**A comparative analysis of software codes for the consequence assessment**

**of CO2 leakage scenarios from onshore facilities and pipelines**

Federica Tamburini\*, Sarah Bonvicini, Valerio Cozzani

*LISES – Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali*

*Alma Mater Studiorum – Università di Bologna, via Terracini n.28, 40131 Bologna, Italy*

*\*Corresponding author E-Mail: federica.tamburini9@unibo.it*

**1.Introduction**

In recent years, the global concentration of CO2 in the atmosphere has increased drastically. At present, the continuous rise in atmospheric CO2 levels is driving climate change and temperature shifts on a worldwide scale. Carbon dioxide Capture and Storage (CCS) technologies have been suggested as a viable option for reducing CO2 emissions. CCS involves mainly three successive steps: capture of CO2 (and possible intermediate storage), transport (usually via pipeline and/or sealine), and permanent geological storage. The safety of CCS infrastructures is of high relevance for the future implementation of this technology. Thus, it is necessary to evaluate the risk caused by accidental CO2 leakage scenarios for humans, for the environment (in particular in case of offshore permanent storage), and for the assets, during all the stages of CCS [1].

Thermodynamically, CO2 behaves differently from the hazardous substances generally considered in the context of the consequence assessment of major accident scenarios. In fact, at atmospheric conditions CO2 is below its triple point, which corresponds to P = 5.2 atm and T = -56.6 °C. This peculiarity implies the formation of a two-phase release of gas containing CO2 solid dry ice particles, as a consequence of the rapid depressurization and phase change the substance undergoes during the release from pressurized equipment into the atmosphere. From a safety point of view, CO2 represents both a mildly toxic and a physical stressor for humans, due to the extremely low temperatures it reaches (-78 °C) after the release. Furthermore, CO2 leakage events might cause damage to assets, because of both the low temperatures and the presence of the abrasive solid particles. In case of an underwater release from a sealine or from a submarine reservoir, CO2 releases have the potential to affect the marine biota, in virtue of the reduction of the seawater pH [2].

In the present study, a benchmarking of the most recent versions of the software codes available for simulating the atmospheric release and the dispersion of CO2 from onshore facilities and pipelines has been carried out, also by their application to some relevant case studies. More specifically, the PHAST software by DNV-GL [3], EFFECTS by Gexcon [4], and OLGA by Schlumberger [5] have been considered. PHAST and EFFECTS are well-known software tools usually adopted for estimating the consequences of major accidents. In fact, they implement source models for characterizing the accidental outflow of hazardous substances from vessels and pipes, as well as dispersion models for simulating the fate of clouds dispersing as plumes or puffs into the atmosphere. Both PHAST and EFFECTS have been adapted to allow their application to the gas-solid outflows of CO2, also taking advantage from the data provided by experimental CO2 leakages [6]. Instead, OLGA is a dynamic multiphase flow simulator capable of modeling the multiphase transportation of oil, gas, and water throughout pipelines. However, it may be adapted to the evaluation of the source term of loss of containment events.

**2. Methods**

In order to compare the OLGA, PHAST and EFFECTS codes, first of all an extensive work has been carried out in order to highlight the input data required by each tool, the assumptions adopted, and the results provided. A specific focus has been devoted to pipeline spills, performing a sensitivity analysis of the features of the CO2 outflow and of the damage distances of the CO2 cloud with respect to the length of the conduit, its diameter, its length, its slope, its inlet pressure, the dimensions of the hole and its position along the pipeline, the depth at which the pipeline is buried and the influence of sectioning by means of the blocking valves. Furthermore, the influence of dry ice on the dispersion has been considered. As a second task, the three codes have been applied to some case studies. A first set of case studies refers to the loss of containment events reported in [7], which include high-pressure cold and high-pressure supercritical releases from vessels, short pipes, and long pipes. A second set of case studies considers leakage scenarios from onshore pipelines differing for the pipeline diameter and the hole size, selected on the basis of the release characterization provided in [8].

Damage distances have been evaluated for both people and assets. The damage thresholds considered for human toxicity are the IDLH (40,000 ppm) and the LC50hmn,30min (92,000 ppm) limits [9]. For cold burns, both the value of -18 °C [10] and the temperature at which solid CO2 particles are totally sublimated [2] have been considered, since there is no accordance in the technical literature on the value to be adopted for this limit. The highest temperature at which dry ice particles are present has to be used also to determine the risk of erosion on assets [11], while the damage threshold for cold embrittlement has been assumed as equal to -40 °C, being this a typical embrittlement temperature of steels [12].

**3. Results and discussion**

As a result of the case studies, the discharge release rates provided by the EFFECTS and OLGA codes were found to differ from the values obtained with PHAST by -34% ÷ +95%, while the concentration profiles of CO2 in air obtained with EFFECTS differ from the ones provided by PHAST by -76% ÷ +58%. Thus, the values of the mass release rate and the damage distances calculated with respect to people and assets typically differ less than a factor 2. Furthermore, the results of the sensitivity analyses allowed determining a set of baseline assumptions for the consequence assessment of pipelines in order to provide a standard for risk analysis, so that the results obtained for different pipelines are consistent and comparable.

**4. Conclusions**

A detailed benchmarking activity has been carried out on the PHAST, EFFECTS and OLGA software codes applied to the consequences of CO2 spill events. Despite significant differences in the modeling approach of the codes, the differences in the results match the expectations. Thus, all the three software tools seem suitable for the consequence assessment of CO2 leakage events. It has also been demonstrated that, in regard to the cold temperature effects on people, the two damage criteria reported in the technical literature provide different damage distances. In addition, the effects of solid particles and low temperatures on both people and assets usually occur at distances below 20 m, where it is acknowledged that the results provided by integral dispersion models are not accurate. For these reasons, in order to get a better understanding of the consequences of the CO2 leakage events near the source point, the adoption of CFD modeling seems more suitable than the application of integral models. Moreover, further experimental data are necessary to reduce the uncertainty concerning the damage thresholds related to cold temperature effects on people and assets.

**References**

1. B. Metz, O. Davidson, H.C. de Coninck, M. Loos, L.A. Meyer (Eds.), IPCC Special Report on Carbon Dioxide Capture and Storage, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2005, pp. 442.
2. DNV GL, 2020, CO2 RISKMAN - Guidance on CCS CO2 Safety and Environment, Major Accident Hazard Risk Management, Level 3 – Generic Guidance.
3. DNV GL, PHAST [Software version 8.4].
4. Gexcon, EFFECTS [Software version 11.0].
5. Schlumberger, OLGA [Software version 2017.2.0].
6. H.W.M. Witlox, M. Harper, A. Oke, J. Stene, Journ. Loss Prev. Proc. Ind. 30 (1) (2012) 243–255.
7. H.W.M. Witlox, J. Stene, M. Harper, S.H. Nilsen, Energy Procedia 4 (2011) 2253-2260.
8. IOGP, Risk Assessment Data Directory, “Riser & Pipeline Release Frequencies”, Report No. 434-04, 2019.
9. P. Harper, Assessment of the major hazard potential of carbon dioxide, Health and Safety Executive (HSE), 2011.
10. E.K. Ungar and K.J. Stroud, Proc. 40th Int. Conf. Environ. Syst. ICES 2012.
11. S. Connolly and L. Cusco, IChemE SYMPOSIUM SERIES NO. 153 (2007).
12. BS EN 10225:2019, 2019, Weldable structural steels for fixed offshore structures - Technical delivery conditions.