A new simplified methodology for Quantitative Risk Assessment of Carbon Capture and Storage Plant

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Abstract: Currently the most quantitative risk assessment performed for Carbon Capture and Storage Project neglected several known consequences, as well as cryogenic effects, visibility issues, focusing only on toxicological characteristics of carbon dioxide.

In this paper, we would like to present as the absolutely not negligible contribution related to cryogenic effects and visibility issues can significantly change the results in terms of risk for personnel, people and assets, proposing a new simplified methodology for performing quantitative risk assessment capable to take into account all the facets of phenomena consequent from carbon dioxide releases (only with the use of PHAST software for consequences evaluation).

In fact, contact of equipment with solid carbon dioxide created during the release when temperature and pressure fallen below the triple point can lead to significant domino effect due to structural embrittlement. Cold burns and visibility issues can increase the risk for people related to carbon dioxide, because the damage distances associated to toxicological effects can be lower than damage distances linked to escape ways impairment and potential personnel injuries.

1. INTRODUCTION

In order to meet key Paris Agreement goal of keeping global warming below two degrees Celsius and therefore of reducing greenhouse gas emissions generated by the most industries [1], the design of Carbon Capture and Storage (CCS) plants is becoming increasingly frequent, since CCS has the potential to remove up to 99% of carbon dioxide emissions also from existing industries.

To carry out the Quantitative Risk Assessment (QRA) of a plant during its design allows to ensure a safe and efficient operation of the plant, once constructed, since the risks for people, personnel, environment and assets are evaluated when additional preventive and/or mitigative risk reduction measures can be adopted easily, if required for keeping residual risk within tolerable range.

Even if the methodology for developing a QRA is well known and can be read in many technical books and Companies standards, the most QRAs performed for CCS plants available on the web take into account only toxicological effects of carbon dioxide, and not the cryogenic effects and visibility issues capable to lead to personnel injuries, domino effects on neighboring assets, and to impair escape ways, as well.

In this paper, after recalling the peculiarities of carbon dioxide, a new simplified methodology for performing Quantitative Risk Assessment capable to take into consideration all the aspects of phenomena resulting from carbon dioxide releases will be proposed and applied to a Case Study, in order to highlight the changes in the results, if the suggested approach versus the common one is adopted.

2. CARBON DIOXIDE PECULIARITIES

Carbon dioxide comprises two oxygen atoms covalently bonded to a single carbon atom, with an O-C-O angle of 180°. As such it is very stable. The triple point of pure carbon dioxide, i.e., the pressure and temperature where three phases (gas, liquid and solid) can exist simultaneously in thermodynamic equilibrium, is at a pressure of 5.11 bar and at temperature of -56.7°C. The sublimination point, that are the conditions at which the gas and solid can co-exist without the presence of liquid as intermediate phase, at 1 atm is -78.5°C.

In the event of an uncontrolled release of carbon dioxide, the escaping fluid will quickly expand: the temperature of the released carbon dioxide gas will fall rapidly due to the pressure drop (Joule-Thompson effect), causing carbon dioxide snow formation. As a result of the low temperature of the carbon dioxide, the surrounding air will be cooled down, which will cause the water vapours in the air to condense locally, like a thick fog, which will continue as long as there is subliming CO_2 snow. Carbon dioxide gas is colourless and has a slightly irritating odour. An escape of carbon dioxide gas, because it is heavier than air, will tend to accumulate in depressions in the ground and in the basements or sumps.

Carbon dioxide has two physiological effects: it acts as an asphyxiant and also has toxicological effects. When the concentration of carbon dioxide in the air is above the partial pressure (around 1.4%), it alters the partial pressure of the CO_2 in the body, so that carbon dioxide is not released from the blood, increasing its acidity. In response to this, the person begins to breathe more frequently and deeply, worsening the situation as the victim takes in more and more carbon dioxide. At carbon dioxide concentrations of 1.5%, humans are likely to suffer symptoms as headaches, tiredness, and increased breathing rate. A further increase of 5% in carbon dioxide concentration can induce visual impairment and loss of consciousness. Above 10% loss of consciousness can occur so rapidly that people are unable to save themselves. Considering an exposure period equal to 5 minutes, SLOT (mortality of 1% of an exposed population), SLOD (mortality of 50% of an exposed population) and concentration to 100% fatalities are equal to concentrations of 8.6%, 11.5% and 16.9%, respectively [2].

Solid Carbon Dioxide can cause cold burns when it comes into contact with eyes or skin.

3. PROPOSED METHODOLOGY

The aim of the Quantitative Risk Assessment will be to assess the risk for assets, personnel and people, following the exposure to accidental scenarios resulting from possible loss of containment events occurring at CCS Plant.

As usual, the main steps of Quantitative Risk Assessment will be the following:

- Identification of potential Loss of Primary Containments (LOPCs);
- Assessment of the Frequencies related to the different loss of containment events;
- Development of the Loss of Containment events into incident scenarios and assessment of the related probabilities (Event Tree Analysis);
- Assessment of the consequences of the accidental scenarios;
- Calculation of the risk for assets, personnel and people;
- Recommendation of risk reduction measures, if needed.

The change of this new methodology in respect of traditional one will be that all the hazardous consequences due to carbon dioxide accidental releases will be taken into account: not only toxic effects will be considered, but also solid formation, high momentum jet impact, cryogenic effects and visibility issues.

3.1. Identification of Potential Loss of Primary Containment

Random rupture analysis will be performed, assuming that loss of containment events capable to affect equipment and piping can be due to different causes, as well as fabrication defects, corrosion, dropped objects, etc.

The following representative hole sizes will be analyzed:

- “Medium release”: 1 inch diameter, representative of the hole sizes lower than 50 mm;
- “Large release”: 4 inches diameter, representative of hole sizes higher than 50 mm.

3.2. Calculation of Leak Frequencies

In order to quantify the frequency of the potential releases, for each release source, for any hole size, Parts Count Technique will be applied based on Process Flow Diagrams (PFDs), Utility Flow Diagrams (UFDs), Heat and Material Balances (H&MBs), preliminary layout and P&IDs.

Areas of the plant will be broken down into sections, according to similar process parameters, to take into account the analogous consequences. The Parts Count will be associated to each Section.

The adopted Leak frequencies database will be, for instance, the IOGP Risk Assessment Data Directory “Process Release Frequencies” [3]. The following association, with respect to the selected representative hole sizes, will be adopted:

- OGP leaks lower than 10 mm and from 10 mm to 50 mm will be associated to “Medium” release category;
- OGP leaks from 50 to 150 mm and greater that 150 mm will be associated to “Large” release category.

The total leak frequency calculated for any section will be then allocated to the release points of the section.

3.3. Calculation of Accidental Scenarios Frequencies

Assets will be assumed damaged due to embrittlement when involved within a high momentum jet giving rise to solid phase deposition on equipment and/or structure. Otherwise, releases will be considered non-hazardous events for assets.

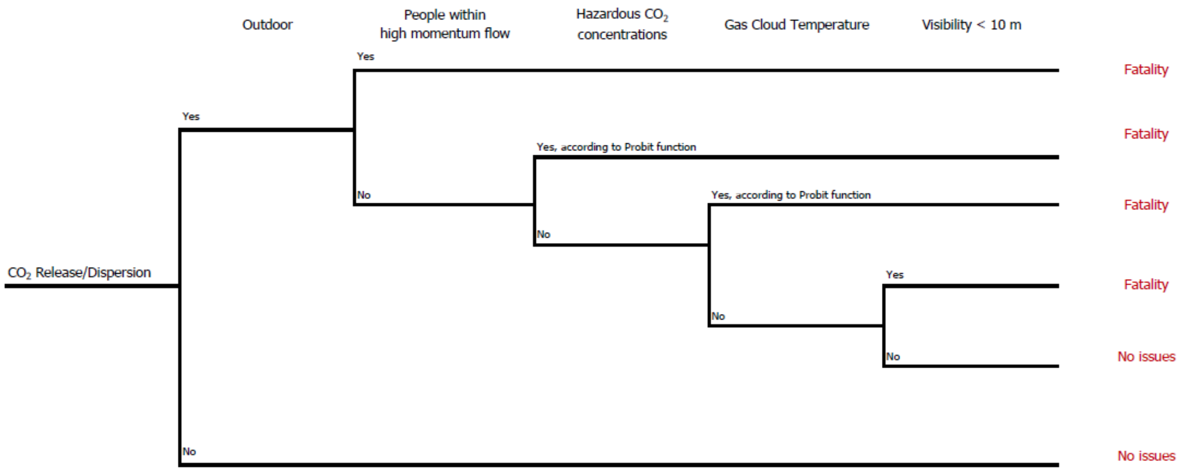
In fact, it is possible for temperature and pressure of the released CO_2 to fall below the triple point, leading to formation of solid CO_2 that can either stay within the CO_2 jet as particles, or it can “snow-out” to form a bank of sublimating solid carbon dioxide.

In order to take into account all phenomena resulting from carbon dioxide releases, the Event Tree shown in Figure 1 has been proposed for assessing risk for people.

Table 1 summarizes the lethality against the concentrations to be determined for each release:

- Lethality associated to toxic doses are based on the CO_2 Probit Function;
- Lethality associated with low temperature exposure has been assumed based on information reported in literature [4];
- It will be assumed that individuals impacted by a high momentum jet will be subject to fatality (equivalent to 100% vulnerability).

Figure 1 – Event Tree for Carbon Dioxide release



The evaluation of risk for people will be performed considering the vulnerability data shown in Table 1.

Table 1: Vulnerability (Probability of Fatality)

Effect	**Toxic Effect**			**Cryogenic Effect**			**Visibility Effect**
Threshold	**169.000 ppm**	**115.000 ppm**	**86.000 ppm**	**- 30 °C**	**- 20 °C**	**- 10 °C**	**0°C**
Vulnerability (%)	100%	50%	1%	100%	50%	1%	10%

3.4. Consequences modeling

For each representative hole size, the consequences of the releases will be modelled by means of DNV PHAST 8.61 software considering the Process parameters (Pressure, Temperature and Fluid Composition) selected according to H&MBs.

Consequences modelling will be evaluated considering the effects at peak conditions (corresponding to the initial time of release), not accounting for detection, isolation and depressurization systems.

The distances from the release sources characterized by high momentum flow will be representative of possible carbon dioxide solid phase formation, if temperature values reached during the expansion to atmospheric conditions are below the sublimation point at 1 atm (-78.5°C).

Equipment located within the high momentum damage distances, characterized by solid CO_2 formation, due to credible accidental scenarios will be subject to further consequences modelling, in order to assess the potential domino effects that may involve the plant. The consequences that will be associated to potential domino effect, if credible, will be calculated considering a resulting large hole size from equipment containing hazardous material.

In order to determine the hazardous scenarios related to the Carbon Dioxide effects to individuals, downwind distances reached by the clouds related to toxic threshold as per Table 1 will be calculated for each release.

3.5. Risk Assessment

Calculated risk will be compared with Client's tolerability criteria. The four risk levels are described hereinafter:

- Low Risk (< 1.00E-06): continuous monitoring to prevent deterioration;
- Medium Risk (As Low as Reasonably Practicable – ALARP - 1.00E-06 ≤ Risk < 1.00E-04): generic control measures are required, provided that is demonstrated that the implementation of such measures is not disproportionate to the benefits;
- Medium-High Risk (ALARP, 1.00E-04 ≤ Risk < 1.00E-03): suitable corrective measures are mandatory, provided that is demonstrated that the implementation of such measures is not disproportionate to the benefits;
- Intolerable Risk (≥ 1.00E-03): risk control measures are required to move the risk to previous regions.

The application of these criteria will provide a first general indication of the acceptability of the risk to plant assets. However, a final decision on the acceptability needs to be conducted in greater details both the extent of the risk areas, and the consequences of the damage to the affected items.

3.6. Risk Reduction Measures

In case the risk levels fall within the ALARP or Intolerable Risk Regions, Risk Reduction Measures will be assessed and proposed on a case by case basis.

Examples of risk reduction measures could be the following:

- assets cold protection,
- relocation outside the ALARP Region,
- self-breathing apparatus to mitigate the Carbon Dioxide toxicologic effects,
- workers clothes capable to withstand cold temperatures.

4. CASE STUDY DESCRIPTION

In this chapter the case study adopted to highlight the different results of new and traditional methodological approaches has been described.

The equipment processing CO_2 in liquid phase of a Carbon Capture and Storage (CCS) plant, including: storage vessel, pumps used to transfer carbon dioxide to the evaporator, evaporator itself and all the others relevant items, as valves and instrumentation, have been analyzed.

The operating conditions utilized for modeling the release of the CO_2 in liquid phase are shown in Table 2.

Table 2: Operating condition

Phase	Item	Temperature [°C]	Pressure [barg]
Liquid	Storage tank (Low pressure)	-26	17
	Pump Discharge (High pressure)	22	60

The releases have been simulated by using the DNV software Phast 8.61. The following data, presented in Table 3, representative of the area where the plant is located, have been considered.

Table 3: Environmental condition

Relative Humidity [%]	Ambient Temperature [°C]	Solar radiation [kW/m^2]
80 %	22.5	0.5

The prevailing wind direction is from Plant East to Plant West. The distribution between the weather conditions 2F and 5D is 30% and 70%, respectively.

The following assumptions have been considered for carrying out the consequence simulations of the Case Study:

- Releases elevation will be set at 1.5 m from the ground level;
- Releases will be directed, along with their frequency distribution, down impinging on the ground;
- The roughness length for the dispersion calculation will be equal to 0.1 m (corresponding to Low crops; occasional large obstacles);
- Effects and damage will be measured at 1.5 m from the ground level and will be reported for any weather condition in terms of reached downwind distances.

5. RESULTS

The results of consequences modelling performed for the Case Study are shown in Table 4.

Table 4: Damage distances

Item	Hole [inch]	Distance related to Toxic Effect [m]			Distance related to Cryogenic Effect [m]			Distance related to Visibility Effect [m]
		169.000 ppm	115.000 ppm	86.000 ppm	- 30 °C	- 20 °C	- 10 °C	0 °C
Storage tank (Low pressure)	1	27	38	45	33	37	44	59
	4	90	135	170	110	128	150	230
Pump Discharge (High pressure)	1	22	33	46	24	32	43	100
	4	77	114	155	84	103	140	240

In all studied cases, it is possible to note that:

- damage distances related to cryogenic effects capable to lead to a vulnerability of 100% are higher than damage distances linked to toxic effects characterized by analogous vulnerability;
- while damage distances related to cryogenic effects capable to lead to a vulnerability below 50% are lower than damage distances linked to toxic effects characterized by similar vulnerability;
- damage distances related to visibility issues overtake damage distances calculated for toxicological effects.

The Figure 2 is showing the LSIR map considering only the toxic effects (as commonly considered in the risk assessment), while the Figure 3 is showing the LSIR contours evaluated considering also the cryogenic effects and the visibility issues.

Figure 2 – LSIR Contour – Toxic Effects

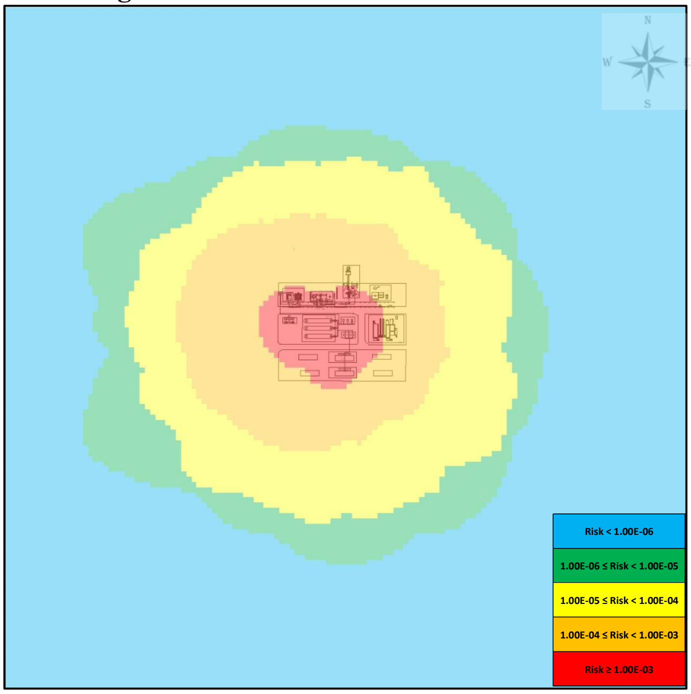
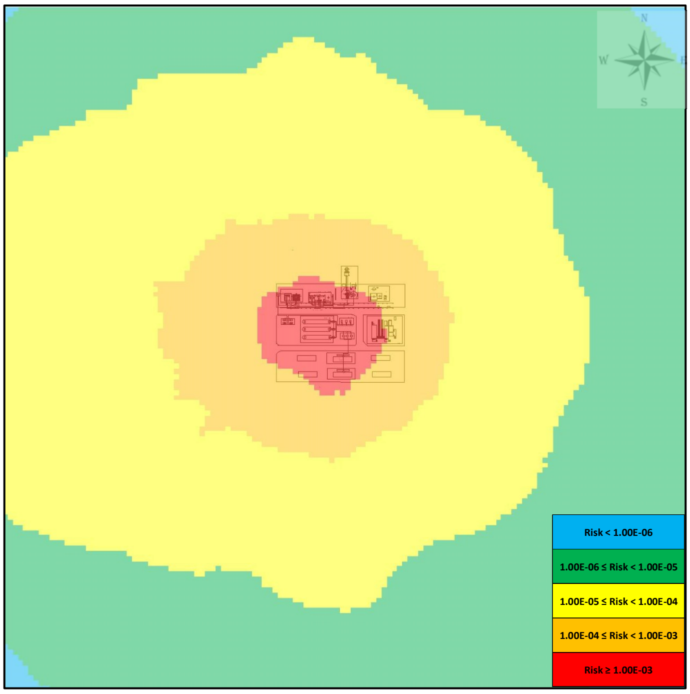


Figure 3 – LSIR Contour – Toxic, Cryogenic and Visibility Effects



Analyzing the obtained LSIR maps, it can be stated that:

- The cryogenic effects increase the risk values in particular in the close proximity of release sources;
- The visibility effects increase the risks mainly far away from release points.

Finally, the IRPA values have been evaluated for both the CCS plant personnel and the external people, considering their different probabilities of presence. The results are shown in **Table 5**, where the contribution of cryogenic and visibility issues can be inferred, having calculated separately the impact of toxicological effects in order to understand the relevance of these new aspects.

Table 5: IRPA value

Worker/ People group	Toxic Effect	Toxic, Cryogenic and visibility Effects	Incremental Risk due to Cryogenic and Visibility Effects (%)
Plant personnel	3.23E-04	3.63E-04	12
External People	3.40E-05	5.25E-05	55

The cryogenic effects and visibility issues seems to be apparently not negligible when a quantitative risk assessment for carbon dioxide is performed.

6. CONCLUSIONS

The most QRAs performed for CCS plants available on the web take into account only toxicological effects of carbon dioxide, and not the cryogenic effects and visibility issues capable to lead to personnel injuries, domino effects on neighboring assets, and to impair escape ways, as well.

In this paper a new simplified methodology (including event trees, Probit functions and threshold values) for performing Quantitative Risk Assessment capable to take into consideration all the aspects of phenomena resulting from carbon dioxide releases has been proposed and applied to a Case Study.

From the results of the application of the new methodology to the case study, it is possible to note that there is a not negligible incremental risk due to cryogenic and visibility effects for both personnel and external people, at least in case of liquid carbon dioxide releases.

Proper investigations should be carried out to set in a more accurate way the vulnerabilities associated to the cryogenic effects and visibility issues, since they can significantly change the results of a Quantitative Risk Assessment of a CCS plant.

References

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[3] IOGP Report 434-01 Rev.3, "*Risk assessment data directory – Process release frequencies*", IOGP, September, 2019.
[4] BCGA TR1 Rev.2, "A Method for estimating the off-site risk from bulk storage of liquefied oxygen", 2018.