as 400 to 1800 million tonnes (Mt) per year of CO_2 could be injected into a variety of geological formations in the United States. The existing U.S. CO2 pipeline infrastructure transports approximately 45 Mt of CO_2 per year over 3500 miles of pipe for enhanced oil recovery (EOR). For comparison, the existing U.S. natural gas pipeline network transports 455 Mt per year of natural gas over 300 000 miles of interstate and intrastate pipe.

Hazardous Liquid Pipeline Act

Carbon dioxide pipelines are regulated to the same degree as hazardous liquids pipelines by the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA), pursuant to the Hazardous Liquid Pipeline Act of 1979 (HLPA). PHMSA's Office of Pipeline Safety (OPS) regulates the design, construction, operation, maintenance, and spill response planning for regulated pipelines. The agency establishes minimum safety standards for interstate pipelines, and has largely pre-empted states from establishing their own standards for interstate pipelines.

Federal regulation (49 CFR Part 195) regarding the management of pipeline integrity

In 2002, the United States Department of Transportation (DOT), through its Office of Pipeline Safety (now the Pipeline and Hazardous Materials Safety Administration, or PHMA), made significant changes to the existing federal regulations (49 CFR Part 195) regarding the management of pipeline integrity. The changes (Section 195.452) mandate pipeline operators to create integrity management plans that include baseline integrity assessments and periodic reassessments of pipelines that could impact High Consequence Areas (HCA's: generally, these are high population density areas or difficult to evacuate facilities, such as hospitals, prisons or schools, and locations where people congregate, such as churches, office buildings, or playgrounds.).

PHMSA final rule

To this end, PHMSA has issued a Final Rule - Implementing Integrity Management – on July 17, 2007 amending 49 CFR Part 195 by:
§ 195.450 Definitions.
§ 195.452 Pipeline integrity management in high consequence areas.
§ 195.588 What standards apply to direct assessment?

Appendix C to Part 195-Guidance for Implementation of an Integrity Management Program

At minimum, each of the following elements must be included in the integrity management program:

(1) A process for identifying which pipeline segments could affect a high consequence area;
(2) A baseline assessment plan (...)
(3) An analysis that integrates all available information about the integrity of the entire pipeline and the consequences of a failure (...);
(4) Criteria for remedial actions to address integrity issues raised by the assessment methods and information analysis (...);
(5) A continual process of assessment and evaluation to maintain a pipeline's integrity (...);
(6) Identification of preventive and mitigative measures to protect the high consequence area (...);
(7) Methods to measure the program's effectiveness (...);
(8) A process for review of integrity assessment results and information analysis by a person qualified to evaluate the results and information (...)

This approach to Integrity Management is very much in line with the ISO 31000 risk management process, see Figure 6.4. The areas of communication plan, context and (quantitative) risk analysis have less emphasis in the Integrity Management Program then in ISO 31000.

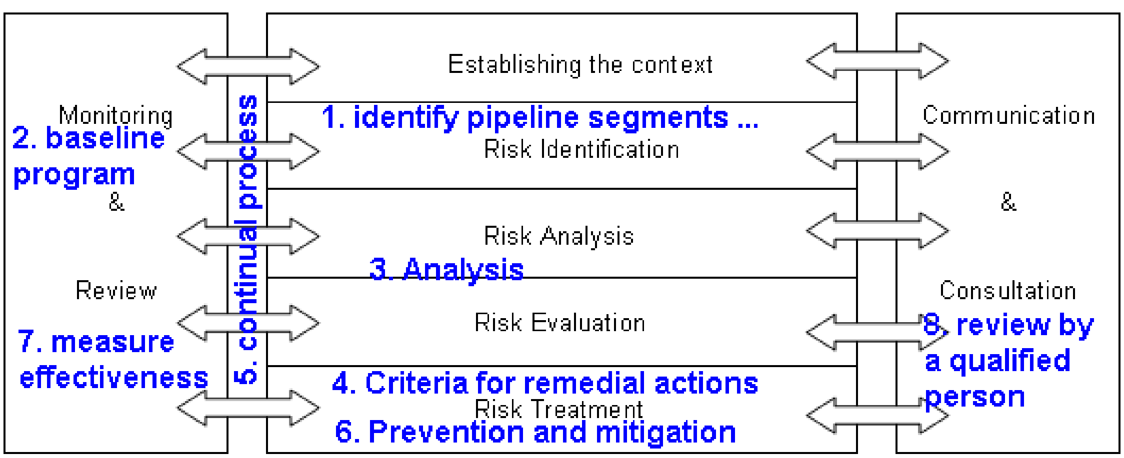


Figure 6.4 PHMSA Integrity Management (**IM, in blue**) Program structure presented in ISO 31000 Risk Management Process

References

R. Nordhaus a.o. *Carbon Dioxide Pipeline Regulation* Energy Law Journal, Vol. 30:85, 2009.

Appendix E - Carbon Dioxide Pipeline Risk Analysis HECA Project Site Kern County, California URS Corporation, May 19, 2009
Asset Integrity- The Key to managing major incident risks International Association of Oil & Gas producers (OGP) December 2008.
Policy Brief: Regulating Carbon Dioxide Pipelines for the Purpose of Transporting Carbon Dioxide to Geologic Sequestration Sites Department of Engineering and Public Policy, Carnegie Mellon University, 2009.

6.3.2 European Union

There is no "EC Pipeline Directive"
There is no EC Directive that is more or less similar the USA Hazardous Liquid Pipeline Act, though there is EC legislation with respect to the European natural gas market. EC legislation to limit the risks of all industrial activities is established in the EC Environmental Impact Assessment Directive. For CO2 pipelines the CCS Directive is also of importance, as explained below.

CCS Directive 2009/31
The CCS Directive 2009/31 EC does not give specific requirements for risk management of CO2 pipelines or related issues. Nevertheless, there are two articles that are of interest:
Article 24 Transboundary cooperation

> In cases of transboundary transport of CO_2, transboundary storage sites or transboundary storage complexes, the competent authorities of the Member States concerned shall jointly meet the requirements of this Directive and of other relevant Community legislation

Article 21 Access to transport network and storage sites

> Member States shall take the necessary measures to ensure that potential users are able to obtain access to transport networks and to storage sites for the purposes of geological storage of the produced and captured CO_2, in accordance with paragraphs 2, 3 and 4.

Transboundary transport of natural gas is common, so the relevant national legislations allow this. Since the same legislation regulates CO_2 transport, transboundary CO_2 pipelines is possible in the regulatory frameworks. The national standards for CO_2 transport may be elaborated in future, but the two articles above imply that Member States should avoid incompatible Standards, since that would block potential users to access the network.

The CCS Directive 2009/31 EC amends Annex I of the EIA Directive 85/337/EEC. As a result, pipelines with a diameter of more than 800 mm and a length of more than 40 km for the transport of carbon dioxide (CO_2) streams for the purposes of geological storage, including associated booster stations are projects are subject to an EIA (Environmental Impact Assessment).

EC Environmental Impact Assessment Directive
The Environmental Impact Assessment will identify, describe and assess in an appropriate manner, the direct and indirect effects of a project on the following factors:

- human beings, fauna and flora,
- soil, water, air, climate and the landscape,
- the inter-action between the factors mentioned in the first and second indents,
- material assets and the cultural heritage.

Annex IV of the EIA Directive 85/337/EEC specifies that the developer supplies information about a.o.:

- the likely significant effects on the environment, including on issues such as biodiversity, population, human health, fauna, flora, soil, water, air, climatic factors, material assets, cultural heritage including architectural and archaeological heritage, landscape and the interrelationship between the above factors;
- the measures envisaged to prevent, reduce and as fully as possible offset any significant adverse effects on the environment of implementing the plan or programme;
- a description of the measures envisaged concerning monitoring of the significant environmental effect

inasmuch as the Member States consider that the information is relevant to a given stage of the consent procedure and to the specific characteristics of a particular project or type of project and of the environmental features likely to be affected.

Measures to prevent significant adverse effects and monitoring are parts of the risk management process, but Member States have some freedom in the implementation of this part of the Directive in the national legal frameworks.

In effect, in each member state, this modification of the EIA act is the legal basis for more detailed Decrees, Ordinances, Rules and Administrative Orders that eventually define what is needed to obtain a license for constructing and operating a pipeline. The basic elements of the risk management process (identification, treatment, monitoring) can be found in this part of the legal systems, but terminology and emphasis differ.

6.3.3 Germany

There is no Pipeline Act
There is no pipeline act; instead there are various Ordinances (Verordnungen) that ensure sufficient protection of the environment and man. These ordinances find their legal basis in the Environmental Impact Act (UVPG), the most relevant ordinance is the Federal Pipeline Ordinance (RohrFLtgV).

Environmental Impacts Act (UVPG)

If CCS is successful in Germany, a drastic expansion of the existing CO_2 pipeline infrastructure is needed. The expected transport distances and amounts require pipelines that are subject to an EIA (Environmental Impact Assessment): see the German Environmental Impacts Assessment Act (UVPG, §§ 20 ff.; Anlage 1 Liste "UVP-pflichtige Vorhaben", Nr. 19.4 , Nr. 19.5). This is in line with the EIA Directive 85/337/EEC.

Federal Pipeline Ordinance

Through § 21 Abs. 4 of the UVPG the Federal Government has established the Federal Pipeline Ordinance (RohrFLtgV). In line with the UVPG, the purpose of the RohrFLtgV is to avoid detriment to the wellbeing of the general public; protection of persons and the environment against harmful effects resulting from the installation, state and operation of long-distance pipelines.

The Ordinance includes the following paragraphs, the main points of which are given here:

- § 3,4 Basic and other requirements: Proper operation and up-to-date documentation and instructions
- § 5 Pipeline installation inspections
- § 6 Independent examination of the pipeline design, the pipeline construction, the pipeline operation, and determination of their conformity with specific requirements, or, on the basis of professional judgement, general requirements.
- § 7 Case of damage:
- § 8 Precautions for cases of damage:
- § 9 Pipeline Commissioning

Technical Rules for Pipelines (TRFL)

In accordance with § 9 para. 5 of the Pipeline Ordinance Technical Rules (Technischen Regel für Rohrfernleitungen: TRFL) have been published in the Federal Gazette. The TRFL is a comprehensive and detailed set of regulations and forms the technical basis for installing, operating and inspecting pipelines for transporting substances in accordance with § 2, para. 1 RohrFLtgV. If these Technical Rules are observed, the requirements of the Pipeline Ordinance are deemed to have been met (§ 3, para. 2 RohrFLtgV).

Risk Management

If a pipeline complies with the Technical Rules (TRFL), the purpose Pipeline Ordinance has been met, i.e. sufficient environmental protection has been achieved. Within this framework there is no need for quantitative risk assessment.
Qualitatively, the articles in the RohrFLtgV ordinance cover most non-quantitative issues of the ISO risk management process, as shown in Figure 6.5.

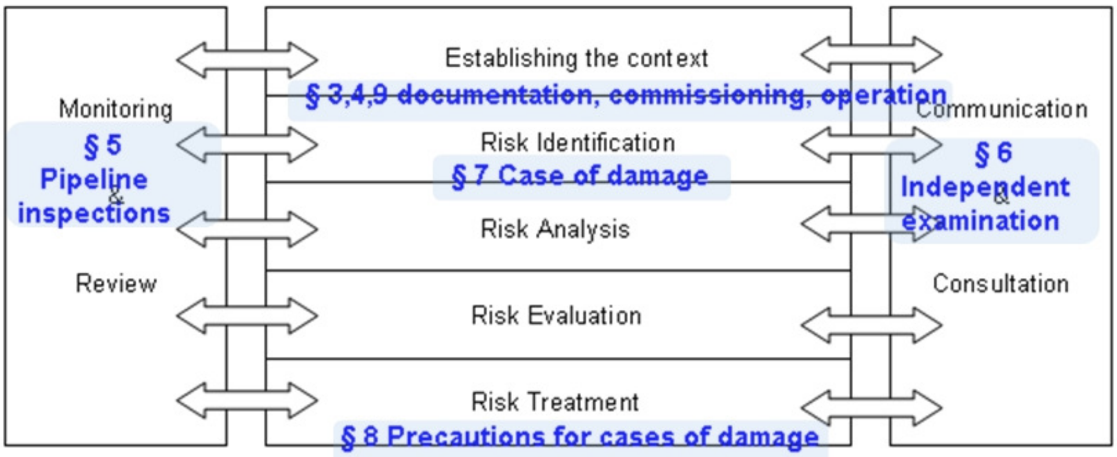


Figure 6.5 Articles in the RohrFLtgV ordinance (**in blue**) presented in ISO 31000 Risk Management Process

The quantitative aspects of the risk management process have been carried out by specialised organisations and have been laid down in obligatory standards (TRFL).

References

Chr. Matthes a.o. *CO2-Abscheidung und –Ablagerung bei Kraftwerken Rechtliche Bewertung, Regulierung, Akzeptanz* Öko-Institut e.V., 22. Juli 2007

R. Konersmann a.o. *On the risks of transporting liquid and gaseous fuels in pipelines* BAM Federal Institute for Materials Research and Testing, Research report 289, Berlin 2009

DVGW Code of Practice G 2000 *Minimum requirements with respect to interoperability and connections to gas supply networks* DVGW (Deutscher Verein des Gas- und Wasserfaches e.V.), July 2009

6.3.4 The Netherlands

There is no Pipeline Act

Similar to Germany, there is no pipeline act, instead there are various Decrees (Besluiten) and Rules (Regelingen) that ensure sufficient protection of the environment and man. These Decrees find their legal basis in the Environmental Impact Act (WM) and the Spatial Planning Act (WRO). However, at the time of writing of this report (April 2011) the amendment that is to be expected as a result of the ratification of the CCS Directive 2009/31 EC (i.e. long CO2 pipelines will be subject to an EIA) has not been implemented yet, but should be implemented in national legislation before 25 June 2011.

Environmental Impacts Act (Wet Milieubeheer - WM)

Presently there is no EIA obligation for CO2 pipelines in The Netherlands. But, the WM allows the authorities to require an EIA through an General Administrative Order

(Algemene Maatregel Van Bestuur) for any project that may have a substantial environmental impact. In practice, e.g. for the Barendrecht CO2 disposal demonstration project, the operators prepare an EIA on a voluntary basis.

Decree External Safety of Pipelines (Besluit externe veiligheid buisleidingen - Bevb)
The Decree External Safety of Pipelines (Bevb) and the associated Rule External Safety of Pipelines (Revb) have become 'in werking' since 2011. The Decree ensures protection of persons and the environment through establishing safety distances based on risk analysis and organizational and operational requirements. From risk management perspective, a key element is the document *safety management system pipelines* (veiligheidsbeheerssysteem buisleiding), covering:

a) Description of the system and a qualitative judgment
b) Goals, criteria and standards
c) Risk inventarisation and evaluation for the full pipeline life cycle.
d) Safety related technical and organizational measures
e) Responsibilities and organizational authorities
f) Organization, controls, procedures and means
g) Monitoring
h) Documentation

In broad lines, this is very similar to the integrity management program described in Section 6.3.1.

However, the Decree is only applicable to pipelines transporting natural gas and 'oil products'. So, even if a CO2-pipeline is subject to an EIA, this Decree would not be applicable (without amending the Decree).

References

Environmental Impact Assessment: Underground storage of CO2 Shell CO2 Storage B.V. December 2008

6.4 International standards

All national regulations rely on a multitude of national and international standards with respect to the technical details of constructions such as pipelines, compressor stations, booster stations, gas treatment systems, etc. Particularly in Europe, however, there are no standards for CO2 pipelines, i.e. standards cover oil and gas pipelines, with the exception of the DNV recommended practice DNV-RP-J202.
For the application of the standards for oil and natural gas pipelines to CO2 pipelines, some modifications and additions are needed. Based on discussions with the pipeline operators, in particular a high focus on controlling the water content in the CO2 before entered into the pipeline, and the strict procedures for shutting down the line in case the dewatering system cannot meet the specifications, is essential. Because of this focus, internal corrosion is not reported as a significant pipeline failure mechanism [DNV]. The

DNV guideline is also applicable to "Conversion of existing pipelines for transportation of fluids containing overwhelmingly CO2", implying that this is technically feasible and safe with proper technical and operational efforts.

References

DNV-RP-J202 lists the following relevant standards and codes:

API 1160 Managing System Integrity for Hazardous Liquid Pipelines
ASME B31.8 Gas Transmission and Distribution Systems
ASME B31.8S Managing System Integrity of Gas Pipelines
CSA Z662-07 Oil and Gas Pipeline Systems. Canadian Standard Association
DNV-RP-F107 Risk Assessment of Pipeline Protection
ISO 3183 Petroleum and natural gas industries – Steel pipe for pipeline transportation systems
ISO 16708 Petroleum and natural gas industries – Pipeline transportation systems – Reliability-based limit state methods
ISO 31000 Risk management -Principles and guidelines
IEC 61511 Functional safety - Safety instrumented systems for the process industry sector
NACE TM0192-2003 Evaluating Electrometric Materials in Carbon Dioxide Decompression Environments
NACE TM 0297-2002 Effects of High-Temperature, High-Pressure Carbon Dioxide Decompression in Electrometric Materials
NORSOK Z-013 Risk and emergency preparedness analysis

6.5 Conclusion and Recommendations

In Task 3.2.4[25] of WP 3.2, the following aspects have been addressed:
(1) the organization of risk management,
(2) the role of inspections,
(3) the responsible bodies,
(4) the availability of standards, and
(5) the safety regulations in the United States,
in relation to risk for society and the local environment related to CO2 transport through pipelines.

6.5.1 Conclusions

The conclusions wit respect to these aspects are:

Risk Management

[25] See the description of Task 3.2.4 in the Work Plan of the CO2Europipe project (Annex B of the Contract)

There is no common understanding of the meaning of 'risk management'. Most national legal systems and standards require a cycle of risk identification, risk treatment and monitoring. A common basis for these various implementations of this cycle is provided by ISO 31000 guideline on risk management, published in 2009. ISO 31000 provides a generally acceptable terminology[26] for key terms such as ‘risk’, ‘risk assessment’ and ‘risk management’.

Role of Inspections

Physical inspections of pipeline systems are carried out with special equipment (such as a PIG and visual inspections of the pipeline lanes) by the operator or by specialized companies hired by the operator. Authorities require inspections to be carried out on a systematic and regular basis, and sometimes require review of the inspection results by independent experts. In the ISO 31000 Risk Management process this is referred to as 'monitoring and review'.

Responsible Bodies

The responsibility for the environmental part of the license (i.e. the EIA), including the risk management cycle, lies with the Ministries of Environment of the member states.
All member states have Environmental Inspectorates to inspect the operators, sometimes connected to the Ministry of Environment, or coupled to other Inspectorates, or sometimes operating as an independent institute.
Finally, all member states have institutes that develop national (technical) Standards. Pipeline systems will have to comply with these Standards, in this context also termed as Codes.

Availability of Standards

In Europe the Norwegian DNV has developed recommended practice DNV-RP-J202 'design and operation of CO2 pipelines'. However, no EU member state has developed a standard (yet). It is expected that many member states in due time will develop national standards for CO2 pipelines as is already the case for pipelines for natural gas.

Safety Regulations in the United States

The United States Department of Transportation (DOT), through its Pipeline and Hazardous Materials Safety Administration (PHMA),has issued a Final Rule - Implementing Integrity Management – on July 17, 2007 amending 49 CFR Part 195. The adopted approach to Integrity Management is very much in line with the ISO 31000 risk management process.

26 Before the publication of ISO 31000 various, sometimes conflicting definitions were in use.

6.5.2 Recommendations

Since the CO2Europipe project aims to summarise all findings in terms of actions to be taken by EU and national governments to facilitate and optimize the development of large-scale, European CCS infrastructure, the following actions should be considered:

1. To develop a European Standard for Pipeline Integrity Management, explicitly based on the ISO 31000 guideline; to resolve discussion about terminology and to avoid misunderstandings and miscommunications.
2. To develop or adopt national Standards for the construction and operation of CO_2 pipelines to avoid ad hoc decisions on licensing, construction and operation of pipelines.
3. EU member states should consider to perform a strategic environmental impact assessment (or SEA: strategic environmental assessment - European SEA Directive 2001/42/EC) for the CO_2 pipeline infrastructure under consideration; since the local environmental effects considered in an EIA are subordinate to strategic infrastructure.

7 Synthesis and conclusions

This final chapter presents a summary/synthesis of the main findings derived from the work reported in the previous Chapters.

Transport of CO_2 poses health and safety risks. Under certain conditions, leakage or rupture of a pipeline can result in the dispersion of CO_2 with the potential to affect humans and the environment. CO2Europipe's scope is on societal and environmental aspects but restricted to external (i.e. safety related) risk to the environment[27]. In addition, the assessment is restricted to the CO_2 pipeline part of the total CCS chain, and to onshore pipelines. Risks of CO_2 transport by ships have not been addressed.[28] Onshore pipeline infrastructure in particular located in densely populated areas will pose the highest health and safety risks. Safety risks in other parts of the CCS chain (e.g. capture of CO_2 or risks associated with CO_2 injection into the underground storage) are also beyond the scope.

The methodologies and methods to assess the safety (or broader: Health, Safety and Environmental, HSE) risks of CO2 transport are well established by use of such methods in other industrial activities (e.g. as used in oil, gas, chemical and nuclear industry) or pipeline infrastructures (e.g. transport of natural gas).

Recommendation: CO2Europipe recommends the use of formal Quantitative Risk Assessment (QRA) methods to determine the HSE risks of CO2 pipeline transport. These QRA's can adequately deal with uncertainties associated with risk analysis.

However, the following knowledge gaps or uncertainties exist:

a. *Physical outflow of CO_2 in case of a leak or rupture in a pipeline*.
   Due to the specific physical nature of CO_2 the physical outflow behaviour in case of a leak or rupture in a pipeline is not fully understood. The numerical models predicting the behaviour of the outflowing gas are not yet fully validated with full-scale experiments; model predictions may therefore not lead to adequate estimates of the safety risk of CO_2 pipelines.
b. *Limited experience on pipeline failure frequencies*.
   Compared to natural gas pipelines, there is only limited experience on CO_2 pipeline failure frequencies. The current experience is mainly related to CO_2 transport used for Enhanced Oil Recovery in the U.S [reference]. Once CCS projects and pipeline infrastructures start to develop, the experience base will grow and can be taken into account in adjusting the failure frequencies.

[27] In accordance with the Annex A description of the WP 3.2 work content.
[28] See recent report (DNV, 2011) for risks of CO_2 transport by barge or sea going vessels.

c. *Dose-effect relationships*.
   Available Environmental Impact Assessments indicate the use of different dose-effect relationships to determine the fatality risk as a result of too high a concentration of CO_2. Until now there is no official generally accepted relationship. E.g. TNO, Tebobin and the UK HSE use different ones leading to different estimates. Some use a conservative relationship with the chance of arriving at risk estimates that are not meaningful to show compliance with risk norms.

Safety risk policies showing compliance with quantitative risk criteria differ in the various EU Member States. Current external risk and industrial safety policies in the various EU Member States and Norway differ. Some Member States require a quantitative (probabilistic) risk analysis to be conducted. The risks calculated have to be compared to clear defined risk criteria. E.g. risk criteria used in the Netherlands are individual risk contours and the group risk. Each type of risk has a separate norm to be met.
Recommendation: The differences in safety risk policies should be taken into account in the permitting process and in case of transboundary pipeline trajectories. It should be noted that this is not different from the case of transboundary natural gas pipelines, so it is expected to be no real barrier.
Recommendation: CO2Europipe recommends a harmonization or even standardization (best practices) to prevent these differences from becoming a barrier to pan-European CO_2 pipeline infrastructure. Recommended standards and practices include those developed by DNV (DNV, 2010) and ISO3100 on Risk Management.

The outcomes of other ongoing projects can help in validating the risk assessment models and to reduce the uncertainties in risk assessment. Projects to be mentioned are: CO_2PipeHaz [29], CO_2PipeTrans (a Joint Industry Project), and the EU CCS Network with its first year's lessons already reported (CCS Network EU, 2011). Also national CCS research programmes (like CATO-2 in the Netherlands) [30] will provide additional insights. More specifically, the Environmental Impact Assessments (EIAs) now in preparation to support the first large demonstration CCS projects will add to the knowledge base and may provide information that reduces the uncertainties.[31]
The various stakeholders in CO_2 infrastructure[32] should incorporate new lessons from other ongoing research and demonstration projects. These lessons can confirm the findings of the CO2Europipe risk work and, more importantly, knowledge gaps identified here can be narrowed down.

[29] www.co2pipehaz.eu
[30] http://www.co2-cato.nl/
[31] The EIA of the ROAD project, one of the CCS demos financed by the EERP is expected to be available for public consultation in the Autumn of this year. An intermediate check by the NCEA was published may of this year (NCEA, 2011).
[32] Stakeholders here: large emitters (e.g. power companies), gas network companies, pipeline construction and compressor companies, storage operators, regulatory and inspection bodies, R&D institutes.

Once the first CCS demos now planned for 2015, are operational, the levels of safety risk estimated from QRAs can be used to judge whether these risks comply with national rules and regulations.

HSE risks are a key factor in public acceptance of CO_2 transport (and storage). Therefore, risk assessment, risk management and proper risk communication are key activities that can aid in public awareness and acceptance. If not properly communicated, the HSE risks as perceived by the public may be a barrier to the development of CCS. Examples are: the Barendrecht case in the Netherlands (Feenstra et al. 2010), and postponing onshore storage in Member States like the Netherlands and Germany. Other projects than CO2Europipe provide more lessons to deal with the issue of public acceptance of CCS, and timely public engagement. One relevant and nearly completed FP7 project in this respect is NearCO2 [33].

[33] http://www.communicationnearco2.eu/documents-and-materials/

8 References

(for Section 1, 2, and 7). Sections 3-6 have their own reference lists)

CO2Europipe consortium, 2010: Deliverable D2.2.1 WP 2.2: Neele et al, 2010

CO2Europipe consortium, 2011: Deliverable D3.3.1 WP 3.3. Mikunda et al, 2011

CCS Network EU (2011): *Risk Management: Lessons learned in 2010 - A report from the European CCS Demonstration Project Network*, May 2011 http://www.ccsnetwork.eu/uploads/publications/new-ccs-risk_management_thematic_report-webversion-may2011.pdf

CIRED (2010): *Actuarial risk assessment of expected fatalities attributable to carbon capture and storage in 2050*, CIREDWorking paper 2010-21, revision 1, February 2011

DNV (2010): *Design and operation of CO_2 pipelines*, DNV-RP-J202, April 2010.

DNV (2011): Final *Public Report - Safety study for Liquid Logistics Shipping Concept*, Final report for Vopak / Anthony Veder, Report No./DNV Reg No.: / 12TUIBY-3, Rev 7, 2011-07-01, Det Norske Veritas, Rotterdam, July 2011. Download from http://www.globalccsinstitute.com/resources/publications/co2-liquid-logistics-shipping-concept-llsc-safety-health-and-environment-she-)

Feenstra, G.F.J., T. Mikunda, S. Brunsting (2010): *What happened in Barendrecht?! Case study on the planned onshore carbon dioxide storage in Barendrecht*, Energy research Centre of the Netherlands, ECN report ECN-E—10-057, Amsterdam, October 2010. Also http://www.ecn.nl/publicaties/default.aspx?nr=ECN-E--10-057

ISO (2009): *ISO 31000 "Risk management - Principles and guidelines*" (ISO 31000:2009, IDT).

NCEA (2011): CCS Maasvlakte (ROAD–project) - Tussentijds toetsingsadvies over het milieueffectrapport (In Dutch), Netherlands Commission on Environmental Assessment (NCEA, in Dutch: Commissie Milieueffectrapportage), 19 May 2011 / report number 2479–55, Utrecht, the Netherlands. http://docs1.eia.nl/mer/p24/p2479/a2479tts.pdf (download on 12 August 2011)

Thielemann, Th. et al (2011): *D4.2.2 WP4.2 final report Second deliverable (month 27) - Making CO2 transport feasible: the German case Rhine/Ruhr area (D) – Hamburg (D) – North Sea (D, DK, NL)*, Revision: 7, July 2011.

