Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 4 (2011) 4193–4198

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

Design of fault trees as a practical method for risk analysis of CCS: application to the different life stages of deep aquifer storage, combining long-term and short-term issues

Régis Farret *, Philippe Gombert, Franz Lahaie, Auxane Cherkaoui, Stéphane Lafortune, Pierre Roux [a]

[a]*INERIS (Institut National de l'Environnement Industriel et des Risques), B.P. 2, 60 550 Verneuil-en-Halatte, France*

Abstract

INERIS (French National Institute for Industrial Environment and Risks) is involved in assessing accidental and chronic risks in industrial or underground activities. Concerning carbon dioxide storage, INERIS performs integrated risk assessment studies, by integrating both its know-how in industrial safety and the knowledge developed in the context of other underground storages: hydrocarbons, landfill, nuclear waste.

Concerning the future development of the CCS technology, a major question is the underground evolution of the CO_2 at medium and long time scales. It is necessary to undertake a systemic approach in order to consider all targets at stake and all stages of the CCS chain. INERIS developed a specific method that includes the tools that are used in environmental, health and safety risks. At first, a risk analysis was performed, leading to identify the relevant risk scenarios. There we took into account the possible high content of impurities, and therefore the different exposure routes for man and for the soil/water environment. 8 main "Impacting phenomena" were defined, they cover the whole CCS chain (capture, transport, injection and long-term storage) and include both accidental and long-term effects.

Each Impacting phenomenon gets a series of causes, that were represented in fault trees and were described in a dynamic graph through an adequate software tool. In a second step, the risk scenarios are to be quantified in terms of transfer and effects to the environment, and the estimated flows are to be compared to critical flows. This overall method consists of an integrated risk assessment, and helps in managing the risk for all life stages and all elements of the CCS chain, either at surface level or in the underground.

Keywords: risk analysis, fault tree, CO_2, impurities, critical flow, integrated method.

* Corresponding author. Tel.: +33 3 44 55 61 27 ; fax: +33 3 44 55 67 00
E-mail address: regis.farret@ineris.fr

doi:10.1016/j.egypro.2011.02.366

1. Introduction

The CCS still needs to demonstrate its feasibility at reasonable cost, but also has to demonstrate its harmlessness, in other terms we have to demonstrate that we know its risks and that we are able to manage them, regarding both environment and human health & safety. This paper grasps this issue by drawing a generic frame for risk assessment of CCS and showing a graphic tool that represents the risk scenarios in a "risk model", before quantifying their impact with a physical model. This framework is based on the present knowledge in underground sciences – including the study of other underground storages such as hydrocarbons and nuclear waste– but also on the experience gained by INERIS in industrial safety (i.e. application of the Seveso Directive) as well as in risk assessment for toxic substances in the environment. The study contributes to designing a risk assessment method this is suitable for the whole CCS risks, both in the shorter and in the longer term, and for surface and underground features.

2. The 4 main elements of the system to be studied

The whole CCS technology can be seen as a chain composed of 4 main elements [9]:
Capture stage, including several process steps and the final compression. Hence the capture system will consist of several sub-systems that are mainly industrial processes.

Transport : the CO_2 is compressed or condensed to be transported by a pipe to a storage area where it will be injected. In case of pipe transport, gates or valves, intermediate storages and re-compression stages may be necessary to operate the pipe or to ensure its safety.

Injection : The injection step is crucial and the CO_2 injectivity study is of utmost importance since it combines the injection well and its main pipe, with its specific technology (casing, tubing with several stages, etc.) and the well foot within the reservoir. It is important to notice that along the well a specific zone within the rock (excavation damaged zone EDZ) will appear during the drilling of the well, and may play a key role in future leakage paths.

Storage : The main issue here is to consider the long-term evolution of the storage, which is essential both to assess the feasibility and to assess the risks. A series of complex processes have to be considered within the storage, especially in the longer term, which raises the issue of the related uncertainty.
It is essential to mention here that these processes are likely to concern other layers over the storage itself: the caprock that has to remain impermeable, the overburden, the EDZ (excavation disturbed zone) around the well, the neighbouring faults or ancient wells (etc.). In our risk method, all these elements are included and each event that will be defined will also be given a relation with the relevant system or sub-system.

Besides, a very specific property of CCS is that very **different time periods have to be considered** [7]. Firstly, the exploitation phase that will last for approximately 50 years -including conception, construction and CO_2 injection. Secondly, a memory phase, for about 200 years after the completion of injection wells, where mankind will keep the memory of the storage ; this phase will include the monitoring of the site, but this monitoring will not necessarily cover the whole phase. And finally a long-term phase, that should cover at least one millenary in order to ensure the efficiency of the CCS; during this phase the existence of the storage is forgotten, hence specific events may occur.

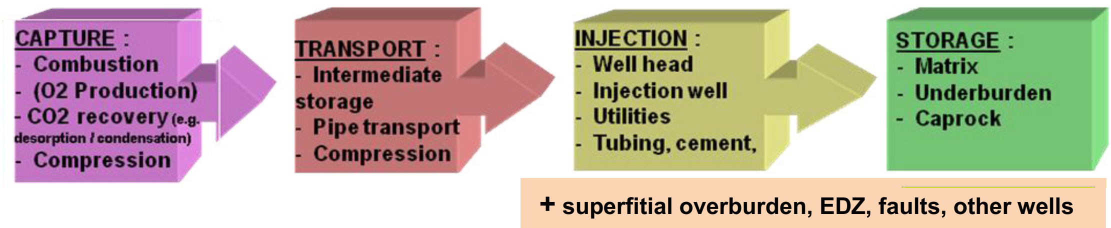

Fig.1 : Simplified scheme of the CCS chain and its 4 main elements

Our risk assessment framework includes this **time dimension**, since the risk scenarios include the events that are likely to occur on each element of the system, during each period that is relevant. Besides, the final calculation of the probability of the events takes into account their duration and the relevant time period [9]. This will allow a final representation of risk scenarios that improves the usual 2-dimentional risk matrix –which combines i) the Severity of effects and ii) the Probability of Occurrence – by including the time dimension.[7]

3. A specific frame for Risk Analysis

A **risk scenario** is a chain of events that begins with a specific hazard –e.g. a toxic substance– that is emitted into the environment, and ends with the exposure of a stake at risk – e.g. affect on an ecosystem after migration of the substance within the environment. The principle is similar for an accidental scenario such as an explosion that causes a human injury after transmission of an overpressure in the air [6] [13]. Risk Analysis first consists of identifying all relevant and plausible scenarios, in order to give a full image of the risk inherent to a CCS system.[15]

The experience of INERIS in risk analysis on both industrial systems and underground sciences shows that all methods used for risk analysis or risk assessment are based on set of events and scenarios, either formalized (e.g in a specific guidance or in a FEPs database : Features, Events , Processes) [18] or not (e.g in the mind of the experts). In the literature, some methods entail a very specific type of analysis and may lose the overview of the whole CCS chain, e.g. being bond to a detailed modeling on the reservoir.

The approach we develop here is close to systematic approaches such as the "What-If" or the PRA method (Preliminary Risk Analysis) -that were already used for small parts of the CCS chain- but the main advantage is that it is **completed by an event-tree analysis method,** with a chart that illustrates the cause-consequence relationships. The final collection of risk scenarios defines the « **risk model** » of the system under study.

In order to carry out this exhaustive approach and to derive adequate relationships between events, we considered 3 major inputs: the scientific literature, the learning from experience (accidents and incidents) and a series of interactive workshops (brainstorming) within an expert group that gathers experience in different scientific or technical fields –the objective is to continue this exercise with other experts and actors, such as industrialists, researchers, and NGOs if possible.

We have defined several specific classification of systems and events, and especially a series of **8 "impacting phenomena"** (IP) [7], e.g. explosion or fire, massive or diffuse emanation at the surface level, groundwater pollution, mechanical effects at the surface level. Each IP is the final event of the risk scenario, with a direct effect on one of the targets at stake (ecosystem, humans, economical activity). These IP are based on a thorough review of the literature and they gather all possible risk scenarios on the whole CCS chain (surface and underground elements). They cover at the same time "altered evolution" of the system - i.e. accidents or events that can only happen if the CO2 does not behave as scheduled - and "normal evolution".

These IP are not related only to the effects of CO_2 itself, but also to other substances, e.g. for the pollution of underground waters and the emanations at the surface level. These substances can have three origins: i) impurities injected with the CO_2 ; ii) native gases that were originally in place in the reservoir (e.g methane) ; iii) other chemical compounds that may be dissolved within the reservoir by the CO_2 or the acidified brine (e.g. heavy metals, actinides) [14] [21].

In order to represent these cause-consequence relationships, INERIS choose the **BowTie** software (under the InOV platform developed together with Interactive), which comprises at the same time i) a database that capitalises the properties of each object (element of the system, or event), ii) a specific graphic interface that helps in defining the events and their cause-consequence relationships, and iii) the possibility to **formally include the MMR** (measures for the management of risks) on the event-trees.

4. Risk scenarios in a graphic event trees : the example of diffuse emanation of CO_2

The figure 4 shows an example of event tree, with all main scenarios leading to a Diffuse Emanation of CO_2 mixture at the surface level (IP #3), in the longer term. The full detail is given only for the events and processes at the beginning of the tree, leading to a migration through the caprock [5] [12] - the migration through the superior overburden, top right of the figure, is continuing. On the right part of the figure we can see the 4 main events or processes that lead to such a migration through the caprock.

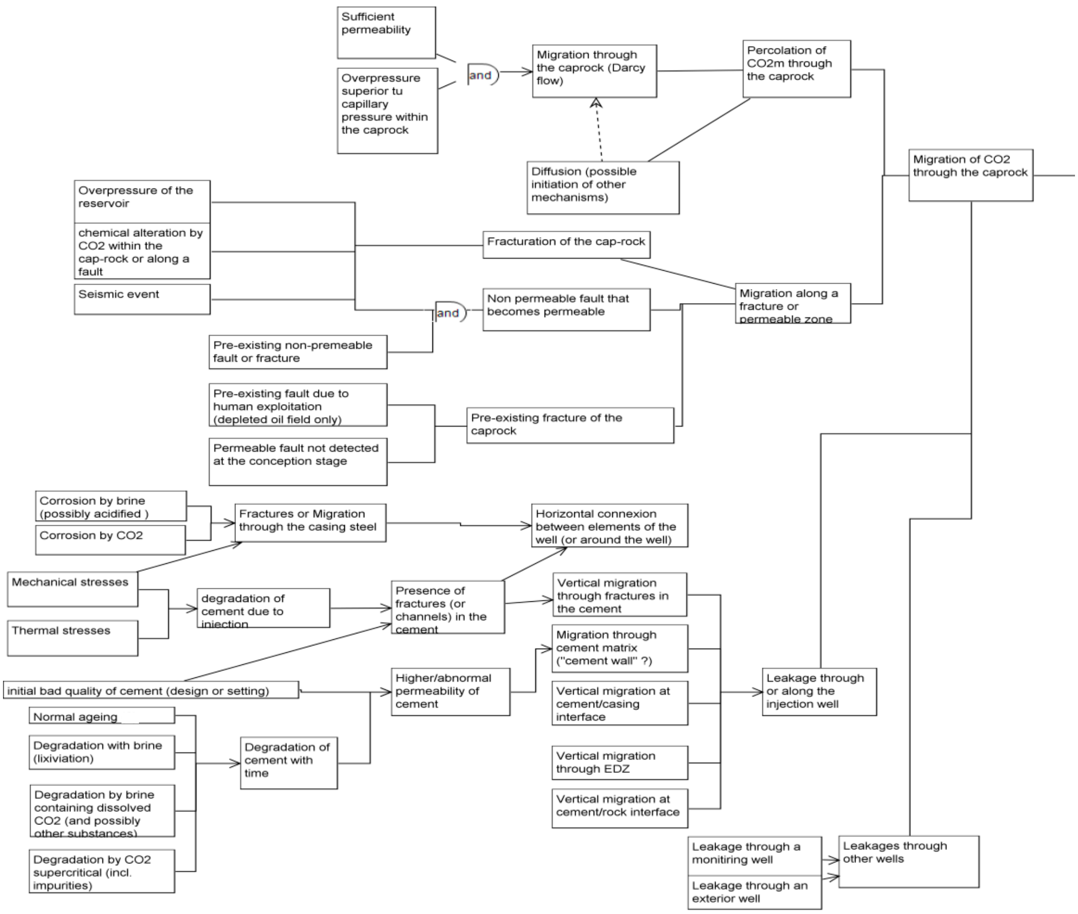

Fig.2. Scenarios leading to a Diffuse Emanation of CO_2 mixture at the surface level (impacting phenomenon #3)

We can detail here the consequence of overpressure due to the injection, which is likely to induce a fracturation of the rock. This effect will most probably be very localised and limited in time since the pressure will be significantly reduced a few decades after the injection stops. We are here in "normal conditions", but they may occur at the interface between the storage and the caprock, hence a migration scenario through the caprock is not impossible [1]. Practically, as shown on the event tree, it is more likely that this overpressure will cause the re-opening of pre-existing fractures, especially if such fractures were present but not detected [11]: see the "And" door in the fault tree.

The lower part of the event tree describes events and processes that may occur at the level of the injection well, gathering both "normal situations" (e.g. degradation of the cement with time, which in turn has several causes : normal ageing, chemical degradation with brine or CO_2...) and "altered situations" such as an initial bad quality of the cement [2] [4]. This part also shows that the possible migration within or along the well may have numerous pathways and especially at the interface between elements of the well: the casing, the cement, the casing-cement interface, the cement-rock interface [3].

Finally this part of the event tree illustrates same possible interactions between processes, e.g. we can identify that cement degradation may be initiated by a mechanical or thermal stress, and that chemical processes in the cement or the steel may induce gas migration. In fact, this shows a second advantage of the software tool, that helps in defining the interaction between processes and events before integrating them into numeric models if necessary. And we should not forget that this graphic tool is connected to a database, where events can be given adequate categories – for example by identifying the categories of mechanical processes, thermal processes, chemical processes, or by distinguishing processes and events that occur in the shorter term vs those that occur only in the longer term (this is not illustrated here in the previous figure, although it is done in the database).

The use of a physical model is of course of great help, for 3 reasons. Firstly, it allows to confirm or infirm a risk scenario. For example Thoraval et al. [20] and Azaroual et al. [1] conclude that in the particular situations they explore, the risk of direct rock fracturation due to normal injection pressure is hardly relevant. Secondly, the quantitative result of the model may be used to estimate the probability of the cause-consequence relationship within this risk scenario – if it is confirmed. And thirdly the model can give a quantitative estimate of the consequence, e.g. the intensity of the CO_2 migration towards the surface or towards an aquifer, like Smyth et al. [19] who estimate that for a specific CO_2 injection site in Texas, there is no trend of degradation of water quality, according to drinking water standards and comparing to neighbouring areas. However we may mention that this estimation does not take into account the fate of impurities or annex substances.

This quantitative estimation led by INERIS will be detailed in a future paper. It can be noted already that the extensive use of a model allows a parametric study, by exploring in a quantitative way a wide range of possible cases – as stated by Nordbotten et al. [17] for a contamination of aquifers, or Meyer et al. [16] for a CO_2 leakage at the surface level along an injection well. Apart from the final representation of all scenarios in a matrix as described earlier, our objective is that for a given risk scenario the quantitative estimate of CO_2 flow -or flow of impurity- is compared to a “critical flow”: this critical flow is the maximum flow that is supposed to cause no effect on the stakes at risk (human health, ecosystem), and it is calculated separately with its proper uncertainty estimation.

5. Conclusion

Abnormal (or altered) evolution scenarios are possible, such as emanation at the surface level, contamination of underground water resources or major pipeline leakages. Even in a normal evolution, the CO2 storage will have an impact on its reservoir and it surroundings, and some specific processes will occur - such as corrosion, slow migration of CO2, dissolution of trace elements in the rock- entailing possible impacts. This paper shows the interest of performing a risk analysis and visualising such scenarios in an adequate graphic “risk model”, with the causalities between events and processes, considered as objects but being handled easily with a graphic fault tree. Such a tree is presented here in a very generic way, but it was developed in order to be applied for specific contexts or case studies. The paper also presents a complete classification of all “impacting phenomena” that are likely to concern any element of the CCS chain, at surface or underground levels, either in the short term or in the longer term. The specific challenge, both from a technical point of view and in a social perspective, is that we have to consider complex processes in the longer term, which brings a specific uncertainty due to our lack of knowledge. This advocates for the use both “risk models” and “physical models”.

References

[1] Azaroual M., André L., Blaisonneau, Sbai A., Lombard J. M., Egermann P. (2007) « Etude des scénarios d’injection de CO2 dans l’aquifère salin du Dogger du Bassin de Paris : établissement de la relation Q-P-T-t », Séminaire « Captage et stockage du CO2 », 12-13 déc. 2007, Pau.

[2] Barlet-Gouédard V., Ayache B., Rimmelé G. (2008) : « Cementitious material behavior under CO2 environment. A laboratory comparison", IEA Greenhouse Gas R&D Programme, 4th wellbore integrity workshop, report n°2008/06, august 2008 : 182-200.

[3] Celia M.A., S. Bachu, Nordbotten J.M., Gasda S.E., Dahle H.K. (2004) : « Quantitative estimation of CO2 leakage from geological storage: analytical models, numerical models and data needs », In Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Volume 1: Peer-Reviewed Papers and Plenary Presentations (E.S. Rubin, D.W. Keith and C.F. Gilboy, ed.), IEA Greenhouse Gas Programme, Cheltenham, UK.

[4] Cotiche C., Herbrich B., Boutayeb M. (2007) : « Étude des puits pétroliers exploitant le gisement de SMB en vue de la réalisation d'un pilote d'injection de CO2 ». contribution au rapport final du programme PICOREF, Projet RTPG RE.4001/05 (PICOREF, 2007).

[5] Damen K., van Troost M., Faaij A., Turkenburg W. (2006)- A comparison of electricity and hydrogen production systems with CO2 capture ans storage. Part A : Review and selection of promising conversion and capture technologies. Progress in Energy and Combustion Science 32 (2006) : 215-246.

[6] Farret R. (2009) : Harmonisation des analyses de risques - Concepts et échelles unifiés pour les différentes réglementations, le risque chronique et le risque accidentel, EAT- DRA-71, rapport INERIS-DRA-09-95321

[7] Farret R., Gombert P., Salmon R., Toulhoat P.(2009), Definition and application of a method for risk analysis of CCS combining CO2 and impurities, long-term and short-term issues. Sustainable Fossil Fuel for Future Energy, Rome , 6-9 July 2009

[8] GIEC (2005) : « Piégeage et stockage du dioxyde de carbone. Résumé à l'intention des décideurs et résumé technique », Rapport spécial du GIEC, 66 p.

[9] Gombert P., Farret R., Lahaie F. (2009). - Adaptation des outils d'analyse de risques aux futurs complexes de stockage géologique de CO2. - Tunnels et Ouvrages Souterrains, 2009, n° 213, pp. 142-154.

[10] Gombert P., Farret R. (2009). Definition of a risk analysis method combining long-term and short-term issues. CO2NET Annual Seminar 2009, Trondheim (N), 18-19 june 2009. [Poster].

[11] Iding M., Ringrose P. (2008). Evaluating the impact of fractures on the long-term performance of the In Salah CO2 storage site. Energy Procedia 00/2008, 8 p.

[12] IPCC (2005). IPCC Special Report on Carbon Dioxide Captage and Storage, Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: 442 p.

[13] ISO/CEI Guide 73 (2002) : Management du risque – Vocabulaire – Principes directeurs pour l'utilisation dans les normes.

[14] Kharaka Y. K.,Thordsen J.J., Hovorka S.D., Nance H.S., Cole D.,R., Phelps T.J., Knauss K.G. (2009). Potential environmental issues of CO2-storage in deep saline aquifers : geochemical results from the Frio-I brine pilot test, Texas, USA. App. Geochemistry 24 (6), 1106-1112.

[15] Kirchsteiger C. (1999) : On the use of probabilistic and deterministic methods in risk analysis, Journal of Loss Prevention in the Process Industries 12, pp 399-419.

[16] Meyer V., Hanssen T.H., Akemu O., Poupard O. (2009). A risk-based approach for well integrity management within a CO2 geological storage project : application to an abandoned well. TCCS-5, Trondheim, 16-17 June 2009.

[17] Nordbotten J., Vetski D., Celia M ., Bachu S. (2008) : Model for CO2 Leakage Including Multiple Geological Layers and Multiple Leaky Wells, Environmental Science & Technology, 43 (3), 743-749, Dec. 2008

[18] Savage, D., Maul, P.R., Benbow, S., Walke, R.C. (2004). A generic FEP database for the assessment of long-term performance and safety of the geological storage of CO2. Quintessa Report QRS-1060A-1.

[19] Smyth R., Hovorka S., Lu J., Romanak K., Partin J., Wong C., Yang C. (2009) : Assessing risk to fresh water resources from long term CO2 injection – laboratory and field studies, Gulf Coast Carbon Center (GCCC) Digital Publication Series #08-03j

[20] Thoraval A. (2006). Impact mécanique d'un stockage de CO2 dans un aquifère du bassin parisien - Contribution au programme ANR GEOCARBONE PICOREF. Rapport INERIS référencé INERIS-DRS-08 71084-04295A.

[21] Toulhoat P., Gombert P., Farret R., Thoraval A., Senfaute G. (2009): "Long-term safety issues in geological storage of CO2", Deep Saline Aquifers for Geological Storage of CO2 and Energy, 27-29 May 2009, Rueil-Malmaison (France).