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Risk Assessment of CO_2 Pipeline Network for CCS – A UK Case Study

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1. Introduction

Carbon Capture and Storage (CCS) requires new processes for the capture of CO_2 using a variety of existing technologies and also potentially new processes which are still under development. Transport of CO_2 in bulk, by pipeline from point sources or ship is also new processes and then can produce emerging risks. The majority of existing CO_2 pipeline in the USA and Canada are located along with substantial in-field pipe work for Enhanced Oil Recovery (EOR) projects (Kelliher et al, 2008; Kadnar, 2008). The USA experience cannot be easily applied to other regions or situations, in particular in Europe, because the CO_2 pipelines in USA are located in areas with low population density. In fact, as stated in the report of the IPCC on CCS (IPCC, 2005), there is a lack of knowledge of safety concerning the pipeline transmission of CO_2 in densely populated areas. External safety is one key aspect that should be assessed prior and during the operational phases of CO_2 transport. Before starting the design a network, it is necessary select and identified the route corridor of the pipeline. For the transportation systems of oil and gas, the pipeline route corridors are selected on the basis of the following factors:

- Areas of environmental concern
- Area whit high population density
- Safety and Risk analysis
- Type of terrain and condition of soil/rock.
- Accessibility to the pipeline for construction area
- Availability of utilities and operating conditions
- Land use and agricultural activities
- Security.

As shown by Koornneef et al., (2009;2010), a QRA of CO_2 pipeline presents a problem of uncertainties in input parameter, because cumulative experience is limited. In particular knowledge gaps exist with regard to failure frequency and dispersion modelling and simulation of consequences. In particular the main problem is define the dispersion model and calculate the consequences. Releases depend on the conditions of transport; we can have three types of release: liquid, gas and supercritical state. For the dispersion of CO_2, the method used is the dispersion of heavy gas. In the literature there are several methods that can be used as:

- TNO method – software EFFECT (Yellow Book, 2005)
- DEGASIS+ (Kruse, Tekiela 1996)
- Universal Dispersion Model (UDM) in the DNV PHAST Software.

The figure 1 summarizes the consequences of a release of CO_2, highlighting models that can be used to calculate the consequences (Koornneef et al. 2009).

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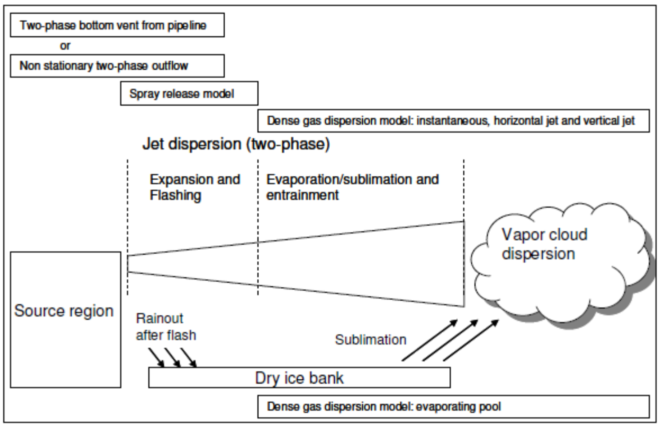

Figure 1: The methodological approach used for a puncture and full rupture of a CO_2 pipeline.

Recently, Vianello et al. 2012, have reviewed the current state of the art in the analysis of risk for CO_2 transport by pipeline. A brief review is presented of current models for CO_2 release, the assessment of impact from such release, and overall risk analysis. n the calculation of the dispersion considered the formation of dry ice should be and then the sublimation that changes the model of heavy gas cloud dispersion. This phenomenon is under study (Mazzoldi, Hill & Colls, 2008; Hulsbosh-Dam et al. 2012), but at the moment there is no model for the calculation of this phenomena. In this paper the calculation of the consequences was carried out with the software PHAST, which considers the release by piping CO_2 under supercritical conditions, as described in the section 4. The following sections describe the hypothetical CO_2 network and the analysis on the calculation of the consequences of a release.

2. Route selection and pipe design

In UK a CO_2 pipeline network has been proposed taking in to account the work conducted by Lone et al, (2010), in this paper techno-economics evaluations of a phased approach to rolling out a comprehensive UK CO_2 onshore pipeline network are been analysed.
The methodology adopted in the study considers the development of onshore pipelines connecting the points of CO_2 sources to a limited number of export terminal located on the coast, table 1.

Table 1 Classification of emitters according to emission

	CO_2 Emission Range [t/y]	Type of emitter
Tier - 0	3 Mt and above	Coal & CCGT power stations, Refineries, Steel industry
Tier - 1	1 Mt– 3 Mt	CCGT & Oil power stations, Refineries, Cement factories, CHP
Tier - 2	0.5 Mt– 1 Mt	Cement factories, CCGT power stations, fertilizer, petrochemical complexes

The design and simulation of network was conducted using the software PIPELINESTUDIO®. This software consist in a hydraulic simulation package by Energy Solutions International that solves fluid dynamics problems in simple or complex pipeline networks in steady as well as in transient states for different conditions of pressures, flows and temperatures.
In this study, have been assumed that, wherever feasible, the CO_2 transmission network will follow the existing route corridors of onshore oil and gas pipeline in the country.
The existing UK's network of oil and gas terminals and the nearest offshore oil and gas sedimentary basins with CO_2 storage potential, as suggested by the British Geological Survey.
The selection of CO_2 sources, that have been considered in this study, are all industrial plants and power stations CO_2 emitting sources in UK current and planned to 2015 with CO_2 emission greater than 500,000 t/y. The pipeline design assumptions are set out in Table 2.

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

Parameters	Value
Pressure rating of value & fitting	100 bar nominal operating pressure
Pipeline material	A105 – Carbon steel
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 pressure to export terminals	85 bar
Minimum pipeline diameter	323.9 mm
Maximum pipeline diameter	1,067 mm

Through the simulation with the PIPELINESTUDIO's package, the following design data are calculated:

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

The network layout are shown in Figure 2, Lone et al (2010).

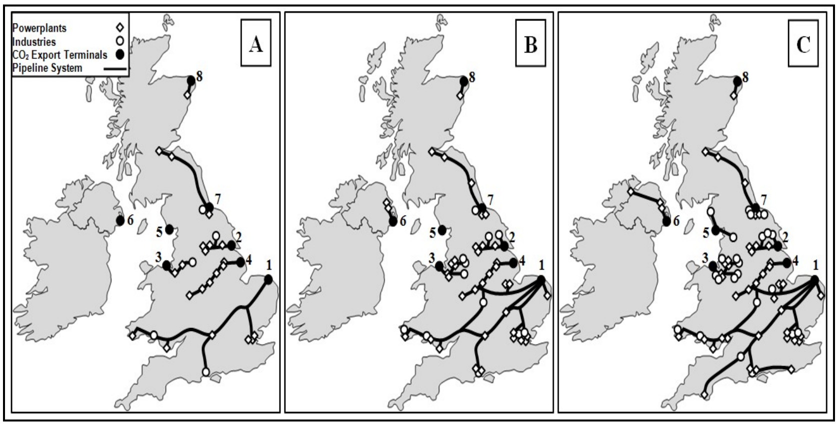

Figure 2: CO_2 transmission network for (A) Tier–0 emitters, (B) Tier–0+1 emitters, (C) Tier –0+1+2 emitters.

The network (C), Tier–0+1+2, has been considered for the analysis of the consequences, as it is the most comprehensive and complex.

3. Safety and risk assessment

Accidents due to a release of CO_2 from pipeline can be described as a spray release and followed by dense gas dispersion.

3.1 Identification of risk

At the moment, CO_2 is not classified as toxic under the Classification, Packaging and Labelling (CPL) Directive (67/548/EEC). But it is demonstrated that high concentrations of CO_2 can cause fatality. In fact, in addition to the hazard of asphyxiation due to release CO_2 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.

CO_2, like nitrogen, can displace oxygen but unlike nitrogen, which does not have a physiological impact on humans, people are exposed at severe threat from the increasing CO_2 concentrations well before of the reduction of the oxygen concentrations. To determine health effects not only the CO2 concentration is important but also the duration of the exposure. CO_2 can cause serious adverse health effects at certain concentration levels and duration of exposure.

An unconsciousness status usually results at 17% CO_2 for an exposure time of 35 s, as a consequence, a level of concentration of 10% CO_2 for 15 minutes was considered to be a conservative estimate for representing unconsciousness leading to death for 50% of the population.

The other value to identify the hazards substance is IDLH (Immediately Dangerous to Life or Health). This value is defined by NIOSH as an exposure to airborne contaminants that is "likely to cause death or

immediate or delayed permanent adverse health effects or prevent escape from such an environment. For the CO_2 this parameter is 40,000 ppm (NIOSH, 2007).
For the study of risk analysis two values are considered that identify the areas of damage:

- Area of strong impact (High lethality) corresponds to the dispersion distance from the release point equivalent to the toxic dose of 110,000 ppm CO_2 for 15 min.
- Area of irreversible damage corresponds to the dispersion distance from the release point equivalent to the toxic dose of corresponds to the dispersion distance from the release point equivalent to the toxic dose of 40,000 ppm (IDLH)

3.2 Failure frequency
For pipelines many studies, simply assume for CO_2 the same failure frequency of natural gas. Natural gas is different from CO_2 and these failure rates may not be valid for CO_2 (Koornneef et al 2010). The NG is transported in pipeline as pressurized gas, while the pipeline proposed for the transport of CO_2 operate in supercritical conditions. Also there are failure rate data for CO_2 supply (Vendrig et al, 2003), based on historical data but these cannot be compared with natural gas because the CO_2 pipeline cumulative experience is limited.

3.3 Dispersion calculation
The PHAST 6.6 version used in the simulation,includes a new model for CO_2 (PHAST Release note for version 6.6). The v6.6 Version 2 UDM accounts for effects of solid formation downstream of the orifice. For the dispersion equations the new model always assumes the equilibrium model without solid deposition ("no rainout"), i.e. snow-out of CO_2 is not modelled. This assumption is justified since for most scenarios snow-out is not expected to occur (or conservative predictions are given if snow-out is ignored). For discharge of supercritical CO_2 from long pipelines v6.6 includes non-ideal compressibility effects as a default option. At very large pressures non-ideal effects are important and may therefore significantly increase the expelled mass.
3.3.1 Long pipeline model
The program contains two models for the time-dependent discharge from a long pipeline: a model for two-phase pipelines, and a model for gas pipelines. The program chooses the appropriate model, depending on the conditions in the pipeline.
For both models, you can specify a release at any location along the pipeline, and you can specify the size of the release (from a small release, 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 not affected by the breach, but remaining at the normal operating flow rate until the upstream section of the pipe has depressurized. The design data are the results of the simulation with PIPELINESTUDIO in study of Lone et al (2010).

4. Consequences calculation
As described above, the estimate of the consequences has been proposed by considering the most comprehensive network that includes industries with emissions greater than 0.5 million of CO_2 per years. To make the simulation was necessary to define the meteorological conditions. In particular the area near Liverpool the temperature is equal to 7.9 °C and the wind speed is 5 m/s. It is assumed that the breaking point is equal to 1/2 the length of the tube, because in this part the release of the substance is higher and therefore the consequences are more severe. The direction of release is horizontal. The estimation of consequences has been carried out for two type of release: from hole with diameter equal to 20 % of section area, from full bore rupture.
The release duration is equal to 300 s, that it is the time of closure of check valves in the network. Table 7 shows the consequences estimate for an area near to the Point of Ayr terminal due to a release from full bore rupture and a release from hole.

Table 7 Consequences of network near Point of Ayr terminal due to release

Name pipe	Diameter	Length	Flow	Distance release dispersion from full bore [m]		Distance release dispersion from hole [m]	
	mm	km	kg/s	LC50	IDLH	LC50	IDLH
Pipe0040	304.80	12.23	11.39	118	263	119	249
Pipe0041	914.40	25.75	626.39	335	711	319	626
Pipe0043	914.40	4.83	483.61	246	529	280	556
Pipe0044	914.40	14.48	416.11	330	700	310	610
Pipe0045	457.20	12.87	230.56	170	371	170	346
Pipe0046	457.20	19.31	63.33	175	380	174	353
Pipe0048	914.40	12.87	130.00	327	694	307	604
Pipe0049	914.40	17.70	115.83	333	706	315	618
Pipe0050	406.40	14.48	64.72	155	339	157	321
Pipe0051	406.40	28.97	38.33	159	348	158	322

Figure 8 highlights that the network passes through a residential area (green zone), because of in this area there is an emitter of CO_2.

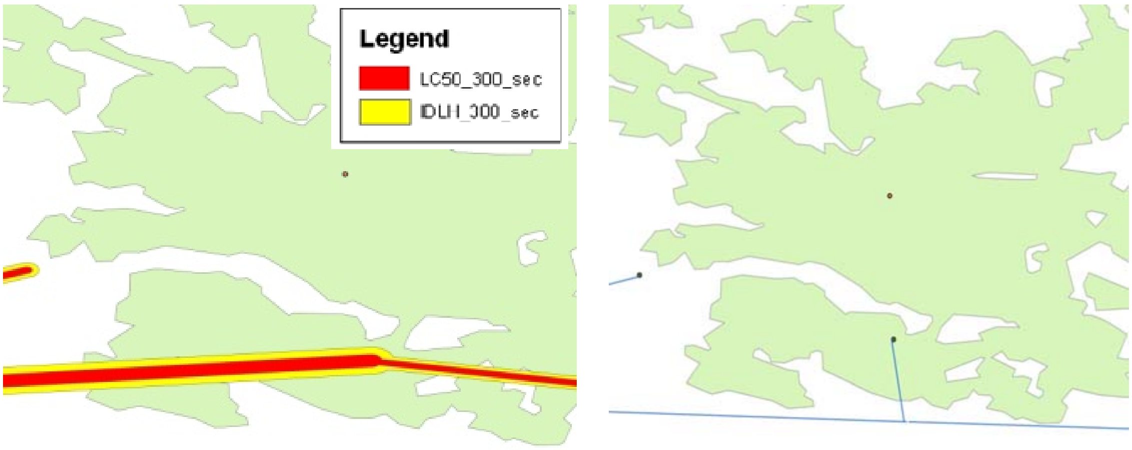

Figure 8 Pipeline network near Manchester city: (a) CO_2 consequences due to full bore rupture near, (b) Redesign network to improvement the safety near center of city.

Considering the consequences produced by a possible release, the CO_2 released could produce serious damage, see Table 9. The population density near Manchester is high equal to 34 persons per hectare (Census 2001). Since the network is still being studied (proposed CO_2 network), it could be, considered from the techno-economic point, the shift of the pipe section outside of residential area, seen Figure 9. Making this change, it is necessary recalculate the consequences to see if this action has brought improvements the safety in the zone in terms of reduction of the societal risk.

The result of moving the network to mitigate the effects is shown in Table 9 (redesign pipe), where it can be noted that the areas of impact is greatly reduced and therefore also the population exposed is less than the previous case.

Table 9 Population expose

	Area [km^2]	Population exposed
pipe0049 e pipe0050	11.5	39,100
Redesigned pipeline	2.7	9,180

Discussion and conclusion

This work shows the results of risk analysis conducted in the proposed network transporting CO_2 deriving by the system of carbon capture and storage.

As pointed out already in section 1, the consequences estimation has gaps. Generally, the release of CO2, considering the transport conditions, can form a spray release with a production of a mixing of solid-liquid-gas phase. The solid phase can be considerable and can produce formation of dry ice. This phenomenon has not been considered in this study, but is not negligible because 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 vapours toxic cloud caused by the sublimation of the block of dry ice.

Considering the results obtained from the analysis of consequences, in proximity of the pipeline network the population can be exposed at serious injuries. Being a network proposal, the actions, that it can take, are to verify from technical and economic point of view, the shift of one or more parts of the network outside the areas with high or medium density population and afterwards it is necessary reconsider the consequences associated with a release to see if the actions had improvements a consequent reduction of the societal risk.

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