Risk assessment in a hypothetical network pipeline in UK transporting Carbon Dioxide

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Abstract

With the advent of Carbon Capture and Storage technology (CCS) the scale and extent of its handling is set to increase. Carbon dioxide (CO_2) capture plants are expected to be situated near to power plants and other large industrial sources. Afterward CO_2 is to be transported to storage site using one or a combination of transport media: truck, train, ship or pipeline. Transport by pipeline is considered the preferred option for large quantities of CO_2 over long distances. The hazard connected with this kind of transportation can be considered an emerging risk and is the subject of this paper.

The paper describes the Quantitative Risk Assessment of a hypothetical network pipeline located in UK, in particular the study of consequences due to a CO_2 release from pipeline.

The risk analysis highlighted that some sections of pipeline network cross densely populated areas. For this reason, some changes in the original path of the network have been proposed in order to achieve a significant reduction in the societal risk.

1. Introduction

The Carbon Capture and Storage (CCS) of CO_2 in geological reservoirs is now considered to be on the most promising solutions to control greenhouse gas emissions (Gough et al., 2014) with a commercial deployment during the 2020s.

The CCS chain involves three stages: the capture of the CO_2 from large stationary sources, its transmission to the storage site and finally the injection into the geological reservoir.

Currently there are over 6,500 km of CCS pipelines mainly located in North – America, Australia, Europe and Africa (Kadnar, 2008; Noothout et al., 2014; Sweatman et al., 2009) and are actually used to transport the CO_2 (in dense or gaseous phase) from power and large industrial plants to storage sites both on- and off- shore. However extensive networks of CO_2 pipelines, especially in dense populated areas, are permitted only if it can be assessed that they are safe and do not represent a risk to local population (Koornneef et al., 2010).

It is has been also recognized that this component of the CCS chain presents some potential risk not covered by existing knowledge from operation of standard gas pipelines or the actual limited experience with CO_2 pipeline. In this sense, compared to natural gas pipelines, CO_2 have orders of magnitude of shorter operating history and existing infrastructures are mainly located in remote areas. Some differences concern also technical aspects. In fact, provide that the CO_2 moisture content is maintained below 500 ppm, both pipelines require similar materials but natural gas is usually moved with operating pressures much lower (< 85 bar) than those required to ensure a dense CO_2 state (85 – 180 bar). In addition, whereas hydrocarbons will dissipate or ignite and explode as a consequence of a release, CO_2 will accumulate in depressions and may cause asphyxia if in high concentrations.

In general it is therefore necessary to identify a suitable CCS infrastructure routing that must be safe, environmental acceptable, economical and practical. A suitable final route should be compatible with the characteristics of crossed territories and their land use (Gough et al., 2014) and very little distinguishes route selection for CO_2 pipelines from that for other gas pipelines. Factors that are usually considered in the infrastructure planning are listed in details in technical reports (Serpa et al., 2011). From a safety perspective, the route must provide a safe and secure environment for the pipeline during construction and over its operational life and ideally be routed away from populated areas. Recently, the methodology for the study of Quantitative risk assessment of the Italian gas distribution network has been described by Vianello and Maschio (Vianello and Maschio, 2014).

The CO_2 handling is quite different and represents an emerging risk with usual QRA procedures lacking some peculiar aspects like failure frequencies, heavy – gas dispersion modeling and consequences estimation (Koornneef et al., 2010, 2009). The current state of the art in the risk analysis for CO_2 has recently been reviewed by some authors (Koornneef et al., 2009; Martynov et al., 2013; Vianello et al., 2012).

The analysis shows that CO_2 release nature is strictly depending on storage conditions with the formation of multi – phase mixtures of gaseous, dense and solid CO_2. Figure 1 summarizes main physical phenomena taking place during the rapid depressurization of the CO_2.

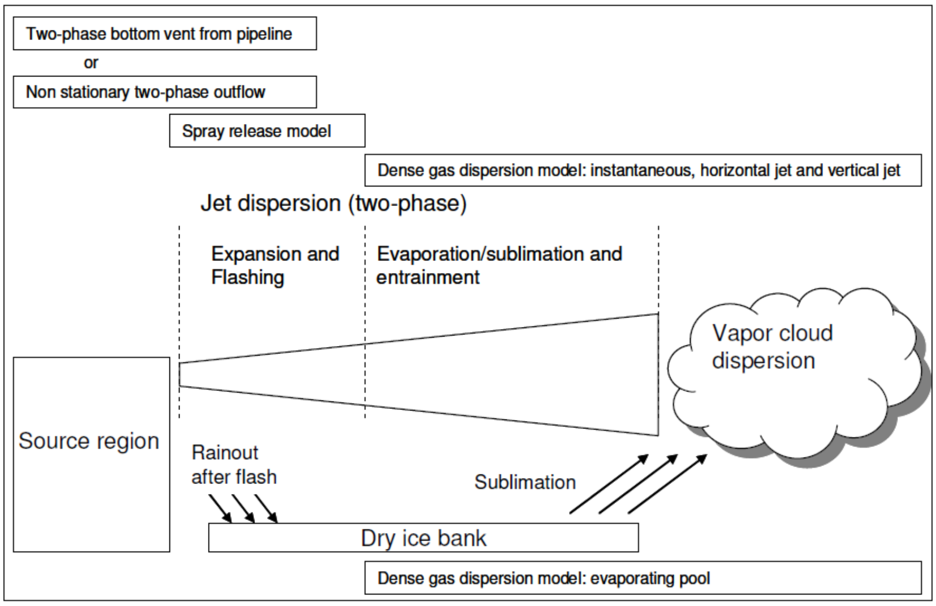


Figure 1 The methodological approach used for a puncture and full rupture of a carbon dioxide pipeline (Koornneef et al., 2009).

As investigated by some authors (Koornneef et al., 2009; Martynov et al., 2013; Mazzoldi et al., 2009; Mocellin et al., 2015) main phenomena related to the CO_2 rapid expansion are firstly assessed with the formation of a bi – phase release of liquid and gaseous CO_2. The dense portion is subjected to breakup phenomena even finally leading to the formation of sublimating dry ice particles (Hulsbosh-dam et al., 2012). The soil deposition of these particles may give rise to a sublimating dry ice bank formation acting as a delayed risk source (Vianello et al., 2014).

The appearance and the persistence of the solid phase is still under investigation and debate with the current state of the art characterized by even conflicting conclusions (Allason et al., 2014; Martynov et al., 2013; Woolley et al., 2014).

The resulting dense gas dispersion taking place after the release acts as a source of risk being the CO_2 asphyxiating at moderate concentrations. In this sense health effects assessment should consider both the concentration and the exposure through suitable Probit functions giving an estimation of the individual death percentage as described in the TNO Green Book (TNO, 2005).

This study is focused on a CO_2 pipeline network located in the UK starting from the work proposed by Lone (Lone et al., 2010) primarily based on technical and economic drivers and described in section 3. Section 4 is dedicated to the aim of this work mainly consisting on the application of a QRA method to the case study with the analysis of actions and workable alternative design options aimed at mitigating risks connected to accidental CO_2 releases.

2. General QRA methodology

The Quantitative Risk Assessment (QRA) is a complex series of analyses, evaluations and calculations that employ many simulation models, particularly in the analysis of physical effects of releases (Egidi et al., 1995). The risk analysis procedure applied to substances carried through pipeline, road, rail or by sea can be summed up in the following main steps (Bubbico et al., 2006; INTeg-Risk, 2012; Milazzo et al., 2010):

- System definition and data collection – all pertinent data are compiled for the risk analysis purposes, including those concerning the pipeline location and characteristics.
- Hazard Identification (HazId) – the pipeline system is characterized in detail in order to formulate potential accident scenarios. This allows the estimation of the accident frequency, the likely release amount as well as the nature and magnitude of resulting impacts.
- Probability Analysis – probability analysis determines the likelihood of an event, expressed in relative (likelihood) or quantitative terms (probability).
- Consequence Analysis – consequence analysis investigates the potential physical impacts and related consequences of a pipeline failure and an accidental release.
- Risk Evaluation – the probability of an event and its combination are numerically combined.

The general procedure is therefore composed by steps as indicated in Figure 2.

In the figure the methodology used for consequence analysis and modeling is expanded in the relevant phases.

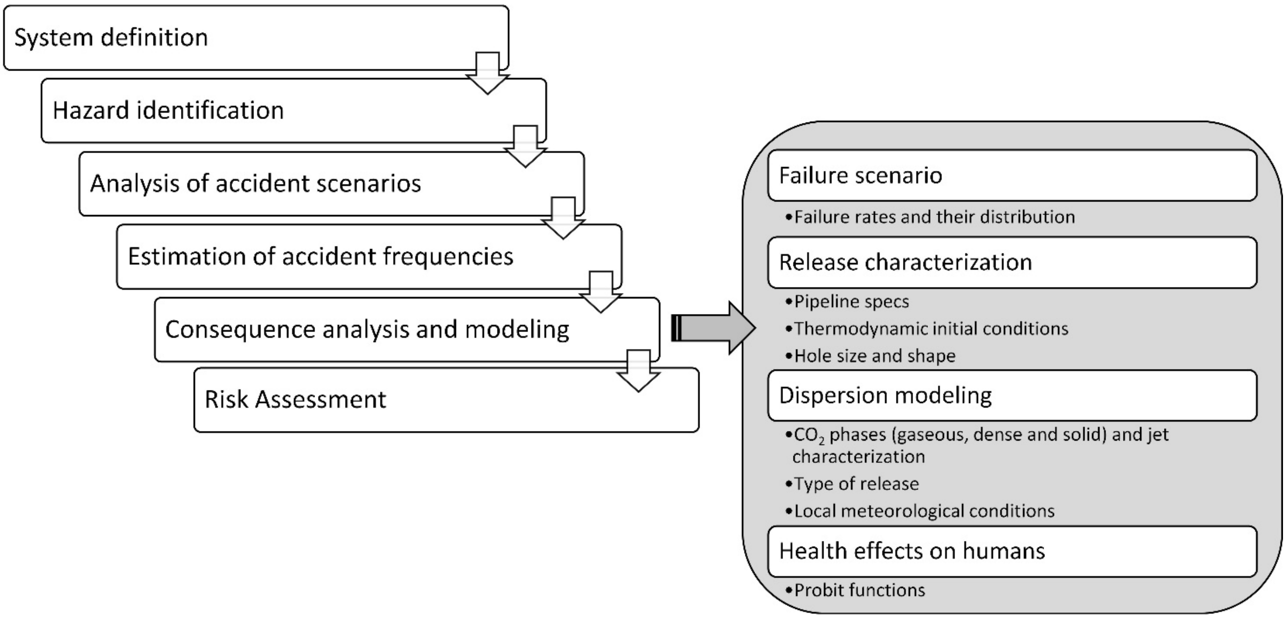


Figure 2 Main steps included in a Quantitative Risk Assessment procedure.

Therefore in performing a QRA for CO_2 pipelines, the evaluation of the effects of a failure scenario is carried out by relying on dedicated models able to give an estimation of the CO_2 concentration at a certain location after an elapse of time. In literature several methods are proposed:

- TNO method (Van den Bosch and Weterings, 2005) – implemented in the EFFECTS software suite;
- DEGADIS+ (Dense Gas Dispersion Model) the software simulates the atmospheric dispersion at ground – level of area source heavy gas (or aerosol);
- Universal Dispersion Model (UDM) – implemented in DNV PHAST software suite.

Recently, Vianello et al. (Vianello et al., 2012) have reviewed the current state of the art in the risk analysis for CO_2 transport by pipeline. A brief review of current models for CO_2 release is presented as well as the impact assessment and the overall risk analysis.

3. A CO_2 pipeline network for the UK - Route selection and pipe design

A CO_2 onshore pipeline network suitable to meet the forecast CCS needs of the UK was proposed by Lone et al, (Lone et al., 2010). This analysis was based on the techno-economic evaluations but they were not considered the aspects of safety and security.

Figure 3 shows the methodology adopted in the study, which only considers the development of onshore pipelines connecting the points of major carbon dioxide sources to a limited number of export terminals located on the coast.

Seven coastal terminals were selected based on the UK's network of oil and gas terminals currently existing and the nearest offshore oil and gas sedimentary basins with CO_2 storage potential, as suggested by the British Geological Survey (http://www.bgs.ac.uk/). The emitters of CO_2 include all industrial plants and power stations in UK that they produce CO_2 emission greater than 500,000 t/a. These UK CO_2 emitters were classified according to emission range (table 1) into three tiers.

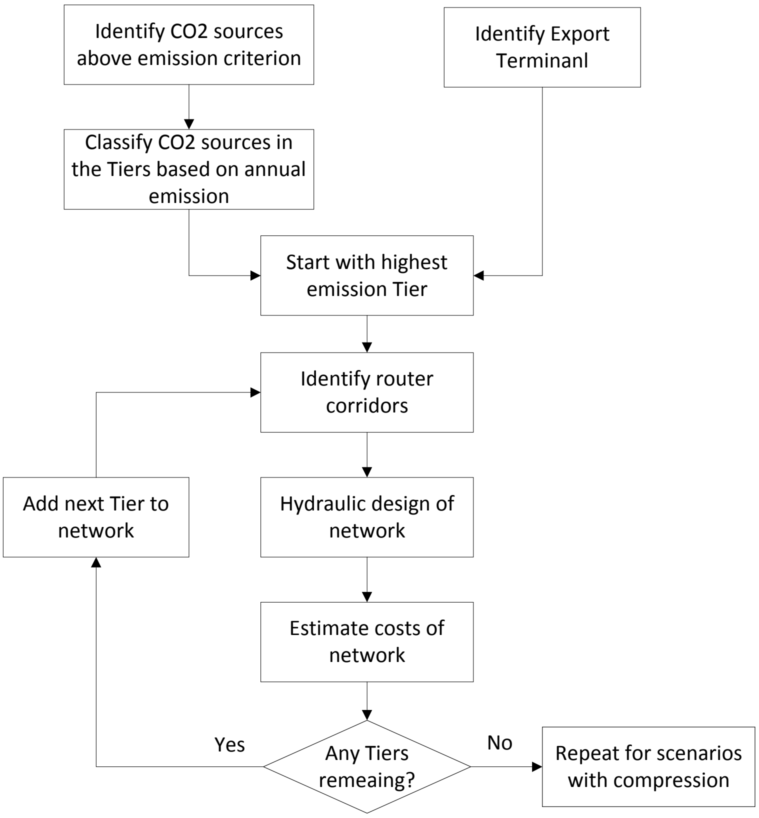


Figure 3 Analytic approach used in the study of Lone et al (2010)

Table 1 Classification of emitters according to emission

	CO_2 Emission Range [tonnes per annum]	**Type of emitter**
Tier - 0	3 million and above	Coal & Combined Cycle Gas Turbine (CCGT) power stations, Refineries, Steel industry
Tier - 1	1 million – 3 million	CCGT & Oil power stations, Refineries, Cement factories, Combined Heat and Power (CHP)
Tier - 2	0.5 million – 1 million	Cement factories, CCGT power stations, fertilizer, petrochemical complexes

The study assumed that a pipeline network would be rolled out in stages, first to meet the largest (Tier-0) requirements, then expanded to meet Tier-1 and finally Tier-2 needs. It also assumed that wherever feasible, the CO_2 transmission network would follow existing route corridors of onshore oil and gas pipeline in the country. The detailed design and simulation of the network was then conducted using the software PIPELINESTUDIO® by Energy Solutions International (http://www.energy-solutions.com/products/pipelinestudio). This software consists of a hydraulic simulation package that solves fluid dynamics problems in simple or complex pipeline networks at steady as well as transient states, for various conditions of pressures, flows and temperatures.

The key pipeline design assumptions are set out in table 2. The assumed fluid characteristics were:

- 100% CO_2 purity
- Phase is supercritical
- Critical temperature is 31°C
- Critical pressure is 74 bar

Through simulations with the PIPELINESTUDIO®'s package, the following design data were calculated:

- Pipelines: diameter, length, flow rate and pressure in each segment
- Compressor / booster stations: number, power and location.

Table 2 Summary of pipeline design assumptions (Lone et al., 2010)

Parameters	Value
Pressure rating of valves & fitting	PN 100 (100 bar nominal operating pressure)
Standard used for pipeline fitting and equipment	DIN 2512
Pipeline material	A105 – Carbon steel
Standard used for pipeline design criteria	BS EN 14161 / BS EN 1594
Maximum allowable operating pressure of pipeline network	110 bar
Pipeline internal design pressure	100 bar
CO_2 pressure leaving emitter's premises	95 bar
CO_2 temperature leaving emitter's premises	35°C
CO_2 arrival pressure at export terminals	85 bar
Minimum pipeline diameter	323.9 mm
Maximum pipeline diameter	1067 mm
Onshore pipeline buried depth	1.2 – 1.8

The network layout for each of the three Tiers is shown in figure 4 (Lone et al., 2010). Finally the study provided results for the capital cost (total and marginal) for each case.

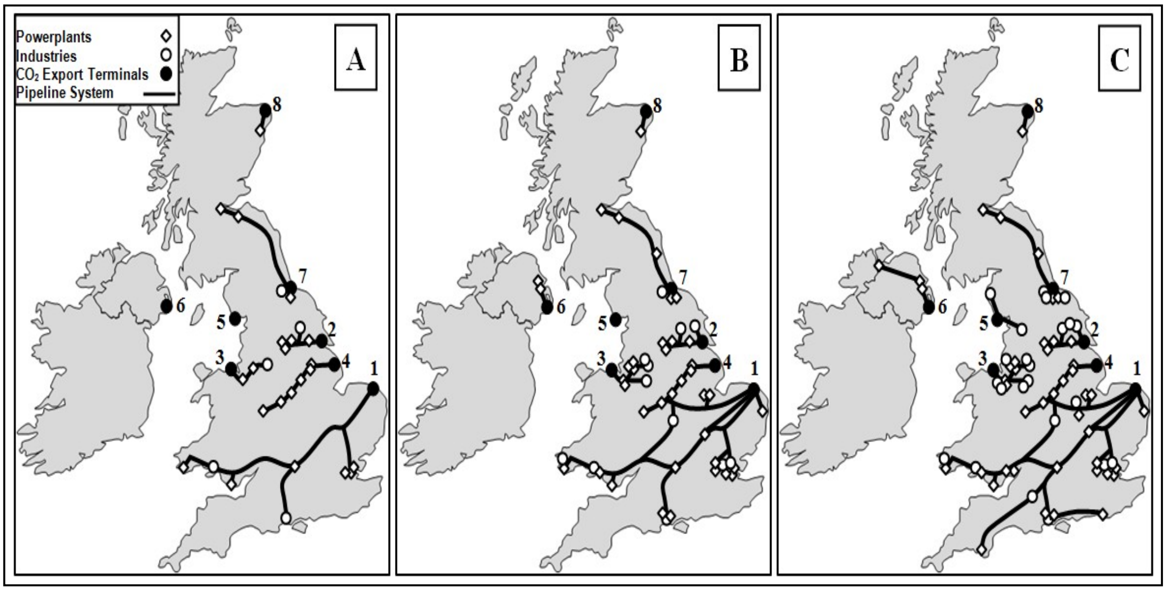


Figure 4 CO_2 transmission network for (A) Tier–0 emitters, (B) Tier–0+1 emitters, (C) Tier –0+1+2emitters.

The pipeline network (C) in Figure 4, defined to meet the requirement for transporting CO_2 captured from all Tier 0+1+2 emitters, was considered here as the basis for the risk assessment, as it is the most comprehensive and complex.

4. QRA: case study

The section is dedicated to the application of a QRA method, describe in section 2, to the case study. Also, the analysis foresees the possibility to propose an alternative design of pipeline route, necessary to mitigating risks connected to accidental CO_2 releases.

4.1. Identification of risk and risk matrics

At the moment, under the European regulation no. 1272/2008, the CO_2 appears to be a compressed gas, asphyxiant in high concentration, but it is not considered as a toxic substance. However it is demonstrated that high concentrations of CO_2 can cause fatality. In fact, in addition to the hazard of asphyxiation due to a CO_2 release that produce the displacement of the oxygen in air, the inhalation of elevated concentrations can increase the acidity of the blood triggering adverse effects on the respiratory, cardiovascular and central nervous systems.

The health effects are determined not only by the CO_2 concentration but also the duration of the exposure, as summarized in table 3 (Hedlund, 2012; Ridgway, 2007).

CO_2 can cause serious adverse health effects at certain concentration levels and duration of exposure. It is also a primary gas associated with volcanic eruptions (Farrar et al., 1999; International Volcano Health Hazard News - IVHHN, 2005).

An important characteristic value for a hazardous substance is Lethal Concentration 50% (LC50), the concentration value for which unconsciousness leads to death for 50% of the population. For CO_2, an unconsciousness status usually results at 17% CO_2 for an exposure time of 35 min. As a consequence, a level of concentration of 10% CO_2 for 15 minutes was chosen here as a conservative estimate of LC50.

Table 3 Concentration and effects of CO_2 (Hedlund, 2012; Ridgway, 2007)

Exposure Threshold (ppm)	**Exposure as function of concentration and time?**	**Comments**
2000 15,000	No	Thresholds are not considered to be lethality thresolds.
70,000 (several min)	It is unclear whether duration of exposure is included in the calculations.	No explicit duration mentioned. Threshold is “conservatively attributed to causing fatality”.
40,000 – 3 min 100,000 – 1 min	It is unclear whether duration of exposure is included in the calculations.	Concentration thresholds are used instead of exposure thresholds.
20,000 – 8 h 40,000 – 8 h 30,000 – 15 min 40,000 – 15 min	It is unclear whether duration of exposure is included in the calculations.	For puncture and rupture different concentration thresholds are used.
50,000 – 1 min	Yes	Exposure threshold explicitly mentioned as 50,000 ppm for 60 s.
100,000	No	Assumed to be fatal concentration.
5000 – 10 min TWA 30,000 STEL	It is unclear whether duration of exposure is included in the calculations.	
	Probit Function $Pr = -90.8 + 1.01 \times \ln(C^8t)$	See Health and Safety Laboratory, 2009.

The other risk value chosen to characterize a hazardous substance is IDLH (Immediately Dangerous to Life or Health). This value is defined by NIOSH (National Institute for Occupational Safety and Health) as the maximum concentration of an toxic substance that a healthy person can be exposed for duration of 30 minutes, without suffering irreversible effects on their health or without the effects that not preventing the escape. For CO_2 this parameter is 40,000 ppm (NIOSH, 2007).

For the study of risk analysis two further measures were chosen that identify the areas of damage:

- LC50 - Area of strong impact - the area limited by a dispersion distance from the release point resulting in a toxic dose of 100,000 ppm of CO_2 for 15 minutes.
- IDLH - Area of irreversible damage – the area limited by a dispersion distance from the release point resulting in a toxic dose of 40,000 ppm (IDLH) for 30 minutes

Figure 5 shows an example of the two areas of damage around a pipeline. The red zone characterizes the area of strong impact while the yellow zone is related to that of irreversible damages.

For the calculation of risk, the consequences must be associated with the Probit function, the measure of the percentage of people exposed who incur a particular injury. This is described in the Green book of TNO (TNO, 2005).

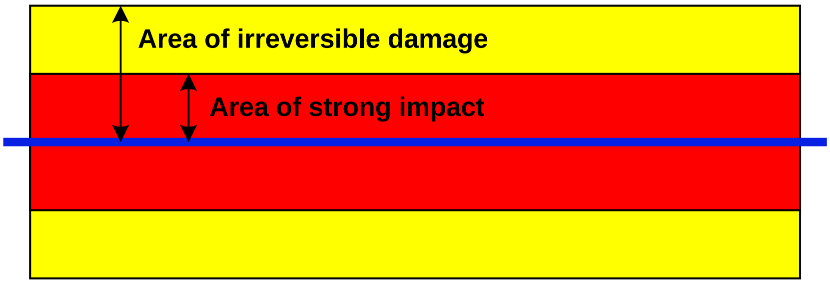


Figure 5 Impact area

The Probit function values for CO_2 was proposed by the UK Health and Safety Executive (Health and Safety Laboratory, 2009). This report outline a method for calculating CO_2 Probit values for use in the consequences tool of PHAST, wherever the dangerous dose calculation option was not available. The Probit function, proposed by HSE and collected in table 3, is used in the simulations.

4.2. Failure frequency

An important step for risk assessment, in particular to calculate the local risk, is the failure frequency of the equipment.

For CO_2 pipelines many studies (Hooper et al., 2005; Turner et al., 2006) propose to assume the same failure frequency of natural gas due to the limited operational experience of CO_2 pipeline

Data for this study was derived from 9th EGIG reports (European Gas Pipeline Incident Data Group - EGIG, 2015) and OGP reports (Oil & Gas Producer - OGP, 2010), that contains information on pipelines and relative incidents.

In the EGIG report, six different causes have been identifies for the natural gas pipeline and are given in table 4.

The failure frequency is calculated by dividing the number of incidents by the exposure. The exposure is the length of a pipeline multiplied by its exposed duration and is expressed in kilometres-years [km·yr].

Table 5 shows some reported values for the cumulative failure frequency of natural gas pipelines. However, natural gas is different from CO_2 and these failure rates may not be valid for CO_2 (Koornneef et al., 2010). Natural gas is transported in pipelines as a pressurized gas, while the pipelines proposed for the transport of CO_2 operate in supercritical conditions. There are some failure rate data for CO_2 supply (Vendrig et al., 2003), based on historical data, summarized in table 6, but these cannot be compared with natural gas because the CO_2 pipeline cumulative experience is limited.

The failure frequencies are expressed as a function of the type of module that constitutes the network and that of the hole can be created in the pipeline. A major rate of failure can be associated with the acidity of this gas and with the cooling effect (and consequential embrittlement of materials) generated during CO_2 release from supercritical conditions.

The failure frequency, that has been taken into consideration, is that proposed by (Vendrig et al., 2003), as it is specific for the network CO_2.

Table.4 Distribution of incidents per cause – natural gas

Cause	Distribution [%]
External Interference	35
Corrosion	24
Construction defect	16
Hot tap made by error	4
Ground movement	13
Other and unknown	8

Table.5 Cumulative frequency - natural gas

Cumulative failure frequency *[incident km^{-1} $year^{-1}$]*	*References*
$6.1 \cdot 10^{-4}$	*(TNO, 1999)*
$1.55 \cdot 10^{-4}$	*(National Energy Board, 1998)*
$1.1 \cdot 10^{-4}$	*(European Gas Pipeline Incident Data Group - EGIG, 2015)*

Table 6 Failure rate distribution, per year, for modules

Module	**Module pipe length**	**Small hole (3 – 10 mm)**	**Medium hole (10 – 50 mm)**	**Large hole (50 – 150 mm)**	**Full-bore rupture (>150 mm)**
CO_2 recovery at source	500 m	9.6×10^{-2}	5.1×10^{-2}	2.0×10^{-3}	5.6×10^{-3}
Converging pipelines	100 m	3.5×10^{-3}	8.8×10^{-4}	1.0×10^{-4}	1.5×10^{-4}
Booster station	100 m	3.5×10^{-2}	3.8×10^{-3}	3.0×10^{-4}	8.8×10^{-4}
Pipelines	10 km	1.4×10^{-4}	9.5×10^{-5}	2.0×10^{-5}	8.5×10^{-5}
Injection plant	500 m	1.2×10^{-1}	5.3×10^{-2}	2.1×10^{-3}	5.8×10^{-3}

4.3. Dispersion calculation

As described in the introduction, the calculation of dispersion due to a release of CO_2 can be modeled with different software.

In this study the software PHAST (DNV-software) was used because, as of version 6.6, has been implemented a module for calculating the release of CO_2 in supercritical conditions. For discharge of supercritical CO_2 from long pipelines a non-ideal gas compressibility model is included as a default option. At very large pressures non-ideal effects are important and may therefore significantly increase the released mass (for example, by a factor of around 1.8 at an initial pressure of 200 bar).

For a most accurate atmospheric-expansion and dispersion calculations of CO_2 release using this model, DNV recommend using the “No Rainout, Equilibrium” option in conjunction with the liquid “Droplet model” and “Version 2” as the “Dispersion Model”. The Phast release v6.6 Version 2 UDM is claimed to account for effects of solid formation downstream of the orifice. However, for the dispersion equations the new model always assumes the equilibrium model without solid deposition (“no rainout”), i.e. the snow-out of CO_2 is not modeled. This assumption is justified on the basis that for most scenarios snow-out is not expected to occur (or conservative predictions are given if snow-out is ignored). Furthermore, Phast v.6.6 does not account for effects of solid formation upstream of the release orifice, but it is claimed it does give appropriate warnings in case this may happen.

4.4. Long pipeline model

The program contains two models for the time-dependent discharge from a long pipeline: one model for two-phase pipelines, and one model for gas pipelines. The program permits to choose the more appropriate model, depending on the operating conditions in the pipeline.

Figure 6 shows the system diagram used in the simulations.

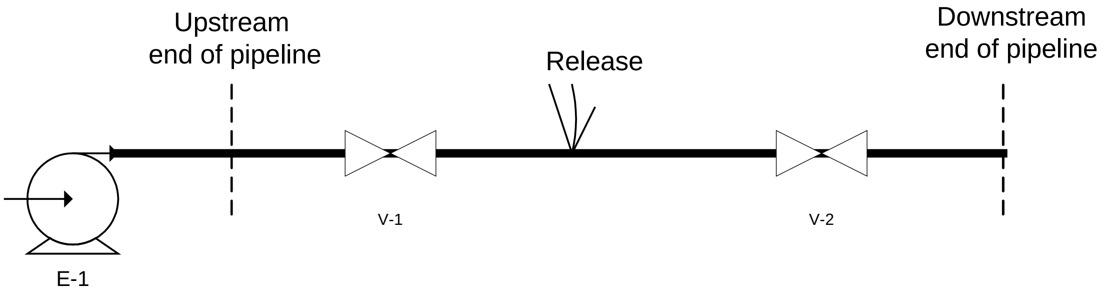


Figure 6 Discharge from “long pipeline”

For both models, it is possible to specify a release at any location along the pipeline, and the size of the release (from a small holes, to a full-bore rupture). The models can consider the effect of a pumped inflow, and of valve closure. If the inflow is pumped, the flow rate is assumed to not be affected by the breach, but to remain at the normal operating flow rate until the upstream section of the pipe has depressurized.

The valves are defined by their distance from the upstream end of the pipe and by their closure time (measured from the start of the release). Once the closure time is reached, the valves are assumed to be instantaneously closed.

The input data required for the long pipeline model are:

- Length pipeline
- Diameter
- Opening of hole, expressed as a fraction or percentage of the pipe flow area
- Distance of breaking point from beginning of pipe segment
- Nominal flow rate
- Release direction
- Weather conditions (atmospheric temperature and wind speed)

For our study, the design data used are those from the PIPELINESTUDIO® simulations in the paper by Lone et al., (Lone et al., 2010) for their most comprehensive network, including transport from all UK emissions sources greater than 0,5 million t/y of CO_2. To complete the input data definition for consequences calculation, meteorological conditions at the point of release must be defined. To represent the variability over the network, weather conditions were identified for each of the seven onshore gas terminals using data collected by the Meteorological Office and Department of Energy & Climate Change (http://www.metoffice.gov.uk/climate/uk/2010/), summarized in table 7.

Table 7 Weather conditions

Terminal	**Region**	**Location**	**Temperature [°C]**	**Wind speed [m/s]**	**Atmospheric Stability Class**
SBacton Gas Terminal	East Anglia	Cambridge	9	5	F
Easington Gas Terminal	England E & NE	Hull - Leeds	8	6	F
Point of Ayr Terminal	England NW & N Wales	Liverpool	8	5	F
Theddlethorpe Gas Terminal	England E & NE	Nottingham	8	5	F
Barrow-In-Furness Terminal	England NW & N Wales	Morecambe	8	5	F
Teesside Gas Terminal	England E & NE	Middlesbrough	7	5	F

4.5. Release calculation

Before starting with the calculation of consequences, it was verified through some rough estimates, the difference of the calculation of the release for two cases:

- case 1: two phase release of CO_2, gas and liquid (as calculated by software Phast)
- case 2: two phase release of CO_2, gas and solid.

In the case 2, the liquid phase of the previous case is considered as solid phase and then there is formation of snow and dry ice bank.

To carry out these simulations, the pipeline under examination has a length of 27 km with diameter 914 mm and a pumped flow equal to 327 kg/s. The CO_2 is transported to pressure of 100 bar and temperature of 35°C. The release was calculated by assuming a hole equal to 20% of the area of pipeline. The release is biphasic, liquid and gas. The temperature of liquid phase is -78°C,that corresponds to the triple point of the state diagram of the CO_2.

The total mass released is equal to 225 tons. Figure 7 shows the formation of the cloud, as a function of distance and amplitude, from the release from the pipeline. The dotted area shows the formation of the cloud where the liquid phase is present. The dispersion with gas and liquid phases is very limited compared with the total extension of the cloud.

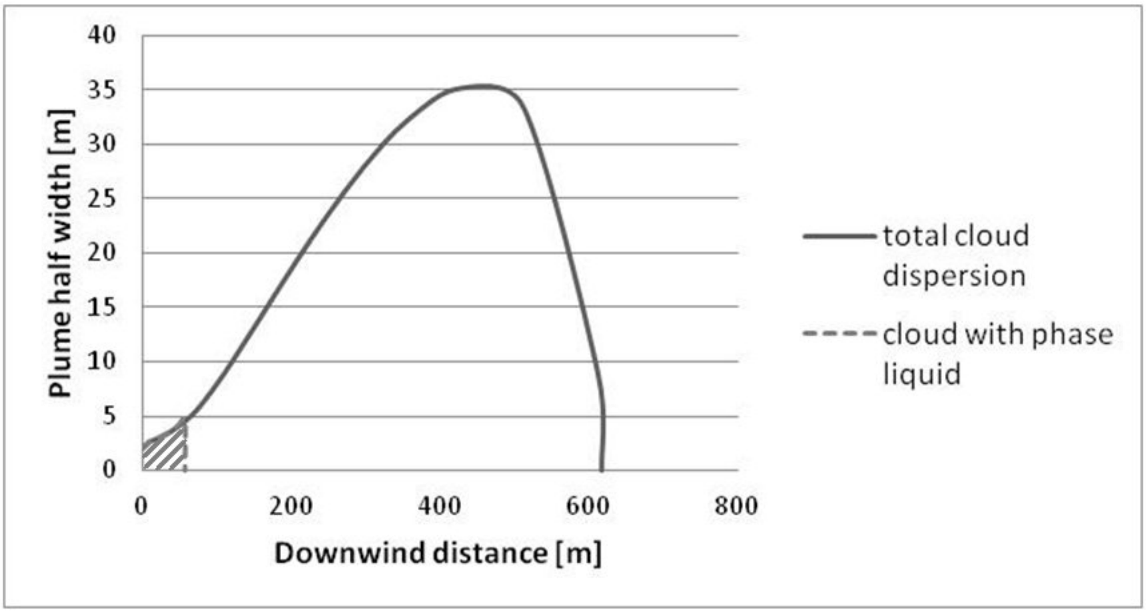


Figure 7 Dispersion of clouds: total dispersion and dispersion that contain liquid phase

The release profile of the case 2 was calculated by assuming that the liquid phase dispersed in the cloud (dotted area in Figure 7) is released in solid phase, so that it produces a snow and dry ice bank when it falls into the ground. The liquid phase present in the cloud has an average of 20% by weight. Whereas the assumptions given above, the area of release of the solid phase and thus the formation of the ice bank is equal to 256 m^2 with a total mass of 49 tons. In the simulation, the block of dry ice was considered uniform throughout its area. The vapour phase which remains in the cloud is 176 tons of CO_2.

The release rate and the consequences related to the vapour phase and to the sublimation of dry ice bank were calculated with the software PHAST.

For the solid phase the data of sublimation rate considered, is proposed by Mazzoldi et al. (Mazzoldi et al., 2008) equal to 2.5 g/m^{2}s. Thus the total time of sublimation of ice bank is equal to 22 hours with a flow rate of 0.64 kg /s.

Figure 8 shows the release rate as a function of time considering:

- Release of cloud liquid and gas, the first case
- Release of the vapor cloud, equal to 176 tons
- Release resulting from the sublimation of dry ice.

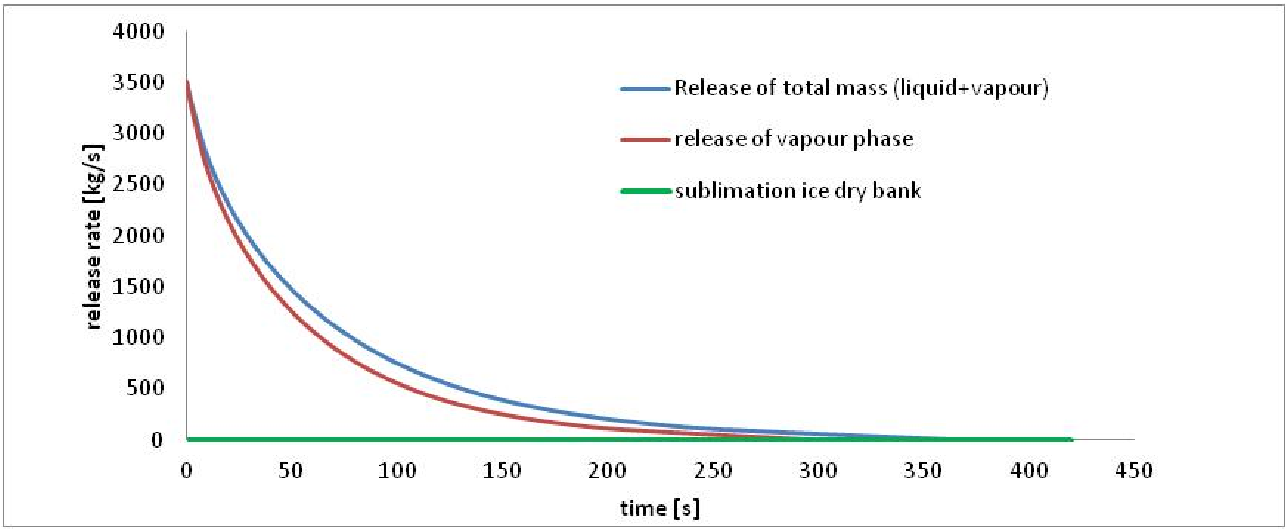


Figure 8 Release rate in function of time

The consequences of each release showed that the worst-case scenarios is obtained without considering the solid phase. The presence of dry ice does not increase the consequences in the long run, but locally there may be problems especially during rescue operation and in the recovery operations of the pipeline (Mocellin et al., 2015).

The calculation of the consequences of network has therefore been made by considering the release composed of liquid and gaseous phase.

4.6. Consequences calculation

Considering what explained in the section 3.5 and neglecting the immediate effects related to the dry ice bank sublimation (whose magnitude is still very low), the release considered the atmospheric emission of a mixture of liquid and gaseous CO_2. This occurrence represents the predominant event in the instants following the pipeline rupture (Mocellin et al., 2015).

The consequences were calculated for the entire UK pipeline network. For reasons of space, as an example, the results of an accidental release in the area near to the Point of Ayr terminal (near Liverpool) are shown. In this location the average weather conditions are: atmospheric temperature equal to 8 °C, a wind speed of 5 m/s and a solar radiation of 105 W/m^2 (World Energy Council, 2013) as derived from Table 7. The corresponding Pasquill – Gifford stability class is F – very stable. These very stable conditions are related to an improved horizontal atmospheric dispersion of the CO_2 linking the study to the investigation of the worst cloud dispersion conditions.

In addition, simulations considered a surface roughness of 250 mm that corresponds to areas characterized by large scattered obstacles. The value selected is corresponding to the network passage through flat zones characterized also by the presence of obstacles, such as the surrounding areas of a city.

It was assumed that the breaking point is at the half way along the length of each pipe segment, since for a release in such point the CO_2 accumulation (holdup) is higher and therefore the consequences are more severe. A release with a total duration of 300 seconds was assumed (that is, the time specified for closure of the check valves in the network).

The estimation of consequences was carried out for two types of release:

- Type A – release from full bore rupture.
- Type B – release from a hole of diameter equal to 20% of the pipe section area

Tables 8 reports the consequences estimated due to a release of Type A and B, respectively. Each row in these table gives the distance in meters from the pipeline corresponding to the two risk metrics LC50 (area of strong impact) and IDHL (area of irreversible damage), for a release half way in that segment.

Table 8 Consequences of release near Point of Ayr terminal

Pipe Segment	Pipe Diameter	Length	Flow	Downwind distance [m] from release point to limit of health impact to humans:			
				Strong impact (LC50)	Irreversible damage (IDLH)	Strong impact (LC50)	Irreversible damage (IDLH)
	[mm]	[km]	[kg/s]	full bore rupture		release from hole (20% of pipe area)	
Pipe0040	304.8	12.23	11	118	263	119	249
Pipe0041	914.4	25.75	626	335	711	319	626
Pipe0043	914.4	4.83	484	246	529	280	556
Pipe0044	914.4	14.48	416	330	700	310	610
Pipe0045	457.2	12.87	231	170	371	170	346
Pipe0046	457.2	19.31	63	175	380	174	353
Pipe0048	914.4	12.87	130	327	694	307	604
Pipe0049	914.4	17.7	116	333	706	315	618
Pipe0050	406.4	14.48	65	155	339	157	321
Pipe0051	406.4	28.97	38	159	348	158	322

Figure 9 shows graphically the same areas around the pipelines. This picture highlights that some segments of the pipeline crosses residential areas (light green zones). In particular, the highlighted inset shows two pipeline segments in the greater Manchester area. A large, Tier-0 industrial emitter of CO_2 is linked by a large pipeline in the initial rollout phase (pipe segment 0049, on the left in the inset), and is later joined by the smaller pipe 0050 (right segment in the insert) linking a Tier-2 emitter to the earlier pipe 0049.

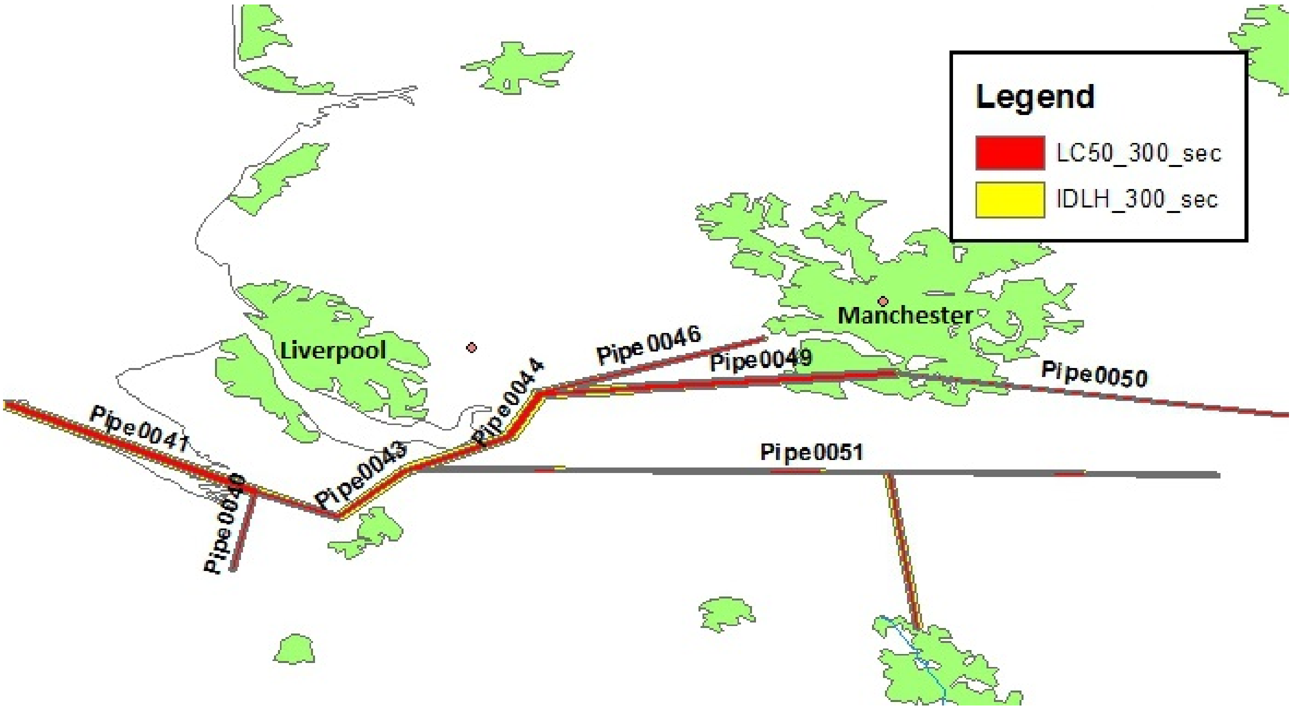


Figure 9 : CO_2 consequences due to full bore rupture.

4.7. Risk Assessment

The risk assessment includes identification and evaluation of the likely accidental scenarios for each fixed installation and each type of transport.

The quantitative area risk evaluation is necessary to identified the measures of local (LR), individual risk (IR) and the F/N curves relevant to the societal risk, that are used as indicators of the area risk resulting from the merging of point risk sources (plants) and linear risk sources (different ways of transportation). The following section describes the methodology to determination the local and societal risk and the results obtained. In this study only the linear sources are treated.

Local risk is defined as the likelihood per year that a person who is continuously and without protection at that location, is fatally injured as a consequence of an event at the transportation route leading to the release of a dangerous good.

The outdoors Local Risk (LR) in a generic point P of a territory is the sum of the risks into it generated by each source present in the area. It is calculated through two steps:

- LR assessment induced by a single branch and a specific type of substances carried;
- extension of the evaluation to all branches and all types of substances transported.

The local risk was calculated using the equation:

$$LR_x = \sum_{i=1}^{n} f_i \cdot P_i \qquad (1)$$

Where x is distance from pipeline, f_i is the frequency of event and P_i is probability of fatalities or damages.

In this case study to determine the local risk, the probability of fatalities derive from Probit function, see section 3.1 and the frequency of event is proposed by Vendrig (Vendrig et al., 2003), see table 6. For release from a hole of diameter equal to 20% of the pipe section area the failure frequency is the same of full bore rupture because the diameter is greater than 150 mm.

The table 9 shows the result of local risk calculated for pipe 0049 and 0050.

In European Countries the value of acceptable local risk in regulating industrial risk varies with each Country (Hill and Catmur, 1994).

Table 9 Local risk results for pipe 0049 and pipe 0050

Distance from pipeline [m]	**Probability of fatalities [%]**		**Local Risk [event/years]**	
	pipe 0049	**pipe 0050**	**pipe 0049**	**pipe 0050**
0	100%	100%	8.50E-05	8.50E-05
25	100%	100%	8.50E-05	8.50E-05
50	100%	100%	8.50E-05	8.50E-05
75	100%	100%	8.50E-05	8.50E-05
100	100%	100%	8.50E-05	8.50E-05
125	100%	87%	8.50E-05	7.40E-05
150	100%	46%	8.50E-05	3.91E-05
175	100%	12%	8.50E-05	1.02E-05
200	100%	2%	8.50E-05	1.70E-06
225	99%	0%	8.42E-05	0
250	93%	0%	7.91E-05	0
275	80%	0%	6.80E-05	0
300	58%	0%	4.93E-05	0
325	37%	0%	3.15E-05	0
350	18%	0%	1.53E-05	0
375	8%	0%	6.80E-06	0
400	3%	0%	2.55E-06	0
425	1%	0%	8.50E-07	0
450	0%	0%	0	0

In the Netherlands, local risk of 10^{-6} events per year is considered the limit value for vulnerable buildings (houses, hospitals, schools etc.), while for less vulnerable buildings like offices, recreation activities and shops, the local risk level of 10^{-6} per year is a target value.

In UK, the HSE quotes the acceptable values for the local risk as 1×10^{-6} events per year as the risk of fatality that is regarded broadly as acceptable for the members of public and workers, 1×10^{-5} and 1×10^{-3} per year as that representing the boundary between tolerable and unacceptable respective for the members of public and workers

Like proposed by Chakrabarti and Parikh (Chakrabarti and Parikh, 2012), figure 10 shows the local risk transects related to pipe 0049 and 0050. The risk transects plot shows the annual risk of fatality due to release from the break point against the perpendicular distance from the pipeline network.

The figure 10 highlights that the values for LR are different for each section, since the consequences of releases depend on the diameter, length, pressure and pumped flow.

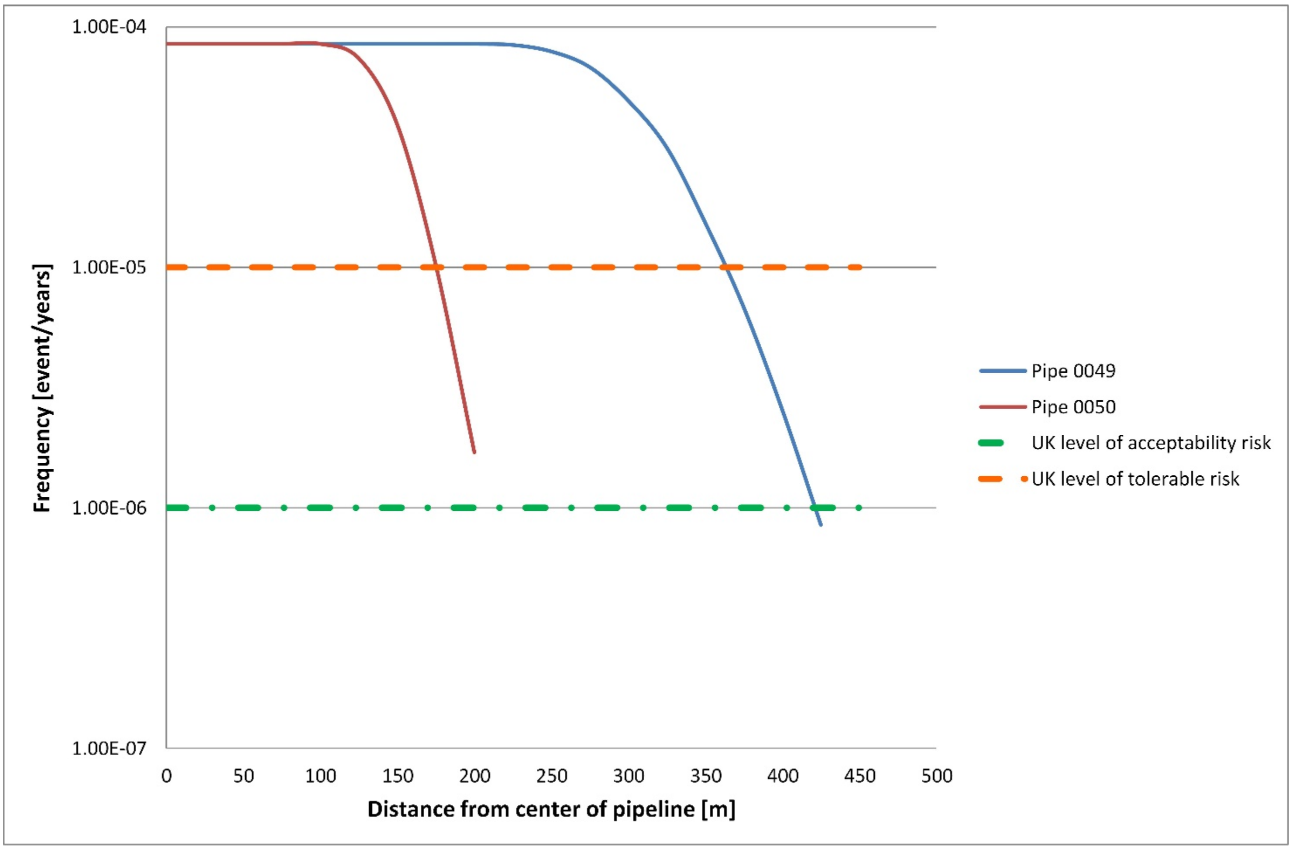


Figure 10 : Local risk transects

With reference to criteria UK, for the pipe 0049 the local risk is tolerable to a distance of about 170 m, while for the pipeline 0050 this distance increases to more than 350 m.

By using the values of local risk is also possible to calculate the Societal Risk (SR).

The societal risk takes into account the population distributed around the area involved in the consequences of an accident.

The Societal Risk represents the frequency of having an accident with N or more fatalities simultaneously. It assume that any protective measures like evacuation, sheltering, etc., and their efficiency is not considered (Uijt de Haag et al., 2001).

In the case of a pipeline network, the societal risk refers to the cumulative probability that a group of at least N people is fatally injured as a direct consequence of their presence within the impact area of the pipeline during a failure. In contrast to the local risk, which assumes a hypothetical person which is present all the time, the societal risk takes into account the actual presence of persons.

The acceptability of the societal risk depends not only on the probability but also on the number of fatalities.

Also the acceptability criterion for societal risk is not standardized among the EU countries. The acceptable level of societal risk has been set down generally as the cumulative frequency multiplied by the square of the number of fatalities to be lower than a certain value.

Various governments have established "tolerable risk" limits based on these analysis methods. Many corporations have also adopted these methods for internal evaluation of the relative risk of projects, plants and businesses, presumably setting their own criteria.

The use of F-N curves for the analysis of the societal risk has also been applied to pipelines, generally with F calculated on a per-length-of-pipeline basis. Such an analysis is useful for comparing the risk. Furthermore, the criteria vary between different countries, as shown in figure 11.

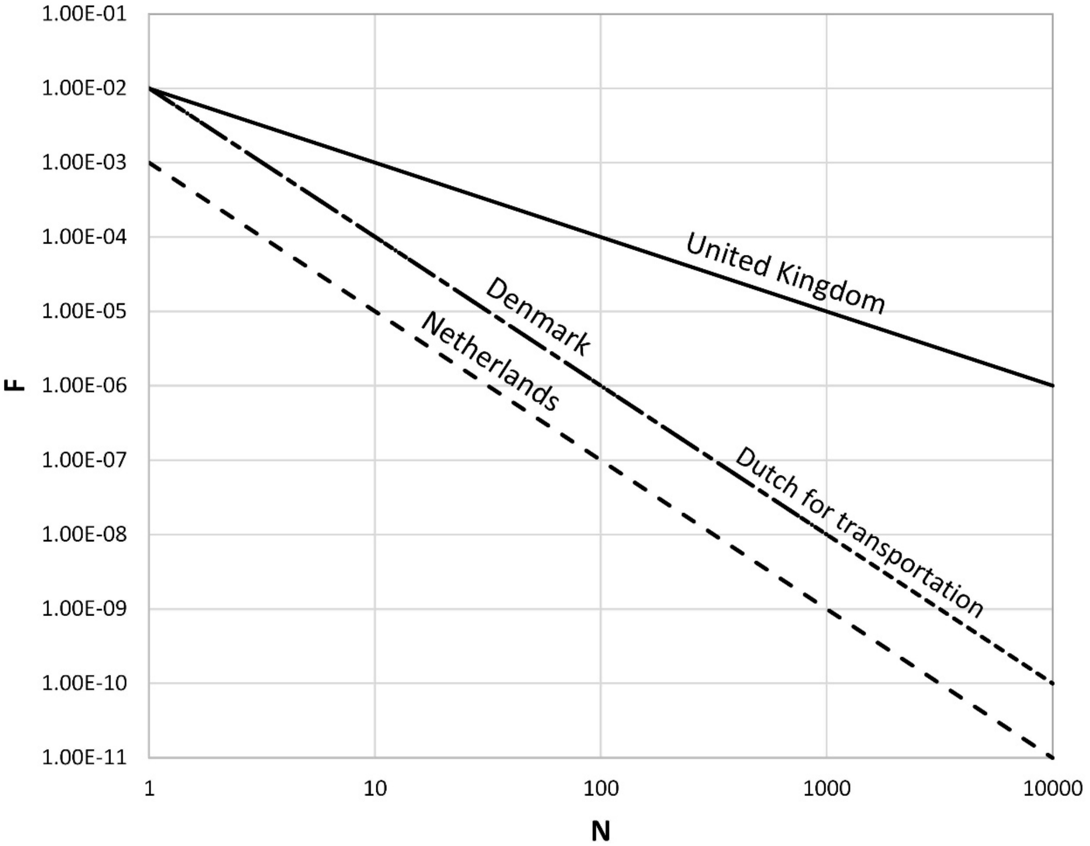


Figure 11 Acceptable level of risk in some countries (Boot, 2013; HSE, 2001; Jonkman et al., 2003; Schork et al., 2012)

As previously described, the distribution network may pass through populated areas and thus can cause injury to the population.

The Societal Risk is presented as an FN curve, where N is the number of fatalities and F the cumulative frequency of accidents and the general procedure for calculation is described the following (CCPS - Center for Chemical Process Safety, 2000).

The number of people affected by each incident outcome case is given by

$$N_i = \sum_{x,y} p_{x,y} \cdot P_i \tag{2}$$

where N_i is the number of fatalities resulting from incident outcome case; $p_{x,y}$ is the number of people at location x, y and P_i probability that incident outcome case i will result in a fatality (percent fatalities from Probit function).

The number of people affected by all incident outcome cases must be determined, resulting in a list of all incident outcome cases, each with a frequency (from frequency analysis) and the number of people affected. This information must then be put in cumulative frequency form in order to plot the F-N curve.

$$F_N = \sum_i F_i \text{ for all incident outcome case }_i\text{ for which } N_i \geq N \tag{3}$$

where F_N is the frequency of all incident outcome cases affecting N or more people, F_i is the frequency of incident outcome case, and N_i is the number of people affected by incident outcome case i. In this case study, the probability of indoor and outdoor population has not been taken into account.

Near Manchester, the population density is about 3400 persons per km^2 (CENSUS, 2001). Whereas the distance with concentration equal to IDLH, a possible CO_2 release could produce serious damage, as shown in table 10.

Table 10 Population exposed

	Damage area [km^2]	**Population exposed**
pipe0049 e pipe0050	11.5	39,100

Figure 12 shows the F–N curves for societal risk relevant to the segment pipe 0049 and pipe 0050. In this figure two lines, representing the acceptability criteria in use in NL and UK, were added to guide value for hazmat transport goods (Boot, 2013).

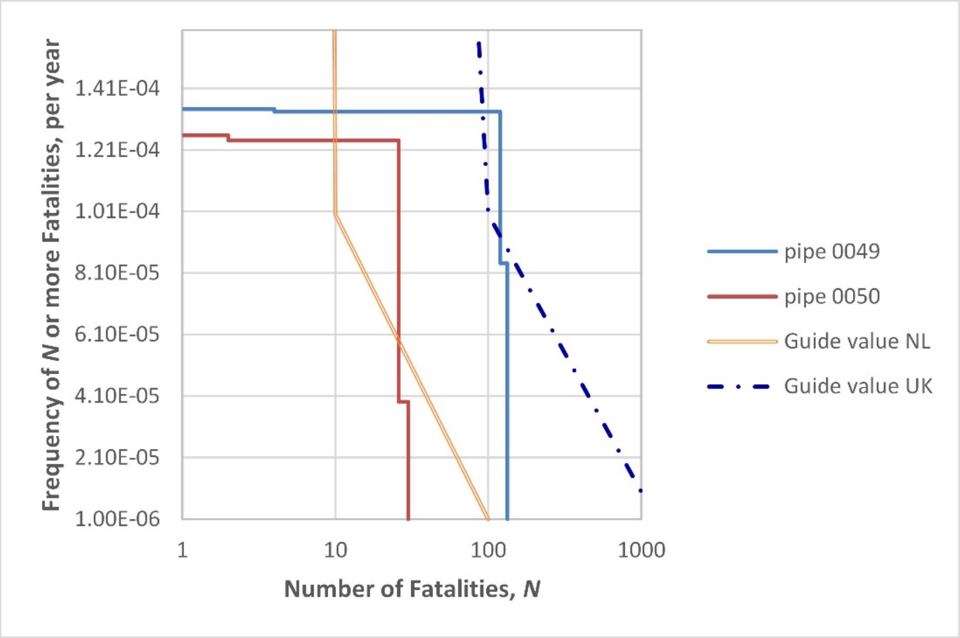


Figure 12: Societal risk - F–N curves

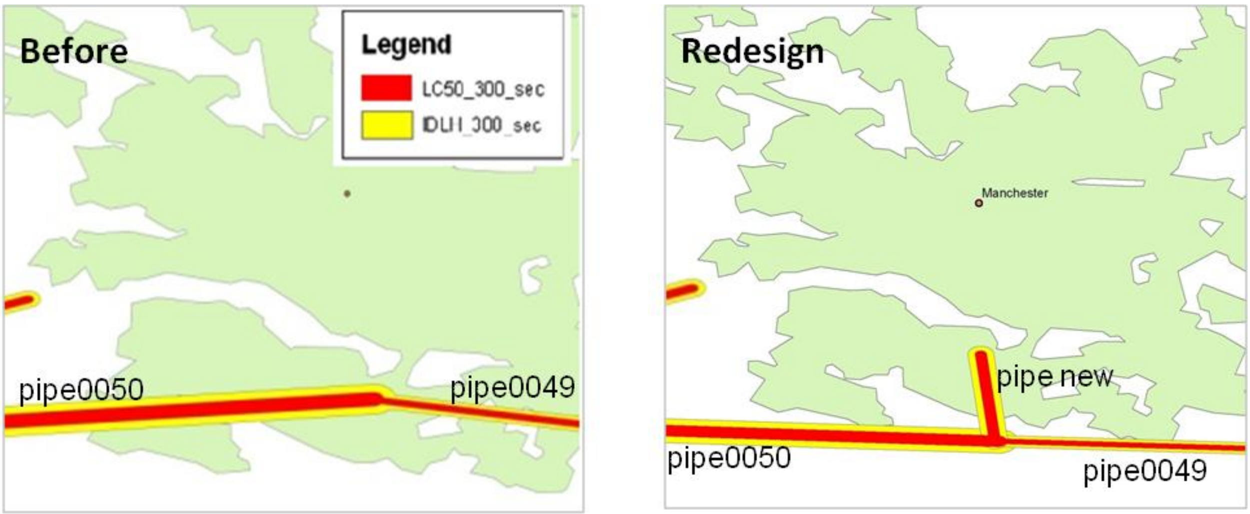
Results show that for NL criterion the societal risk related to both pipeline segments is totally unacceptable. Considering UK criterion, the societal risk connected with pipe 0050 can be considered acceptable while segment 0049 again needs attention.

Given this it could be appropriate to adopt measures to reduce societal risk so as to bring the profiles under acceptable conditions. In the following section a modification in the pipeline network is investigated.

4.8. Pipeline network modification

Taking into account the fact that the network is still at the initial phase of design, various alternatives may be considered, taking into account the results of both techno-economic analysis (based on capital and operating costs) and quantitative risk analysis (based on potential societal costs). In order to reduce the risk society, it is possible to propose a new route of the pipeline, as shown in the Figure 13, to prevent the passage in the proximity of highly populated areas.

The initial main pipe connecting the Tier-0 source (Fig.13a) will now be slightly shifted from the main residential area (Fig.13b). However its extra costs are partly compensated by a slightly shorter length (and cost) of the later Tier-2 pipe addition. A recalculation of release dispersion and consequences for this alternative shows a significant reduction in the size of the impact areas and population exposed (table 11).



(a) (b)

Figure 13 Redesign network near Manchester: (a) before the shift of pipeline, (b) after the shift of pipeline

Table 11 Population exposed after pipeline redesign

	Damage area [km^2]	**Population exposed**
pipe new	2.7	9,180

Figures 14 and 15 show the local risk and social risk of the new pipeline compared to the results of the original pipeline prior to the change of the network. Both values of local and societal of risk are significantly reduced and acceptable with reference to the UK criteria, even if the societal risk is still in the area of unacceptability with reference to the NL criterion, that is significantly more restrictive. The figures show that the shift of the network with initial pipe connecting the Tier-0 source decreases the risk in the case of release of CO_2. In fact the distance of acceptability of local risk from the more critical pipe is reduced from 350 m to 225 m. The displacement of the pipeline significantly affects also the values of the societal risk, greatly reducing the maximum value.

The particular area involved gives space to several “vulnerability centers”, such as proximity to motorways and an airport. This analysis should be therefore greatly refined, possibly including other measures for the mitigation of the risks. Nonetheless the general approach and tradeoffs could yield important information at the stage of preliminary pipeline route selection.

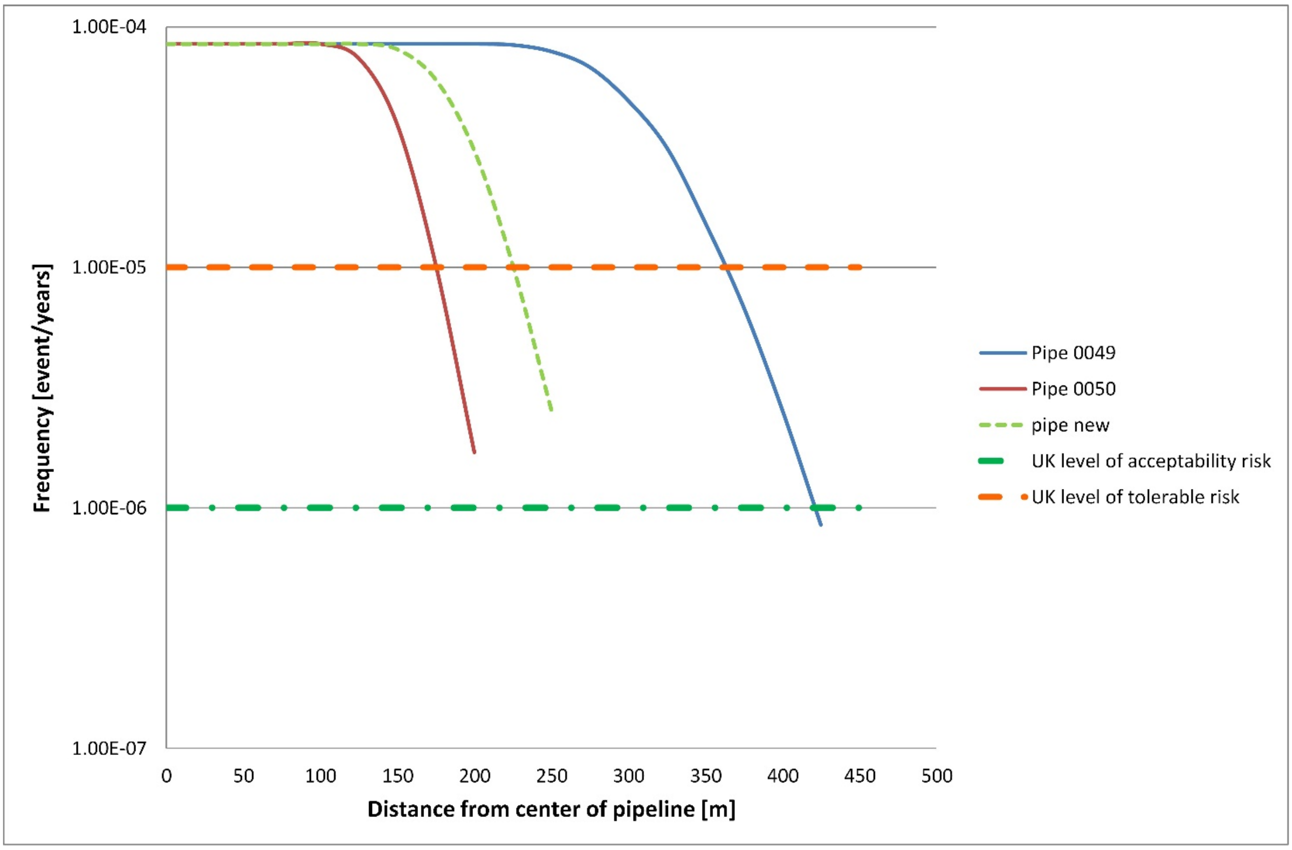


Figure 14 Local risk: a comparison of Redesign network and before the shift of pipeline

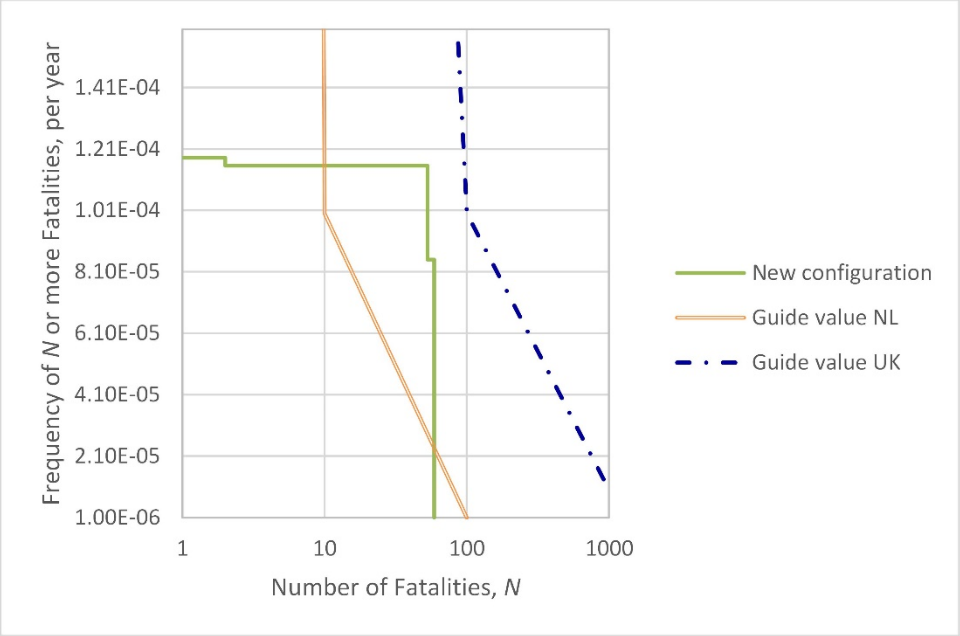


Figure 15 Societal risk: a comparison of Redesign network and before the shift of pipeline

An additional protective measure which can be adopted for the reduction of risk consequences is the insertion of block valves along the pipe. From the regulatory, the block valves are inserted on average every 30 km in oil and gas pipeline network. Adding valves, the distance between one and the other decreases and then decreases the amount released (Medina et al., 2012). The pipeline, that was simulated, is 30 km long with a diameter of 914 mm and a flow rate of 468 kg/s. Through the software PHAST, the damage areas were calculated increasing the number of valves on the pipeline. Valves are placed equidistant from each other, and then divide the pipeline into several segments, as shown in the table 12.

Table 12 number of valves in function of distances

Number of valves	Distances between valves [km]
2	30
3	15
4	10
5	5
10	3

Figure 16 shows the consequences trend depending on the number of valves. The distance of the release corresponds to the distance traveled by the cloud until it reaches the threshold value defined by IDLH and LC50. The results show that the impact area of releases decreases with an increase of the number of valves.

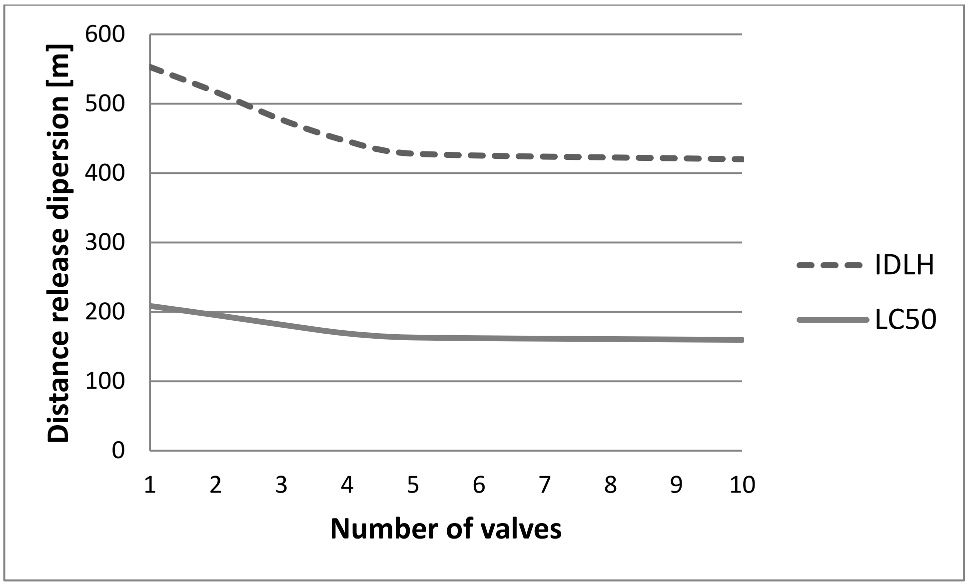


Figure 16 Distance release dispersion in function of number of shutdown valves

In this case an asymptotic value is reached using 4 valves, i.e. one every 10 km.

To adopt this solution an economic analysis must be conducted, since the valves have their cost and so a compromise must be found between the reduction of the consequences and the increase of economic costs. Anyway it is evident that the reduction of risk reaches a horizontal asymptotic value after the insertion of a very limited number of valves especially in more critical areas.

5. Discussion and conclusion

This study shows the results of a quantitative risk analysis conducted for a proposed UK onshore pipeline network transporting CO_2 from main carbon capture sites to selected coastal terminals, for final storage offshore.

In the distribution network, the local risks shows that a CO_2 release has consequences that exceed the acceptable criteria.

The analysis of the societal risk has shown that there are pipelines that pass close to zones with medium population density and thus a release could give negative effects on the population. The results of the quantitative area risk assessment demonstrate that in some cases the societal risk exceeded both the NL and UK guide values to acceptability, then mitigation and prevention actions may be adopted.

The reduction in the frequencies of external interferences can strongly reduce the values of local and societal risk. For this reason an improvement in the identification of the pipeline path is necessary as well as the adoption of accurate preventive measures especially when excavating in areas crossed by pipes.

More information about the pipeline location is essential when performing interventions from outside (like excavations) as well as a strong communication between different institutions or facilities.

Safety distances in the proximity of pipelines may be plotted in diagrams against independent variables. These diagrams could be used in loss prevention applications as well as in safer land-use planning.

To conclude, more critical areas crossed by CCS infrastructures should be protected against risks with additional measures, particularly oriented toward the arrangement of additional block valves. The aim is to limit the amount of CO_2 emitted in the case of a leakage. It should be considered that critical issues may arise also from the fact that under atmospheric conditions CO_2 behaves as a denser than air gas. In this sense the presence of un-flat terrains (depressions, trenches, …) may lead to local hazardous confinements and CO_2 concentrations.

Furthermore the proposed methodology for risk assessment may be useful for risk management during the planning and building stages of a new pipeline. In very critical conditions the modification of a buried pipeline could also be suggested.

Some final remarks concerning the uncertainties in the modeling of carbon dioxide releases must be taken into account.

As pointed out in section 1, the estimation of consequences has many gaps. Generally, a release of dense or supercritical CO_2 from pipelines will be in the form of a spray with production of a mix of solid, liquid and gas phases. Solid phase formation may be considerable and may result in the deposit of a dry ice bank (Martynov et al., 2013). This phenomenon has not been considered in this study, but is likely not negligible. Near a release point the dry ice could cause effects on the pipeline with the formation of cracks in the surface of pipeline due to the low temperature, and effects on the vapors cloud caused by the sublimation of the dry ice block have an asphyxiant effect. The sublimation of dry ice will produce a delayed release of gaseous CO_2 that should be taken in to account when evaluating consequences. Dry ice may well not increase the consequences of vapor cloud dispersion in the long run but locally it may cause problems especially during rescue operations and in the pipeline recovery (Mocellin et al., 2015). The modeling of this phenomenon needs to be studied in more detail.

Neglecting for the time being dry ice formation, an analysis of consequences was carried out for a full CO_2 pipeline network proposed in a previous study, focusing on the evaluation of potential impact areas and population exposure in an area of high population density. The study indicates that in such cases a significant number of people could be exposed to serious effects. It also shows that a quantitative risk analysis may be very useful, if used at an early stage in the selection of pipeline routes and design, to explore alternatives which could significantly mitigate risks to population.

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